Local Buckling of Steel Pipelines with Multiple Internal Corrosion Defects

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by

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Abstract

Initiation of local buckling in buried pipeline subjected to compressive deformation can be considered as a limit state for pipeline failure. A finite element analysis parametric study has been carried out to investigate the critical buckling response of line pipe subjected to combined loading with single and two corrosion defects of equal and unequal depth. Effects of material properties, D/t ratio, internal pressure ratio, axial load ratio, defect axial length ratio, defect hoop length ratio and defect depth ratio on the pipe local buckling response have been evaluated. The defect depth ratio and defect hoop length ratio appear to be the most influential parameters on the critical buckling limit ratios (corroded to plain pipe ratio). Non-dimensional equations for critical local moment, critical compressive strain and critical local curvature ratios have been developed from the parametric study results through multi-variable non-linear regression analyses. A good agreement has been achieved between the predicted results through the developed equations and FEA critical buckling limit ratios. A better agreement has been achieved for the critical local moment ratio compared to both critical compressive strain and critical local curvature ratios.

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List of Symbols and Abbreviations

a	-	defect axial length
A	-	local area of metal loss in the longitudinal plane
A_o	-	local original metal area
A_r	-	circumferential area reduction factor
bb_a	-	critical buckling limits for single corrosion defect with axial length of a
bb_{2a}	-	critical buckling limits for single corrosion defect with axial length of $2a$
bb_{G-g}	-	critical buckling limits for two corrosion defects with a clear spacing of gap g
bc_0	-	critical buckling limits for two corrosion defects of unequal depth and zero spacing (contiguous defects)
bc_{G-g}	-	critical buckling limits for two corrosion defects of unequal depth at a clear spacing of gap g
CO_2	-	carbon dioxide
d	-	defect depth
d_e	-	equivalent defect depth
d_p	-	depth of the primary corrosion defect
d_s	-	depth of the secondary corrosion defect
D	-	diameter of the pipe
E	-	modulus of elasticity
f_u	-	tensile strength

F	-	axial force
FEA	-	finite element analysis
F_x	-	external applied longitudinal force
F_y	-	effective specified yield strength
g	-	gap between two defects along axial direction
h	-	defect hoop length
H_2S	-	hydrogen sulphide
imp	-	pipe imperfection
J	-	joint factor
l_a	-	axial length of the corrosion defect
l_{ac}	-	axial length of the corrosion defect
l_{acp}	-	axial length of the primary corrosion defect
l_{acs}	-	axial length of the secondary corrosion defect
l_c	-	circumferential length of the corrosion defect
l_h	-	hoop length of the corrosion defect
l_{hc}	-	hoop length of the corrosion defect
l_{hcp}	-	hoop length of the primary corrosion defect
l_{hcs}	-	hoop length of the secondary corrosion defect
l_l	-	longitudinal length of the corrosion defect
L	-	length of the specimen
L_a	-	defect axial length
L_f	-	location factor
M	-	material properties

M_b	-	bulging stress modification factor
M_g	-	global moment
M_l	-	local moment
M_{lc}	-	critical local moment of a corroded pipe
M_{lp}	-	critical local moment of a plain pipe
M_y	-	bending moment
M_g^{crit}	-	critical global moment
M_l^{crit}	-	critical local moment
MFL	-	magnetic flux leakage
MOP	-	maximum operating pressure
p	-	internal pressure
pig	-	pipeline integrity gauge
p_e	-	maximum external pressure
p_i	-	maximum internal pressure
p_y	-	yield pressure
P	-	pressure load ratio
P_r	-	predicted critical buckling limits
P_{corr}	-	pressure resistance
P_F	-	failure pressure
P_{r_m}	-	modified predicted critical buckling limits
Q	-	corrosion length factor
s_l	-	specific length of the pipe
S	-	longitudinal spacing between adjacent defects

SF	-	factor of safety
SMUS	-	specified minimum ultimate strength
SMYS	-	specified minimum yield strength
S_{flow}	-	flow stress
S_F	-	failure stress
t	-	pipe wall thickness
T	-	temperature factor
Z_c	-	subdivided circumferential length of the pipe
Z_l	-	subdivided longitudinal length of the pipe
α	-	coefficient of thermal expansion
γ_m	-	partial safety factor
δ_y	-	lateral distance from extreme compression and tension face
Δ_{cD}	-	change in length of the two points on the extreme compression face
Δ_s	-	deformation of the two points measured over specific length
Δ_{tD}	-	change in length of the two points on the extreme tension face
ϵ_{cf}	-	factored compressive strain in longitudinal or hoop direction
ϵ_e	-	engineering strain
ϵ_{er}	-	relative engineering strain at peak stress
ϵ_{lc}	-	critical compressive strain of a corroded pipe
ϵ_{lp}	-	critical compressive strain of a plain pipe
ϵ_t	-	true strain
ϵ_{tp0}	-	true plastic strain at the end of yield plateau
ϵ_y	-	strain at yield stress

ϵ_c^{crit}	-	compressive strain limit
$\epsilon_{cD}^{\text{crit}}$	-	critical D local compressive strain
θ_x	-	angular change at end of the pipe
ν	-	Poisson's ratio
ξ	-	usage factor for longitudinal stress
σ_a	-	axial stress
σ_e	-	engineering stress
σ_{er}	-	ultimate to yield strength ratio
σ_{ef}	-	ultimate stress
σ_{e0}	-	stress at the end of yield plateau
σ_h	-	hoop stress
σ_p	-	stress at the proportional limit
σ_t	-	true stress
σ_{tf}	-	true stress corresponding to the point at peak engineering stress
σ_{t0}	-	true stress at proportional limit
σ_u	-	ultimate stress
σ_y	-	yield stress
σ_A	-	longitudinal stress due to external axial force
σ_B	-	longitudinal stress due to the external applied bending moment
σ_L	-	nominal longitudinal stress due to external force
Φ_g	-	global curvature
Φ_{lc}	-	critical local curvature of a corroded pipe
Φ_{lp}	-	critical local curvature of a plain pipe

Φ_g^{crit}	-	critical global curvature
$\Phi_{\text{ID}}^{\text{crit}}$	-	critical D local curvature
Φ_{ec}	-	resistance factor for the compressive strain

1 Chapter: Introduction

Natural gases and crude oil are some of the common natural resources used to generate energy in our day to day life. These natural resources are mostly found in remote regions that are away from locations in which they are eventually processed and refined into consumable form of energy. While there are many forms of transportation methods used to move these products to cities and market places, pipelines are the most efficient, economical, and safest way to transfer these natural resources.

Pipelines used in transporting these products are mostly buried underground for safety reason. As these products are moved through differential pressure, parts of a pipeline can be subjected to a high internal pressure. Axial load is also induced due to the temperature difference between pipeline operation and construction in addition to that from the internal pressure. Bending moment can also be generated in the straight pipeline due to differential ground movement. The combined effects of all these loads can result in the failure of a pipeline by either bursting or local buckling (wrinkling).

As most of the oil and gas pipelines are made of steel, the degradation of the pipe due to corrosion is one of the main safety concern of the pipeline operators. Statistics from Alberta Energy Regulator (AER 2013) show that about 50% of the failure in the energy pipeline was due to internal corrosion, while around 60% of the approximate 36 reported gas pipeline ruptures in British Columbia (BCOGC 2010) during the period of 2009 and 2010 were due to internal corrosion. With the loss of metal due to corrosion, bursting and local buckling of the pipe can occur at much lower load than that for an uncorroded pipe. Corrosion in the pipeline mostly occur in colonies. Thus, it may be necessary to take into account the interaction of closely spaced corrosion defects when considering their effects

on bursting and local buckling of the pipeline.

Most of the design standards and specifications have provisions to account for pipeline bursting due to corrosion and the interaction of corrosion defects. These standards and specifications also have provisions to account for the local buckling, but only for pipe without any corrosion defects. A Few studies have also been conducted on local buckling of the pipe with a single corrosion defect. However, there has been no study and design provision on local buckling of the pipeline considering the interaction of multiple corrosion defects. Thus, it would be useful to study and provide guidelines (equations) to predict the local buckling of a pipeline with multiple corrosion defects.

1.1 Objective of the Thesis

The objective of this study is to investigate local buckling and develop non-dimensional equations to predict critical local buckling limits (critical local moment ratio, critical compressive strain ratio and critical local curvature ratio) of a pipe segment with multiple internal corrosion defects, specifically two corrosion defects aligned along the axial direction. Parameters on material properties, loading and corrosion defects such as ultimate to yield strength ratio, axial load, internal pressure, diameter to thickness ratio of the pipe, axial length, hoop length and depth of the defects are considered in developing the non-dimensional equations.

1.2 Research Methodology

This study on pipeline local buckling is carried out using the finite element software ABAQUS (Dassault Systèmes 2013). A finite element model of the actual test has been developed and validated against the test results. This model has been subsequently

modified to be used in the study. A preliminary study has been conducted to study effects of corrosion defect sizes and distributions on the local buckling behavior. Based on results of this study, a finite element analysis parametric study has been carried for a range of material properties, loading and corrosion defect sizes for parameters such as the material ultimate to yield strength ratio, pipe diameter to its thickness ratio, axial load to yield axial load ratio, internal pressure to yield internal pressure ratio, defect axial length to pipe diameter ratio, defect hoop length to pipe diameter ratio and defect depth to pipe thickness ratio. Non-dimensional equations to predict critical local buckling limits have been developed utilizing results of the parametric study through a multi variable non-linear regression analysis. The developed equations are validated against results for selective cases of finite element analyses for different material properties, pipe geometries, loading, and corrosion defect sizes.

1.3 Organization of the Thesis

Chapter 2 provides a literature review of the experimental and numerical studies on local buckling in oil and gas pipelines with and without corrosion defect. Parameters that influence the local buckling behavior are discussed. Provisions to account for pipe rupture due to corrosion defects in the design standards and specifications, and as well as the strain limit for local buckling are reviewed. A brief discussion is also provided on the type, mechanism, detection and mitigation of pipe corrosion.

Chapter 3 discusses the construction of the finite element model of the pipe specimen and the mesh refinement study. The proposed finite element model is validated against results of actual tests. Based on these studies, an optimum mesh configuration has been selected to be used in the study.

Chapter 4 provides discussions on the generation of material properties used in the parametric study and a preliminary study on effects of the corrosion defect size on the local buckling response.

Chapter 5 presents the parameters and their ranges considered in the parametric study. Methods used in populating some of the critical buckling limits, and results of finite element parametric analyses and effects of each parameter on the local buckling response are discussed. Non-dimensional equations to predict critical local buckling limits have also been developed using results of the parametric study and validated with results of finite element analyses for the parametric combinations that are not considered in generating the non-dimensional equations.

Chapter 6 summarize the thesis along with conclusion and recommendations for future work.

Appendices consist of examples outlining procedures for estimating critical buckling limits for pipes with two corrosion defects aligned along the axial direction at a different spacing from that considered in the parametric finite element analyses and for pipes with multiple corrosion defects in the hoop direction that are distributed symmetrically about the plane perpendicular to the bending axis. Material properties used in the parametric study and results of the parametric analyses are also provided in the appendices.

2 Chapter: Literature Review

Effects of internal corrosion on buried pipelines have been the major contributing causes to safety and environmental protection problems in oil and gas industry. The reduction in pipe wall thickness due to corrosion can lead to premature rupturing, bursting and local buckling (wrinkling) of pipelines. There is a good probability for a corroded pipeline to buckle before fracture under a combined loading. While most of the standards and specifications have provisions to account for pipeline bursting due to corrosion, there is no such provision for local buckling. There have been studies conducted to investigate local buckling of plain pipes and pipes with a single area of machined metal loss to stimulate a corrosion defect. As corrosion in pipelines occurs mostly in colonies, treating them as a single patch may not yield an accurate pipeline failure prediction. A number of experimental and finite element analysis studies have been conducted on pipeline bursting considering corrosion defect interaction. However, there has been no study conducted to investigate effects of corrosion defect interaction on the local buckling (wrinkling) in a pipeline. A few of the studies on pipe local buckling and bursting will be discussed in the following sections.

2.1 Corrosion in Oil and Gas Industry

According to Alberta Energy Regulators (AER 2013), around 90% of the pipelines used in oil and gas industry are made up of steel that are prone to corrosion. The two main types of corrosion encountered in oil and gas industry are sweet and sour corrosion. The weak acid gas carbon dioxide (CO_2) dissolves in water to form carbonic acid that is corrosive in nature. Presence of carbonic acid in pipeline leads to pitting, mesa (sharp edged corners

with flat bottom metal loss) and flow induced localized corrosions, which are usually called sweet corrosion. Environments containing hydrogen sulphide (H_2S) and other sulphur compounds are defined as sour system. Sulphur is highly corrosive in nature. Its presence in the flow is the cause of sulphide stress cracking and localized pitting corrosion (Papavinasam 2013).

Incidents in a pipeline can be divided into three categories, which are hit, leak and rupture. It is considered as hit when the pipe is struck with no product loss, while a minor pipe failure with a product loss is referred to as a leak. Pipelines with leaks continue to operate until leaks are detected. A rupture is a major pipe failure where pipeline cannot continue to operate. Statistics released by Alberta Energy Regulator (AER 2013) show that the highest number of incidents in energy pipeline, including multi-phase, crude oil, sour gas and natural gas, are due to internal corrosion. Around 17,605 incidents (hit, leak and rupture) on pipeline corrosion were reported in Alberta from 1990 through 2012. Most of these incidents are due to leakage with less than 7% of the total recorded as rupture in pipeline due to corrosion. In the above mentioned period, around 52% of the failure in the energy pipeline is due to internal corrosion. Until the end of 2010 (BCOGC 2010), the total length of sour and natural gas pipeline in British Columbia was about 30,669 (km). During the period of 2009 and 2010, there were approximately 36 gas pipeline ruptures in British Columbia, of which more than 57% of these ruptures are due to internal corrosion.

2.1.1 Corrosion Types

Internal corrosion on oil and gas pipelines are mostly localized in nature. They are characterized by metal loss at individual areas that have various geometric shapes. Circular shaped corrosions, usually tapered with smooth sides, are described as pits. Bigger

rectangular pits with flat bottomed are referred as mesa corrosion. Localized attack in the form of parallel grooves along the flow direction are known as flow induced localized corrosion.

Pitting and mesa corrosion is usually found on passive metals when the passive ultra-thin film is damaged chemically or mechanically. The formation of these corrosions are dependent on the chemical properties of steel and the substance transferred in the pipe. One of the prominent failure mechanism in the field is due to flow induced corrosion, which is mostly due to clustering of pits and mesa attack on localized area. It starts with the deposition of debris in bottom of the pipe, which damage the oxide protective film on the internal pipe surface. The damaged zone enables water molecules and sulphide compounds in the transported fluid to interact with the unprotected pipe surface to initiate the corrosion. The last stage involves the corrosion propagation along flow (axial) direction and penetration into the pipe wall.

2.1.2 Internal Corrosion Inspection, Measurements, and Mitigation

Pipelines are monitored continuously in order to locate internal defects. Few of the most widely used procedures to classify and measure the internal corrosion in pipelines are explained below

Visual examination is a qualitative method, which is ‘after the fact analyses’ that reports the condition of the pipeline. With the help of visual examination results, surface analyses are carried out to characterize the corrosion morphology. Sophisticated instruments, such as scanning electron microscope and focus-ion beam, are used in surface analyses to obtain the chemical composition.

The mass loss method gives a quantitative time average based result on corrosion. Coupons are inserted inside the pipeline infrastructure and after a period of time, coupons are retrieved and mass loss are calculated. The rate of mass loss is related to the corrosion behavior. Results of the calculated mass loss together with the composition of fluid transmitted can be used to help studying the corrosion behavior inside the pipe.

Non-intrusive and intrusive techniques are adopted to measure the internal corrosion defects. When the sensors are attached to the external surface of the pipeline to measure the corrosion dimension, it is referred as a non-intrusive technique. Intrusive technique is also known as inline inspection method, where the sensors are sent into the infrastructure. Ultrasonic and magnetic flux leakage are commonly used methods in both the techniques.

In the ultrasonic method, high frequency mechanical vibrations are passed across the thickness of the pipe using transducers with piezoelectric crystals. Ultrasonic transducers are calibrated using a material with predefined pipe wall thickness. Transducers can be fixed outside of the pipe to inspect the corrosion growth or they can be sent inside the pipe by use of a pigging device. Pigging device are instruments initially used to remove the debris from the pipe. With the advancement in technology, intelligent pigs have been developed with an in-built corrosion inspection capability. Pig launcher and receiver zones are required when using pigging device to execute cleaning or inspection (Kanaikin et al. 2007).

Magnetic flux leakage (MFL) is the second most commonly used method. MFL works on the basic principle of flux leakage which are passed through the thickness of the pipe. The sensors attached to the instrument used in the magnetic flux leakage will be able to emit

and absorb the magnetic flux wave. This leakage (loss) in flux wave is used for locating corrosion. The dimension of the corrosion is also predicted, but is not as accurate as the ultrasonic method. The resolution of the MFL can be altered to obtain a better result. Also, the flow rate in the pipeline has a considerable effect on accuracy of the defect location (Afzal and Upda, 2002).

Internal corrosion can be effectively mitigated by cleaning the internal surface of the pipeline, and by adding inhibitors and biocides. Cleaning the water and debris on the internal surface of the pipe decreases the probability of corrosion. Pipeline internal surface cleaning is mostly carried out by pipeline integrity gauge (pig). According to Canadian Association of Petroleum Procedures (CAPP 2009), solid deposition is considered to be the most important cause of internal corrosion and the effective method to prevent internal corrosion is by cleaning the internal surface of pipe at a specific interval of time. Corrosion inhibitors and biocides are used extensively to control internal corrosion on pipelines. They are chemical compounds that are added in small concentrations to the fluid transmitted in the pipe to reduce the growth of corrosion. Corrosion inhibitors and biocides are available in both liquid and vapor phase in order to flow with the transmitted fluid. Most of the corrosion inhibitors used in oil and gas industry work either by bonding chemically with the metal surface (chemisorb) or forming a film on the metal surface (Finsgar and Jackson, 2014).

2.2 Corrosion Evaluation Methods

A number of evaluation methods from various standards and specifications have been used to calculate the maximum operating pressure of corroded pipeline. One of them is the

Manual for Determining the Remaining Strength of Corroded Pipelines B31G published by the American Society of Mechanical Engineers (ASME 2012). This standard provides four levels of analyses in accordance with the available data. These levels are defined as follow.

Level 0 evaluation utilizes the table provided in the manual on the allowable length and depth of corrosion for a range of pipeline dimension. The table is designed with a minimum factor of safety of 1.39 and a hoop stress of 0.72 times the specified minimum yield strength (SMYS) at ambient condition.

Level 1 evaluation is performed with the maximum depth (d) and the longitudinal length (l_a) of the corroded area. The maximum operating pressure (MOP) can be calculated as

$$MOP = \frac{P_F}{SF} \quad (2.1)$$

where SF and P_F are the factor of safety and estimated failure pressure respectively. The estimated failure pressure (P_F) can be calculated as

$$P_F = \frac{2S_F t}{D} \quad (2.2)$$

where, S_F is the estimated failure stress level, t is the pipe wall thickness, and D is the specified outside diameter of the pipe.

Two methods can be used to estimate the failure stress level (S_F), which are the original B31G and the modified B31G.

In the original B31G,

$$S_F = S_{\text{flow}} \left[\frac{M \left(1 - \frac{2}{3} \left(\frac{d}{t} \right) \right)}{M - \frac{2}{3} \left(\frac{d}{t} \right)} \right] \quad \text{for } \left(\frac{L_a^2}{Dt} \right) \leq 20 \quad \text{and} \quad (2.3)$$

$$S_F = S_{\text{flow}} \left[1 - \frac{d}{t} \right] \quad \text{for } \left(\frac{L_a^2}{Dt} \right) > 20 \quad (2.4)$$

where S_{flow} is the flow stress and the bulging stress modification factor (M) is given by

$$M = \sqrt{1 + 0.8 \left(\frac{L_a^2}{Dt} \right)} \quad (2.5)$$

where L_a and d are the axial length and depth of metal loss.

For plain carbon steel operating under an operating temperature of 120°C, the flow stress is taken as

$$S_{\text{flow}} = 1.1 \times \text{SMYS} \quad (2.6)$$

in which SMYS is the specified minimum yield strength at ambient condition.

In the modified B31G,

$$S_F = S_{\text{flow}} \left[\frac{M \left(1 - 0.85 \left(\frac{d}{t} \right) \right)}{M - 0.85 \left(\frac{d}{t} \right)} \right], \text{ with} \quad (2.7)$$

$$M = \left(1 + 0.6275 \left(\frac{L_a^2}{Dt} \right) - 0.003375 \left(\frac{L_a^2}{Dt} \right)^2 \right)^{1/2} \quad \text{for } \left(\frac{L_a^2}{Dt} \right) \leq 50 \quad \text{and} \quad (2.8)$$

$$M = 0.032 \left(\frac{L_a^2}{Dt} \right) + 3.3 \quad \text{for } \left(\frac{L_a^2}{Dt} \right) > 50. \quad (2.9)$$

The flow stress is taken as

$$S_{\text{flow}} = \text{SMYS} + 69\text{MPa} \quad \text{for SMYS} \leq 483 \text{ MPa and} \quad (2.10)$$

$$S_{\text{flow}} = \frac{(\text{SMYS} + \text{SMUS})}{2} \quad \text{for SMYS} > 483 \text{ MPa} \quad (2.11)$$

where SMUS is the specified minimum ultimate strength.

Level 2 evaluation is a detailed procedure in which the complete profile of metal loss is needed to be identified and measured. A possible combination of metal loss area (A) is evaluated by iteration with respect to the original metal area (A_o) in order to estimate the critical corroded region. This procedure is referred as Effective Area Method and the failure pressure can be expressed as

$$S_F = S_{\text{flow}} \left[\frac{M \left(1 - \left(\frac{A}{A_o} \right) \right)}{M - \left(\frac{A}{A_o} \right)} \right] \quad (2.12)$$

where S_{flow} and M are the flow stress and bulging stress modification factor respectively.

Level 3 evaluation involves with more detailed procedures using finite element analyses considering all the factors affecting the accuracy of the results including material properties, internal pressure, external loading, geometry and boundary conditions. The strain criterion should be developed in accordance with the fracture resistance characteristics of the material.

Following with ASME B31G, the Canadian Standard of Oil and Gas Pipeline Z662-11 (CSA 2011) has provisions to calculate the Maximum Operating Pressure (MOP) using the failure stress given by Eqs. (2.7) or (2.12) as

$$MOP \leq P_F * (F * L_f * J * T) \quad (2.13)$$

where F , L_f , J and T are the design factor, location factor, joint factor, and temperature factor respectively.

Det Norske Veritas DNV- RP-F101 Recommended practice for Corroded Pipelines (DNV 2015) also provides guidelines on the evaluation of corroded pipelines subjected to internal pressure loading and combined loading (internal pressure and compressive stress loading). For a single corrosion defect as shown in Fig. 2.1 with its longitudinal length greater than the circumferential length and subjected to an internal pressure loading, the pressure resistance (P_{corr}) is calculated as follow,

$$P_{corr} = \gamma_m \frac{2t f_u}{(D-t)} \frac{(1 - \gamma_d (d/t)^*)}{\left(1 - \frac{\gamma_d (d/t)^*}{Q}\right)} \quad (2.14)$$

where γ_m is the partial safety factor for the longitudinal corrosion model prediction, f_u is the tensile strength, D is the pipe diameter and t is its thickness. The length corrosion factor (Q) and $(d/t)^*$ are calculated as

$$Q = \sqrt{1 + 0.31 \left(\frac{l_l}{\sqrt{Dt}} \right)^2} \quad (2.15)$$

$$\left(\frac{d}{t} \right)^* = \left(\frac{d}{t} \right)_{meas} + \varepsilon_d StD \left[\frac{d}{t} \right] \quad (2.16)$$

where l_l is the longitudinal length of the corrosion, ε_d is the factor for defining a fractile value for the corrosion depth, S is the longitudinal spacing between adjacent defects and (d/t) is the defect depth to thickness of the pipe ratio and the subscript *meas* refers to the measured value.

As the burst capacity decreases with the increase in compressive longitudinal stress, different sets of equations are used to predict the corrosion resistance (P_{corr}) for single longitudinal corrosion defect subjected to a combined loading. Two step procedure is used to estimate the pressure resistance of a pipe with single longitudinal corrosion defect subjected to a combined internal pressure and longitudinal compressive loading.

Step 1: The combined nominal longitudinal stress (σ_L) due to external force is initially calculated by summing the longitudinal stress (σ_A) due to the external axial force and the longitudinal stress (σ_B) due to the external applied bending moment based on the nominal wall thickness, which can be expressed as

$$\sigma_L = \sigma_A + \sigma_B, \quad (2.17)$$

$$\sigma_A = \frac{F_x}{\pi(D-t)t}, \text{ and} \quad (2.18)$$

$$\sigma_B = \frac{4M_y}{\pi(D-t)^2 t} \quad (2.19)$$

where D is the diameter and t is the thickness of the pipe, F_x is the external applied longitudinal force and M_y is the bending moment.

Step 2: If the calculated longitudinal stress is compressive, then the pressure resistance ($P_{\text{corr,comp}}$) taking into account of the effect of the compressive longitudinal stress is calculated as

$$p_{\text{corr,comp}} = \gamma_m \frac{2tf_u}{(D-t)} \frac{(1 - \gamma_d (d/t)^*)}{\left(1 - \frac{\gamma_d (d/t)^*}{Q}\right)} H_1, \text{ with} \quad (2.20)$$

$$H_1 = \frac{1 + \frac{\sigma_L}{\xi f_u} \frac{1}{A_r}}{1 - \frac{\gamma_m}{2\xi A_r} \left(\frac{1 - \gamma_d (d/t)^*}{1 - \frac{\gamma_d (d/t)^*}{Q}} \right)} \quad \text{and} \quad A_r = \left(1 - \frac{d}{t} \theta_c \right) \quad (2.21)$$

where ξ is the usage factor for longitudinal stress, A_r is the circumferential area reduction factor and θ_c is the ratio of the circumferential length of the corroded region to the nominal outside circumference of the pipe.

Nevertheless, the failure pressure limits given by the standards ASME B31G (ASME 2012), DNV-RP-F101 (DNV 2015) and CSA Z662-11 (CSA 2011) are for bursting failures. There is no provision in any of these standards and specifications to account for local buckling failure of the pipeline due to corrosion defects.

2.3 Flaw Size Determination and Interaction

According to ASME B31G (ASME 2012), flaw interaction is defined as the interaction of multiple areas of metal loss that are closely spaced along transverse or longitudinal direction. This interaction may lead to lower the failure pressure than that of a single metal loss area. With reference to Fig. 2.2, the following guidelines are suggested.

- When the distance between two flaws is 3 times the wall thickness (3t) along longitudinal or circumferential direction, they are considered as interacting flaws.
- When the distance between two flaws is more than (3t) apart, they are considered as non-interacting flaws, and they can be evaluated as a separate flaw.

Det Norske Veritas DNV- RP-F101 (DNV 2015) also provides guidelines to consider the

interaction of defects subjected to internal pressure and superimposed longitudinal compressive stresses. The length of the pipe is subdivided into Z_l along the longitudinal direction and Z_c along the circumferential direction, with

$$Z_l = 5\sqrt{Dt} \text{ and} \quad (2.22)$$

$$Z_c = 360\sqrt{\frac{t}{D}} \text{ (degree)} \quad (2.23)$$

where D is the diameter of the pipe and t is its thickness.

Any metal losses within the length of Z_l are considered to be interacting along the longitudinal direction and metal losses within $\pm Z_c$ are considered to be interacting along the circumferential direction. The longitudinal and circumferential lengths of the combined interacting defects as shown in Fig. 2.3 are considered to be to the total length including the gap between them. The metal loss with the maximum depth within this interacting region is considered to be the depth of the combined interacting defects. The calculated length and depth are used in Eqs. (2.14) to (2.16) to predict the pressure resistance for combined interacting defects individually. The minimum of all the pressure resistance of the combined interacting defects and single defect will be considered as the pressure resistance of the line pipe. Additional guidelines are also provided to consider a more complex interaction between flaws for internal pressure loading only, which will not be discussed further here.

2.4 Local Buckling of Pipeline

Pipe fracture can be considered as a limit state for a buried pipeline. In case of a pipe with corrosion, depending on its metal loss dimension, material properties and loading

conditions, fracture (rupture) can occur before or after the initiation of local buckling. However, there is no actual buckling initiation (bifurcation) in a corroded pipe since the local deformation occurs from the start of the loading. This deformation continues to increase with the loading until it reaches the peak moment. There is also a stress and deformation concentration at the region of corrosion. For a highly pressurized pipe, the possibility of the initiation of local buckling before rupturing decreases as the corrosion depth increases. With the advances in the corrosion mitigation techniques, the occurrence of drastic metal loss due to chemical reactions has been substantially reduced. When the corroded region in a pressurized pipe is also subjected to axial compression and bending, buckling normally precedes pipe fracture since corrosion does not occur instantaneously. After the initiation of local buckling, additional deformation is localized in the buckling region. Pipelines also experience thermal and pressure loading cycles. These can further accelerate the degradation of the material at the region of local buckling due to low cycle fatigue. Hence, it is reasonable to consider the initiation of local buckling as a limit state for pipeline failure. Since corrosion defects occurs mostly in colonies, it is important to study the effects due to the interaction of multiple corrosion defects on local buckling.

The buckling initiation (failure) point of a pipe can be taken as the point of peak moment on the moment versus deformation curve under a combined loading. This point can be represented by critical moment, critical strain and critical curvature. Although it is not strictly the point of buckling initiation (bifurcation), the point of peak moment for a corroded pipe is still being considered as the buckling initiation point for the purpose of discussion. Numerous tests and studies have been carried out to study the buckling behavior of pipe under a combined loading. Some of these will be discussed below. Various

terms used to represent the point of buckling initiation are also defined to facilitate the discussion.

2.4.1 Buckling of Pipes

When a slender structure is subjected to a compression loading, it may lose its load carrying capacity and buckle. With an increasing external load, buckling will be followed by an uncontrolled collapse of the structure. In a buried pipeline, buckling normally occurs due to an increasing imposed deformation. This results in a reduction in the resistance (bending moment) of the pipe after buckling rather than an uncontrolled collapse. Two common shapes of pipe buckling have been observed in the experiments conducted under combined loading by Mohareb et al. (1994) , DelCol et al. (1998), Dorey et al. (2001) and Chen et al. (2010). These shapes are shown in Fig. 2.4. The diamond shape buckling with the inward-outward deformation of the pipe wall for zero pressure loading and the bulge shape buckling with outwards deformation when there is an internal pressure.

2.4.2 Critical Buckling Moment

In the tests by DelCol et al. (1998), Dorey et al. (2001) and Chen et al. (2010), the bending moment in the pipe specimen was generated by applying monotonically increasing end rotations. The global moment (M_g) can be considered as the average of the applied end moments on both sides of the pipe. When there is an external axial force applied in the structure, an additional moment is induced in the mid-span of the pipe due to the second order effect, as shown in the Fig. 2.5. The location of the local buckling depends on the corrosion or imperfection. For any particular cross section, the local moment taking into

consideration of second order effect, can be expressed as

$$M_l = M_g + (F \cdot \delta_y) \quad (2.24)$$

where F is the applied axial force, δ_y is the average lateral distance from the extreme compression and tension faces of the pipe to the line of axial force application and M_l is the local moment. The peak local moment at the location of buckling is defined as the critical local moment (M_l^{crit}) and the peak global moment is defined as the critical global moment (M_g^{crit}).

2.4.3 Critical Buckling Strain

In the test, the deformation of a plain pipe was found to be generally uniform along the length until the specimen buckled locally. After buckling, additional deformation was localized to the region of buckling. Since the local buckling only involves a short segment of the pipe, the deformation response of a pipeline to the loading can be represented by local strain at the region of buckling. Unlike a plain pipe, there is a larger deformation at the region of corrosion in a corroded pipe compared to the rest of the un-corroded area. Since buckling would be expected to occur at the region of corrosion, it would also be appropriate to use local strain to describe the deformation response up to and after buckling for a corroded pipe. There are many different ways to quantify local strain. One approach is to take the local strain to be the deformation over the distance of two points that are not far apart. The local strain over a specific length (s_1) of the pipe at the location of local buckling can be taken as

$$\epsilon_s = \frac{\Delta_s}{s_1} \quad (2.25)$$

where Δ_s is the deformation of the two points measured over the length of s_1 in a straight line.

Experiments conducted by Mohareb et al. (1994) , DelCol et al. (1998), Dorey et al. (2001) and Chen et al. (2010) have shown that the buckled profile of the pipe generally falls within the length equal to the diameter of the pipe. Following results of these studies, the local strain over a distance of the pipe diameter, the D local compressive and tensile strains are taken as

$$\epsilon_{cD} = \frac{\Delta_{cD}}{D} \quad \text{and} \quad (2.26)$$

$$\epsilon_{tD} = \frac{\Delta_{tD}}{D} \quad (2.27)$$

where Δ_{cD} and Δ_{tD} are the change in length of the two points at a D distance apart on the extreme compression and tension faces of the pipe respectively. The D local compressive strain corresponding to the critical local moment (M_l^{crit}) is referred as critical D local compressive strain (ϵ_{cD}^{crit}).

2.4.4 Critical Buckling Curvature

Another method of describing the deformation is the curvature. From Fig. 2.5, the global curvature (ϕ_g) can be calculated as the average angle of change per unit length over the length of the pipe specimen (L),

$$\phi_g = \frac{\theta_{x1} + \theta_{x2}}{L} \quad (2.28)$$

where θ_{x1} and θ_{x2} are the angular change at both ends of the pipe, respectively.

The D local curvature taken as the average curvature over a length equal to the pipe diameter at the location where the local buckling occurs can be calculated as

$$\phi_{ID} = \frac{\varepsilon_{cD} + \varepsilon_{tD}}{D} \quad (2.29)$$

where D is the diameter of the pipe. The critical D local curvature (ϕ_{ID}^{crit}) is the local curvature corresponding to the critical local moment (M_l^{crit}) and the critical global curvature (ϕ_g^{crit}) is the global curvature corresponding to the critical global moment (M_g^{crit}).

2.5 Influential Parameters on Pipe Buckling

The pipeline buckling response is affected by the pipe material properties, geometries and as well as the loading. Results from experiments have shown that parameters such as diameter to thickness ratio (D/t), internal pressure, axial load, material properties (stress-strain curve) and size of the corrosion defect have significant effects on the buckling behavior.

2.5.1 Diameter to Thickness Ratio (D/t)

One of the influential parameter in pipe buckling response is the pipe diameter to its thickness ratio. Sherman (1976) conducted complete three-point full scale bending test with no axial load or internal pressure to study the flexural behavior of tubes with 6 D/t ratios ranging from 18 to 102. The results from the tests showed that the critical local curvature decreases with the increase in the D/t ratio.

Korol (1979) conducted an experimental study with eleven pipe specimens subjected to only bending. D/t ratios ranging from 29 to 80 has been considered in the study. The critical buckling moments from the tests showed an inverse relationship with the D/t ratio. Mohareb et al. (1994) conducted experiments on plain pipe under a combined internal pressure, axial load and bending moment loading. Seven full-scale tests of 1690 mm long pipe specimens were carried out with the bending moment applied through end rotations. These specimens consisted of grade X52 (52 ksi yield strength) pipe with either D/t ratio of 51 or D/t ratio of 64. It was found that the critical global moment and curvature increases as the D/t ratio decreases.

Zimmerman et al. (1995) performed five full-scale tests with the test setup and boundary conditions similar to Mohareb et al. (1994) on specimens with a D/t ratio of either 41 or 87. Results from the test showed a similar inverse relationship between the D/t ratio with the critical global moment, critical local compressive strain and critical local curvature.

2.5.2 Internal Pressure

Another important parameter affecting the buckling behavior is the internal pressure. Tests conducted by Zimmerman et al. (1995) with pressurized and non-pressurized specimens showed that the critical local compressive strain and critical local curvature to be higher for the pressurized specimens. On the other hand, non-pressurized specimens were found to have a higher critical global moment compared to those that were pressurized. Four plain pipe specimens with the D/t ratio of 92 were tested under the combined loading by DelCol et al. (1998). These specimens were subjected to different levels of internal pressure varying from 0% to 80% of yield pressure (P_y). The yield pressure is the internal pressure required to generate the level of hoop stress that is equal to the yield strength. Results from

the tests were found to be similar that for Zimmerman et al. (1995) where the critical local compressive strain and critical local curvature increases with the internal pressure. Similar results were found from tests conducted by Dorey et al. (2001) on plain pipe and Zimmerman et al. (2004) on spirally welded pipes.

The buckling profile of the pipe were also found to depend mainly on the level of internal pressure. As shown in Fig. 2.4. Tests conducted by Mohareb et al. (1994), Zimmerman et al. (1995), DelCol et al. (1998) and Chen et al. (2010) exhibited the buckling profile with an outward bulging mode shape with the presence of an internal pressure and inward-outward diamond mode shape with no internal pressure.

2.5.3 Axial Load

The axial load has also been found to have effects on the pipe buckling behavior. Tests conducted by Mohareb et al. (1994) showed a decrease in critical global moment and curvature with the increase in compressive net axial load. The specimen tested by Zimmerman et al. (1995) with same internal pressure under tensile net axial load was found to have a higher critical global moment, critical local compressive strain and critical local curvature compared to that for the test with zero net axial load. Dorey et al. (2001) conducted a series of tests on plain and girth-welded pipes with a D/t ratio of 92. Results from the tests with the same level of pressure but varying net axial load showed a decrease in the critical global moment and critical compressive strain with an increase in the compressive net axial load.

2.5.4 Material Properties

Material properties play a vital role in a structure having different load versus deformation

response even when subjected to the same loading. Separate tests were conducted by DelCol et al. (1998) and Dorey et al. (2001) under the same loading condition on specimens of the same material grade. There were significant differences in the critical curvature and critical strain exhibited among these tests but not on the peak global moment. Dorey et al. (2001) found that the material properties such as the material stress-strain curve, yield strength and length of yield plateau, have significant effects on the buckling response of the pipe. The presence of yield plateau was found to lower the moment capacity but elevate the critical strain and curvature.

2.5.5 Corrosion Dimension

In a pipeline, the size (axial length, hoop length and depth) of the corrosion defect can have a significant influence on the buckling behavior. Corrosion can be on the external and internal surface of the pipeline. It can either be on the tension or compression face of the pipe in bending.

Thirteen full-scale tests of corroded pipe under a combined loading were conducted by Stephen et al. (1996). The corroded area in the specimen was machined externally on either compression or tension face of the pipe. Different combinations of corrosion axial length, hoop length and depth were considered in the test. Seven of the specimens failed (reached peak load) under wrinkling before fracture.

Tests conducted by Smith et al. (1998) on four specimens under a combined loading showed results similar to that of Stephen et al. (1996). The critical moment was found to decrease with the increase in the hoop length and/or the depth of the corrosion defect. Chen et al. (2010) conducted ten full-scale test under a combined loading including six with a machined external corrosion defect. The critical local moment, critical compressive strain

and critical local curvature of the corroded specimen were considerably reduced compared to those of the specimens without any corrosion defect.

Dewanbabee et al. (2010) conducted three full-scale test subjected to internal pressure followed by axial deformation. An external corrosion defect with same axial and hoop length (50mm x 50mm) were machined on the steel pipe with the D/t ratio of 34. Two of the specimens were machined with the corrosion depth of 25% and 50% of wall thickness respectively. Results from the tests showed that the load carrying capacity and the critical strain of the pipe decreased with an increase in the corrosion depth. The critical strain of a corroded pipe was found to be significantly lower than that for the plain pipe. Levold et al. (2015) have carried out an experimental study on X70 pipes with the $D/t=26.5$ under a combined loading. Machined defects of $0.5D$ in hoop length with axial length x depth of either $0.5D \times 0.3t$ or $1.0D \times 0.5t$ were considered. Local buckling preceded rupture of the pipe wall in tests with the defect on the compression face of the specimen in bending.

2.5.6 Corrosion Interaction

It can be expected that two or more corrosion defects to exist in close proximity to each other in a pipeline. Thus, the interaction of these corrosion defects may have an effect on the load versus deformation response of the pipe compared to that of a single corrosion defect occurring in isolation. No experimental study has been found to have been carried out to study the buckling behavior of a pipe with multiple corrosion defects. Most experimental studies with multiple corrosion defects focused mainly on their effect on bursting pressure. In the absence of any experimental study on the buckling behavior with multiple corrosion defects, only a brief discussion for a few studies involving the bursting pressure are presented.

Lee et al. (2005) conducted full scale burst tests on a X65 grade pipe with the D/t ratio of 44. Specimens with up to five square pits aligned along the longitudinal direction were tested. Each pit was $0.065D$ in length and width, and 50% in the wall thickness depth with the bottom corners rounded to a radius of 5mm. Three different gap ranges from $0.04D$ to $0.1D$ between each pit along axial direction has been considered. Test result showed that the burst pressure decreased with the increase in the number of pits along the longitudinal direction.

Andrade et al. (2006) conducted seven full-scale tests with rectangular corrosion defects on a X80 pipe with the D/t ratio of 58. Two were control specimens that had no corrosion and a single corrosion defect, while the other five specimens had multiple defects. The length and width of the corrosion defect ranges from 0.07 to 0.1 times the diameter of the pipe, the depth ranges from 0.65 to 0.70 times the thickness of the pipe respectively and with the distance between defects ranges from 1 to 4 times the thickness of the pipe. It was found that having additional corrosion defects along the axial direction greatly affected the bursting pressure, but there was no considerable effect for having any additional corrosion defect along the hoop direction. There was a minimum of 10% drop in the bursting pressure for the pipe with the multiple corrosion defects along the longitudinal direction compared to that with a single corrosion defect.

2.6 Computational Studies on Pipe Buckling

Numerous computational studies have been carried out to study the buckling behavior of pipes. Most of these studies have been conducted using the commercial finite element analysis software ABAQUS (Dassault Systèmes, 2013).

2.6.1 Computational Studies on Plain Pipe

Mohareb et al. (1994) carried out finite element analyses of the pipe under a combined loading using S4RF shell element with an aspect ratio of 1.13 to 1.78. Taking advantage of symmetry perpendicular to the bending axis, only half the pipe was modelled in the analyses. Material properties along the longitudinal direction of the pipe obtained from the tension coupon test were used in the analyses. Results from the analyses were in a reasonable good agreement with those from the tests. A larger difference between results of the test and analyses was found for specimens having a higher internal pressure and a lower D/t ratio. Parametric finite element analysis study was also performed using the validated model to study the behavior of buckling for different loadings and pipe geometries.

Delcol et al (1998) performed numerical simulations using S4R shell element to model their tests. The analyses were carried out with a full pipe model incorporating the measured initial imperfection. The average material properties obtained from tests carried out on the tension coupons taken along both the axial and circumferential directions of the pipe were used in the numerical simulations. Overall, there is a good agreement between test and FEA results.

Similarly, Dorey et al. (2001) carried out the numerical simulations using the S4R shell element to model the whole pipe specimen. Material properties used in the analyses were obtained from tension coupons taken along the longitudinal direction of the pipe. A better agreement between the test and the analytical results was achieved by incorporating the initial imperfections into the model. A finite element analysis parametric study was also carried out to study effects of D/t ratio, internal pressure ratio (p/p_y), material grade and

initial imperfection have on the critical buckling strain of the pipe.

Utilizing the symmetry perpendicular to the bending axis, Tan (2008) modelled half a pipe specimen with S4R shell element. An imperfection was introduced in the model by reducing the pipe wall thickness at the mid length to either 99.95% or 99.9% of its original wall thickness. The model was validated against test results from Mohareb et al. (1994), Delcol et al. (1998) and Chen et al. (2010). A parametric finite element analysis study was carried out using the model to investigate the buckling response of the pipe for different combinations of loading, pipe geometries, and material properties including both with and without yield plateau.

2.6.2 Computational studied on corroded pipes

Smith et al. (1998) constructed a finite element model using S4R shell element to simulate the response of a corroded pipe subjected to a combined loading. Assuming symmetry in a plane perpendicular to the bending axis and about the mid-length of the specimen, only a quarter of a pipe was modeled. Analyses were carried out using material properties of the pipe in the longitudinal and circumferential direction obtained from tension coupon tests and a multi-linear kinetic hardening material model. A good agreement was found between the test and finite element analysis results.

Instead of using multi-linear kinematic hardening, Chen et al. (2010) carried out the finite element analyses of the corroded pipe under a combined loading assuming the material to follow isotropic hardening. Again, S4R shell element was used to model half the pipe specimen assuming symmetry in a plane perpendicular to the axis of bending. Material properties in the longitudinal direction of the pipe obtained from tension coupon test were used in the analyses. Corrosion defect was modelled using shell elements with a reduced

pipe wall thickness. There is a good agreement between results of the test and analyses. Using the validated model, a parametric study with over 150 combinations of pipe geometries, loading and corrosion defect sizes was conducted.

Alenezi (2015) carried out a finite element analysis parametric study to develop non-dimensional equations to predict the buckling limits for line pipes with an internal axial groove corrosion. S4R shell element was used to model half the pipe specimen assuming symmetry in a plane perpendicular to the bending axis. Metal loss due to corrosion was modelled with a reduced pipe wall thickness shell element. The model was validated against test results of Chen et al. (2010) with analyses using isotropic hardening material model adopting the material properties obtained from tests of tension coupons taken along the longitudinal direction of the pipe. Using the validated model, a parametric study was carried out for more than 700 combinations of material properties, loading, circumferential length and depth of corrosion defect. Levold et al. (2015) also conducted finite element analyses using the material properties from tests of tension coupons taken in the longitudinal direction of the pipe. Good agreement was also found between test and FEA results.

However, none of the computational studies found so far has been conducted to predict the buckling behavior of the pipeline with multiple corrosion defects. There were a number of studies conducted on pipeline bursting with multiple corrosion defects, including those by Lee et al. (2005) and Andrade et al. (2006).

2.7 Compressive Strain Limit in the Canadian Standard

Various standards and specifications have provisions to address the local buckling of the linepipe subjected to the combined loading (internal pressure, axial load and bending

moment). In the Canadian Standard of Oil and Gas pipeline Z662-11 (CSA 2011), the factored compressive strain (ϵ_{cf}) in the longitudinal or circumferential direction is limited to

$$\epsilon_{cf} \leq \phi_{ec} \epsilon_c^{crit} \quad (2.30)$$

where ϕ_{ec} is the resistance factor for the compressive strain, which is taken as 0.8. The factored compressive strain (ϵ_{cf}) is dependent on the compressive strain limit (ϵ_c^{crit}) taken as

$$\epsilon_c^{crit} = 0.5 \frac{t}{D} - 0.0025 + 3000 \left(\frac{(p_i - p_e)D}{2tE} \right)^2 \quad \text{for} \quad \frac{(p_i - p_e)D}{2tF_y} < 0.4 \quad \text{or} \quad (2.31)$$

$$\epsilon_c^{crit} = 0.5 \frac{t}{D} - 0.0025 + 3000 \left(\frac{0.4F_y}{E} \right)^2 \quad \text{for} \quad \frac{(p_i - p_e)D}{2tF_y} \geq 0.4 \quad (2.32)$$

where p_i and p_e are the maximum internal and external pressure, E is the modulus of elasticity taken as 207000 MPa and F_y is the effective specified yield strength. However, the compressive strain limit in CSA Z662-11 is not applicable for a pipeline with any corrosion defect since it does not consider effects of metal loss.

2.8 Critical Buckling Strain Equations

Pipe geometries, loading, material properties and corrosion dimensions affect the buckling behavior of a pipeline. A number of equations have been proposed to predict the critical buckling strain of the pipe. However, none has been developed to predict the critical buckling strain considering the interaction of multiple corrosion defects. Nevertheless, a review of a few of these equations for plain and corroded pipes are provided. They would be helpful in developing the critical buckling strain equations that consider the interaction

of multiple corrosion defects.

Vitali et al. (1999) developed an equation to calculate critical buckling compressive strain based on the D/t ratio, internal pressure ratio and material properties without yield plateau.

The proposed equation for the critical buckling strain take the form

$$\epsilon_{lc} = \left(\frac{t}{D} - 0.01 \right) \left(1 + 5 \frac{\sigma_h}{\sigma_y} \right) \left(\frac{\sigma_u}{\sigma_y} \right)^{1.5} \quad (2.33)$$

where σ_h is the hoop stress, σ_y is the yield strength and σ_u is the ultimate strength.

Using results of the parametric finite element analysis study, Dorey et al. (2006) generated a set of critical strain equations for plain and girth-welded pipes. Effects of D/t ratio, internal pressure, material properties (with and without yield plateau) and initial imperfection were considered. For a plain pipe with the material properties (stress-strain curve) without a yield plateau, the equation can be expressed as

$$\epsilon_{lc} = \left(\frac{2.94}{\frac{D}{t}} \right)^{1.59} \left(1 - 0.868 \left(\frac{p}{p_y} \right) \right)^{-1} \left(\frac{E}{\sigma_y} \right)^{0.854} (1.27 - \text{imp}^{0.15}) \quad (2.34)$$

where imp is the pipe imperfection taken as a ratio to the pipe wall thickness.

Tan (2008) proposed a general critical buckling strain equation derived from the finite element analysis parametric study that consisted of 3 D/t ratios, 12 load combinations and 12 different material properties (stress-strain curves). No initial imperfection pattern was considered in the proposed equation. The equation calibrated for each stress-strain curve is defined as

$$\epsilon_{lc} = k_s \left(\frac{D}{t} \right)^{V_{ds}} \left(1 - \frac{\sigma_a}{\sigma_y} \right)^{V_{as}} \left(1 - V_{ps} \frac{p}{p_y} \right)^{-1} \quad (2.35)$$

where k_s , V_{ds} , V_{as} and V_{ps} are the constants that varies with material properties. Other equations for the compressive strain limit of a plain pipe have also been developed based on the experimental data and/or finite element analyses by Liu et al. (2008), DeGeer and Tsuru (2009), and Zhang et al. (2014).

Alenezi (2015) developed a buckling equation based on the results of a finite element analysis parametric study carried out for a pipe with a single internal corrosion defect at a fixed axial length. Parametric combinations of 3 D/t ratios, 9 load combinations, 3 material properties (stress-strain curves), 3 depths and 3 circumferential lengths of the corrosion defect are considered. The proposed buckling strain equation for a uniform depth single corrosion defect is given as

$$\frac{\varepsilon_{lc}}{\varepsilon_{lp}} = 1 - \left[U_s + U_{sDt} \left(\frac{D}{t} \right)^{V_{sDt}} \left(1 + \left(\frac{p}{p_y} \right)^{V_{sp}} \right) \left(1 - \frac{\sigma_a}{\sigma_y} \right)^{V_{sa}} \right] \left[\left(\frac{l_c}{D} \right)^{V_{slc}} \left(\frac{d}{t} \right)^{V_{sd}} \right] \quad (2.36)$$

where ε_{lp} is the critical local compressive strain of a plain pipe, l_c and d are the circumferential length and depth of the corrosion respectively. Parameters U_s , U_{sDt} , V_{sDt} , V_{sp} , V_{sa} , V_{slc} and V_{sd} are constants that vary for each stress-strain curve (material properties). Both Tan (2008) and Alenezi (2015) also proposed equations to predict the critical local moment and curvature.

Figure 2.1 Single corrosion defect (modified from DNV 2015)

Figure 2.2 Corrosion defect interaction (modified from ASME 2012)

Figure 2.3 Corrosion defects interaction dimension (modified from DNV 2015)

Bulge shape

Diamond shape

Figure 2.4 Shapes of local buckling (adopted from Chen et al. 2010)

Figure 2.5 Loading conditions in the pipe (modified from Tan 2008)

3 Chapter: Proposed Model and Validation

The pipeline buckling behavior can best be captured and measured through physical testing. However, it is not economically feasible to test pipe specimens for all situations. Thus, finite element analyses can be used as alternatives in studying the pipeline buckling behavior over a wide range of parameters. The proposed FEA models used in the parametric study are based on the test setup and validated against the test results of Chen et al. (2010). Mesh refinement study has also been conducted to select the mesh configuration appropriate for the parametric study. There are different local compressive strain and curvature measurements. In order to avoid ambiguity, the (critical) local compressive strain or compressive strain and local curvature are henceforth referred to as the compressive strain and curvature taken over a distance of the pipe outside diameter D .

3.1 Experimental Setup

Chen et al. (2010) conducted tests on nine full-scale X70 (SMYS 483 MPa) pipe specimens under a combined loading. All specimens have an outside diameter (D) of 609.6 mm and a length (L) of 2300 mm. Based on the D/t ratio and loading, nine test specimens were classified into three groups as LB-I, LB-II and LB-III. Each group consisted of a plain pipe and two pipes with an external machined defect. The loading and specimen geometry are shown in Table 3.1.

All three groups have the same external machined defect dimension relative to the diameter and thickness of the pipe. As shown in Table 3.1, both externally machined defects in each group have the same circumferential length of $0.5D$, but with two different axial length $\times$ depth combinations of $5t \times 0.55t$ and $0.5D \times 0.3t$ respectively. A zero internal pressure

along with a compressive axial load was considered for group LB-III specimens that have the highest D/t ratio. The LB-II group specimens, with a D/t ratio of 69, were tested at an internal pressure of 40% SMYS hoop stress and no axial load. A tensile axial load with the highest hoop tension stress (80% SMYS) due to the internal pressure were applied to the specimen in the LB-I group that have the lowest D/t ratio. Material properties of the pipes from results of the tensile coupon tests taken along the longitudinal direction are shown in Table A.1 and Figs. A1 to A3 in Appendix A.

3.2 Finite Element Model

In this study, the commercial finite element software ABAQUS (Dassault Systèmes, 2013) has been used to simulate the tests of Chen et al. (2010). The software chosen for the model validation and parametric study were used in previous numerical studies on the pipeline local buckling (wrinkling) conducted by Mohareb et al. (1994), DelCol et al. (1998), Dorey et al. (2001), Tan (2008), Dewanbabee (2009) and Alenezi (2015). There was a good agreement between the numerical and experimental results from these studies on a pipe specimen with or without corrosion defects under a combined loading. The FEA models used in the subsequent parametric study are constructed based on the validated models.

3.2.1 Model Construction

The finite element model was constructed in accordance to the tests by Chen et al. (2010). As shown in Fig. 3.1, the test specimen was fixed with end plates of 76mm thickness on both ends of the pipe to enable the application of axial load, end rotation and internal pressure. The axial load was applied through the MTS testing system and the end rotation (bending moment) by the hydraulic jacks through the loading beams about the pivot point.

A collar of 150mm length was provided at each end of the 2300mm long pipe to reduce the end effects in the test. Corrosion defects were mechanically machined onto the pipe.

Fig 3.2 shows the schematic design of the loading and boundary conditions. The finite element model used is shown on Fig. 3.3, only one half of the pipe specimen is modelled by making use of the symmetry about the plane (X-Z plane) normal to the bending axis. A three-node elastic rigid thin shell element STRI3 has been used to model the end plates. The node in the center of the rigid elastic plate is linked to all the nodes along the circumference of the same plate using rigid beam. The axial load and end rotations are (bending moment) applied to the node at the pivot point, which is linked to the node at the center of the rigid elastic plate. The pipe is modeled with S4R shell element, a four-node bi-linear element with reduced integration. This element can account for finite membrane strain, which is suitable for simulating large deformation problems. Elements within the collar at both ends of the specimen have been assigned twice the pipe wall thickness in order to model the effect of collars practically.

As shown in Fig. 3.4, there are a number of ways to model a defect. The reference surface of a shell element is defined by its nodes. An imperfection (minor defect) or a defect can be modelled by using different reference surfaces for the non-corroded region (no metal loss) and the corroded (imperfection, defect) region that has a reduction in wall thickness without any offset from the center line of the wall thickness to the reference surface. The nodes at the boundary between non-corroded and corroded regions are joined together using the rigid beam constraint. Alternatively, an imperfection or a defect can be modelled with a single reference surface for the whole specimen using a different offset to define the center line of the wall thickness at the corroded (imperfection) region to the reference

surface. However, using different reference surfaces to model the corroded region has been found to have less trouble achieving convergence past the critical buckling limit (peak moment) in the finite element analysis, and thus the scheme with different reference surfaces has been adopted.

Plain pipes are modelled with a circumferential imperfection band of $0.2D$ axial length with a depth of $0.005t$ at pipe mid-length to initiate the buckling at the mid-segment of the pipe in order to avoid the influence of end effects due to the boundary conditions on the buckling behavior. The depth of the circumferential imperfection band is increased up to 1% of pipe wall thickness for certain (non-pressurized and tensile axial load) cases to initiate the local buckling at the imperfection region.

Corrosion defects are placed asymmetrically in the longitudinal direction in order to prevent the initiation of double buckling that is symmetric about the mid-length from occurring. As shown in Fig. 3.5, the centerline of a single corrosion defect is offset at a quarter of the defect axial length ($0.25l_a$) from the mid-length of the specimen. For two corrosion defects, the centerline of the primary (larger or deeper) defect or one of the equal size defect, is located at the mid-length of the specimen.

3.2.1.1 Loading

As shown in Fig. 3.2, the axial load was applied to the top of the pivot point and end moments were applied by inducing two equal rotations at the top and bottom of the pipe about the pivot points. Internal pressure was applied (normal) to the internal surface of the pipe and end plates. A two-step loading sequence has been used in the analysis. The axial load and internal pressure are first applied incrementally to their specified levels. These are maintained for the rest of the analysis. On the second step, end rotations are incrementally

applied until the pipe failed (buckled) locally.

3.2.1.2 Material Properties

The material properties calculated (measured) from results of tensile coupon tests for the pipe specimen along the longitudinal direction are used in the analysis. Even though the pipe material properties vary in the longitudinal and circumferential directions, previous analyses conducted by Mohareb et al. (1994), DelCol et al. (1998), Dorey et al. (2001), Tan (2008), Dewanbabe (2009) and Alenezi (2015), have shown that there is a good agreement between the test and FEA results using the material properties along the longitudinal direction. The material was assumed to be isotropic and deform according to the incremental theory of plasticity with isotropic hardening in those analyses. Furthermore, local buckling of the pipe is mainly due to the combined longitudinal loading, and hence it is more influenced by the mechanical properties of the pipe along the longitudinal direction. Therefore in this study, the pipe material has also been assumed to be isotropic and deform according to the incremental theory of plasticity with isotropic hardening based on the properties in the longitudinal direction. The elastic modulus is taken as $E=200000\text{MPa}$ and Poisson's ratio as $\nu=0.3$. In the analyses, a multi-linear true stress-true plastic strain curve has been used to define the plastic hardening of the material.

3.2.1.3 Model Mesh and Mesh Size

Finite element mesh plays a vital role in the accuracy and efficiency of a finite element analysis. A significant reduction in the computational time for the analysis can be attained by reducing the number of degrees of freedom without sacrificing the accuracy of the numerical results. This can be achieved by modelling one half of the pipe due to symmetry

and using different element sizes along the longitudinal direction. Fig. 3.3 shows the finite element mesh used in the parametric study, which has the same mesh schemes as models used in the simulations of the tests by Chen et al. (2010) except that the model is 5D long in the parametric study. The model is divided into refined zone, transitions zones, general zones and collar regions along the longitudinal direction. The refined zone, where corrosion defects or imperfection is located, has the finest element size. This is also the region where the local (buckling) failure is expected to occur. The total length of the model is 3.77D (3.77 times the diameter of the pipe), in which the length of the refined zone has been taken as 2D in order to capture the local deformation with better accuracy. A transition zone of 0.5D is also introduced on both sides of the refined zone to allow for a smoother transition from the refined zone to general zone. A multi-point constraint along circumferential direction is applied between the transition and refined zone to ensure displacement continuity. The rest of the pipe is designed as the general zone and collar region with a length of $0.5(L-3.5D)$ and $0.25D$ respectively.

3.3 Model Selection and Validation

In order to select the optimum element size and model length for the parametric study, models with different mesh densities and lengths have been analyzed. In total, five different mesh densities for each of nine test specimens by Chen et al. (2010) have been modeled and analyzed.

3.3.1 Element Sizes

The pipe model in the study to select the optimum element size has a length of 2300 mm (3.77D), similar to the length of the test specimens by Chen et al. (2010). The model using

the nominal pipe dimensions has constructed according to the length of refined, transition and general zones, and collar regions as shown in Fig. 3.3. It is essential to have sufficient number of elements within the corroded region to capture the behavior of local buckling. Table 3.2 shows the number of elements over a length of $5t$ in the refined zone of a specimen with a D/t ratio of 92 for various mesh schemes. Mesh A1 has been designed with the element size of 0.018×0.018 times the pipe outer diameter (D) in the refined zone. Mesh scheme A2 and A3 have an element size of $0.01D$ and $0.005D$ with an aspect ratio of 1 in the refined region respectively. The number of elements in the corroded region of an axial length of $5t$ for a D/t ratio of 92 pipe are 5 and 11 for schemes A2 and A3 respectively. Even smaller element sizes are used in the refined zone for mesh schemes A4 and A5 while still maintaining the element aspect ratio of 1. Schemes A4 and A5 have 16 and 22 elements within the $5t$ axial length of corroded region respectively. The element dimension in the transition zone in all the models are twice their refined zone element size. Elements in the general zone and collar region have the same hoop dimension as the element in the transition zone but with different aspect ratios of approximately 1.5 and 2 respectively. The number of elements within the $5t$ axial length of the corroded region in the model increases for specimens with the D/t ratio less than 92. Thus, a worst-case scenario has been considered in selecting the element dimension.

Results of the numerical analyses with different mesh schemes for the tests by Chen et al. (2010) are shown in Tables 3.3 to 3.5. Table 3.3 shows results for plain pipes with different mesh schemes. There is little difference in the predicted critical local moment between all mesh schemes, while the predicted critical local compressive strain and curvature differs by a maximum of about 1% between mesh schemes A3 to A5, and 2% between A2 and

A5. Thus, the mesh scheme A2 with the element size of $0.01D \times 0.01D$ in the refined zone appears to be appropriate for modelling plain pipes.

Tables 3.4 and 3.5 show the predicted critical buckling limits of corroded pipes for mesh schemes A1 to A5. As expected, the predicted buckling limits for the patch corrosion specimen, as shown in Table 3.5, converge at a larger element size than that for the circumferential groove corrosion specimen since there are more elements within the axial length of the patch corrosion compared to the circumferential groove corrosion. Among results for the circumferential groove corrosion specimens, the percentage change in the predicted buckling limits from mesh schemes A1 to A2 decreases with the increase in the number of elements within the axial direction of the corrosion (LB-III to LB-II). From Table 3.4, there is a small change of less than 2% in the predicted critical buckling limits for LB-III-2 ($D/t=90$) between mesh schemes A3 to A5, and for LB-I-2 and LB-II-2 between mesh schemes A2 to A5. Thus, the minimum element size required in the refined zone to model a corroded pipe can be taken as the minimum of

- the dimension that provides at least 10 elements axially within the corroded region, and
- no greater than 0.01×0.01 times the outer diameter of the pipe (D).

All subsequent finite element analyses have been carried out using the model with the minimum element size in the refined zone based on the above criteria.

3.3.2 Model Validation

The finite element model validation will be carried out using results of Chen et al. (2010). Criteria on the minimum element size in the refined zone set in Section 3.3.1 have been used to model the pipe. In addition, the element size of the refined zone has been altered slightly to fit the exact defect dimensions. Actual measured dimensions of the pipe

specimens and loading are used in the FEA simulations. Material properties from the tension coupon tests of Chen et al. (2010) have been used in analyses, which are shown in Table A.1 and Figs. A1 to A3 in Appendix A. A small time-step has been used for loading in order to capture the behavior of local buckling precisely.

The experimental and FEA results are compared and summarized in Table 3.6 and the graphical comparisons are presented in Figs. 3.6 to 3.11. Critical buckling limits are values correspond to the peak local moment determined through interpolation (curve fitting) of the data around the peak moment. The critical local moment has been expected to be higher than the experimental results because the material properties used in the finite element analyses are from the dynamic readings of coupon tests at a low continuous deformation rate. As expected, the critical local moment in all the nine cases are higher than the experimental results. The critical local moment obtained from the finite element analyses is 5% higher on average compared to that of the test results.

The critical local compressive strain and critical local curvature have also shown good agreement compared to experimental results, but have a greater variability compared to the critical local moment. The main reason for the greater variability is due to the shape of load-deformation curves. As seen in Figs. 3.6 to 3.11, some of the moment-deformation curves have been observed to be quite flat close to the peak moment. Due to this reason, there is a greater variability and uncertainty in the determination of the critical local strain and curvature corresponding to the peak local moment. Nevertheless, the test and predicted critical local compressive strain and curvature are within 10%. The average predicted ratio of critical local compressive strain and critical local curvature are about 1.0. Overall, there is a good agreement between the experimental and predicted results. Fig 3.12 shows the

predicted bulge and diamond buckled shapes typically of the pressurized and non-pressurized pipes from FEA simulations.

3.3.3 Model Length

A pipe model with a sufficient length is required to reduce the end effects due to the boundary conditions imposed in the modelling. Finite element analyses have been carried out under various loading conditions for plain and corroded pipe model at 3.77D, 5.0D and 7.0D long in order to study effects of model length in the buckling behavior and to find the optimum length to be used in the parametric study. FEA simulations have been carried out with the corrosion size and loading for some of the tests by Chen et al. (2010). The predicted buckling limits for plain and corroded pipes at different model lengths are shown in the Table 3.7. Predicted buckling limits from the pressurized corroded pipe (LB-II) show a slightly higher change at a maximum of 4%, with the increase in the pipe model length from 3.77D to 5.0D. However, the differences between results for 5.0D and 7.0D long models are less than 1%. With the small differences between the predicted buckling limits of 5.0D and 7.0D long models, a pipe model with 5.0D long has been considered to be sufficient long enough to have reduced or eliminated the end effects of modelling. Thus, the pipe model of a length 5.0D has been adopted for all subsequent finite element analyses.

3.3.4 Mesh Study for Two Corrosion Defects

It is expected that the criteria set in Section 3.3.1 for the minimum element size in the refined zone to be used in the model is appropriate with two corrosion defects aligned along the axial direction. Thus, no exhaustive study has been carried out to investigate the appropriate minimum element size required to model pipes with two axially aligned

corrosion defects. Only numerical simulations at one pipe size of $D/t=70$ and $5.0D$ length for two different internal pressures have been conducted to reaffirm the criteria adopted on the minimum element size. Two axially aligned corrosion defects of equal size with the axial x circumferential length of $0.4D \times 0.26D$, and a depth of $0.3t$. There is a clear spacing of $3t$ between defects edges. The material properties (stress-strain curve) used in this study have been adopted from Alenezi (2015) for a material with the ultimate to yield strength ratio (σ_{er}) of 1.65 and a corresponding strain at peak stress of 0.12. Additional information on this are provided in the following Chapters 4 and 5. The lengths of the refined, transition and general zones, and collar regions are in accordance to Fig. 3.3. and Section 3.2.1. Three different mesh densities similar to that in Section 3.3.1 have also been considered. Numerical simulations have been carried out for an axial load ratio (σ_a/σ_y) of 0.2 with two different internal pressure ratios (p/p_y) of 0.0 and 0.4. Results of the simulations for various mesh schemes are shown in Table 3.8. It can be seen that there is no significant difference between the predicted buckling limits for mesh schemes A2 and A3, and the differences are even small between scheme A1 and A2. Hence, the mesh density in the refined zone adopted in Section 3.3.1 also appears to be appropriate for a pipe with two corrosion defects that are to be considered in the following parametric study. Mesh scheme A1 has the same number of elements along the axial direction within the defect axial length $0.4D$ as scheme A2 for a defect axial length of $0.2D$. Thus, mesh scheme A2 is appropriate for modelling a defect axial length $0.2D$ while scheme A1 is appropriate for a defect axial length of $0.4D$. This is consistent with results of mesh refinement study in Section. 3.2.1.3. Note that in the finite element analysis parametric study, which is to be discussed in the following chapter, no defect axial length less than $0.2D$ has been considered.

Table 3.1 Geometry and loading of tests performed by Chen et al. (2010)

Specimen	Pipe geometry		D/t	Corrosion defect size (mm)			Loading conditions	
	Pipe size (mm)			Axial	Circumferential	Depth	Internal pressure (SMYS)	Axial load (SMYS)
	D	t						
I-1	609.6	12.7	48	No defect			80%	-30%
I-2	609.6	12.7	48	5t	0.5D	0.55t	80%	-30%
I-4	609.6	12.7	48	0.5D	0.5D	0.3t	80%	-30%
II-1	609.6	8.8	69	No defect			40%	0
II-2	609.6	8.8	69	5t	0.5D	0.55t	40%	0
II-4	609.6	8.8	69	0.5D	0.5D	0.3t	40%	0
III-1	609.6	6.6	92	No defect			0	20%
III-2	609.6	6.6	92	5t	0.5D	0.55t	0	20%
III-4	609.6	6.6	92	0.5D	0.5D	0.3t	0	20%

Table 3.2 Number of elements within the corroded region for D/t=90

Model	Element sizes	Number of elements in 0.5D (D=609.6mm)	Number of elements in 5t (t=6.10mm)
A1	0.0180D x 0.0180D	14	3
A2	0.0100D x 0.0100D	24	5
A3	0.0050D x 0.0050D	46	11
A4	0.0033D x 0.0033D	70	16
A5	0.0025D x 0.0025D	94	22

Table 3.3 Comparison of results between different mesh schemes – plain pipe

Plain pipe									
	Critical buckling limits								
Model	LB-I-1			LB-II-1			LB-III-1		
	Local moment (kNm)	Local compressive strain (mm/mm x 10 ⁻⁶)	Local curvature (rad/mm x 10 ⁻⁶)	Local moment (kNm)	Local compressive strain (mm/mm x 10 ⁻⁶)	Local curvature (rad/mm x 10 ⁻⁶)	Local moment (kNm)	Local compressive strain (mm/mm x 10 ⁻⁶)	Local curvature (rad/mm x 10 ⁻⁶)
A1	2160	28337	86.61	1439	8367	20.56	910	4131	10.13
A2	2165	28869	89.34	1440	8242	20.52	910	4038	9.92
A3	2171	29152	90.75	1442	8215	20.32	911	4030	9.91
A4	2169	29061	90.68	1444	8165	20.16	911	4020	9.92
A5	2174	29252	91.78	1442	8211	20.30	911	4029	9.91
A1/A2	0.998	0.982	0.969	1.000	1.015	1.002	0.999	1.023	1.022
A2/A3	0.997	0.990	0.985	0.998	1.003	1.010	1.000	1.002	1.000
A3/A4	1.001	1.003	1.001	0.999	1.006	1.008	1.000	1.002	1.000
A3/A5	0.999	0.997	0.989	1.000	1.000	1.001	1.000	1.000	1.000
A4/A5	0.998	0.993	0.988	1.001	0.994	0.993	1.000	0.998	1.001

Table 3.4 Comparison of results between different mesh schemes – circumferential groove corrosion (0.5D x 5t x 0.55t)

Axial groove corroded pipe									
Model	Critical buckling limits								
	LB-I-2			LB-II-2			LB-III-2		
	Local moment (kNm)	Local compressive strain (mm/mm x 10 ⁻⁶)	Local curvature (rad/mm x 10 ⁻⁶)	Local moment (kNm)	Local compressive strain (mm/mm x 10 ⁻⁶)	Local curvature (rad/mm x 10 ⁻⁶)	Local moment (kNm)	Local compressive strain (mm/mm x 10 ⁻⁶)	Local curvature (rad/mm x 10 ⁻⁶)
A1	1794	40316	88.57	1140	11919	23.76	604	6359	12.51
A2	1810	37917	82.93	1065	14663	28.28	547	10016	18.39
A3	1818	37732	82.20	1055	14798	28.46	539	10392	19.02
A4	1830	38201	83.32	1057	14896	28.61	534	10539	19.09
A5	1831	38223	83.59	1055	14921	28.65	531	10553	19.14
A1/A2	0.991	1.063	1.068	1.070	0.813	0.840	1.106	0.635	0.680
A2/A3	0.995	1.005	1.009	1.009	0.991	0.994	1.015	0.964	0.967
A3/A4	0.994	0.988	0.987	0.999	0.993	0.995	1.009	0.986	0.996
A3/A5	0.993	0.987	0.983	1.000	0.992	0.994	1.015	0.985	0.994
A4/A5	0.999	0.999	0.997	1.002	0.998	0.999	1.006	0.999	0.997

Table 3.5 Comparison of results between different mesh schemes – patch corrosion (0.5D x 0.5D x 0.3t)

Patch corroded pipe									
Model	Critical buckling limits								
	LB-I-4			LB-II-4			LB-III-4		
	Local moment (kNm)	Local compressive strain (mm/mm x 10 ⁻⁶)	Local curvature (rad/mm x 10 ⁻⁶)	Local moment (kNm)	Local compressive strain (mm/mm x 10 ⁻⁶)	Local curvature (rad/mm x 10 ⁻⁶)	Local moment (kNm)	Local compressive strain (mm/mm x 10 ⁻⁶)	Local curvature (rad/mm x 10 ⁻⁶)
A1	1794	38153	82.25	1145	12291	24.25	581	3254	7.12
A2	1797	37434	80.75	1139	12235	24.13	593	3273	7.16
A3	1774	37514	80.89	1136	11936	24.40	602	3307	7.21
A4	1774	37554	81.00	1132	11918	24.42	601	3319	7.20
A5	1793	37589	81.01	1126	11982	24.23	604	3323	7.19
A1/A2	0.998	1.019	1.019	1.005	1.005	1.005	0.980	0.994	0.995
A2/A3	1.013	0.998	0.998	1.003	1.025	0.989	0.986	0.990	0.993
A3/A4	1.000	0.999	0.999	1.003	1.001	0.999	1.001	0.996	1.001
A3/A5	0.990	0.998	0.998	1.008	0.996	1.007	0.997	0.995	1.002
A4/A5	0.989	0.999	1.000	1.005	0.995	1.008	0.995	0.999	1.001

Table 3.6 Comparisons of experimental and FEA results for test by Chen et al. (2010)

Model LB	Experimental			FEA			FEA/Experimental		
	Critical values (peak local moment and corresponding local compressive strain and local curvature)								
	Local moment (kNm)	Local compressive strain (mm/mm x 10 ⁻⁶)	Local curvature (rad/mm x 10 ⁻⁶)	Local moment (kNm)	Local compressive strain (mm/mm x 10 ⁻⁶)	Local curvature (rad/mm x 10 ⁻⁶)	Local moment ratios	Local compressive strain ratios	Local curvature ratios
I-1	2034	27800	89.59	2145	28721	91.55	1.055	1.033	1.022
I-2	1771	39700	90.72	1828	37507	87.22	1.032	0.945	0.961
I-4	1722	40000	89.98	1806	38627	84.87	1.049	0.966	0.943
II-1	868	4100	10.28	908	4138	10.42	1.046	1.009	1.014
II-2	516	11900	21.39	539	10818	19.84	1.045	0.909	0.928
II-4	578	3200	7.05	619	3376	7.49	1.071	1.055	1.062
III-1	1375	7330	19.02	1441	7941	20.18	1.048	1.083	1.061
III-2	1000	15640	30.45	1057	16296	31.65	1.057	1.042	1.039
III-4	1071	12580	25.76	1124	11428	23.70	1.049	0.908	0.920
Average							1.050	0.995	0.995

Table 3.7 Results comparisons between various model lengths

Model	Model length	Critical local moment (kNm) or ratio	Critical local compressive strain (mm/mm x 10 ⁻⁶) or ratio	Critical local curvature (rad/mm x 10 ⁻⁶) or ratio
LB-II-1	3.77D	1440	8242	19.52
	5.0D	1449	8297	19.68
	7.0D	1455	8316	19.70
	Test	1383	8517	21.34
	3.77D/5.0D	0.994	0.993	0.992
	5.0D/7.0D	0.996	0.998	0.999
LB-II-4	3.77D	1136	11936	24.40
	5.0D	1110	12179	25.32
	7.0D	1117	12250	25.16
	Test	1073	12580	25.76
	3.77D/5.0D	1.024	0.980	0.964
	5.0D/7.0D	0.994	0.994	1.006
LB-III-1	3.77D	911	4038	9.91
	5.0D	903	4008	9.69
	7.0D	899	3998	9.67
	Test	871	4100	9.97
	3.77D/5.0D	1.009	1.007	1.023
	5.0D/7.0D	1.005	1.003	1.002
LB-III-4	3.77D	602	3307	7.12
	5.0D	581	3209	7.01
	7.0D	583	3228	7.02
	Test	578	3504	7.50
	3.77D/5.0D	1.036	1.031	1.016
	5.0D/7.0D	0.997	0.994	0.999

Table 3.8 Comparisons of results between different mesh schemes – two corrosion defects

Ultimate to yield strength ratio $\sigma_{er}=1.65$, diameter $D=762\text{mm}$, thickness $t=10.88\text{mm}$ and axial load ratio $\sigma_a/\sigma_y=0.2$							
Defect axial length $=0.4D$, defect circumferential length $=0.26D$ and defect depth $=0.3t$							
Scheme	Element dimension in refined zone	$p/p_y=0.0$			$p/p_y=0.4$		
		Local moment (kNm) or ratio	Local compressive strain (mm/mm $\times 10^{-6}$) or ratio	Local curvature (rad/mm $\times 10^{-6}$) or ratio	Local moment (kNm) or ratio	Local compressive strain (mm/mm $\times 10^{-6}$) or ratio	Local curvature (rad/mm $\times 10^{-6}$) or ratio
A1	0.02D X 0.02D	1491	8733	18.62	1409	10912	22.97
A2	0.01D X 0.01D	1471	8813	18.98	1388	10807	22.54
A3	0.005D X 0.005D	1463	8833	19.03	1384	10788	22.39
A1/A2		1.013	0.990	0.981	1.015	1.009	1.019
A2/A3		1.005	0.997	0.997	1.002	1.001	1.006

Figure 3.1 Test setup for Chen et al. (2010) (modified from Chen et al. 2010)

Figure 3.2 Loading and boundary conditions

Figure 3.3 View of FEA model used in parametric study

Figure 3.4 Corrosion defect modelling

Figure 3.5 Corrosion defect location in the model

Figure 3.6 Test and predicted local moment versus local compressive strain for LB-I group of Chen et al. (2010)

Figure 3.7 Test and predicted local moment versus local curvature for LB-I group of Chen et al. (2010)

Figure 3.8 Test and predicted local moment versus local compressive strain for LB-II group of Chen et al. (2010)

Figure 3.9 Test and predicted local moment versus local curvature for LB-II group of Chen et al. (2010)

Figure 3.10 Test and predicted local moment versus local compressive strain for LB-III group of Chen et al. (2010)

Figure 3.11 Test and predicted local moment versus local curvature for LB-III group of Chen et al. (2010)

LB-I-4 - FEA

LB-III-4 - FEA

Figure 3.12 Predicted buckling deformation shapes for corroded pipes

4 Chapter: Material Properties and Corrosion Defects

Properties (stress-strain curve) of the material and corrosion defect sizes have very strong effects on the buckling response of a line pipe. For steel, the material properties and engineering stress-engineering strain curve are normally obtained from a tension coupon material test. The stress-strain curve and its shape can be approximately defined with a few parameters, such as ultimate to yield stress ratio, yield stress, length of yield plateau and strain at the ultimate stress. In most finite element analyses of steel structures involving large deformation, the material properties input includes the true stress-true plastic strain data. Thus, it is necessary to convert the engineering stress-engineering strain curve from the tension coupon material test to a true stress-true plastic strain curve to be used in finite element analyses. However, it may also more beneficial for some instances to use the artificially generated true stress-true strain data in the finite element analyses in order to study the response of the structure to a wide range of material properties that can be encountered.

Similar to the material properties, there are different corrosion sizes and configurations that can develop in oil and gas pipelines. Corrosion defects can occur singly or in colonies, and can act independently or interactively to affect the buckling response of pipelines. Thus, the size of the corrosion defect and the defect interaction that can be expected should be considered in the parametric study. This study will focus mainly on effects due to corrosion defects that develop close to each other.

4.1 True Stress-True Strain Data

In finite element analyses of steel structures, the material properties used can be the actual

values, artificially generated values or a mix of both. Brief discussions on the conversion of the engineering stress-engineering strain data to the true stress-true plastic strain data and various equations that can be used to generate artificial true stress-true plastic strain data are provided to establish the bases for using the artificially generated true stress-true strain data in the study.

4.1.1 True Stress – True Strain Data Conversion

Engineering stress-engineering strain data of a material are obtained in a tension coupon test. However, the material properties in the form of true stress-true plastic strain are required in most finite element analyses of steel structures. Taking the material volume change to be zero for plastic deformation, and assuming the deformation to be completely plastic, the current dimension can be related to the undeformed dimension as

$$LA = L_0A_0 \quad \text{or} \quad \frac{L}{L_0} = \frac{A_0}{A} \quad (4.1)$$

where L_0 and L are the initial and current lengths, and A_0 and A are the initial and current cross section areas. A number of established equations that are widely used to transform engineering stress and engineering strain to true stress and true strain can be summarized as

$$\sigma_t = \sigma_e (1 + \varepsilon_e), \quad (4.2)$$

$$\varepsilon_t = \ln \left(\frac{L}{L_0} \right) = \ln (1 + \varepsilon_e), \quad (4.3)$$

$$\varepsilon_t = \ln \left(\frac{A}{A_0} \right), \quad (4.4)$$

$$\varepsilon_{tp} = \varepsilon_t - \frac{\sigma_t}{E} \quad (4.5)$$

where ε_t and ε_e are the true and engineering strains, F is the force, σ_t and σ_e are the true and engineering stresses, E is the elastic modulus and ε_{tp} is the true plastic strain. These equations are valid up to the point of maximum stress on the engineering stress-engineering strain curve of a tension coupon test before the initiation of necking.

4.1.2 True Stress – True Strain Equations

There have been many equations proposed for generating the true stress – true (plastic) strain curve that are representative of steel (metal). Most of these equations are based on either power law or exponential law relationships. Only a few of these will be discussed in the following section.

Using the power law relationship, Nadai (1939) proposed an expression to relate the true stress versus true strain as

$$\varepsilon_t = \frac{\sigma_t}{E} \quad \text{for } \sigma_t < \sigma_p \quad (4.6)$$

$$\varepsilon_t = \frac{\sigma_t}{E} + \varepsilon_y \left(\frac{\sigma_t - \sigma_p}{\sigma_y - \sigma_p} \right)^q \quad \text{for } \sigma_t \geq \sigma_p \quad (4.7)$$

where ε_t and σ_t are the true strain and true stress respectively, ε_y is the strain at yield stress (σ_y), σ_p is the stress at the proportional limit, E is Young's modulus and q is a constant.

Based on Nadai (1939), Ramberg-Osgood (1943) developed a simple and widely used equation to represent the stress-strain curves that do not exhibit a yield plateau. The equation is only a function of three parameters, which is given as

$$\varepsilon_t = \frac{\sigma_t}{E} + k \left(\frac{\sigma_t}{E} \right)^r \quad (4.8)$$

where k and r are constants.

Following Nadai (1939) and Ramberg-Osgood (1943), Naqvi and Khoo (2007) proposed a more general equation that can account for the presence of yield plateau. The true plastic strain as a function of true stress can be expressed as

$$\varepsilon_{tp} = C \left[\left(\frac{\sigma_t}{\sigma_{t0}} \right)^n - 1 \right] + \varepsilon_{tp0} \quad (4.9)$$

where ε_{tp0} is the true plastic strain at the end of yield plateau or taken to be zero when there is no yield plateau in the stress-strain curve, σ_{t0} is the true stress at ε_{tp0} , C and n are constants. Tan (2008) and Alenezi (2015) have used this equation to generate the true stress-true plastic strain curves in the respective parametric studies conducted on plain pipes and pipes with a single corrosion patch. This equation has been shown to be able to closely generate the true stress-true strain curve of the steel pipe material by Tan (2008) and Alenezi (2015). Thus, this equation is also being adopted to generate the true stress – true plastic strain curves used in this current study.

4.1.3 Stress – Strain Curve Characterization and Generation

There is a wide range of material properties in steel pipes. Therefore, the response of a pipeline subjected to the combined loading should be investigated over the expected range of material properties. Some of the material properties are normally determined from the material engineering stress-engineering strain curve, which is measured from a tension coupon test. The varying shape of the engineering stress-engineering strain curve can be

characterized with few parameters that are related to some strategic points on the curve. Parameters such as the stress at yield plateau or proportional limit, the ultimate to yield strength (stress) ratio, the strain at ultimate stress and the length of the yield plateau, can be used to define the shape of the engineering stress-engineering strain curve.

For a material that exhibits an engineering stress-engineering strain curve with a yield plateau, the yield strength is normally taken as the stress at the yield plateau. However, when there is no yield plateau, the yield strength determined according to ASTM-E8-04 (ASTM 2004) is dependent on the shape of the engineering stress-engineering strain curve. In order to avoid any ambiguity, the yield strength (stress) is taken as the engineering stress at the proportional limit for a material with no yield plateau in this study. Thus, the ultimate to yield strength ratio can be expressed as

$$\sigma_{er} = \frac{\sigma_{ef}}{\sigma_{e0}} \quad (4.10)$$

where σ_{ef} is the ultimate stress, and σ_{e0} is the stress at end of yield plateau or the proportional limit if there is no yield plateau.

For the Eq. (4.9) by Naqvi and Khoo (2007), ε_{tp0} and σ_{t0} can be calculated directly from the engineering stress-engineering strain curve using Eqs. (4.2) to (4.5) for a specific σ_{e0} (yield stress) and yield plateau length. The other two constants C and n are dependent on the ultimate to yield strength ratio (σ_{er}) and the strain at ultimate stress in addition to σ_{e0} and yield plateau length. Using Eqs. (4.2) to (4.5) and (4.9), Tan and Khoo (2009) derived two relationships to relate C and n to the characteristic parameters of the stress-strain curve that are expressed as

$$C = \frac{\varepsilon_{tpf} - \varepsilon_{tp0}}{\left(\frac{\sigma_{tf}}{\sigma_{t0}}\right)^n - 1} \text{ and} \quad (4.11)$$

$$\sigma_{tf} + E \left[\frac{n(\varepsilon_{tpf} - \varepsilon_{tp0}) \left(\frac{\sigma_{tf}}{\sigma_{t0}}\right)^n}{\left(\frac{\sigma_{tf}}{\sigma_{t0}}\right)^n - 1} \right] = 0 \quad (4.12)$$

where, σ_{tf} and ε_{tpf} are the true stress and true plastic strain correspond to the point at peak engineering stress and σ_{ef} is the peak engineering stress. Constants C and n can be calculated using Eqs. (4.11) and (4.12) of a stress-strain curve with specific characteristics. The strain at peak stress is normally not well defined on the engineering stress-engineering strain curve from a tension coupon test. In this situation, the strain at peak stress is adjusted until the true stress-true plastic strain curve generated with the calculated C and n from Eqs. (4.11) and (4.12) closely matches that of the true stress-true plastic strain curve calculated up to the point of peak stress from the engineering stress-engineering strain curve of a tension coupon test. In addition, Eq. (4.9) can also be used to extend the true stress-true plastic strain data beyond the point corresponding to the peak stress of a tension coupon test engineering stress-engineering strain curve as Eqs. (4.2) and (4.3) are not valid beyond the point of peak stress. From the analyses of Tan and Khoo (2009), constants C and n were found not to vary much with the yield stress and length of yield plateau if the ultimate to yield strength ratio and the strain at peak stress remain unchanged.

Most of the steel used in oil and gas pipelines can be expected to have the ultimate to yield strength ratio within the range of 1.1 to 1.5 based on the yield strength measured according to the testing standard. In the pipe specimens tested by Delcol et al. (1998), Dorey et al.

(2001) and Chen et al. (2010), the ultimate to yield strength ratio was found to be in the range of 1.1 to 1.4. For the material with no yield plateau, the proportional limit is always lower than the yield strength determined according to the testing standards ASTM-E8-04 (ASTM 2004). Thus, the ultimate to yield strength ratio (σ_{er}) calculated according to Eq. (4.10) adopted for this study can be significantly higher than the actual ratio since the stress at the proportional limit can be significantly lower than the actual yield strength. The ultimate to actual (testing standard) yield strength ratio range of 1.1 to 1.5 translates to the range of 1.3 to 2.0 for the ultimate to yield strength ratio (σ_{er}) adopted for this study for a ratio of the proportional limit to actual (testing standard) yield strength that ranges from 0.75 to 0.85. Similar to Alenezi (2015), the ultimate to yield strength ratios (σ_{er}) of 1.30, 1.65 and 2.00 are considered for the engineering stress-engineering strain curves without yield plateau in the following parametric study. In the studies by Tan (2008) and Alenezi (2015), no consistent pattern can be found in the change of critical buckling limits (moment, strain and curvature) with respect to the loading, pipe and corrosion defect geometries when the stress-strain curve of the pipe material has a yield plateau. For this reason, only stress-strain curves without yield plateau will be considered in this study. The other parameter that characterizes the stress-strain curve is the strain at peak stress or the relative strain at peak stress (the difference between the engineering strain at peak stress and the engineering strain at the end of yield plateau). Analyses carried out by Alenezi (2015) showed that there was no considerable difference in the ratio of the critical local moment, critical local compressive strain and critical local curvature of a corroded pipe to those the corresponding plain pipe between pipes with material stress-strain curves that have the relative strains at peak stress of 0.07 and 0.15. The strain at peak stress of steel

used in the pipeline typically falls within 0.07 to 0.15. Thus, similar to Alenezi (2015), only the relative engineering strain at peak stress (ϵ_{er}) of 0.12 will be considered in the parametric study.

Taking the Poisson's ratio to be 0.3, the elastic modulus (E) as 200000MPa, the true stress at the proportional limit of 480MPa and the relative strain at peak stress (ϵ_{er}) to be 0.12, three material stress-strain curves with the ultimate to yield strength ratio of 1.30, 1.65 and 2.00 are considered in the current parametric study. These are similar to some of the stress-strain curves by Alenezi (2015). Material properties parameters used to generate these true stress-true plastic strain curves are listed in Table 4.1 and the curves are shown in Fig. 4.1.

4.2 Multiple Corrosion Defects on Pipe Buckling

Corrosion defect sizes and their distribution affect the buckling response of the pipe. Although the defect is irregular in shape and depth, it is being idealized to be a rectangular in shape with a uniform depth that has sides oriented parallel to the axial and circumferential directions of the pipe. Corrosion defect may occur singly or in colonies. The defects can also distribute axially, circumferentially and diagonally, or a combination of these directions. Every corrosion defect may alter the stress and strain field of a pipeline and the interaction of the defects may have a significant influence on the local buckling behavior. Due to the higher possibility of flow induced corrosion occurring as noted in the literature review, only corrosion defects aligned the along axial direction will be considered in this study.

A preliminary study has been conducted to investigate the influence on local buckling behavior due to the change in the number of corrosion defects and their sizes. The distance of 3 times the wall thickness between the corrosion defects are being considered in this

study, which is the maximum distance between two flaws (corrosion) that are considered to be interactive according to ASME B31G (ASME 2012). Two axially aligned corrosion defects are considered when investigating the effect of corrosion sizes, and with the larger or deeper corrosion defect being the primary defect. The axial length of corrosion ratio (l_{ac}/D), hoop length of corrosion ratio (l_{hc}/D) and depth of corrosion ratio (d/t) of both primary and secondary corrosion defects are varied in this study. Subscripts p and s denote the primary and secondary corrosion defects. Material properties for $\sigma_{er} = 1.65$ and $\epsilon_{er} = 0.12$, pipe diameter (D) = 609.6 mm, pipe diameter to thickness ratio (D/t) = 70, axial load ratio (σ_a/σ_y) = 0.2 and internal pressure ratio (p/p_y) of 0.0 and 0.40 are considered.

4.2.1 Number of Corrosion Defects

Four different corrosion defect patterns are considered in investigating effects of having different number of corrosion defects along the axial direction. The four patterns consist of 1, 2, 3 and 4 corrosion defects. Each of the corrosion defect has the axial x circumferential lengths of $0.2D \times 0.25D$, and with a depth of $0.3t$. The corrosion defects are distributed evenly along the axial direction at a clear spacing of $3t$ between defects. Results of the analyses are shown in Table. 4.2. There are only small differences in the critical buckling limits between pipes with two or more corrosion defects with the defect axial length of $0.2D$ each. Hence, it appears appropriate to consider only up to two corrosion defects along the axial direction to study effects due to corrosion defects of two different sizes.

The analyses are carried out at a clear spacing of $3t$ between defects. However, critical local buckling limits at another clear spacing other than $3t$ for two corrosion defects of the same size can be estimated with the proposed equation

$$bb_{G-g} = bb_a + (bb_{2a} - bb_a)e^{-\alpha g} \quad (4.13)$$

where bb_a and bb_{2a} are the critical buckling limits (critical local moment, critical compressive strain and critical local curvature) for single corrosion defect with axial lengths of a and $2a$, bb_{G-g} are the critical buckling limits for two corrosion defects with a clear spacing (gap) g between defects, and α is a constant. The constant α can be calculated from the known critical buckling limits for the single corrosion defect and two corrosion defects with a with a clear spacing between defects of $3t$. For two corrosion defects with two different depths, the critical buckling limits at another spacing can be estimated with the proposed equation

$$bc_{G-g} = bc_o + (bc_o - bb_a)e^{-\alpha g} \quad (4.14)$$

where bc_{G-g} and bc_o are the critical buckling limits for two corrosion defects of unequal depth at clear spacing (gap) g and zero spacing (contiguous defects), and α is the constant from Eq. (4.13). The critical buckling limits bc_o can be calculated from the known critical buckling limits bb_a and bc_{G-g} at a clear spacing (gap) $3t$. All the corrosion defects have the same hoop and axial lengths. Examples on predicting the critical buckling limits for a different corrosion defect spacing the along the axial direction using Eqs. (4.13) and (4.14) and the validation are presented in Appendix B.

4.2.2 Axial Length of Corrosion Defect

The influence of axial length of corrosion defects on the local buckling behavior is being investigated using three different axial lengths for both primary and secondary corrosion defects with a constant defect hoop length $l_{hcp}=l_{hcs}=0.26D$ and depth $d_p=d_s=0.3t$. Numerical simulations are carried out for the axial lengths of the secondary corrosion defect of $0.2D$,

0.4D and 0.6D and the axial length of primary corrosion defect fixed at 0.6D. Similarly, numerical simulations are also carried out for the axial lengths of primary corrosion defect of 0.2D, 0.4D and 0.6D and the axial length of the secondary corrosion defect fixed at 0.2D. In all cases, the size of primary corrosion defect is equal to or greater than the secondary corrosion defect. The local buckling is expected to occur at the region with the higher metal loss.

Results of the analyses are shown in Fig. 4.2. There is no significant difference in the ratio of the critical local moment with respect to that for a plain pipe (M_{lc}/M_{lp}) with the change in axial length of primary and secondary corrosion defects. Similarly, there is no significant change in the critical compressive strain and local curvature ratios with the change in the axial length of the secondary corrosion defect. However, the critical compressive strain and critical local curvature ratios increase with the axial length of primary corrosion defect. Hence, the axial length of the secondary corrosion defect is taken to be the same as the primary corrosion defect in the parametric study.

4.2.3 Hoop Length of Corrosion Defect

Similar to the investigation on the effect of the axial length of the corrosion defect, the effect of the hoop length of corrosion defect on the local buckling response is studied by using three hoop lengths of both primary and secondary corrosion defects with a constant defect axial length $l_{acp}=l_{acs}=0.4D$ and a depth $d_p=d_s=0.3t$.

Numerical simulations are carried out for the hoop lengths of the secondary corrosion defect of 0.1D, 0.26D and 0.50D with the hoop length of the primary corrosion defect fixed at 0.5D and hoop lengths of primary corrosion defect of 0.1D, 0.26D and 0.5D with the hoop length of the secondary corrosion defect fixed at 0.1D. As shown in Fig. 4.3, there is

no significant difference in the local buckling response with the change in the hoop length of the secondary corrosion defect. However, the critical local moment, critical compressive strain and critical local curvature ratios decrease with the increase in the hoop length of the primary corrosion defect. Hence, the primary and secondary corrosion defects with equal hoop length are considered in the parametric study.

4.2.4 Corrosion Defect Depth

The study conducted by Alenezi (2015) showed that the depth of the corrosion defect plays a vital role in the buckling response of the pipe with a single patch corrosion. Similar to the study conducted on the effect of the axial and hoop lengths of primary and secondary corrosion defects, a preliminary study is being conducted to study the effect of corrosion depth with a constant defect hoop length $l_{hcp}=l_{hcs}=0.26D$ and axial length $l_{acp}=l_{acs}=0.4D$. Numerical simulations are carried out for secondary corrosion defect depths of $0.2t$, $0.3t$ and $0.4t$ with the depth of the primary corrosion fixed at $0.4t$ and primary corrosion defect depths of $0.2t$, $0.3t$ and $0.4t$ with the depth of secondary corrosion defect fixed at $0.2t$.

Results of numerical simulations are shown in Fig. 4.4. It can be seen that the critical buckling limits changes significantly with the increase in the primary corrosion defect depth. There is a smaller change in the critical local compressive strain and curvature ratios with the increase in the secondary corrosion defect depth, but appear to be greater than varying the defect axial and hoop length of the secondary corrosion in Sections 4.2.2 and 4.2.3. Similar to varying the axial and hoop lengths of the secondary corrosion, there is no significant change in the critical local moment with the change in the defect depth of the secondary corrosion. For this reason, primary and secondary corrosion defects with different depths are considered in the parametric study.

Although flow induced corrosion occurs in colonies along the flow direction of the pipeline, the depth of the corrosion defect may not be uniform along the hoop direction. Considering the corrosion defects as a single defect with a constant depth equal to the maximum of the defect depth may significantly underestimate the critical buckling limits. Thus, a corrosion defect of the same axial and hoop lengths, but with an equivalent depth may be considered instead. The equivalent depth can be calculated according to the proposed equation as

$$d_e = \frac{\int_0^{\theta_1} d \cos \theta d\theta}{\int_0^{\theta_1} \cos \theta d\theta} \quad (4.15)$$

where d is the depth of corrosion defect, θ is the angle measured at the compression face from the plane perpendicular to the bending axis, θ_1 is the angle at the end of the corrosion defect segment being considered in the hoop direction. Corrosion defects are assumed to be symmetric about the same plane where the angle θ is measured from. Examples on estimating the critical buckling limits with an equivalent depth and the validation of the procedure are presented in Appendix C.

Table 4.1 Material properties parameters for the FEA parametric study

Material type	σ_{er}	C	n
M1	1.30	4.729×10^{-3}	8.539
M2	1.65	4.640×10^{-4}	8.930
M3	2.00	7.600×10^{-5}	9.029

Parameters	Value
Modulus of Elasticity	200000 MPa
Poisson's ratio	0.30
True stress at proportional limit σ_{t0}	480 MPa
Relative strain at peak stress ε_{er}	0.12
Strain at the end of yield plateau ε_{tp0}	0

C and n values are adopted from Alenezi (2015).

Table 4.2 Results on corrosion defects interaction for $\sigma_{er}=1.65$, $D/t=70$, $\sigma_a/\sigma_y=0.2$,
 $l_{ac}/D=0.2$, $l_{hc}/D=0.25$, $d/t=0.3$ and $gap=3t$

p/p _y =0.4				
Model	No. of corrosion defect along axial direction	Critical local moment (kNm)	Critical compressive strain (mm/mm x 10 ⁻⁶)	Critical local curvature (rad/mm x 10 ⁻⁶)
A1	1	1268	10652	21.35
A2	2	1336	11726	23.92
A3	3	1353	11894	23.99
A4	4	1359	11932	24.08
A2/A1		1.05	1.10	1.12
A3/A1		1.07	1.12	1.12
A4/A1		1.07	1.12	1.13

p/p _y =0.0				
Model	No. of corrosion defect along axial direction	Critical local moment (kNm)	Critical compressive strain (mm/mm x 10 ⁻⁶)	Critical local curvature (rad/mm x 10 ⁻⁶)
A1	1	1456	7927	16.27
A2	2	1423	8746	18.27
A3	3	1437	8895	18.52
A4	4	1444	8950	18.66
A2/A1		0.98	1.10	1.12
A3/A1		0.99	1.12	1.14
A4/A1		0.99	1.13	1.15

Figure 4.1 True stress versus true plastic strain

Figure 4.2 Critical buckling limit ratio versus axial length of the corrosion defect with respect to P/P_y ratio for $\sigma_{er}=1.65$, $D/t=70$, $\sigma_a/\sigma_y=0.2$, $d_p/t=d_s/t=0.3$ and $l_{hcp}/D=l_{hcs}/D=0.26$

Figure 4.3 Critical buckling limit ratio versus hoop length of the corrosion defect with respect to P/P_y ratio for $\sigma_{er}=1.65$, $D/t=70$, $\sigma_a/\sigma_y=0.2$, $d_p/t=d_s/t=0.3$ and $l_{acp}/D=l_{acs}/D=0.4$

Figure 4.4 Critical buckling limit ratio versus depth of the corrosion defects with respect to P/P_y ratio for $\sigma_{er}=1.65$, $D/t=70$, $\sigma_a/\sigma_y=0.2$, $l_{hcp}/D=l_{hcs}/D=0.26$ and $l_{acp}/D=l_{acs}/D=0.4$

5 Chapter: FEA Simulation Results and Analyses

A finite element analysis parametric study has been conducted to quantify the buckling response of line pipes subjected to a combined loading with corrosion defects aligned along the axial direction. Utilizing the numerical simulation results from the parametric study, non-dimension equations are developed to predict the critical buckling limits (critical local moment, critical compressive strain and critical local curvature) of the corroded pipe. Equations are validated by comparing the predicted values against results from finite element analyses for a range of pipe geometry, loading and corrosion defect size.

5.1 Parameters in the Parametric Study

The buckling response (bending) of a plain pipe is affected by the material properties, pipe geometry and loading conditions. In this study, only the engineering stress-engineering strain curve without yield plateau will be considered. Taking the proportional limit or yield strength as 480 MPa and the relative strain at peak stress to be 0.12, the only parameter that has to be considered to define the engineering stress-engineering strain curve is the ultimate to yield strength ratio (σ_{er}). The geometry of the pipe can be characterized with the outside pipe diameter to its thickness ratio (D/t), while the loading such as axial load and internal pressure can be defined relative to the yield strength as axial load ratio (σ_a/σ_y) and internal pressure ratio (p/p_y).

For a corroded pipe, the buckling response (failure) is further influenced by the size of the corrosion defect. The corrosion defect is idealized to be rectangular with sides aligned along the longitudinal and circumferential directions even though there are infinite shapes for the actual defect. Nevertheless, no sensitivity study has been carried out to investigate

the effects of defect shape on the critical buckling limits. In the preliminary study, effects of axially aligned corrosion defects are found not to be significantly affected by the axial and circumferential lengths of the secondary corrosion defect. Thus, only the primary and secondary corrosion defects of the same axial and circumferential lengths spaced at one constant multiple of the pipe wall thickness are considered. In addition to two corrosion defects, the specimen (model) with a single corrosion defect is also included in the parametric study.

Non-dimensional equations to predict the critical buckling limits of a corroded pipe under a combined loading are developed based on the above parameters on the material properties, pipe geometry, loading and corrosion defect size. The critical local moment, critical compressive strain and critical local curvature ratios as a function of these parameters can be expressed in a form as shown below.

The corroded to plain pipe critical local moment ratio

$$\frac{M_{lc}}{M_{lp}} = f \left\{ \sigma_{er}, \frac{D}{t}, \frac{p}{p_y}, \frac{\sigma_a}{\sigma_y}, \frac{l_{ac}}{D}, \frac{l_{hc}}{D}, \frac{d_p}{t}, \frac{d_s}{t} \right\}, \quad (5.1)$$

the corroded to plain pipe local compressive strain ratio

$$\frac{\varepsilon_{lc}}{\varepsilon_{lp}} = g \left\{ \sigma_{er}, \frac{D}{t}, \frac{p}{p_y}, \frac{\sigma_a}{\sigma_y}, \frac{l_{ac}}{D}, \frac{l_{hc}}{D}, \frac{d_p}{t}, \frac{d_s}{t} \right\} \text{ and} \quad (5.2)$$

the corroded to plain pipe critical local curvature ratio

$$\frac{\Phi_{lc}}{\Phi_{lp}} = h \left\{ \sigma_{er}, \frac{D}{t}, \frac{p}{p_y}, \frac{\sigma_a}{\sigma_y}, \frac{l_{ac}}{D}, \frac{l_{hc}}{D}, \frac{d_p}{t}, \frac{d_s}{t} \right\} \quad (5.3)$$

where l_{ac} and l_{hc} are the axial and hoop lengths of the corrosion defect, and d_p and d_s are the primary and secondary corrosion defect depths respectively. Following the discussions on

the buckling response of the pipe in Chapters 2 and 4, the ranges of the parameters considered in the parametric study are discussed below.

5.1.1 Ranges of Material Properties, Pipe Geometry and Loading

Ranges of pipe geometry, material properties and loading considered in the parametric study are similar to that by Alenezi. (2015). As noted in Chapter 4, the ultimate to yield (proportional limit) strength ratio (σ_{er}) of the steel can range from 1.3 to 2.0. For the parametric study, the material stress-strain curves generated for the ultimate to yield strength ratios of 1.3, 1.65 and 2.0 are considered.

The maximum diameter to thickness ratio (D/t) permissible according to the Canadian Standard of Oil and Gas Pipeline System CAN/CSA-Z662-11 (CSA 2011) is close to 200, but the D/t ratio of oil and gas pipelines are generally between 40 and 100. Thus, three D/t ratios of 40, 70 and 100 are considered in the parametric study.

Beside the applied rotation, the pipe is subjected to internal pressure and axial load in the parametric study. According to CAN/CSA-Z662-11 (CSA 2011), the maximum allowable internal pressure ratio (p/p_y) is 0.8. Thus, the internal pressure ratios of 0.0, 0.4, and 0.8 are considered for three materials in the parametric study. The proportional limit is taken as the yield strength (proportional limit) of the material in the parametric study instead of the actual material yield strength determined according to the standard. Hence, p/p_y of 1.0 is also included for the material with σ_{er} of 2.0 as the actual yield strength can be significantly greater than the proportional limit.

The other loading parameter is the axial load ratio (σ_a/σ_y), which is the ratio of the average longitudinal stress (σ_a) in the pipe wall to the (yield stress) material proportional limit (σ_y).

Internal pressure and change in temperature can produce an axial load in the pipe. Due to the Poisson's ratio effect, tensile axial stress is generated in the pipe by the hoop stress from the internal pressure. Taking the axial stress to be positive in compression, the axial stress due to Poisson's effect can be expressed as

$$\sigma_a = -\nu \frac{p}{p_y} \sigma_y \quad (5.4)$$

where σ_y and ν are the yield strength and Poisson's ratio respectively. This gives $\sigma_a/\sigma_y=0.24$ for $p/p_y=0.8$ and $\nu=0.3$. The axial stress due to temperature change is given by

$$\sigma_a = E * \alpha * \Delta_T \quad (5.5)$$

where Δ_T is the temperature difference and α is the coefficient of thermal expansion of steel pipe. According to Mohareb et al. (1994), the temperature difference between installation and operation of the pipe can reach up to 45°C. Taking α as $11.7 \times 10^{-6}/^\circ\text{C}$, the axial stress will approximately be 105 MPa. This translates into the axial stress ratio (σ_a/σ_y) of 0.35 and 0.22 for the yield strengths of 300MPa and 480MPa respectively. Thus, the axial stress ratio (σ_a/σ_y) of -0.2, 0.0, 0.2 and 0.4 are considered in the parametric study. The ratios 0.0 to 0.4 cover the condition of the maximum possible temperature difference between installation and operation together with the internal pressure (p/p_y) of 0.0 to 0.8, while the ratio -0.2 covers the situation when there is no temperature difference. Since the local buckling limit tends to improve with a higher tensile axial load, the axial stress ratio (σ_a/σ_y) of -0.2 is considered only for a few selective cases in the parametric study.

5.1.2 Ranges of Corrosion Defect Size

Single corrosion defect and two axially aligned corrosion defects with equal and unequal

depth at one fixed clear spacing between defects are considered in the parametric study. The defect sizes are defined by the axial (l_{ac}/D) and circumferential (l_{hc}/D) lengths relative to the pipe diameter, and the depth of primary (d_p/t) and secondary (d_s/t) corrosion defects relative to the pipe thickness. According to ASME B31G (ASME 2012), the defects are considered to be contagious if the spacing is less than 3 times the wall thickness. A clear spacing between corrosion defects of 3 times the wall thickness ($3t$) has been adopted for the parametric study. In the case study by Palmer-Jones et al. (2007), the maximum average axial length of a corrosion defect was found to reach around 60% of the pipe diameter ($0.6D$) and the hoop length of the defect was found to be less than 50% of the pipe diameter ($0.5D$). For the material with the ultimate to yield strength ratio of $\sigma_{er}=1.3$, bursting occurs at an internal pressure ratio of $p/p_y=0.8$ for a long axial groove corrosion defect with no axial applied stress when the corrosion defect depth reaches 40% ($0.4t$) of the wall thickness. For the ultimate to yield strength and pressure ratios of $\sigma_{er}=1.65$ and $p/p_y=0.8$, and $\sigma_{er}=2.0$ and $p/p_y=1.0$, the corresponding corrosion defect depth for bursting is $0.5t$. Thus, the corrosion defect up to a depth of 40% pipe thickness ($0.4t$) with the axial length ratios (l_{ac}/D) of 0.2, 0.4 and 0.6 and hoop length ratios (l_{hc}/D) of 0.1, 0.26 and 0.5 are considered in the parametric study.

The various primary and secondary corrosion defect depths considered in the parametric study are shown in Table. 5.1. Corrosion defect depth combinations consist of (d_p1 , d_p2 , d_p3) x (d_s6) for single corrosion defect, (d_p1d_s1), (d_p2d_s2) and (d_p3d_s3) for two corrosion defects with equal depth, and (d_p3d_s5) and (d_p2d_s4) for two corrosion defects with unequal depth. One of the defect depth combinations for two corrosion defects with unequal depth is the combination (d_p3d_s5) with the primary defect depth ratio $d_p/t=0.4$ and secondary

depth ratio $d_s/t=0.1$, which together gives a secondary to primary defect depth ratio of $d_s/d_p=0.25$. The other combination ($d_p=2d_s$) has the corresponding primary and secondary defect depth ratios of $d_p/t = 0.3$ and $d_s/t = 0.2$ to give a secondary to primary defect depth ratio of $d_s/d_p=0.67$. These combinations cover the full range of corrosion defect depth ratio d_s/d_p from 0.0 to 1.0.

The finite element model adopted in the parametric study is based on the model discussed in Chapter 3. The mesh configurations are slightly altered to match the axial and hoop lengths of the corrosion defect. The aspect ratio of the refined zone is maintained to be close to 1.0 for all the models. The outer diameter of the pipe (D) is taken as 609.6 mm and the length to be 3048 mm, which is 5 times the outer diameter of the pipe. Parameters considered in the parametric study and their designations are shown in Table 5.1. The primary parametric combinations for the material, pipe geometry and loading consist of ($M1, M2, M3$) x ($D1, D2, D3$) x ($P1, P2, P3$) x ($A1, A2, A3$). Analyses with the tensile axial load ratio ($A4$) is considered only for the combinations with the material $M2$, geometry $D2$ and pressure $P2$ ($M2D2P2A4$). Also, the maximum pressure ratio $P4$ is considered only for $M3, D2$ and $A2$ ($M3D2P4A2$). These combinations are combined with the corrosion defect size combinations.

5.1.3 Indirect Populating Critical Buckling Limits

There are a large number of parametric combinations considered, and hence a huge amount of FEA simulations to be carried out. Thus, it is desirable to explore options to reduce the number of finite element analyses and computing effort required. One of the option is to consider the possibility of populating the critical buckling limits data without carrying out the FEA simulations for all the parametric combinations. A number of consistent trends

can be observed in the change of the critical buckling limits with the change in some of the parameters. On this basis, two schemes have been developed to indirectly populate (predict) the critical buckling limits of pipes with two corrosion defects of the same depth ($d_p=d_s$) and pipes with single corrosion defect ($d_s=0$) using only FEA results from a reduced set of parametric combinations. Some of the predicted critical buckling limits from these schemes are compared to results from the finite element analyses for validation.

5.1.3.1 Populating Critical Buckling limits for Two Corrosion Defects with Equal Depth

It has been observed that the rate of change in the local buckling limit ratio with an increasing hoop length of the corrosion defect is nearly the same for different corrosion defect axial lengths. Based on this, the FEA results for the corrosion defect sizes of $(a_1, a_2, a_3) \times (h_2)$ and $(a_2) \times (h_1, h_3)$ are used to populate (estimate) the critical buckling limits for the defect sizes of $(a_1, a_3) \times (h_1, h_3)$ of the same loading, pipe geometry, material and defect depth with the assumption that the ratio of the reduction in the critical buckling limit ratio between different defect hoop lengths is independent of the defect axial length. The critical buckling limit ratio can be estimated with

$$Ca(j)h(k) = 1 - \left[\frac{(1 - Ca_2h(k))}{(1 - Ca_2h_2)} \times (1 - Ca(j)h_2) \right] \text{ for } j=1, 3 \text{ and } k=1, 3 \quad (5.6)$$

based on the assumption

$$\frac{1 - Ca(j)h(k)}{1 - Ca(j)h_2} = \frac{1 - Ca_2h(k)}{1 - Ca_2h_2} \quad (5.7)$$

where $Ca(j)h(k)$, $Ca_2h(k)$, Ca_2h_2 and $Ca(j)h_2$ are the critical local buckling ratios for the pipes with the axial and hoop corrosion defect sizes of $a(j)h(k)$, $a_2h(k)$, a_2h_2 and $a(j)h_2$ respectively. This scheme has been employed to populate the critical buckling limit data of

the parametric study for all parametric combinations with two corrosion defects of equal depth ($d_p=d_s$) and a few combinations with a single corrosion defect. The combinations associated with a single corrosion defect are identified and discussed in the next section.

The predicted results for two corrosion defect of equal depth are compared to FEA results of the parametric combinations in Table. 5.2 for validation. The ratios and differences of the critical buckling limit ratios between the predicted values (Pr) and FEA results are plotted with respect to FEA results in Figs. 5.1 to 5.6. Overall, there is a good agreement between the predicted and FEA critical buckling limit ratios with the ratio between the predicted to FEA results (Pr/FEA) within 6% and the difference ($Pr-FEA$) between the predicted and FEA results within ± 0.04 .

5.1.3.2 Populating Critical Buckling limit for Single Corrosion Defect

Another scheme has also been developed to populate the critical buckling limit data of pipes with the single corrosion defect. In the parametric study, FEA simulations are carried out for all parametric combinations with two corrosion defects of unequal depth. The parametric combinations with primary defect depth ratio $d_p/t=0.4$ (d_{p3}) and secondary defect depth ratio $d_s/t=0.1$ (d_{s5}) have the corrosion defect geometry that is close to the combinations with a single corrosion defect having the primary defect depth $d_p/t=0.4$ (d_{p3}). It has been found and expected that the critical buckling limit ratios are very close between pipes with these two corrosion defect geometries ($d_{p3}d_{s5}$, $d_{p3}d_{s6}$) having the same parametric combination other than the defect depth. It is assumed that there is a relationship between the critical buckling limit ratios of single corrosion defect at $d_p/t=0.4$ ($d_{p3}d_{s6}$), two corrosion defects with equal depth at $d_p/t=d_s/t=0.4$ ($d_{p3}d_{s3}$) and two corrosion defects with unequal depth at $d_p/t=0.4$ and $d_s/t=0.1$ ($d_{p3}d_{s5}$) having the parametric combinations of the

same loading, pipe D/t ratio and defect axial length ratio. The relationship can be expressed as

$$\left[\frac{(D4)-(D41)}{(D4)-(D44)} \right] = \left[\frac{(D4h)-(D41h)}{(D4h)-(D44h)} \right] \quad (5.8)$$

where D4h, D44h and D41h are the known critical buckling limit ratios for single corrosion defect (d_p3d_s6), two corrosion defects with equal depth (d_p3d_s3) and unequal depth (d_p3d_s5) respectively of the same material and defect hoop length ratio, while D4, D44 and D41 are the critical buckling limit ratios for single corrosion defect (d_p3d_s6), two corrosion defects with equal depth (d_p3d_s3) and unequal depth (d_p3d_s5) of another material and/or at another defect hoop length ratio. However, all six of these ratios are for the same loading, pipe D/t ratio and defect axial length ratio. The unknown critical buckling limit ratio, D4, is calculated from Eq. (5.8) with the expression

$$D4 = \frac{(D41 - R41 * D44)}{(1 - R41)} \quad \text{and} \quad (5.9)$$

$$R41 = \frac{(D4h - D41h)}{(D4h - D44h)} \quad \text{with } 0 \leq R41 \leq 0.2 \quad (5.10)$$

The limits are set for R41 due to the uncertainty error from finite element analysis and ill-conditioning that may be introduced when $(D4h-D41h)$ and $(D4h-D44h)$ are close to zero. The ratio R41 is expected to be greater than zero because the critical buckling limit ratio trend is either $D4h > D41h > D44h$ or $D4h < D41h < D44h$ based on the corrosion defect geometry. The upper limit of 0.2 is set based on the ratio of 0.25 (d_s5/d_s3) between the secondary corrosion defect depth for two corrosion defects of unequal depth and that of equal depth. Finite element analysis simulations for single corrosion defect at the depth

$d_p/t=0.4$ for material M2 and defect hoop length ratio h_2 ($M_2h_2d_p3d_s6$) at combinations $(D_1, D_2, D_3) \times (A_1, A_2, A_3) \times (P_1, P_2, P_3) \times (a_1, a_2, a_3)$ are carried out to supply the seed value for D_4h in Eqs. (5.8) and (5.10) to calculate D_4 (d_p3d_s6) for the $[(M_1, M_3) \times (h_1, h_2, h_3), (M_2) \times (h_1, h_3)] \times (D_1, D_2, D_3) \times (A_1, A_2, A_3) \times (P_1, P_2, P_3) \times (a_1, a_2, a_3)$ parametric combinations. In addition, FEA simulations for single corrosion defect are also carried out for the parametric combinations of $(M_2h_2d_p3d_s6P_2D_2A_4) \times (a_1, a_2, a_3)$ and $(M_3h_2d_p3d_s6P_4D_2A_2) \times (a_1, a_2, a_3)$ to supply the seed value for D_4h to calculate D_4 (d_p3d_s6) $\times (M_2P_2D_2A_4, M_3P_4D_2A_2) \times (h_1, h_3) \times (a_1, a_2, a_3)$ for the two special parametric combination sets.

The critical buckling limit ratio for single corrosion defect at other depths are estimated by assuming the proportion of the loss in the critical buckling limit ratio due to the depth is the same for single corrosion defect and two corrosion defects of equal depth according to the relationship

$$\frac{1-D_a}{1-D_{aa}} = \frac{1-D_b}{1-D_{bb}} \text{ with} \quad (5.11)$$

$$D_a = 1 - \frac{(1-D_b)}{(1-D_{bb})}(1-D_{aa}) \quad (5.12)$$

where D_a and D_b are critical buckling limit ratios at the same defect depth for single corrosion defect and two corrosion defects of equal depth, and D_{aa} and D_{bb} are the critical buckling limit ratios corresponding to the deepest defect depth at which both the ratios (D_{aa}, D_{bb}) for single corrosion defect and two corrosion defects of equal depth are considered to be valid. The critical buckling limit ratio is considered to be invalid if it is higher than the ratio at a shallower defect depth. This can occur for a pressurized pipe with a deep corrosion defect due to the effect of biaxial tension generated in the pipe wall at the

defect that can delay the deformation at which the critical local buckling moment is reached. A more detailed discussion of this phenomenon will be provided in the following section. It has been observed that the increase in the critical buckling limit ratio with the increase in the defect depth due to the biaxial tension effect occurs at about the same depth for single corrosion defect and two corrosion defects of equal depth that have the same parametric combinations of material, pipe D/t ratio, loading, axial and hoop corrosion defect lengths. Finite element analysis simulations with single corrosion defect have also been carried out at and around the parametric combinations where the critical buckling limit ratio for two corrosion defects with equal depth exhibits the biaxial tension effect to ensure that biaxial tension effect does not manifest at a shallower defect depth for a pipe with single corrosion defect than that with two corrosion defects when using Eqs. (5.9) and (5.10). Only the critical buckling limit ratio D44 for a single corrosion defect $d_p/t=0.4$ with valid D44 and D44h (no biaxial tension effect) can be estimated with Eqs. (5.9) and (5.10). For other situations, the critical buckling limit ratio for a single corrosion defect at the next shallower corrosion defect depth (d_p2d_s6 or d_p1d_s6) for which the critical buckling limit ratio for two corrosion defects with equal depth (d_p2d_s2 or d_p1d_s1) is valid is estimated using the procedure outlined in Section 5.1.3.1 or calculated directly from the FEA simulation. The critical buckling limit ratios at shallower defect depths are then calculated (estimated) using Eq. (5.12). Numerical simulations are also carried out for any single corrosion defect combination of $h2 \times (D1, D2, D3) \times (P1, P2, P3) \times (A1, A2, A3) \times (a1, a2, a3)$ with material M3 for which the critical buckling limit ratio (D44) of two corrosion defects at equal depth $d_p/t=d_s/t=0.4$ (d_p3d_s3) is valid, but the ratio (D44h) is not valid for the same parametric combination with material M2. The critical buckling limit ratio

obtained from this FEA simulation is used as a seed value D_{4h} in Eq. (5.10) for this situation together with D_{41} and D_{44} for the same parametric combination with material M3 as D_{41h} and D_{44h} in place of the values calculated with material M2 outlined previously.

The predicted results for single corrosion defect are compared to FEA results of the parametric combinations in Table. 5.3 for validation. The ratios and differences of the critical buckling limit ratios between the predicted values (Pr) and FEA results are plotted with respect to FEA results in Figs. 5.7 to 5.12. Overall, there is a good agreement between the predicted and FEA the critical local moment ratio with the ratio between the predicted and FEA results (Pr/FEA) within 5%, but mainly 4% and the difference between the predicted and FEA results (Pr-FEA) within ± 0.05 . Similarly, for critical local compressive strain and local curvature ratios, the ratio between the predicted and FEA results (Pr/FEA) is within 6%, but mainly 4%, and the difference between the predicted and FEA results (Pr-FEA) within ± 0.06 , but mainly ± 0.04 .

Additional FEA simulations for single corrosion defect have also been carried out for parametric combinations of (M2) x (D1, D2, D3) x (A1, A2, A3) x (P1, P2, P3) x (a1, a2, a3) x (h2) x (d_{p1}, d_{p2}) x (d_{s6}) and (M1, M3) x (D1, D2, D3) x (A1, A2, A3) x (P1, P2, P3) x (a2) x (h1, h3) x (d_{p1}d_{s6}, d_{p2}d_{s6}). In all cases, FEA results are used in the parametric study when available instead of the values predicted from the procedures in Sections 5.1.3.1 and 5.1.3.2.

5.2 Effects of the Parameters

In order to help developing equations to predict the critical buckling limits, effects of various parameters are investigated. Around 6000 combinations of different geometries,

loading conditions and corrosion defect sizes have been considered in this study. Non-dimensional values are used to evaluate the effects of the parameters on the critical buckling limits, which are represented by ratios of the critical local moment, critical compressive strain and critical local curvature with respect to the plain pipe buckling (failure) limits.

5.2.1 Effects of Geometry and Loading condition

Effects of D/t ratio, pressure and axial load ratios (p/p_y , σ_a/σ_y) on the critical buckling limits are investigated for single corrosion defect, two corrosion defects with equal and unequal depth at the defect axial length of $0.4D$ (a_2) and hoop length of $0.26D$ (h_2). Only material (M2) is being considered in this investigation as the change in the buckling response with various parameters are generally the same for different material ultimate to yield strength ratios.

Figs. 5.13 to 5.15 show critical buckling limits versus D/t ratio at 0% and 80% pressure ratios. The critical local moment ratio decreases with the increase in D/t ratio at zero pressure, but there is only a small change with the D/t ratio at a higher pressure ratio of (p/p_y) of 80%. The critical compressive strain and curvature ratios decrease with the increase in D/t ratio at zero pressure, but increase with the D/t ratio at a higher pressure ratio (p/p_y) of 80%.

Figs. 5.16 to 5.18 show the critical buckling limits versus axial load ratio (σ_a/σ_y) at 0% and 80% pressure ratios. The critical local moment ratio decreases with the increase in the axial load ratio at both pressure ratios (p/p_y) of 0% and 80%, but there is no considerable change in the critical compressive strain and curvature ratios with the axial load ratio. Figs. 5.19 to 5.21 show the critical buckling limits versus internal pressure ratio (p/p_y) at 0% and 40%

of the axial load ratio (σ_a/σ_y). As expected, the critical local moment ratio generally decreases with the internal pressure ratio at both axial load ratios, but the critical compressive strain and curvature ratios generally increase with the internal pressure ratio. The rate of decrease in the critical local moment is higher at a lower D/t ratio, but the rate of increase in the critical compressive strain and curvature ratios is lower at a lower D/t ratio. In addition, the rate of change in the critical compressive strain and local curvature ratios appears to be close to constant and to be dependent on the D/t ratio over the range of pressure ratio considered.

5.2.2 Effects of Defect Axial, Hoop Length and Depth Ratio

Figs. 5.22 to 5.30 show the critical buckling limit ratios versus defect hoop length and depth ratios for different loading and geometry conditions with material M2 and the corrosion defect axial length ratio (l_{ac}/D) of 0.4. It can be seen that the critical local moment (M_{lc}/M_{lp}), critical compressive strain ($\epsilon_{lc}/\epsilon_{lp}$) and critical local curvature (Φ_{lc}/Φ_{lp}) ratios generally decrease with the increase in the defect hoop length and depth ratios.

The critical buckling limit ratios decrease at a reducing rate with the increase in the corrosion defect depth, but the limits appear to have initially decreased at an increasing rate with the increase in the defect hoop length ratio before changing to a reducing rate at a higher defect hoop length ratio. The change in the decrease rate with the defect hoop length ratio is more pronounced at a shallower defect depth. In a few cases (Figs. 5.23, 5.24, 5.29 and 5.30), the critical compressive strain and local curvature ratios initially decrease with the increase in the defect depth ratio before turning to an increase with the subsequent increase in the defect depth ratio. These situations normally occur for a highly pressurized pipe with a deep corrosion defect. A bulge forms in the corroded region of a pipe when it

is pressurized. This creates an additional axial tension stress in the local buckling zone. Together with the hoop tension stress, the biaxial tension stress may delay the deformation at which the local moment reaches its critical limit (peak). The bulge becomes more acute with the increase in pressure and corrosion defect depth.

Fig. 5.31 shows the critical buckling limit ratios versus defect axial length ratio for various combinations of the defect depth along the axial direction at internal pressure ratios (p/p_y) of 0.0 and 0.4. It can be seen that the interaction of the defects aligned along the axial direction has a greater effect on the critical compressive strain and local curvature ratio than the critical local moment ratio. The effects of the interaction also appear to be greater for a pressurized than a non-pressurized pipe. From the plots, the critical buckling limits appear to reach a minimum around the corrosion defect axial length of $0.2D$. In the study by Alenezi. (2015) for a single corrosion defect with the defect axial length ratio from 0.1 to 1.5, the critical buckling limits appear to reach a minimum around the defect axial length ratio of 0.25 with only a small change in the limits at the defect axial length ratio greater than 0.5. However, the exact defect axial length ratio at which the minimum occurs varies with the loading, material properties, pipe geometry and other dimensions (hoop length and depth) of the corrosion defect. A preliminary study found that the dip in the critical buckling limits with the increase in the defect axial length ratio is affected by the profile of the corrosion defect. A corrosion defect that has a gradual change in thickness produces a shallower dip compared to a defect that has a sudden change in thickness. With the location of dip being affected by many factors, it is decided not to include the defect axial length ratio as a variable in the non-dimensional equations to predict the critical buckling limits. Furthermore, additional analyses at defect axial length ratio less than 0.2 will be required

in order to provide a better estimate of the minimum. Additional study to look into this effect is outside the scope of this research and has not been carried out.

The parametric study results are listed in Appendix D with cells in the table denoted with F to represent the FEA simulations where the analysis stopped (pipe model failed) before the application of any end rotation. In addition, some FEA simulations are labelled with a trailing (*) to indicate that the critical compressive strain and local curvature ratios have been excluded in developing the non-dimensional equations to predict the critical buckling limits due to biaxial tension effect.

5.3 Generating the Critical Buckling Limit Equations

Based on the results of parametric finite element analyses, separate equations have been developed to predict the critical local moment ratio (M_{lc}/M_{lp}), critical compressive strain ratio ($\epsilon_{lc}/\epsilon_{lp}$) and critical local curvature ratio (Φ_{lc}/Φ_{lp}) for each of the material ultimate to yield strength ratio (σ_{er}) and corrosion defect axial length ratio (l_{ac}/D). Separate equations are also developed for single corrosion defect and two corrosion defects for each of the primary to secondary defect depth ratio. Results from analyses that failed before the application of end rotation, and critical compressive strain and local curvature ratios that exhibit the biaxial tension effect where the buckling limit ratio increases with the increase in the corrosion defect depth are excluded in developing the critical buckling limit equations. Critical compressive strain and local curvature limit ratios for two corrosion defects with unequal depth are also excluded if the ratio from two corrosion defects with equal depth at the same primary defect depth ratio have been excluded.

Non-dimension equations have been generated based on the parametric finite element analysis results and the observed change in the critical buckling limits with respect to

various parameters of D/t , p/p_y , σ_a/σ_y , l_{hc}/D and d_p/t through a multi-variable regression analysis. The final forms of the non-dimensional equations have been arrived at through trial and error. Since the local curvature is calculated based on the compressive strain, the same form of proposed equations are used for predicting the critical compressive strain ratio and critical local curvature ratio.

The proposed equations for single corrosion defect and two corrosion defects with equal depth are shown below

$$\frac{M_{lc}}{M_{lp}} = 1 - \left(k_{1m} + \left(k_{2m} * \left(\frac{D}{t} \right)^{k_{3m}} \right) * \left(1 + k_{4m} * \left(\frac{p}{p_y} \right)^{k_{5m}} \right) * \left(1 - k_{6m} * \left(\frac{\sigma_a}{\sigma_y} \right) \right) \right) * \left(\left(\left(-k_{11m} * \left(\frac{l_{hc}}{D} \right)^{k_{7m}} \right) * e^{\left(-k_{12m} * \left(\frac{l_{hc}}{D} \right) \right)} \right) * \left(\left(1 - \frac{d_p}{t} \right)^{k_{8m}} \right) + \left(\frac{l_{hc}}{D} \right)^{k_{9m}} \right) * \left(\frac{d_p}{t} \right)^{k_{10m}} \right) \quad (5.13)$$

$$\frac{\varepsilon_{lc}}{\varepsilon_{lp}} = 1 - \left(k_{1s} + \left(k_{2s} * \left(\frac{D}{t} \right)^{k_{3s}} \right) * \left(1 + k_{4s} * \left(\left(\frac{D}{t} \right)^{k_{13s}} \right) * \left(\frac{p}{p_y} \right)^{k_{5s}} \right) * \left(1 - k_{6s} * \left(\frac{\sigma_a}{\sigma_y} \right) \right) \right) * \left(\left(\left(-k_{11s} * \left(\frac{l_{hc}}{D} \right)^{k_{7s}} \right) * e^{\left(-k_{12s} * \left(\frac{l_{hc}}{D} \right) \right)} \right) * \left(\left(1 - \frac{d_p}{t} \right)^{k_{8s}} \right) + \left(\frac{l_{hc}}{D} \right)^{k_{9s}} \right) * \left(\frac{d_p}{t} \right)^{k_{10s}} \right) \quad (5.14)$$

$$\frac{\Phi_{lc}}{\Phi_{lp}} = 1 - \left(k_{1c} + \left(k_{2c} * \left(\frac{D}{t} \right)^{k_{3c}} \right) * \left(1 + k_{4c} * \left(\left(\frac{D}{t} \right)^{k_{13c}} \right) * \left(\frac{p}{p_y} \right)^{k_{5c}} \right) * \left(1 - k_{6c} * \left(\frac{\sigma_a}{\sigma_y} \right) \right) \right) * \left(\left(\left(-k_{11c} * \left(\frac{l_{hc}}{D} \right)^{k_{7c}} \right) * e^{\left(-k_{12c} * \left(\frac{l_{hc}}{D} \right) \right)} \right) * \left(\left(1 - \frac{d_p}{t} \right)^{k_{8c}} \right) + \left(\frac{l_{hc}}{D} \right)^{k_{9c}} \right) * \left(\frac{d_p}{t} \right)^{k_{10c}} \right) \quad (5.15)$$

where k_{am} , k_{as} and k_{ac} are parameters determined through the non-linear regression analysis based on the least square difference between predicted and FEA results of the buckling limits. Parameters determined for the equations, and the comparison of the predicted results (Pr) using these equations to the FEA results on the mean, standard deviation, and coefficient of variation of Pr/FEA and the

mean and standard deviation for of Pr-FEA are shown in Tables 5.4 to 5.9.

The proposed equations for two corrosion defects with unequal depth are shown below

$$\frac{M_{lc}}{M_{lp}} = 1 - \left(r1m + \left(r2m * \left(\frac{D}{t} \right)^{r3m} \right) * \left(1 + r4m * \left(\frac{p}{p_y} \right)^{r5m} \right) * \left(1 - r6m * \left(\frac{\sigma_a}{\sigma_y} \right) \right) \right) * \left(\left(\left(-r9m * \left(\frac{l_{hc}}{D} \right)^{r7m} \right) * e^{\left(-r10m * \left(\frac{l_{hc}}{D} \right) \right)} \right) + \left(\frac{l_{hc}}{D} \right)^{r8m} \right) \quad (5.16)$$

$$\frac{\varepsilon_{lc}}{\varepsilon_{lp}} = 1 - \left(r1s + \left(r2s * \left(\frac{D}{t} \right)^{r3s} \right) * \left(1 + r4s * \left(\left(\frac{D}{t} \right)^{r1ls} \right) * \left(\frac{p}{p_y} \right)^{r5s} \right) * \left(1 - r6s * \left(\frac{\sigma_a}{\sigma_y} \right) \right) \right) * \left(\left(\left(-r9s * \left(\frac{l_{hc}}{D} \right)^{r7s} \right) * e^{\left(-r10s * \left(\frac{l_{hc}}{D} \right) \right)} \right) + \left(\frac{l_{hc}}{D} \right)^{r8s} \right) \quad (5.17)$$

$$\frac{\Phi_{lc}}{\Phi_{lp}} = 1 - \left(r1c + \left(r2c * \left(\frac{D}{t} \right)^{r3c} \right) * \left(1 + r4c * \left(\left(\frac{D}{t} \right)^{r1lc} \right) * \left(\frac{p}{p_y} \right)^{r5c} \right) * \left(1 - r6c * \left(\frac{\sigma_a}{\sigma_y} \right) \right) \right) * \left(\left(\left(-r9c * \left(\frac{l_{hc}}{D} \right)^{r7c} \right) * e^{\left(-r10c * \left(\frac{l_{hc}}{D} \right) \right)} \right) + \left(\frac{l_{hc}}{D} \right)^{r8c} \right) \quad (5.18)$$

where $r\beta m$, $r\beta s$ and $r\beta c$ are parameters determined through the non-linear regression analysis based on the least square difference

between predicted and FEA results of the buckling limits. Parameters determined for the equations, and the comparison of the predicted results (Pr) using these equations to the FEA results on the mean, standard deviation, and coefficient of variation of Pr/FEA and the mean and standard deviation for of Pr-FEA are shown in Tables. 5.10 to 5.15.

The graphical comparison of model predicted results (Pr) and FEA results are shown in Figs. 5.32 to 5.37 for Pr/FEA and Pr-FEA with respect to FEA critical buckling limit ratio. Overall, there is a good agreement between the predicted and FEA results, with a better agreement achieved for the critical local moment ratios than both the critical compressive strain and local curvature ratios. The ratio Pr/FEA becomes larger as the FEA critical buckling limit ratio decreases. This is expected since the regression analysis minimizes the difference Pr-FEA. As can be seen in Figs. 5.32 and 5.33, the Pr/FEA ratio for the critical local moment ratio is within 15%, but mostly 8%, and the difference Pr-FEA is within ± 0.08 , but mostly ± 0.05 . For the critical compressive strain and local curvature ratios comparison shown in Figs. 5.34 to 5.37, the Pr/FEA ratio within 24%, but mostly 13%, and the difference Pr-FEA is within ± 0.12 , but mostly ± 0.08 .

Based on the results of the parametric study and Figs. 5.13 to 5.31, the corrosion defect depth ratio (d_p/t) appears to be most important parameter on the critical buckling limit ratios. This is followed by the defect hoop length ratio (l_{hc}/D) as the next most influential parameter. The defect axial length ratio (l_{ac}/D) is less important for the range of ratio considered in this study. Among the three other parameters (D/t , p/p_y and σ_a/σ_y ratios), D/t and p/p_y ratios appear to have the same importance with the σ_a/σ_y ratio being the least important.

5.3.1 Evaluation of Critical Buckling Limit Equations

The developed equations to predict the critical buckling limits are validated against results of some FEA simulations with different geometries, loading conditions and corrosion sizes mostly within the range of parameters considered in the parametric study. The considered parametric combinations for the validation are shown in Table 5.16, which include single corrosion defect, two corrosion defect with equal and unequal depth.

Comparison of the predicted results (Pr) using Eqs. (5.13) to (5.18), and constants from Tables 5.4 to 5.15 to the FEA results for Pr/FEA and Pr-FEA are shown in Table. 5.17, and Figs. 5.38 to 5.43. There is a reasonable agreement between the predicted and FEA critical buckling limit ratios. The accuracy is comparable to the comparisons between the predicted and FEA results used in developing the critical buckling equations. For the critical local moment ratio, Pr/FEA is within 9%, but mostly 6%, and the difference Pr-FEA is within ± 0.07 , but mostly within ± 0.05 . As for the critical compressive strain and local curvature ratios, Pr/FEA ratio is within 15% but mostly 10%, and the difference Pr-FEA is within ± 0.10 , but mostly ± 0.07 .

Since the critical buckling limit equations are developed through regression analyses based on the least square method of the difference between the predicted and FEA critical buckling limit ratio, it is expected that the equations to over predict almost half of the data points. A simple correction can be applied to the equations to compensate the over prediction to give a more conservative estimate of the FEA results for most situations. For the critical local moment ratio (M_{lc}/M_{lp}), the correction can be added to give a modified predicted critical local moment ratio as

$$\begin{aligned} Pr_m &= P_r - 0.05 \geq 0.0 && \text{for } Pr < 0.9 \text{ and} \\ &= 1.50P_r - 0.50 \leq 1.0 && \text{for } P_r \geq 0.9 \end{aligned} \quad (5.19)$$

The critical compressive strain and local curvature ratios can be modified to incorporate a different correction to give a modified predicted critical compressive strain and local curvature ratios as

$$\begin{aligned} Pr_m &= P_r - 0.08 \geq 0.0 && \text{for } Pr < 0.92 \text{ and} \\ &= 2.0P_r - 1.0 \leq 1.0 && \text{for } P_r \geq 0.92 \end{aligned} \quad (5.20)$$

Figs. 5.44 to 5.46 show Pr -FEA versus Pr for the critical buckling limit data used in the regression analyses together with the value of the correction to be applied to Pr . It can be seen that the modified predicted ratio (Pr_m) gives a conservative prediction of the FEA result for most of the cases except for a few outliers.

Table 5.1 Parameters, their labeling, and combinations in the parametric study

Material	σ_{er}	Geometry	D/t	Pressure load	p/p _y	Axial load	σ_a/σ_y
M1	1.30	D1	40	P1	0.0	A1	0.0
M2	1.65	D2	70	P2	0.4	A2	0.2
M3	2.00	D3	100	P3	0.8	A3	0.4
				P4	1.0	A4	-0.2

Defect axial length	l_{ac}/D	Defect hoop length	l_{hc}/D	Primary corrosion depth	d_p/t	Secondary corrosion depth	d_s/t
a1	0.20	h1	0.10	d_{p1}	0.16	d_{s1}	0.16
a2	0.40	h2	0.26	d_{p2}	0.30	d_{s2}	0.30
a3	0.60	h3	0.50	d_{p3}	0.40	d_{s3}	0.40
						d_{s4}	0.20
						d_{s5}	0.10
						d_{s6}	0.00

(a1, a2, a3) x (h1, h2, h3)
x
(M1, M2, M3) x (D1, D2, D3) x (P1, P2, P3) x (A1, A2, A3), (M2D2P2A4), (M3D2P4A2)
x
(d_{p1} , d_{p2} , d_{p3}) x (d_{s1} , d_{s2} , d_{s3}), (d_{p1} , d_{p2} , d_{p3}) x (d_{s6}), (d_{p3} d_{s5}), (d_{p2} d_{s4})

Table 5.2 Parameters considered in the validation of the two corrosion defects of equal depth

Material properties	D/t ratio	Axial load ratio	Pressure load ratio	Axial length of the defect	Hoop length of the defect	Depth of the primary and secondary defect $d_p/t = d_s/t$
M1	D1, D3	A2	P1, P3	a1	h1, h3	d_{p2}
M2	D2	A1, A3	P2	a3	h1, h3	d_{p1}, d_{p3}
M3	D1, D3	A2	P2	a3	h1, h3	d_{p1}, d_{p3}
M2	D1, D3	A2	P1, P3	a1	h1, h3	d_{p2}

Table 5.3 Parameters considered in the validation of the single corrosion defect

Material properties	D/t ratio	Axial load ratio	Pressure load ratio	Axial length of the defect	Hoop length of the defect	Depth of the primary defect
M1, M3	D2	A2	P1, P3	a1, a3	h1, h3	d_{p1}
M1, M3	D2	A2	P1, P3	a1, a3	h1, h3	d_{p2}
M1, M3	D2	A2	P1, P3	a1, a3	h1, h3	d_{p3}
M2	D1, D3	A1, A3	P2	a1, a3	h1, h3	d_{p2}, d_{p3}

Table 5.4 Parameters for the critical local moment ratio (M_{lc}/M_{lp}) and statistics of Pr/FEA and Pr-FEA for a single corrosion defect

Material (σ_{er})	1.3	1.3	1.3	1.65	1.65	1.65	2	2	2
Axial length (lac/D)	0.2	0.4	0.6	0.2	0.4	0.6	0.2	0.4	0.6
k1m	0.374	0.552	0.368	-1.509	-1.207	-2.336	-1.002	-2.524	-1.700
k2m	0.0907	0.0843	0.0712	0.9150	1.0429	1.4753	0.4991	1.7731	0.8945
k3m	0.450	0.375	0.363	0.269	0.184	0.196	0.385	0.192	0.267
k4m	4.3910	7.3395	6.4560	0.5360	0.6220	0.5280	0.3981	0.3206	0.1601
k5m	2.954	3.275	3.262	1.773	2.694	3.284	1.260	4.632	3.000
k6m	-4.0977	-5.2341	-5.0650	-0.8272	-0.7629	-0.4835	-0.7795	-0.3963	-0.4709
k7m	0.927	0.674	0.620	0.627	0.671	0.769	0.666	0.732	0.772
k8m	2.935	1.476	1.394	1.542	1.245	2.337	1.042	1.519	2.115
k9m	0.577	0.538	0.545	0.562	0.419	0.620	0.545	0.580	0.568
k10m	0.995	0.925	0.664	1.163	0.973	0.756	1.164	1.014	0.776
k11m	5.257	1.836	1.385	2.040	3.072	2.415	1.505	2.093	2.872
k12m	9.392	5.421	3.670	9.392	6.419	4.481	5.416	5.458	5.458
Pr/FEA mean	1.000	1.002	1.002	1.000	1.002	1.002	1.000	1.002	0.997
Pr/FEA std. dev.	0.061	0.044	0.049	0.043	0.045	0.048	0.039	0.039	0.045
Pr/FEA cov	6.1%	4.4%	4.9%	4.3%	4.5%	4.8%	3.9%	3.9%	4.5%
Pr-FEA mean	-0.002	0.001	0.001	-0.001	0.000	-0.002	-0.001	0.001	-0.001
Pr-FEA std. dev.	0.037	0.027	0.036	0.029	0.035	0.036	0.028	0.030	0.035

Table 5.5 Parameters for the critical local compressive strain ratio ($\epsilon_{lc}/\epsilon_{lp}$) and statistics of Pr/FEA and Pr-FEA for a single corrosion defect

Material (σ_{er})	1.3	1.3	1.3	1.65	1.65	1.65	2	2	2
Axial length (lac/D)	0.2	0.4	0.6	0.2	0.4	0.6	0.2	0.4	0.6
k1s	1.022	4.486	1.700	0.659	2.004	0.759	-0.213	-0.153	0.830
k2s	-0.0072	-1.9521	-0.3160	0.0134	-0.4460	0.0364	0.4911	0.7567	0.0167
k3s	0.932	0.161	0.177	0.545	0.155	0.706	0.156	0.160	0.919
k4s	0.0066	0.2867	0.0111	-0.0222	0.0025	-0.0155	-0.0093	-0.0091	-0.5937
k5s	0.258	1.074	0.191	0.135	0.305	0.167	0.141	0.151	0.248
k6s	0.4979	-0.0228	-0.0070	-0.0880	-0.2267	-0.0863	-0.0787	0.2127	-0.0759
k7s	0.334	0.488	0.973	0.434	0.439	0.534	0.451	0.484	0.536
k8s	2.446	1.031	1.038	3.503	1.027	1.033	7.446	3.567	1.034
k9s	0.209	0.449	0.563	0.298	0.362	0.491	0.415	0.445	0.493
k10s	0.359	0.179	0.509	0.175	0.541	0.790	0.056	0.563	0.874
k11s	1.662	0.399	2.296	2.668	0.965	0.937	2.436	1.793	0.853
k12s	5.209	5.305	4.241	5.271	5.274	5.334	2.751	5.302	5.335
k13s	1.042	-0.193	0.977	1.054	1.276	1.009	0.832	0.928	0.210
Pr/FEA mean	1.007	1.006	1.008	1.007	1.008	1.009	1.006	1.007	1.005
Pr/FEA std. dev.	0.061	0.051	0.060	0.076	0.076	0.069	0.071	0.071	0.076
Pr/FEA cov	6.1%	5.1%	6.0%	7.5%	7.5%	6.8%	7.1%	7.1%	7.6%
Pr-FEA mean	-0.001	-0.001	-0.001	0.001	0.001	0.003	-0.002	0.001	0.000
Pr-FEA std. dev.	0.043	0.039	0.041	0.039	0.039	0.037	0.039	0.034	0.039

Table 5.6 Parameters for the critical local curvature ratio (Φ_{lc}/Φ_{lp}) and statistics of Pr/FEA and Pr-FEA for a single corrosion defect

Material (σ_{er})	1.3	1.3	1.3	1.65	1.65	1.65	2	2	2
Axial length (lac/D)	0.2	0.4	0.6	0.2	0.4	0.6	0.2	0.4	0.6
k1c	1.110	4.878	3.096	0.856	1.683	1.550	0.640	0.225	1.338
k2c	-0.0066	-1.9851	-0.9182	0.0134	-0.2091	-0.0323	0.0221	0.5431	0.0167
k3c	0.932	0.161	0.177	0.417	0.243	0.167	0.454	0.160	0.583
k4c	0.0045	0.1096	0.0063	-0.0298	0.0024	0.0308	-0.0146	-0.0020	-0.9818
k5c	0.711	2.333	0.385	0.135	0.666	0.390	0.241	0.185	0.550
k6c	0.4170	-0.0686	-0.1603	-0.8797	-0.5473	-1.6135	-0.0713	0.3761	-1.5634
k7c	0.334	0.488	0.712	0.434	0.439	0.534	0.451	0.484	0.536
k8c	2.653	1.031	1.038	3.344	1.455	1.033	3.100	2.712	1.034
k9c	0.209	0.408	0.563	0.301	0.275	0.491	0.282	0.374	0.460
k10c	0.335	0.372	0.533	0.241	0.426	0.660	0.124	0.470	0.737
k11c	2.329	0.965	0.993	2.678	1.760	0.808	2.946	2.169	1.041
k12c	5.209	5.305	5.383	5.271	5.274	5.334	5.282	5.302	5.335
k13c	1.132	0.135	0.793	1.054	1.305	1.307	1.056	1.263	0.335
Pr/FEA mean	1.008	1.007	1.007	1.007	1.008	1.008	1.007	1.005	1.003
Pr/FEA std. dev.	0.059	0.057	0.085	0.069	0.081	0.071	0.069	0.074	0.074
Pr/FEA cov	5.9%	5.7%	8.4%	6.9%	8.0%	7.0%	6.9%	7.4%	7.4%
Pr-FEA mean	0.001	-0.001	-0.002	-0.001	0.000	0.000	0.000	0.000	0.001
Pr-FEA std. dev.	0.040	0.041	0.039	0.036	0.041	0.033	0.044	0.038	0.042

Table 5.7 Parameters for the critical local moment ratio (M_{lc}/M_{lp}) and statistics of Pr/FEA and Pr-FEA for a two corrosion defects with equal depth

Material (σ_{er})	1.3	1.3	1.3	1.65	1.65	1.65	2	2	2
Axial length (lac/D)	0.2	0.4	0.6	0.2	0.4	0.6	0.2	0.4	0.6
k1m	0.144	0.225	0.223	-0.031	-1.892	-0.483	-0.859	-2.252	-0.386
k2m	0.0434	0.0850	0.0862	0.0834	1.1357	0.2514	0.3983	1.2835	0.1789
k3m	0.597	0.460	0.458	0.582	0.216	0.396	0.366	0.228	0.488
k4m	3.3321	4.9874	4.9711	0.3072	0.3887	0.6169	0.0301	0.1645	0.2603
k5m	3.401	3.220	3.219	1.537	2.416	2.391	0.168	2.457	2.429
k6m	-2.9020	-3.5641	-3.5494	-1.6171	-0.5679	-1.1044	-0.6466	-0.4019	-0.8782
k7m	0.669	0.680	0.689	0.667	0.490	0.464	0.537	0.516	0.500
k8m	3.071	1.042	1.043	1.676	1.031	1.029	1.034	1.032	1.031
k9m	0.615	0.573	0.577	0.535	0.426	0.401	0.448	0.457	0.439
k10m	0.476	0.861	0.862	0.776	0.899	0.881	0.794	0.924	0.903
k11m	1.699	1.356	1.359	1.990	1.669	1.710	1.768	1.682	1.711
k12m	2.418	5.425	5.431	5.417	5.306	5.290	5.336	5.322	5.312
Pr/FEA mean	0.999	1.000	1.001	0.999	1.000	1.000	0.999	1.000	1.000
Pr/FEA std. dev.	0.048	0.052	0.045	0.027	0.029	0.022	0.025	0.023	0.017
Pr/FEA cov	4.8%	5.2%	4.5%	2.7%	2.9%	2.2%	2.5%	2.3%	1.7%
Pr-FEA mean	-0.002	-0.002	0.001	-0.001	0.000	0.000	-0.001	-0.001	-0.001
Pr-FEA std. dev.	0.033	0.034	0.030	0.019	0.023	0.018	0.018	0.018	0.014

Table 5.8 Parameters for the critical local compressive strain ratio ($\epsilon_{lc}/\epsilon_{lp}$) and statistics of Pr/FEA and Pr-FEA for a two corrosion defects with equal depth

Material (σ_{er})	1.3	1.3	1.3	1.65	1.65	1.65	2	2	2
Axial length (lac/D)	0.2	0.4	0.6	0.2	0.4	0.6	0.2	0.4	0.6
k1s	0.873	0.846	0.846	0.488	0.356	0.503	0.407	-1.426	0.053
k2s	0.0326	0.0640	0.0640	0.2115	0.0612	0.0581	0.3256	1.0621	0.2544
k3s	0.171	0.116	0.116	0.253	0.608	0.593	0.132	0.212	0.336
k4s	-0.2870	-0.0012	-0.0012	-0.9785	-0.0012	-0.0058	-3.2817	-0.0050	-0.1085
k5s	1.404	1.601	1.601	0.651	1.224	0.786	0.597	1.001	0.713
k6s	0.0450	0.1786	0.1785	0.4146	0.3175	0.3479	0.2066	0.0400	0.1402
k7s	0.564	0.512	0.512	0.559	0.490	0.464	0.537	0.516	0.500
k8s	1.574	1.456	1.456	1.618	1.886	2.162	1.354	1.855	2.387
k9s	0.407	0.363	0.363	0.400	0.336	0.341	0.381	0.377	0.329
k10s	0.530	0.504	0.504	0.364	0.537	0.527	0.294	0.528	0.451
k11s	2.024	1.975	1.975	2.039	2.101	2.073	1.893	1.755	2.493
k12s	5.353	5.320	5.320	5.349	5.306	5.290	5.336	5.322	5.312
k13s	0.955	2.064	2.064	0.110	1.509	1.154	-0.200	0.913	0.371
Pr/FEA mean	1.007	1.006	1.005	1.006	1.005	1.007	1.005	1.002	1.004
Pr/FEA std. dev.	0.080	0.071	0.076	0.083	0.079	0.081	0.061	0.061	0.054
Pr/FEA cov	7.9%	7.0%	7.6%	8.2%	7.9%	8.0%	6.1%	6.0%	5.4%
Pr-FEA mean	0.002	0.001	-0.001	0.001	0.000	0.000	0.002	-0.001	0.000
Pr-FEA std. dev.	0.043	0.054	0.047	0.047	0.046	0.049	0.045	0.041	0.046

Table 5.9 Parameters for the critical local curvature ratio (Φ_{lc}/Φ_{lp}) and statistics of Pr/FEA and Pr-FEA for a two corrosion defects
with equal depth

Material (σ_{er})	1.3	1.3	1.3	1.65	1.65	1.65	2	2	2
Axial length (lac/D)	0.2	0.4	0.6	0.2	0.4	0.6	0.2	0.4	0.6
k1c	0.918	0.928	0.928	0.259	0.671	0.649	-1.052	-1.845	-1.061
k2c	0.0326	0.0640	0.0640	0.5612	0.0612	0.0581	1.3929	1.9229	1.3964
k3c	0.171	0.116	0.116	0.117	0.543	0.549	0.117	0.116	0.116
k4c	-1.6041	-0.0013	-0.0013	-0.6247	-0.0007	-0.0004	-0.0146	-0.0021	-0.0143
k5c	2.034	2.585	2.585	0.906	1.619	0.880	1.003	1.299	1.003
k6c	-1.5016	-0.0068	-0.0070	0.3975	0.4890	0.4466	0.0475	0.0449	0.0470
k7c	0.564	0.512	0.512	0.559	0.490	0.464	0.537	0.516	0.500
k8c	3.790	2.577	2.576	3.008	3.778	2.395	2.820	2.120	2.474
k9c	0.476	0.390	0.390	0.388	0.471	0.290	0.386	0.385	0.357
k10c	0.424	0.458	0.458	0.346	0.438	0.511	0.483	0.531	0.486
k11c	2.440	2.324	2.324	2.807	1.495	2.677	2.466	1.984	2.355
k12c	5.353	5.320	5.320	5.349	3.306	5.290	5.336	5.322	5.312
k13c	0.482	2.064	2.064	0.072	1.681	1.728	0.624	1.018	0.625
Pr/FEA mean	1.007	1.006	1.005	1.006	1.005	1.007	1.005	1.002	1.004
Pr/FEA std. dev.	0.083	0.079	0.080	0.086	0.079	0.080	0.061	0.056	0.052
Pr/FEA cov	8.2%	7.9%	8.0%	8.5%	7.9%	7.9%	6.1%	5.6%	5.2%
Pr-FEA mean	0.001	0.000	-0.002	0.000	-0.001	0.000	-0.001	-0.001	0.000
Pr-FEA std. dev.	0.042	0.056	0.045	0.048	0.045	0.048	0.490	0.036	0.036

Table 5.10 Parameters for the critical local moment ratio (M_{lc}/M_{lp}) and statistics of Pr/FEA and Pr-FEA for a two corrosion defects
with $d_p/t=0.4$ and $d_s/t=0.1$

Material (σ_{er})	1.3	1.3	1.3	1.65	1.65	1.65	2	2	2
Axial length (lac/D)	0.2	0.4	0.6	0.2	0.4	0.6	0.2	0.4	0.6
r1m	-0.119	-0.021	0.670	-0.090	-0.297	-0.917	0.097	-1.251	-0.207
r2m	0.0944	0.1220	-0.0099	0.0548	0.2038	0.5059	0.0134	0.7228	0.0853
r3m	0.389	0.294	0.330	0.529	0.297	0.234	0.810	0.218	0.494
r4m	1.7634	4.7827	16.4085	1.0568	1.3728	0.4533	0.8551	0.2417	0.3103
r5m	2.018	3.287	3.756	1.588	3.052	2.817	1.075	2.885	2.677
r6m	-1.7162	-2.0869	36.3573	-1.3147	-0.9006	-0.4891	-1.4015	-0.3078	-0.7566
r7m	0.570	0.644	0.763	0.545	0.654	0.653	0.662	0.685	0.681
r8m	0.183	0.472	0.592	0.198	0.404	0.518	0.531	0.510	0.466
r9m	2.671	1.224	0.955	2.590	2.107	1.494	0.997	1.274	1.787
r10m	5.181	5.402	1.402	5.198	7.677	8.778	5.412	5.428	7.482
Pr/FEA mean	1.000	1.001	1.006	1.002	1.001	1.000	0.999	1.000	0.999
Pr/FEA std. dev.	0.044	0.045	0.047	0.022	0.041	0.029	0.018	0.037	0.027
Pr/FEA cov	4.4%	4.5%	4.7%	2.2%	4.1%	2.9%	1.8%	3.7%	2.7%
Pr-FEA mean	-0.002	-0.001	0.002	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001
Pr-FEA std. dev.	0.030	0.030	0.029	0.016	0.029	0.021	0.012	0.024	0.018

Table 5.11 Parameters for the critical local compressive strain ratio ($\epsilon_{lc}/\epsilon_{lp}$) and statistics of Pr/FEA and Pr-FEA for a two corrosion defects with $d_p/t=0.4$ and $d_s/t=0.1$

Material (σ_{er})	1.3	1.3	1.3	1.65	1.65	1.65	2	2	2
Axial length (lac/D)	0.2	0.4	0.6	0.2	0.4	0.6	0.2	0.4	0.6
r1s	0.626	1.622	0.707	0.669	0.351	0.729	0.891	-1.538	0.300
r2s	-0.0024	-0.0465	-0.0025	-0.0019	0.1840	-0.0192	-0.0763	1.4056	0.0117
r3s	0.914	0.590	0.119	0.110	0.118	0.116	0.111	0.113	0.844
r4s	0.0021	0.0021	1.6175	19.4106	-0.0135	2.1262	3.3676	-0.0033	-3.3676
r5s	0.679	1.106	0.191	0.635	0.117	0.163	0.420	0.135	0.810
r6s	0.5839	-0.7496	0.2629	0.1738	0.4593	-0.1814	0.0527	0.0590	0.1844
r7s	0.290	0.543	0.612	0.317	0.507	0.521	0.403	0.431	0.541
r8s	0.181	0.436	0.563	0.292	0.272	0.360	0.215	0.277	0.378
r9s	0.610	0.859	0.951	0.236	1.443	1.359	0.826	0.967	1.113
r10s	5.181	1.296	4.192	3.626	8.274	5.326	2.200	5.269	5.338
r11s	1.493	1.351	1.036	0.410	0.984	0.407	-0.075	0.895	-0.152
Pr/FEA mean	1.003	1.002	1.002	1.001	1.002	1.005	1.006	1.008	1.007
Pr/FEA std. dev.	0.084	0.077	0.073	0.081	0.079	0.076	0.081	0.076	0.079
Pr/FEA cov	8.4%	7.7%	7.3%	8.1%	7.9%	7.5%	8.1%	7.5%	7.8%
Pr-FEA mean	0.000	-0.001	0.002	0.001	0.000	0.000	0.001	0.003	-0.002
Pr-FEA std. dev.	0.043	0.047	0.047	0.048	0.044	0.047	0.051	0.046	0.047

Table 5.12 Parameters for the critical local curvature ratio (Φ_{lc}/Φ_{lp}) and statistics of Pr/FEA and Pr-FEA for a two corrosion defects
with $d_p/t=0.4$ and $d_s/t=0.1$

Material (σ_{er})	1.3	1.3	1.3	1.65	1.65	1.65	2	2	2
Axial length (lac/D)	0.2	0.4	0.6	0.2	0.4	0.6	0.2	0.4	0.6
r1c	0.746	3.209	1.154	0.737	0.273	0.774	0.768	-0.774	0.481
r2c	-0.0032	-1.5434	-0.2600	-0.0013	0.2996	-0.0062	-0.0486	0.8947	0.0091
r3c	0.914	0.115	0.119	0.110	0.111	0.116	0.111	0.130	0.822
r4c	8.8128	0.0021	0.0165	5.2234	-0.0005	2.2387	3.3676	-0.0021	-3.3676
r5c	4.290	4.474	0.191	0.861	0.230	0.813	0.376	0.201	0.986
r6c	0.3335	-0.1473	-0.3336	-0.3671	0.4163	-1.7427	-0.0629	0.0880	0.0576
r7c	0.290	0.527	0.612	0.317	0.425	0.521	0.616	0.431	0.541
r8c	0.181	0.297	0.443	0.292	0.264	0.360	0.232	0.279	0.378
r9c	0.619	1.184	1.164	0.297	1.171	1.078	1.240	0.896	1.022
r10c	5.181	4.502	5.383	3.825	8.035	5.326	5.215	5.269	5.338
r11c	-0.299	0.851	0.840	0.736	1.581	0.629	-0.124	1.018	-0.145
Pr/FEA mean	1.006	1.008	1.002	1.001	1.002	1.005	1.007	1.008	1.008
Pr/FEA std. dev.	0.086	0.071	0.086	0.080	0.073	0.072	0.078	0.078	0.063
Pr/FEA cov	8.5%	7.0%	8.6%	8.0%	7.3%	7.2%	7.7%	7.7%	6.2%
Pr-FEA mean	0.000	-0.003	0.001	0.001	-0.003	0.000	0.001	0.002	-0.001
Pr-FEA std. dev.	0.044	0.048	0.050	0.047	0.040	0.043	0.046	0.041	0.038

Table 5.13 Parameters for the critical local moment ratio (M_{lc}/M_{lp}) and statistics of Pr/FEA and Pr-FEA for a two corrosion defects
with $d_p/t=0.3$ and $d_s/t=0.2$

Material (σ_{er})	1.3	1.3	1.3	1.65	1.65	1.65	2	2	2
Axial length (lac/D)	0.2	0.4	0.6	0.2	0.4	0.6	0.2	0.4	0.6
r1m	-0.060	0.197	-0.188	-0.333	-1.332	-0.401	-0.329	-1.633	-0.302
r2m	0.0672	0.0107	0.0947	0.1635	0.9326	0.1989	0.1437	1.1604	0.1339
r3m	0.389	0.533	0.385	0.323	0.137	0.303	0.368	0.131	0.376
r4m	2.0591	8.2125	2.2999	0.4154	0.2632	0.3500	0.2498	0.1380	0.1917
r5m	2.452	3.506	3.011	1.416	2.850	2.213	1.094	3.918	2.588
r6m	-2.2649	-7.0259	-1.4282	-0.8471	-0.3405	-0.7444	-0.6461	-0.2404	-0.6696
r7m	0.537	0.665	0.685	0.397	0.486	0.510	0.363	0.477	0.518
r8m	0.404	0.491	0.510	0.224	0.327	0.349	0.332	0.435	0.383
r9m	1.062	1.199	1.293	1.679	1.597	1.572	1.073	1.079	1.451
r10m	5.336	5.415	5.428	5.223	5.304	5.319	5.026	4.911	5.324
Pr/FEA mean	1.000	1.001	1.000	0.999	1.000	1.000	0.999	1.000	0.999
Pr/FEA std. dev.	0.046	0.051	0.030	0.019	0.029	0.021	0.014	0.023	0.017
Pr/FEA cov	4.6%	5.1%	3.0%	1.9%	2.9%	2.1%	1.4%	2.3%	1.7%
Pr-FEA mean	-0.002	-0.002	-0.001	-0.001	0.000	0.000	-0.001	0.000	-0.001
Pr-FEA std. dev.	0.030	0.037	0.023	0.014	0.023	0.016	0.010	0.018	0.013

Table 5.14 Parameters for the critical local compressive strain ratio ($\epsilon_{lc}/\epsilon_{lp}$) and statistics of Pr/FEA and Pr-FEA for a two corrosion defects with $d_p/t=0.3$ and $d_s/t=0.2$

Material (σ_{er})	1.3	1.3	1.3	1.65	1.65	1.65	2	2	2
Axial length (lac/D)	0.2	0.4	0.6	0.2	0.4	0.6	0.2	0.4	0.6
r1s	1.573	0.801	0.692	0.602	0.635	0.605	0.373	0.371	-0.050
r2s	-0.4757	-0.0229	-0.0227	-0.0029	-0.0100	-0.0098	0.0033	0.0086	0.1339
r3s	0.199	0.596	0.486	0.111	0.115	0.116	0.943	0.807	0.377
r4s	8.9670	0.0214	0.0170	7.0326	0.4317	5.2113	-5.9708	-1.7439	-0.1271
r5s	2.053	1.592	0.956	0.730	1.171	1.030	0.772	0.662	0.927
r6s	-0.0474	-0.3590	-1.0176	-0.0302	0.0792	0.1575	0.2182	0.2558	0.0877
r7s	0.344	0.491	0.602	0.358	0.486	0.510	0.363	0.477	0.518
r8s	0.215	0.452	0.434	0.286	0.327	0.353	0.227	0.319	0.360
r9s	0.734	0.582	1.464	0.439	1.038	1.140	0.719	0.988	1.029
r10s	5.215	5.204	5.377	4.099	5.304	5.319	5.227	5.298	5.324
r11s	-0.871	0.849	0.964	0.533	0.992	0.407	-0.280	-0.020	0.409
Pr/FEA mean	1.002	1.002	1.000	1.002	1.004	1.001	1.002	1.003	1.000
Pr/FEA std. dev.	0.045	0.055	0.035	0.043	0.053	0.049	0.036	0.048	0.048
Pr/FEA cov	4.5%	5.5%	3.5%	4.3%	5.3%	4.9%	3.6%	4.8%	4.8%
Pr-FEA mean	0.000	0.000	-0.001	0.000	0.001	-0.001	0.001	0.000	-0.001
Pr-FEA std. dev.	0.033	0.040	0.029	0.029	0.039	0.034	0.027	0.037	0.028

Table 5.15 Parameters for the critical local curvature ratio (Φ_{lc}/Φ_{lp}) and statistics of Pr/FEA and Pr-FEA for a two corrosion defects
with $d_p/t=0.3$ and $d_s/t=0.2$

Material (σ_{er})	1.3	1.3	1.3	1.65	1.65	1.65	2	2	2
Axial length (lac/D)	0.2	0.4	0.6	0.2	0.4	0.6	0.2	0.4	0.6
r1c	2.381	2.293	1.422	0.662	0.678	0.663	-0.020	-0.405	-0.631
r2c	-1.1433	-1.0451	-0.3931	-0.0200	-0.0020	-0.0068	0.3573	0.6712	0.8010
r3c	0.111	0.115	0.169	0.111	0.115	0.116	0.135	0.115	0.116
r4c	8.4317	0.1630	0.0129	0.4240	0.2364	2.6567	-0.1719	-0.0153	-0.0366
r5c	3.121	4.491	3.931	1.341	1.664	1.732	1.299	0.831	1.189
r6c	-0.0369	-0.1107	-0.3761	-0.2929	-0.1852	-0.8654	0.0601	0.0408	0.0647
r7c	0.344	0.491	0.602	0.358	0.475	0.510	0.363	0.477	0.518
r8c	0.215	0.332	0.434	0.223	0.317	0.350	0.227	0.319	0.356
r9c	0.763	1.027	1.183	0.805	1.020	1.067	0.823	1.033	1.088
r10c	5.215	5.307	5.377	5.223	5.297	5.319	5.227	5.298	5.324
r11c	-0.924	0.133	1.000	0.719	1.475	0.629	0.216	0.685	0.487
Pr/FEA mean	1.002	1.002	1.000	1.002	1.004	1.001	1.002	1.003	1.000
Pr/FEA std. dev.	0.061	0.066	0.054	0.048	0.053	0.047	0.042	0.048	0.040
Pr/FEA cov	6.1%	6.6%	5.4%	4.8%	5.2%	4.7%	4.2%	4.7%	4.0%
Pr-FEA mean	0.000	0.000	-0.001	0.000	0.000	0.000	0.000	0.000	-0.001
Pr-FEA std. dev.	0.040	0.046	0.041	0.031	0.037	0.031	0.029	0.034	0.028

Table 5.16 Parametric combinations considered for the validation of the critical buckling limit equations

σ_{er}	D/t	p/p _y	σ_a/σ_y	l_{ac}/D	l_{hc}/D	d _p /t	d _s /t
1.5, 1.8	55, 80	0.2, 0.6	0.1, 0.3	0.3, 0.5	0.34, 0.6	0.35, 0.2	0.2, 0.0

Table 5.17 Summary of the comparisons of Pr/FEA and Pr-FEA for the validation of the critical buckling limit equations

	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}
Pr/FEA mean	1.019	0.991	0.992
Pr/FEA std. dev.	0.064	0.056	0.057
Pr/FEA cov	6.28%	5.57%	5.74%
Pr-FEA mean	0.012	-0.011	0.049
Pr-FEA std. dev.	0.038	0.042	0.043

Figure 5.1 Pr/FEA of the critical local moment ratio for two corrosion defects of equal depth

Figure 5.2 Pr-FEA of the critical local moment ratio for two corrosion defects of equal depth

Figure 5.3 Pr/FEA of the critical local compressive strain ratio for two corrosion defects of equal depth

Figure 5.4 Pr-FEA of the critical local compressive strain ratio for two corrosion defects of equal depth

Figure 5.5 Pr/FEA of the critical local curvature ratio for two corrosion defects of equal depth

Figure 5.6 Pr-FEA of the critical local curvature ratio for two corrosion defects of equal depth

Figure 5.7 Pr/FEA of the critical local moment ratio for single corrosion defect

Figure 5.8 Pr-FEA of the critical local moment ratio for single corrosion defect

Figure 5.9 Pr/FEA of the critical local compressive strain ratio for single corrosion defect

Figure 5.10 Pr-FEA of the critical local compressive strain ratio for single corrosion defect

Figure 5.11 Pr/FEA of the critical local curvature ratio for single corrosion defect

Figure 5.12 Pr-FEA of the critical local curvature ratio for single corrosion defect

Figure 5.13 Critical local moment ratio versus diameter to thickness ratio of the material M2 with respect to σ_a/σ_y ratio for $l_{ac}/D=0.4$ and $l_{hc}/D=0.26$

Figure 5.14 Critical compressive strain ratio versus diameter to thickness ratio of the material M2 with respect to σ_a/σ_y ratio for $l_{ac}/D=0.4$ and $l_{hc}/D=0.26$

Figure 5.15 Critical local curvature ratio versus diameter to thickness ratio of the material M2 with respect to σ_a/σ_y ratio for $l_{ac}/D=0.4$ and $l_{hc}/D=0.26$

Figure 5.16 Critical local moment ratio versus axial load ratio of the material M2 with respect to D/t ratio for $l_{ac}/D=0.4$ and $l_{hc}/D=0.26$

Figure 5.17 Critical compressive strain ratio versus axial load ratio of the material M2 with respect to D/t ratio for $l_{ac}/D=0.4$ and $l_{hc}/D=0.26$

Figure 5.18 Critical local curvature ratio versus axial load ratio of the material M2 with respect to D/t ratio for $l_{ac}/D=0.4$ and $l_{hc}/D=0.26$

Figure 5.19 Critical local moment ratio versus pressure load ratio of the material M2 with respect to D/t ratio for $l_{ac}/D=0.4$ and $l_{hc}/D=0.26$

Figure 5.20 Critical compressive strain ratio versus pressure load ratio of the material M2 with respect to D/t ratio for $l_{ac}/D=0.4$ and $l_{hc}/D=0.26$

Figure 5.21 Critical local curvature ratio versus pressure load ratio of the material M2 with respect to D/t ratio for $l_{ac}/D=0.4$ and $l_{hc}/D=0.26$

Figure 5.22 Critical local moment ratio versus hoop length and depth ratios of corrosion defect for material M2 with respect to p/py ratio for $l_{ac}/D=0.4$, $\sigma_a/\sigma_y=0.2$ and $D/t=70$.

Figure 5.23 Critical compressive strain ratio versus hoop length and depth ratios of corrosion defect for material M2 with respect to p/py ratio for $l_{ac}/D=0.4$, $\sigma_a/\sigma_y=0.2$ and $D/t=70$.

Figure 5.24 Critical local curvature ratio versus hoop length and depth ratios of corrosion defect for material M2 with respect to p/py ratio for $l_{ac}/D=0.4$, $\sigma_a/\sigma_y=0.2$ and $D/t=70$.

Figure 5.25 Critical local moment ratio versus hoop length and depth ratios of corrosion defect for material M2 with respect to σ_a/σ_y ratio for $l_{ac}/D=0.4$, $p/p_y=0.4$ and $D/t=70$.

Figure 5.26 Critical compressive strain ratio versus hoop length and depth ratios of corrosion defect for material M2 with respect to σ_a/σ_y ratio for $l_{ac}/D=0.4$, $p/p_y=0.4$ and $D/t=70$.

Figure 5.27 Critical local curvature ratio versus hoop length and depth ratios of corrosion defect for material M2 with respect to σ_a/σ_y ratio for $l_{ac}/D=0.4$, $p/p_y=0.4$ and $D/t=70$.

Figure 5.28 Critical local moment ratio versus hoop length and depth ratios of corrosion defect for material M2 with respect to D/t ratio for $l_{ac}/D=0.4$, $\sigma_a/\sigma_y=0.2$ and $p/p_y=0.4$.

Figure 5.29 Critical compressive strain ratio versus hoop length and depth ratios of corrosion defect for material M2 with respect to D/t ratio for $l_{ac}/D=0.4$, $\sigma_a/\sigma_y=0.2$ and $p/p_y=0.4$.

Figure 5.30 Critical local curvature ratio versus hoop length and depth ratios of corrosion defect for material M2 with respect to D/t ratio for $l_{ac}/D=0.4$, $\sigma_a/\sigma_y=0.2$ and $p/p_y=0.4$.

Figure 5.31 Critical buckling limit ratios versus axial length ratio for material M2 with respect to corrosion defect configurations for $D/t=70$, $\sigma_a/\sigma_y=0.2$, and $p/p_v=0.0$ and 0.4 .

Figure 5.32 Pr/FEA versus FEA of the critical local moment ratio

Figure 5.33 Pr-FEA versus FEA of the critical local moment ratio

Figure 5.34 Pr/FEA versus FEA of the critical compressive strain ratio

Figure 5.35 Pr-FEA versus FEA of the critical compressive strain ratio

Figure 5.36 Pr/FEA versus FEA of the critical local curvature ratio

Figure 5.37 Pr-FEA versus FEA of the critical local curvature ratio

Figure 5.38 Pr/FEA of the critical local moment ratio (validation)

Figure 5.39 Pr-FEA of the critical local moment ratio (validation)

Figure 5.40 Pr/FEA of the critical compressive strain ratio (validation)

Figure 5.41 Pr-FEA of the critical compressive strain ratio (validation)

Figure 5.42 Pr/FEA of the critical local curvature ratio (validation)

Figure 5.43 Pr-FEA of the critical local curvature ratio (validation)

Figure 5.44 Pr-FEA versus Pr of the critical local moment ratio with the correction factor

Figure 5.45 Pr-FEA versus Pr of the critical compressive strain ratio with the correction factor

Figure 5.46 Pr-FEA versus Pr of the critical local curvature ratio with the correction factor

6 Chapter: Summary, Conclusions and Recommendations

6.1 Summary

A brief literature review on types of corrosion, and corrosion inspection, measuring and mitigation techniques in oil and gas pipelines have been provided. Evaluation methods from some of the standards and specifications for pipe rupturing due to corrosion defects and their interaction have been presented. Previous studies on buckling behavior and buckling initiation have been reviewed. In addition, some of the proposed critical strain equations to predict buckling initiation are presented. Numerical studies focusing on key parameters that affect the buckling behavior have also been summarized.

A finite element model has been developed to simulate the actual test specimen subjected to the combined loading. Results from the simulations of the FEA model have been validated against full-scale experimental test results. Mesh refinement and model length effect studies of the pipe specimens with single and multiple corrosion defects have been conducted using the validated model. Based on these results, a suitable modified model has been constructed for carrying out the parametric study.

Material properties (true stress-true plastic strain curve) used in the parametric study are generated with a constant relative engineering strain at peak stress of 0.12. Three different ultimate to yield strength ratios ranging from 1.3 to 2.0 with no yield plateau have been considered for the study. A preliminary study has been conducted to assess the importance of various parameters on the local buckling response of a pipeline with multiple corrosion defects along the axial direction.

Finite element analyses to predict the pipe local buckling for a wide range of parametric

values have been conducted. Values of the parameters considered consist of the pipe diameter to thickness ratio (D/t) ranging from 40 to 100, axial load ratio (σ_a/σ_y) ranging from -0.2 to 0.4, internal pressure ratio (p/p_y) ranging from 0.0 to 1.0, axial length of corrosion defect ranging from 0.2 to 0.6 times the outer diameter of the pipe, hoop length of the corrosion defect ranging from 0.1 to 0.5 times the outer diameter of the pipe, and depth of the corrosion defect ranging from 0.16 to 0.4 times the thickness of the pipe. Only a maximum of two axially aligned corrosion defects having the same axial length and hoop length that are spaced at a fixed clear spacing of 3 times the pipe wall thickness ($3t$) are considered. Procedures have been provided to estimate the critical buckling limit ratio using results of finite element analysis parametric study for a pipe with two corrosion defects that has a clear spacing between defects other than that considered in the parametric study and for a pipe with multiple corrosion defects aligned along circumferentially that are distributed symmetrically about the plane perpendicular to the axis of bending on the compression face of the pipe.

The parametric combinations of corroded pipes considered in the finite element analysis parametric study can be grouped into 3 categories into pipes with single corrosion defect, pipes with two corrosion defect of equal depth and pipes with two corrosion defect of unequal depth. Finite element analyses were carried out in all parametric combinations for pipes with two corrosion defects of unequal depth, while only finite element analyses in a subset of parametric combinations for pipes with single corrosion defect and two corrosion defects of equal depth. The predicted critical buckling limits in the remaining combinations for pipe with single corrosion defect and two corrosion defects of equal depth were populated based on the observed pattern from results of the computed finite element

analyses for single corrosion defect, and two corrosion defects of equal and unequal depth. The populated critical buckling limits were validated against results of selective finite element analyses.

Around 6000 parametric combinations of different geometries, loading and corrosion defect sizes have been considered in developing 108 non-dimensional equations to predict critical buckling limits through multi-variable nonlinear regression analysis. The proposed equations for critical local moment ratio, critical compressive strain ratio and critical local curvature ratio have been validated with results of selective finite element analyses for the parametric combinations that are not considered in generating the non-dimensional equations. Correction factors have been proposed to give a more conservative prediction of critical buckling limits with these equations.

6.2 Conclusions

- The change in the critical buckling limit with the increase in the number of corrosion defects is small when there are two or more evenly spaced corrosion defects of the same size along the axial direction.
- For a pipe specimen with two corrosion (primary and secondary) defects aligned along the axial direction, the influence of the change in the axial or hoop length of the secondary (smaller defect) corrosion defect on critical buckling limits was found to be smaller compared to the change in the depth of the secondary corrosion defect.
- The trend of the change in the local buckling response with various parameters are generally the same for different material ultimate to yield strength ratios. However,

the critical buckling limits (ratios) are dependent on the material ultimate to yield strength ratio.

- At zero internal pressure, the critical local moment, critical compressive strain and critical local curvature ratios decrease with the increase in D/t ratio. At a higher internal pressure, the rate of decrease in the critical local moment ratio with the increase in D/t ratio is considerably lower than that at zero internal pressure, while the critical compressive strain and local curvature ratios have instead increased with the D/t ratio.
- The critical local moment ratio decreases with the increase in the axial load ratio, but there is no considerable change in the critical compressive strain and local curvature ratios with the axial load ratio.
- The critical local moment, critical compressive strain and critical local curvature ratios generally decrease with the increase in the hoop length and depth of the corrosion defect. The critical buckling limits decrease at a reducing rate with the increase in the corrosion defect depth. On the other hand, the limits appear to have initially decreased at an increasing rate with the increase in the defect hoop length before changing to a reducing rate at a higher defect hoop length. The change in the rate of decrease with the increase in the defect hoop length ratio is more pronounced at a shallower defect depth.
- The exact defect axial length ratio at which the minimum critical buckling limit ratio occurs varies with the loading, material properties, pipe geometry and other dimensions (hoop length and depth) of the corrosion defect. Hence, the defect axial length ratio is not included as a variable in the non-dimensional equations to predict

the critical buckling limits.

- The difference between the predicted critical buckling limit ratios from the proposed equations and FEA results fall within a range of ± 0.1 for most cases. Correction factors to be used with the proposed equations have also been provided to give a more conservative prediction.

6.3 Recommendations for Future Work

- The proposed equations for critical buckling limits are currently validated against FEA results due to lack of experimental test data. Experimental tests with internal corrosion defects (single and multiple) are needed to further validate the proposed equations.
- The minimum critical buckling limit ratio can occur below the range of the defect axial length ratio considered in this study although the minimum is not expected to be much lower than the smallest critical buckling limit ratio within the range currently considered. Nevertheless, additional analyses at the defect axial length ratio less than 0.2 will help in getting a better estimate of the minimum.
- Only material properties that having the stress-strain curve without a yield plateau have been considered in this study. A finite element analysis parametric study should be carried out to develop equations or data to predict the critical buckling limit for the material with the stress-strain curve with a yield plateau.
- Additional analyses should be carried out to validate the proposed procedure to predict the critical buckling limit of a pipe using results of a single corrosion defect in the circumferential direction for multiple corrosion defects of equal axial length

that are symmetrically distributed about the plane perpendicular to the axis of bending in the hoop direction. Currently, the procedure has been validated against results of only a small number of cases of finite element analyses. A study should also be carried out to investigate the local buckling response for a pipe with multiple corrosion defects that have unequal axial length and/or not aligned circumferentially nor distributed symmetrically.

- Non-dimensional critical buckling limit equations for single corrosion defects and two corrosion defects of equal depth have been developed using results that were not entirely from finite element analyses. Having finite element analysis results of the remaining parametric combinations for pipes with single corrosion defect and two corrosion defects of equal depth will allow improved non-dimensional critical buckling limit equations to be developed.

References

1. AER (Alberta Energy Regulator). (2013). *Pipeline Performance in Alberta, 1990–2012*, Report 2013-B, Calgary, AB, Canada.
2. Afzal, M., & Udpa, S. (2002). “Advanced signal processing of magnetic flux leakage data obtained from seamless gas pipeline.” *Ndt & E International.*, 35(7), 449-457.
3. Alenezi, A. (2015). *The local buckling response of internally corroded steel pipelines under combined loads*. M.A.Sc. thesis, Carleton University, Ottawa, Canada.
4. ASME (The American Society of Mechanical Engineers). (2012). *Manual for determining the remaining strength of corroded pipelines*, B31G-2012, New York, NY, US.
5. ASTM (American Society for Testing and Materials). (2004), *Standard Test Methods for Tension Testing of Metallic Materials [Metric]*, ASTM–E8–04, Philadelphia, Pennsylvania, US.
6. BCOGC (BC Oil and Gas Commission). (2010). *Pipeline Performance and Activity Report*, Victoria, BC, Canada.
7. CAPP (Canadian Association of Petroleum Products). (2009). *Mitigation of internal corrosion in oil effluent pipeline systems: Best Management Practice 2009-0012*, Calgary, AB, Canada.
8. Chen, Q., Khoo, H. A., Cheng, R., and Zhou, J. (2010). “Remaining local buckling resistance of corroded pipelines.” *Proc., The 8th Int. Pipeline Conf.*, ASME, 737-745.

9. CSA (Canadian Standards Association). (2011). *Oil and gas pipeline system*, Z662-11, Mississauga, ON, Canada.
10. Dassault Systèmes Simulia Corp. (2013). *Abaqus 6.13 Theory Manual*, Providence RI, USA.
11. de Andrade, E. Q., Benjamin, A. C., Machado, P. R., Pereira, L. C., Jacob, B. P., Carneiro, E. G., and Noronha, D. B. (2006). "Finite element modeling of the failure behavior of pipelines containing interacting corrosion defects." *Proc., 25th International Conference on Offshore Mechanics and Arctic Engineering*, ASME, 315-325.
12. DelCol P. R., Grondin, G Y., Chen, J. J. R., and Murray, D. W. (1998). "Critical buckling strains in energy pipelines." *Struc. Eng. Rep. No. 224*, Dept. of Civ. Eng., University of Alberta, Edmonton, AB, Canada.
13. DeGeer, D., Timms, C., Wolodko, J., Yarmuch, M., Preston, R., and MacKinnon, D. (2007). "Local Buckling Assessments for the Medgaz Pipeline", *Proc., 26th International Conference on Offshore Mechanics and Arctic Engineering*, ASME, 453-463.
14. Dewanbabee, H., Silva, J., Rafi, A., and Das, S. (2010). "Behaviour of Externally Corroded Pipelines Under Axial Deformation." *Proc., 8th International Pipeline Conference*, ASME, 1-6.
15. DNV (Det Norske Veritas). (2015). *Recommended practice RP-F101 for corroded pipelines*, Norway.

16. Dorey, A. B., Chen, J. J. R., and Murray, D. W. (2001). "Critical buckling strains in energy pipelines" Struc. Eng. Rep. No. 237, Dept. of Civ. Eng., University of Alberta, Edmonton, AB, Canada.
17. Dorey, A. B., Murray, D. W., and Cheng, J. J. R. (2006) "Critical Buckling Strain Equations for Energy Pipelines-A Parametric Study" *J. Offshore Mech. and Arctic Eng.*, ASME, 248-255.
18. Finšgar, M., & Jackson, J. (2014). "Application of corrosion inhibitors for steels in acidic media for the oil and gas industry: A review." *Corrosion Science*, 17-41.
19. Kanaikin, V. A., Loskutov, V. E., Matvienko, A. F., and Patramanskii, B. V. (2007). "In-tube nondestructive testing of main gas pipelines." *Russian Journal of Nondestructive Testing*, 43(5), 302-309.
20. Korol, R. M. (1979). "Critical buckling strains of round tubes in flexure." *Int. J. Mech. Sci.*, 21(12), 719-730.
21. Lee, Y. K., Kim, Y. P., Moon, M. W., Bang, W. H., Oh, K. H., and Kim, W. S. (2005). "The prediction of failure pressure of gas pipeline with multi corroded region." *In Materials Science Forum*, Trans Tech Publications, 3323-3326.
22. Levold, E., Restelli, A., Marchionni, L., Malinori, C., and Ozkan, I. F. (2015). "Strength and deformation capacity of corroded pipe: laboratory tests and FEM analyses." *J. Offshore. and Polar Eng.*, ASME, 212-220.
23. Liu, B., Liu, X. J., & Zhang, H. (2008). "Compressive strain capacity of pipelines for strain-based design." *Proc., 7th International Pipeline Conference*, ASME, 523-531.

24. Mohareb, M. E., Elwi, A. E., Kulak G. L., and Murray, D. W. (1994). "Deformational behaviour of line pipe." Struc. Eng. Rep. No. 202, Dept. of Civ. Eng., University of Alberta, Edmonton, AB, Canada.
25. Naqvi, Z. and Khoo, H. (2007). "Modelling of weld metal and heat-affected zone." *Proc., Annu. Conf. of the Canadian Society for Civ. Eng.*, Yellowknife, NT, Canada, 484-493.
26. Palmer-Jones, R., and Paisley, D. (2000). "Repairing internal corrosion defects in pipelines—a case study." *Proc., 4th International Pipeline Rehabilitation and Maintenance Conference*, 1-25.
27. Papavinasam, S. (2013). *Corrosion control in the oil and gas industry*. Elsevier Science.
28. Ramberg, W., and Osgood, W. B. (1943). "Description of Stress-Strain Curves by Three Parameters", Technical Note 902, National Advisory Committee for Aeronautics, Washington D. C.
29. Sherman, D. R. (1976). "Test of circular steel tubes in bending." *J. of the Struc. Div.*, ASME, 102(11), 2181-2195.
30. Smith, M. Q., Nicolella, D. P., and Waldhart, C. J. (1998). "Full-scale wrinkling tests and analyses of large diameter corroded pipes." *Proc., The Int. Pipeline Conf.*, ASME, Calgary, AB, Canada, 543-551.
31. Tan, Z. (2008). *A finite element analysis parametric study of pipe buckling*, M.A.Sc. thesis, Carleton University, Ottawa, ON, Canada.
32. Tan, Z. and Khoo, H. (2009). "Generation of material stress-strain curves for the parametric study of pipeline buckling." *Proc., Annual Conf. of the Canadian Society for Civ. Eng.*, St. John's, NL, Canada, 1502-1510.

33. Vitali, L., Bruschi, R., Mork, K. J., Levold, E., and Verley, R. (1999), "Hotpipe Project: Capacity of Pipes Subject to Internal Pressure, Axial Force and Bending Moment", *Proc., international Offshore and Polar engineering Conference*, Brest, Paper No. ISOPE-I-99-123.
34. Zhang, Z., Yu, Z., Liu, M., Kotian, K., and Zhang, F. (2014). "Application of compressive strain capacity models to multiple grades of pipelines." *Proc., 10th International Pipeline Conference*, IPC, Calgary, ASME, Paper No. V004T11A019.
35. Zimmerman, T. J. E., Stephens, M. J., DeGeer, D. D., and Chen, Q. (1995). "Compressive strain limits for buried pipelines." *Proc., of the Int. Conf. on Offshore Mech. and Arct. Eng.*, ASME, Copenhagen, Denmark, 365-378.
36. Zimmerman, T. J. E., Xie, J., Timms, C., and Asante, J. (2004). "Buckling Resistance of Large Diameter Spiral Welded Line Pipe", *Proc., of International Pipeline Conference (IPC2004)*. ASME, Calgary, Alberta, Paper No. IPC04-0364.

Appendix A Material Properties used in Model Validation

Table A.1 True stress and true plastic strain by Chen et al. (2010)

LB-I		LB-II		LB-III	
σ_t	ϵ_{tp}	σ_t	ϵ_{tp}	σ_t	ϵ_{tp}
435.08	0	447.86	0	434.27	0
466.84	0.00016	473.65	0.00013	459.01	0.0002
498.14	0.0005	506.13	0.00046	485.55	0.00057
518.76	0.0009	525.82	0.00086	501.07	0.00099
540.21	0.00179	537.04	0.00131	503.73	0.00446
552.58	0.00322	546.29	0.00226	507.4	0.00939
560.15	0.00517	549.98	0.00423	509.45	0.01333
572.43	0.01104	553.12	0.00718	511.79	0.0192
587.94	0.01882	563.67	0.01306	528.99	0.02691
605.94	0.03041	583.69	0.0208	553.83	0.04029
630.09	0.05134	599.11	0.0285	576.23	0.05539
645.62	0.07002	634.34	0.05037	597.76	0.07397
665.58	0.10103	651.42	0.0644	622.36	0.10125
682.22	0.13112	669.39	0.08283	645.52	0.13305
		683.87	0.10094		
		707.77	0.13622

Figure A.1 True stress versus true plastic strain for specimen LB-I by Chen et al. (2010)

Figure A.2 True stress versus true plastic strain for specimen LB-II by Chen et al. (2010)

Figure A.3 True stress versus true plastic strain for specimen LB-III by Chen et al. (2010)

Appendix B Critical Buckling Limit Ratios for Different Corrosion Defect Gaps

Corrosion defects in pipelines used in oil and gas industry normally occur in colonies. However, the spacing between defects is neither predictable nor constant. Nevertheless, the spacing between corrosion defects can have a considerable influence on the critical buckling limits. A constant clear spacing ($3t$) between corrosion defects has been considered in the parametric study. Equations have been proposed to estimate the critical buckling limit ratios for a different spacing between defects of both equal and unequal depth from the spacing considered in the parametric study. Examples are provided in the following subsections to illustrate the procedure. The estimated critical buckling limits are compared to the FEA results for validation. All the numerical analyses have been carried out for the material ultimate to yield strength ratio (σ_{er}) of 1.65, internal pressure ratio (p/p_y) of 0.4, axial load ratio (σ_a/σ_y) of 0.2, diameter to thickness ratio (D/t) of 70, pipe diameter $D = 609.6$ mm and hoop length of corrosion defect (l_{hc}) of $0.26D$.

B.1 Critical Buckling Limit Ratios-Corrosion Defect with Equal Depth

The critical buckling limits for a pipe specimen with two corrosion defects of equal depth at a different defect clear spacing can be estimated with

$$bb_{G-g} = bb_a + (bb_{2a} - bb_a)e^{-\alpha g} \quad (B.1)$$

where bb_a and bb_{2a} are the critical buckling limits (critical local moment, critical compressive strain and critical local curvature) for single corrosion defect with an axial length of a and $2a$, bb_{G-g} are the critical buckling limits for two corrosion defects with a clear spacing (gap) of g between defects, and α is a constant. The constant α can be calculated from the known results of the single corrosion defect and two corrosion defects with a clear spacing between defects of 3 times the thickness of the pipe ($3t$). Using the

calculated α , critical buckling limits at a different spacing between defects can be predicted using Eq. (B.1). Besides the defect axial length ratio and spacing between corrosion defects, all other parameters are otherwise identical for all the pipe specimens considered in Eq. (B.1).

In the parametric study, only three corrosion axial length ratios (l_{ac}/D) of 0.2, 0.4 and 0.6 are considered. Thus, only α for two corrosion defects that each the defect axial length ratio of 0.2 can be calculated. This α is assumed to be also applicable for two corrosion defects that each has either the axial length ratio of 0.4 or 0.6. Two examples to estimate the critical buckling limit ratios for a different spacing between defects are provided below for the defect axial length ratios of 0.2 and 0.4 for each of two corrosion defects.

Example 1: Defect Axial Length Ratio 0.2

Each of the two corrosion defects has the defect axial length ratio of 0.2 with the defect depth of $0.3t$. Predicted critical buckling limit ratios calculated using Eq. (B.1) at a defect clear spacing of $12t$ are compared to the FEA results. Results of the analyses are shown in Table. B.1. The α is calculated from Eq. (B.1) from the known bb_{G-3t} , bb_a and bb_{2a} from the parametric study (FEA). The critical buckling limit ratios at a defect clear spacing of $12t$ (bb_{G-12t}) are calculated from Eq. (B.1) with the calculated α . Comparisons show that the predicted limits are within 2% of that from FEA.

Example 2: Defect Axial Length Ratio 0.4

Each of the two corrosion defects has the defect axial length ratio 0.4 with the defect depth of $0.3t$. Predicted critical buckling limit ratios calculated with Eq. (B.1) at clear spaces of 0 and $12t$ are compared to FEA results. Results of the analyses are shown in Table B.2.

The constant α is taken from Example 1, which has been calculated from the defect axial length ratio of 0.2. The critical buckling limit ratios (bb_{2a} , bb_{G-12t}) at clear spaces of 0 and $12t$ between defects are calculated from Eq. (B.1) with the constant α from Example 1, and bb_{G-3t} and bb_a from the parametric study (FEA). Comparisons show that the predicted limits are within 3% of those from FEA. Two defects with the defect axial length ratio a at zero clear spacing is identical to a single defect with the defect axial length ratio $2a$.

B.2 Critical Buckling Limit Ratios-Corrosion Defects with Unequal Depth

The critical buckling limits for two corrosion defects with unequal depth at a different defect clear spacing can be estimated

$$bc_{G-g} = bb_a + (bc_0 - bb_a)e^{-\alpha g} \quad (B.2)$$

where bc_{G-g} and bc_0 are the critical buckling limits for two corrosion defects of unequal depth at a clear spacing (gap) g and zero spacing (contiguous defects), and α is the constant.

The constant α is taken from Example 1 with the defect axial length ratio of 0.2 for each of the two defects. Besides the defect axial length ratio and spacing between corrosion defects, all other parameters are otherwise identical for all the pipe specimens considered in Eqs. (B.1) and (B.2) with the depth of the primary corrosion defect (two corrosion defects with unequal depth) equal to the depth of the defect for two corrosion defects with equal depth.

Example 3: Defect Axial Length Ratios of 0.2 and 0.4

Both the primary and secondary corrosion defects have the same defect axial length ratio. The primary corrosion defect has a defect depth (d_p) of $0.3t$, while the secondary corrosion defect has a defect depth of $0.2t$. Defect axial length ratios of 0.2 and 0.4 are considered in this example.

Predicted critical buckling limit ratios calculated with Eq. (B.2) at clear spaces of 0 and $12t$ between defects are compared to FEA results. Results of the analyses for the defect axial length ratios of 0.2 and 0.4 are shown in Tables B.3 and B.4 respectively. The constant α is taken from Example 1, which has been calculated from results of two corrosion defects of equal depth with the defect axial length ratio of 0.2. The critical buckling limit ratios (bc_0 , bc_{G12t}) at clear spaces of 0 and $12t$ between defects are calculated from Eq. (B.2) with the constant α from Example 1, and bc_{G-3t} and bb_a from the parametric study (FEA). Comparison show that the predicted limits are within 3% of those from FEA for the axial length ratio of 0.2 and within 4% for the axial length ratio of 0.4. Overall, a better estimation is obtained for the critical local moment ratio.

Table B.1 Critical buckling ratio for bb_{G-12t} with $l_{ac}/D=0.2$ – defects with equal depth

		Critical local moment ratio M_{lc}/M_{lp}	Critical compressive strain ratio $\varepsilon_{lc}/\varepsilon_{lp}$	Critical local curvature ratio Φ_{lc}/Φ_{lp}
	bb_{G-3t} FEA	0.798	0.837	0.750
	bb_a FEA	0.756	0.718	0.652
	bb_{2a} FEA	0.815	0.877	0.767
	α	0.106	0.0953	0.0535
bb_{G-12t}	Predicted	0.772	0.768	0.713
	FEA	0.779	0.781	0.722
	Predicted/FEA	0.991	0.984	0.988

Table B.2 Critical buckling ratio for bb_{G-12t} with $l_{ac}/D=0.4$ – defects with equal depth

		Critical local moment ratio M_{lc}/M_{lp}	Critical compressive strain ratio $\varepsilon_{lc}/\varepsilon_{lp}$	Critical local curvature ratio Φ_{lc}/Φ_{lp}
	bb_{G-3t} FEA	0.776	0.803	0.702
	bb_a FEA	0.815	0.877	0.767
	α	0.106	0.0953	0.0535
bb_{2a}	Predicted	0.761	0.778	0.681
	FEA	0.764	0.758	0.675
	Predicted/FEA	0.997	1.027	0.992
bb_{G-12t}	Predicted	0.801	0.845	0.738
	FEA	0.809	0.865	0.758
	Predicted/FEA	0.989	0.977	0.974

Table B.3 Critical buckling ratio for bb_{G-12t} with $l_{ac}/D=0.2$ – defects with unequal depth

		Critical local moment ratio M_{lc}/M_{lp}	Critical compressive strain ratio $\varepsilon_{lc}/\varepsilon_{lp}$	Critical local curvature ratio Φ_{lc}/Φ_{lp}
	bc_{G-3t} FEA	0.765	0.749	0.678
	bb_a FEA	0.756	0.718	0.652
	α	0.1057	0.0953	0.0535
bc_0	Predicted	0.769	0.759	0.682
	FEA	0.778	0.781	0.701
	Predicted/FEA	0.988	0.972	0.973
bc_{G-12t}	Predicted	0.759	0.731	0.668
	FEA	0.761	0.726	0.661
	Predicted/FEA	0.997	1.007	1.011

Table B.4 Critical buckling ratio for bb_{G-12t} with $l_{ac}/D=0.4$ – defects with unequal depth

		Critical local moment ratio M_{lc}/M_{lp}	Critical compressive strain ratio $\varepsilon_{lc}/\varepsilon_{lp}$	Critical local curvature ratio Φ_{lc}/Φ_{lp}
	bc_{G-3t} FEA	0.818	0.771	0.710
	bb_a FEA	0.815	0.877	0.767
	α	0.1057	0.0953	0.0535
bc_0	Predicted	0.819	0.737	0.701
	FEA	0.823	0.712	0.691
	Predicted/FEA	0.995	1.035	1.023
bc_{G-12t}	Predicted	0.817	0.816	0.725
	FEA	0.816	0.795	0.732
	Predicted/FEA	1.001	1.026	0.991

Appendix C Multiple Corrosion Defects Along the Hoop Direction

The parametric study considered only multiple corrosion defects along the axial direction. However, analyses have shown that the hoop length and depth of a corrosion defect have a very significant effect on the critical buckling limits. Although flow induced corrosion occurs in colonies along the flow direction in the pipeline, the depth of the corrosion defect will not be uniform along the hoop direction. Considering the corrosion defects as a single defect with a constant depth at the maximum of the defect depth could significantly underestimate the critical buckling limits. However, it may be possible to consider an equivalent single corrosion defect with a constant defect depth to represent multiple hoop corrosion defects and/or a single hoop corrosion defect with non-uniform defect depth.

C.1 Equivalent Single Corrosion Defect

The depth and hoop length of the corrosion defect are inversely proportional to the critical buckling limit ratios. As the depth or hoop length of the corrosion defect increases, the critical local moment ratio, critical compressive strain ratio, and critical local curvature ratio decreases.

An equation has been proposed to calculate the equivalent defect depth of a single corrosion defect with a constant depth to represent multiple corrosion defects that distributed symmetrically along the hoop direction about the plane perpendicular to the axis of bending on the compression face. The equivalent depth for the single corrosion depth can be taken as

$$d_e = \frac{\int_{\theta_1}^{\theta_2} d_i \cos \theta d\theta + \int_{\theta_2}^{\theta_3} d_i \cos \theta d\theta + \dots + \int_{\theta_{n-1}}^{\theta_n} d_i \cos \theta d\theta}{\int_0^{\theta_n} \cos \theta d\theta} \quad \text{for } i=1, 2, 3, \dots n. \quad (C.1)$$

where d_e is the equivalent depth, t is the thickness of the pipe specimen, d_i is the depth of the corrosion defect i and θ is the angle measured from the axis of symmetry from the compression face. The corrosion defect distribution shown in Fig. C.1 is used as an illustration to assist in the following discussion.

Three corrosion defects C_1 , C_2 , and C_1 aligned along the hoop direction with depths of d_1 , d_2 , and d_1 , and hoop lengths of h_1 , h_2 , and h_1 are considered. Defects are separated by the gap G_1 of a length g_1 . The corrosion defects are distributed symmetrically about y-axis. All the corrosion defects have the same axial length.

The influence of the corrosion defect C_1 on the critical buckling limit depends on its size and the length of the gap. Thus, a separate equivalent single corrosion defect should be considered for every change in the defect depth. The hoop length of the corrosion defect is taken as the length measured from the axis of symmetry to the point of change in the depth with the equivalent depth for single corrosion defect given by Eq. (C.1). The lowest critical buckling limit from among all possible equivalent single corrosion defects is taken as the equivalent limit for the multiple corrosion defects. In this illustration, there are three possible equivalent defects labelled as H_{e1} , H_{e2} and H_{e3} . The equivalent corrosion defect H_{e1} has the hoop length h_2 , H_{e2} has the hoop length of h_2+2g_1 , and H_{e3} has the length of $2h_1+h_2+2g_1$. The equivalent depth of the corrosion H_{e1} is taken as $d_e=d_2$. For the corrosion defect H_{e2} , the equivalent defect depth is

$$d_e = \frac{\int_0^{\theta_1} d_2 \cos \theta d\theta}{\int_0^{\theta_2} \cos \theta d\theta} = \frac{d_2 \sin \theta \big|_0^{\theta_1}}{\sin \theta \big|_0^{\theta_2}} \quad (C.2)$$

Lastly, the equivalent depth of corrosion defect He₃ is

$$d_e = \frac{\int_0^{\theta_1} d_2 \cos \theta d\theta + \int_{\theta_2}^{\theta_3} d_1 \cos \theta d\theta}{\int_0^{\theta_3} \cos \theta d\theta} = \frac{d_2 \sin \theta \big|_0^{\theta_1} + d_1 \sin \theta \big|_{\theta_2}^{\theta_3}}{\sin \theta \big|_0^{\theta_3}} \quad (C.3)$$

For this illustration, the corrosion defect He₂ is unlikely to be the governing equivalent defect.

C.2 Numerical Simulations and Validation

Numerical simulations based on the defect pattern in Fig. C.1 and the corresponding equivalent single corrosion defect have been carried out to demonstrate and validate the procedure. Ten combinations of corrosion defect patterns with hoop lengths h_1 and h_2 of 0.1D and 0.2D, and gap length g_1 of 0, 0.15D, 0.3D and 0.5D are considered. Three permutations of defect depths 0.1t and 0.2t for defects C₁ and C₂ are considered for gap 0, 0.15D and 0.3D. For the gap 0.5D, the corrosion defect depths for C₁ and C₂ are 0.05t and 0.2t respectively. All corrosion defects have an axial length of 0.2D. The combinations and their equivalent single corrosion defects are shown in Table D.1. There is no equivalent corrosion defect He₂ in cases 1, 4 and 7 as the gap is zero. Numerical simulations have been carried out for the material ultimate to yield strength ratio (σ_{er}) of 1.65, internal pressure ratio (p/p_y) of 0.4, axial load ratio (σ_a/σ_y) of 0.2, diameter to thickness ratio (D/t) of 70 and pipe diameter D = 609.6 mm.

Results of the analyses are shown in Tables. C.2(a) and C.2(b). There is a good agreement between the predicted critical buckling limits from analyses modelled with the actual multiple corrosion defects and those with the equivalent single corrosion defect. In all the cases, the minimum critical buckling limit ratio of the equivalent single corrosion defect is within 3% of the ratio from the analyses modelled with the actual multiple corrosion defects for all except case 6 that is within 4%. Nevertheless, analyses should be carried out for different geometry, loading and corrosion defect pattern combinations to further validate the procedure.

Table C.1 Defect depth and gap combinations, and equivalent single corrosion defect

Case	Actual corrosion defect			Equivalent single defect					
	d_1/t	d_2/t	g_1/D	He ₁		He ₂		He ₃	
				l_{hc}/D	d_e/t	l_{hc}/D	d_e/t	l_{hc}/D	d_e/t
1	0.20	0.20	0.00	0.20	0.200	-	-	0.40	0.200
2	0.20	0.20	0.15	0.20	0.200	0.50	0.0829	0.70	0.113
3	0.20	0.20	0.30	0.20	0.200	0.80	0.0554	1.00	0.077
4	0.20	0.10	0.00	0.20	0.100	-	-	0.40	0.149
5	0.20	0.10	0.15	0.20	0.100	0.50	0.0414	0.70	0.082
6	0.20	0.10	0.30	0.20	0.100	0.80	0.0277	1.00	0.053
7	0.10	0.20	0.00	0.20	0.200	-	-	0.40	0.151
8	0.10	0.20	0.15	0.20	0.200	0.50	0.0829	0.70	0.087
9	0.10	0.20	0.30	0.20	0.200	0.80	0.0554	1.00	0.062
10	0.05	0.20	0.50	0.20	0.200	1.20	0.0426	1.40	0.043

Table C.2(a) Critical buckling ratios for multiple hoop corrosion defects – actual and equivalent

Case	Critical local moment ratio (M_{lc}/M_{lp})				Critical compressive strain ratio ($\epsilon_{lc}/\epsilon_{lc}$)				Critical local curvature ratio (Φ_{lc}/Φ_{lp})			
	Actual (H_a)	He ₁	He ₂	He ₃	Actual (H_a)	He ₁	He ₂	He ₃	Actual (H_a)	He ₁	He ₂	He ₃
1	0.734	0.836	-	0.734	0.614	0.659	-	0.614	0.564	0.621	-	0.564
2	0.766	0.836	0.841	0.762	0.588	0.659	0.651	0.591	0.543	0.621	0.618	0.543
3	0.802	0.836	0.852	0.797	0.602	0.659	0.649	0.589	0.565	0.621	0.620	0.552
4	0.788	0.904	-	0.786	0.622	0.739	-	0.625	0.575	0.717	-	0.577
5	0.824	0.904	0.908	0.812	0.619	0.739	0.740	0.615	0.586	0.717	0.720	0.578
6	0.861	0.904	0.915	0.846	0.655	0.739	0.750	0.637	0.631	0.717	0.734	0.608
7	0.782	0.836	-	0.784	0.630	0.659	-	0.624	0.579	0.621	-	0.575
8	0.800	0.836	0.841	0.804	0.617	0.659	0.651	0.609	0.576	0.621	0.618	0.570
9	0.820	0.836	0.852	0.827	0.628	0.659	0.649	0.615	0.590	0.621	0.620	0.583
10	0.835	0.836	0.865	0.862	0.656	0.659	0.659	0.653	0.621	0.621	0.634	0.629

Table C.2(b) Critical buckling ratios for multiple hoop corrosion defects – actual and equivalent

Case	Critical local moment ratio (M_{lc}/M_{lp})			Critical compressive strain ratio ($\epsilon_{lc}/\epsilon_{lc}$)			Critical local curvature ratio (Φ_{lc}/Φ_{lp})		
	He_1/H_a	He_2/H_a	He_3/H_a	He_1/H_a	He_2/H_a	He_3/H_a	He_1/H_a	He_2/H_a	He_3/H_a
1	1.140	-	1.000	1.073	-	1.000	1.102	-	1.000
2	1.091	1.098	0.994	1.121	1.108	1.006	1.145	1.140	1.001
3	1.043	1.063	0.994	1.094	1.077	0.978	1.101	1.098	0.977
4	1.147	-	0.998	1.188	-	1.005	1.247	-	1.002
5	1.097	1.101	0.986	1.193	1.195	0.993	1.223	1.228	0.985
6	1.050	1.062	0.983	1.127	1.144	0.971	1.137	1.163	0.963
7	1.069	-	1.003	1.046	-	0.991	1.073	-	0.993
8	1.045	1.051	1.005	1.068	1.056	0.988	1.079	1.074	0.990
9	1.021	1.040	1.009	1.049	1.033	0.979	1.052	1.050	0.988
10	1.002	1.036	1.033	1.004	1.004	0.995	1.001	1.022	1.014

Figure C.1 Cross section of a pipe specimen with three hoop internal corrosion defects

Appendix D FEA Results of the Parametric Study

Table D.1 Critical buckling limits for specimens with no corrosion defect (plain pipe)

Model	Local moment (kNm)	Compressive strain (mm/mm $\times 10^{-6}$)	Local curvature (rad/mm $\times 10^{-6}$)	Model	Local moment (kNm)	Compressive strain (mm/mm $\times 10^{-6}$)	Local curvature (rad/mm $\times 10^{-6}$)
M1D1A1H1	2860	24549	66.17	M2D2A2H3	1312	17949	35.77
M1D1A1H2	2845	31932	81.10	M2D2A3H1	1590	12557	25.74
M1D1A1H3	2278	44863	95.81	M2D2A3H2	1398	14131	28.00
M1D1A2H1	2758	24293	54.54	M2D2A3H3	950	17546	31.38
M1D1A2H2	2515	29805	64.07	M2D3A1H1	1235	8379	22.54
M1D1A2H3	1730	42540	79.32	M2D3A1H2	1207	9478	24.56
M1D1A3H1	2448	23491	46.42	M2D3A1H3	1003	12084	27.04
M1D1A3H2	2008	28613	54.25	M2D3A2H1	1151	8231	19.12
M1D1A3H3	1041	41083	66.46	M2D3A2H2	1056	9325	20.81
M1D2A1H1	1548	10447	26.70	M2D3A2H3	789	11817	23.31
M1D2A1H2	1475	12868	31.85	M2D3A3H1	999	8245	17.32
M1D2A1H3	1108	20354	42.22	M2D3A3H2	841	9131	18.10
M1D2A2H1	1439	9886	21.50	M2D3A3H3	529	11448	19.83
M1D2A2H2	1252	12328	25.77	M3D1A1H1	4216	25983	68.93
M1D2A2H3	757	19799	35.96	M3D1A1H2	4396	30761	82.25
M1D2A3H1	1188	9437	18.60	M3D1A1H3	4098	35279	85.86
M1D2A3H2	905	12004	22.50	M3D1A2H1	4129	26192	61.67
M1D2A3H3	341	18703	27.04	M3D1A2H2	4148	29568	70.13
M1D3A1H1	1011	5642	14.73	M3D1A2H3	3721	34020	74.37
M1D3A1H2	951	7104	17.41	M3D1A3H1	3904	25955	55.53
M1D3A1H3	693	12655	25.80	M3D1A3H2	3782	28704	61.59
M1D3A2H1	892	5423	12.51	M3D1A3H3	3233	33083	65.97
M1D3A2H2	755	6891	14.54	M3D2A1H1	2210	12675	33.31
M1D3A2H3	429	12294	22.15	M3D2A1H2	2249	14556	38.37
M1D3A3H1	696	5162	10.35	M3D2A1H3	2034	16772	39.91
M1D3A3H2	521	6567	12.07	M3D2A2H1	2111	12660	29.75
M1D3A3H3	141	11391	13.86	M3D2A2H2	2071	14230	33.24
M2D1A1H1	3525	26525	70.72	M3D2A2H3	1783	16367	34.88
M2D1A1H2	3633	32354	84.93	M3D2A3H1	1934	12449	26.66
M2D1A1H3	3236	39315	91.07	M3D2A3H2	1819	13949	29.40
M2D1A2H1	3436	26806	61.84	M3D2A3H3	1466	16059	31.14
M2D1A2H2	3354	30806	70.37	M3D3A1H1	1456	8813	24.03
M2D1A2H3	2796	37672	77.28	M3D3A1H2	1443	9481	24.79

Table D.1 Critical buckling limits for specimens with no corrosion defect (plain pipe) -
continue

Model	Local moment (kNm)	Compressive strain (mm/mm x 10 ⁻⁶)	Local curvature (rad/mm x 10 ⁻⁶)	Model	Local moment (kNm)	Compressive strain (mm/mm x 10 ⁻⁶)	Local curvature (rad/mm x 10 ⁻⁶)
M2D1A3H1	3181	26399	54.59	M3D3A1H3	1278	11017	26.23
M2D1A3H2	2935	29741	60.61	M3D3A2H1	1342	8571	20.67
M2D1A3H3	2230	36480	67.47	M3D3A2H2	1313	10407	23.79
M2D2A1H1	1876	13011	33.87	M3D3A2H3	1086	10829	23.04
M2D2A1H2	1868	14906	38.31	M3D3A3H1	1212	8477	18.62
M2D2A1H3	1596	18472	41.70	M3D3A3H2	1108	9216	19.52
M2D2A2H1	1779	12625	28.62	M3D3A3H3	856	10659	20.51
M2D2A2H2	1676	14439	32.13				

Table D.2 Critical buckling limit ratios for specimens with single corrosion defect of
 $d_p/t=0.16$

Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}	Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}
M1D1A1P1a1h1	0.962	0.781	0.919	M2D2A2P2a3h2	0.851	0.894	0.855
M1D1A1P1a2h1	0.968	0.902	0.918	M2D2A2P3a1h2	0.832	0.731	0.718
M1D1A1P1a3h1	0.977	0.843	0.910	M2D2A2P3a2h2	0.858	0.865	0.835
M1D1A1P2a1h1	0.953	0.806	0.830	M2D2A2P3a3h2	0.794	0.886	0.856
M1D1A1P2a2h1	0.973	0.682	0.709	M2D2A2P1a1h3	0.836	0.616	0.587
M1D1A1P2a3h1	0.944	0.784	0.772	M2D2A2P1a2h3	0.841	0.747	0.666
M1D1A1P3a1h1	0.929	0.858	0.724	M2D2A2P1a3h3	0.801	0.847	0.760
M1D1A1P3a2h1	0.901	0.785	0.801	M2D2A2P2a1h3	0.795	0.631	0.602
M1D1A1P3a3h1	0.876	0.827	0.812	M2D2A2P2a2h3	0.803	0.755	0.690
M1D1A1P1a1h2	0.940	0.651	0.623	M2D2A2P2a3h3	0.736	0.851	0.788
M1D1A1P1a2h2	0.932	0.383	0.567	M2D2A2P3a1h3	0.729	0.607	0.585
M1D1A1P1a3h2	0.940	0.692	0.624	M2D2A2P3a2h3	0.740	0.756	0.712
M1D1A1P2a1h2	0.920	0.711	0.684	M2D2A2P3a3h3	0.634	0.822	0.771
M1D1A1P2a2h2	0.860	0.621	0.580	M2D2A3P1a1h1	0.935	0.849	0.842
M1D1A1P2a3h2	0.880	0.712	0.670	M2D2A3P1a2h1	0.951	0.979	0.937
M1D1A1P3a1h2	0.847	0.700	0.670	M2D2A3P1a3h1	0.979	0.976	0.965
M1D1A1P3a2h2	0.818	0.720	0.687	M2D2A3P2a1h1	0.922	0.863	0.860
M1D1A1P3a3h2	0.870	0.717	0.684	M2D2A3P2a2h1	0.951	0.960	0.969
M1D1A1P1a1h3	0.909	0.502	0.553	M2D2A3P2a3h1	0.968	0.979	0.980
M1D1A1P1a2h3	0.893	0.456	0.541	M2D2A3P3a1h1	0.884	0.949	0.921
M1D1A1P1a3h3	0.880	0.569	0.543	M2D2A3P3a2h1	0.930	0.959	0.950
M1D1A1P2a1h3	0.878	0.639	0.593	M2D2A3P3a3h1	0.974	0.978	0.968

Table D.2 Critical buckling limit ratios for specimens with single corrosion defect of $d_p/t=0.16$ - continue

Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}	Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}
M1D1A1P2a2h3	0.796	0.536	0.475	M2D2A3P1a1h2	0.862	0.714	0.706
M1D1A1P2a3h3	0.830	0.676	0.612	M2D2A3P1a2h2	0.885	0.825	0.782
M1D1A1P3a1h3	0.758	0.680	0.610	M2D2A3P1a3h2	0.902	0.934	0.891
M1D1A1P3a2h3	0.729	0.706	0.636	M2D2A3P2a1h2	0.827	0.720	0.710
M1D1A1P3a3h3	0.596	0.727	0.663	M2D2A3P2a2h2	0.858	0.959	0.976
M1D1A2P1a1h1	0.964	0.843	0.965	M2D2A3P2a3h2	0.869	0.941	0.916
M1D1A2P1a2h1	0.957	0.600	0.961	M2D2A3P3a1h2	0.777	0.683	0.668
M1D1A2P1a3h1	0.968	0.859	0.914	M2D2A3P3a2h2	0.800	0.836	0.799
M1D1A2P2a1h1	0.959	0.829	0.897	M2D2A3P3a3h2	0.834	0.945	0.907
M1D1A2P2a2h1	0.974	0.749	0.796	M2D2A3P1a1h3	0.802	0.632	0.605
M1D1A2P2a3h1	0.931	0.805	0.838	M2D2A3P1a2h3	0.818	0.880	0.890
M1D1A2P3a1h1	0.924	0.804	0.832	M2D2A3P1a3h3	0.812	0.880	0.806
M1D1A2P3a2h1	0.886	0.843	0.840	M2D2A3P2a1h3	0.736	0.637	0.619
M1D1A2P3a3h1	0.833	0.815	0.803	M2D2A3P2a2h3	0.728	0.750	0.685
M1D1A2P1a1h2	0.911	0.703	0.680	M2D2A3P2a3h3	0.741	0.867	0.820
M1D1A2P1a2h2	0.907	0.392	0.450	M2D2A3P3a1h3	0.674	0.631	0.588
M1D1A2P1a3h2	0.919	0.782	0.713	M2D2A3P3a2h3	0.711	0.940	0.952
M1D1A2P2a1h2	0.892	0.779	0.757	M2D2A3P3a3h3	0.642	0.848	0.784
M1D1A2P2a2h2	0.832	0.682	0.640	M2D3A1P1a1h1	0.973	0.978	0.957
M1D1A2P2a3h2	0.861	0.787	0.748	M2D3A1P1a2h1	0.967	0.963	0.952
M1D1A2P3a1h2	0.777	0.617	0.457	M2D3A1P1a3h1	0.960	0.973	0.979
M1D1A2P3a2h2	0.753	0.779	0.754	M2D3A1P2a1h1	0.972	0.966	0.980
M1D1A2P3a3h2	0.829	0.751	0.721	M2D3A1P2a2h1	0.966	0.971	0.979
M1D1A2P1a1h3	0.860	0.722	0.698	M2D3A1P2a3h1	0.956	0.951	0.948
M1D1A2P1a2h3	0.810	0.415	0.382	M2D3A1P3a1h1	0.973	0.963	0.976
M1D1A2P1a3h3	0.871	0.808	0.700	M2D3A1P3a2h1	0.965	0.950	0.976
M1D1A2P2a1h3	0.820	0.715	0.683	M2D3A1P3a3h1	0.948	0.956	0.961
M1D1A2P2a2h3	0.747	0.609	0.550	M2D3A1P1a1h2	0.938	0.821	0.773
M1D1A2P2a3h3	0.797	0.762	0.704	M2D3A1P1a2h2	0.913	0.855	0.779
M1D1A2P3a1h3	0.637	0.545	0.308	M2D3A1P1a3h2	0.928	0.962	0.977
M1D1A2P3a2h3	0.622	0.741	0.702	M2D3A1P2a1h2	0.922	0.823	0.783
M1D1A2P3a3h3	0.704	0.732	0.683	M2D3A1P2a2h2	0.901	0.881	0.816
M1D1A3P1a1h1	0.966	0.846	0.805	M2D3A1P2a3h2	0.917	0.877	0.856
M1D1A3P1a2h1	0.945	0.747	0.697	M2D3A1P3a1h2	0.905	0.844	0.808
M1D1A3P1a3h1	0.964	0.620	0.687	M2D3A1P3a2h2	0.881	0.894	0.845
M1D1A3P2a1h1	0.961	0.891	0.899	M2D3A1P3a3h2	0.893	0.896	0.921
M1D1A3P2a2h1	0.980	0.534	0.613	M2D3A1P1a1h3	0.889	0.711	0.634
M1D1A3P2a3h1	0.930	0.830	0.833	M2D3A1P1a2h3	0.853	0.750	0.636
M1D1A3P3a1h1	0.884	0.970	0.979	M2D3A1P1a3h3	0.897	0.971	0.976
M1D1A3P3a2h1	0.847	0.871	0.893	M2D3A1P2a1h3	0.861	0.722	0.656

Table D.2 Critical buckling limit ratios for specimens with single corrosion defect of $d_p/t=0.16$ - continue

Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}	Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}
M1D1A3P3a3h1	0.746	0.810	0.791	M2D3A1P2a2h3	0.826	0.789	0.689
M1D1A3P1a1h2	0.890	0.729	0.720	M2D3A1P2a3h3	0.878	0.804	0.799
M1D1A3P1a2h2	0.846	0.395	0.432	M2D3A1P3a1h3	0.827	0.752	0.694
M1D1A3P1a3h2	0.899	0.838	0.783	M2D3A1P3a2h3	0.785	0.809	0.730
M1D1A3P2a1h2	0.865	0.808	0.800	M2D3A1P3a3h3	0.838	0.856	0.844
M1D1A3P2a2h2	0.779	0.687	0.656	M2D3A2P1a1h1	0.957	0.929	0.912
M1D1A3P2a3h2	0.809	0.824	0.795	M2D3A2P1a2h1	0.972	0.972	0.973
M1D1A3P3a1h2	0.668	0.496	0.700	M2D3A2P1a3h1	0.963	0.980	0.976
M1D1A3P3a2h2	0.625	0.778	0.813	M2D3A2P2a1h1	0.953	0.943	0.925
M1D1A3P3a3h2	0.537	0.783	0.801	M2D3A2P2a2h1	0.972	0.962	0.980
M1D1A3P1a1h3	0.827	0.715	0.676	M2D3A2P2a3h1	0.959	0.977	0.978
M1D1A3P1a2h3	0.776	0.652	0.684	M2D3A2P3a1h1	0.941	0.925	0.914
M1D1A3P1a3h3	0.743	0.851	0.771	M2D3A2P3a2h1	0.971	0.975	0.971
M1D1A3P2a1h3	0.771	0.768	0.753	M2D3A2P3a3h1	0.951	0.977	0.973
M1D1A3P2a2h3	0.639	0.484	0.472	M2D3A2P1a1h2	0.909	0.835	0.791
M1D1A3P2a3h3	0.630	0.780	0.737	M2D3A2P1a2h2	0.900	0.921	0.836
M1D1A3P3a1h3	0.472	0.825	0.596	M2D3A2P1a3h2	0.887	0.980	0.905
M1D1A3P3a2h3	0.439	0.849	0.879	M2D3A2P2a1h2	0.889	0.850	0.809
M1D1A3P3a3h3	0.318	0.708	0.719	M2D3A2P2a2h2	0.878	0.919	0.849
M1D2A1P1a1h1	0.979	0.974	0.970	M2D3A2P2a3h2	0.856	0.940	0.935
M1D2A1P1a2h1	0.974	0.947	0.966	M2D3A2P3a1h2	0.853	0.826	0.801
M1D2A1P1a3h1	0.939	0.875	0.876	M2D3A2P3a2h2	0.842	0.941	0.895
M1D2A1P2a1h1	0.977	0.947	0.980	M2D3A2P3a3h2	0.801	0.959	0.946
M1D2A1P2a2h1	0.970	0.966	0.980	M2D3A2P1a1h3	0.859	0.774	0.712
M1D2A1P2a3h1	0.971	0.863	0.931	M2D3A2P1a2h3	0.826	0.879	0.740
M1D2A1P3a1h1	0.974	0.944	0.970	M2D3A2P1a3h3	0.806	0.980	0.864
M1D2A1P3a2h1	0.955	0.942	0.975	M2D3A2P2a1h3	0.823	0.795	0.741
M1D2A1P3a3h1	0.898	0.899	0.885	M2D3A2P2a2h3	0.781	0.877	0.767
M1D2A1P1a1h2	0.949	0.848	0.782	M2D3A2P2a3h3	0.746	0.916	0.911
M1D2A1P1a2h2	0.927	0.874	0.784	M2D3A2P3a1h3	0.764	0.749	0.710
M1D2A1P1a3h2	0.867	0.788	0.694	M2D3A2P3a2h3	0.710	0.904	0.823
M1D2A1P2a1h2	0.941	0.779	0.742	M2D3A2P3a3h3	0.647	0.916	0.923
M1D2A1P2a2h2	0.916	0.865	0.802	M2D3A3P1a1h1	0.939	0.851	0.840
M1D2A1P2a3h2	0.898	0.770	0.716	M2D3A3P1a2h1	0.952	0.980	0.944
M1D2A1P3a1h2*	0.925	0.968	0.932	M2D3A3P1a3h1	0.979	0.979	0.974
M1D2A1P3a2h2*	0.873	0.907	0.861	M2D3A3P2a1h1	0.925	0.867	0.864
M1D2A1P3a3h2*	0.879	0.856	0.815	M2D3A3P2a2h1	0.950	0.655	0.651
M1D2A1P1a1h3	0.908	0.765	0.672	M2D3A3P2a3h1	0.963	0.967	0.980
M1D2A1P1a2h3	0.874	0.792	0.668	M2D3A3P3a1h1	0.887	0.954	0.929
M1D2A1P1a3h3	0.799	0.749	0.636	M2D3A3P3a2h1	0.937	0.972	0.962

Table D.2 Critical buckling limit ratios for specimens with single corrosion defect of $d_p/t=0.16$ - continue

Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}	Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}
M1D2A1P2a1h3	0.889	0.690	0.607	M2D3A3P3a3h1	0.972	0.964	0.967
M1D2A1P2a2h3	0.847	0.786	0.680	M2D3A3P1a1h2	0.871	0.717	0.702
M1D2A1P2a3h3	0.746	0.746	0.653	M2D3A3P1a2h2	0.886	0.906	0.813
M1D2A1P3a1h3*	0.869	0.907	0.841	M2D3A3P1a3h2	0.874	0.950	0.945
M1D2A1P3a2h3*	0.777	0.892	0.801	M2D3A3P2a1h2	0.835	0.730	0.720
M1D2A1P3a3h3*	0.643	0.885	0.808	M2D3A3P2a2h2	0.856	0.897	0.846
M1D2A2P1a1h1	0.959	0.908	0.876	M2D3A3P2a3h2	0.827	0.967	0.977
M1D2A2P1a2h1	0.980	0.960	0.970	M2D3A3P3a1h2	0.785	0.727	0.707
M1D2A2P1a3h1	0.969	0.976	0.974	M2D3A3P3a2h2	0.825	0.924	0.870
M1D2A2P2a1h1	0.949	0.804	0.951	M2D3A3P3a3h2	0.776	0.941	0.897
M1D2A2P2a2h1	0.972	0.907	0.980	M2D3A3P1a1h3	0.816	0.636	0.599
M1D2A2P2a3h1	0.959	0.924	0.978	M2D3A3P1a2h3	0.820	0.932	0.904
M1D2A2P3a1h1	0.925	0.843	0.728	M2D3A3P1a3h3	0.751	0.917	0.912
M1D2A2P3a2h1	0.945	0.968	0.968	M2D3A3P2a1h3	0.749	0.649	0.632
M1D2A2P3a3h1	0.932	0.967	0.961	M2D3A3P2a2h3	0.726	0.626	0.593
M1D2A2P1a1h2	0.867	0.832	0.794	M2D3A3P2a3h3	0.650	0.979	0.973
M1D2A2P1a2h2	0.897	0.896	0.854	M2D3A3P3a1h3	0.686	0.683	0.637
M1D2A2P1a3h2	0.878	0.918	0.876	M2D3A3P3a2h3	0.748	0.964	0.963
M1D2A2P2a1h2	0.875	0.777	0.746	M2D3A3P3a3h3	0.507	0.945	0.912
M1D2A2P2a2h2	0.880	0.879	0.830	M3D1A1P1a1h1	0.964	0.903	0.900
M1D2A2P2a3h2	0.849	0.899	0.861	M3D1A1P1a2h1	0.971	0.869	0.911
M1D2A2P3a1h2*	0.819	0.943	0.897	M3D1A1P1a3h1	0.979	0.895	0.891
M1D2A2P3a2h2*	0.793	0.910	0.891	M3D1A1P2a1h1	0.966	0.859	0.937
M1D2A2P3a3h2*	0.756	0.924	0.906	M3D1A1P2a2h1	0.952	0.962	0.927
M1D2A2P1a1h3	0.775	0.751	0.694	M3D1A1P2a3h1	0.976	0.966	0.931
M1D2A2P1a2h3	0.817	0.824	0.753	M3D1A1P3a1h1	0.963	0.834	0.908
M1D2A2P1a3h3	0.785	0.879	0.806	M3D1A1P3a2h1	0.945	0.944	0.918
M1D2A2P2a1h3	0.779	0.711	0.667	M3D1A1P3a3h1	0.942	0.956	0.932
M1D2A2P2a2h3	0.768	0.822	0.746	M3D1A1P1a1h2	0.930	0.701	0.690
M1D2A2P2a3h3	0.717	0.868	0.805	M3D1A1P1a2h2	0.977	0.728	0.661
M1D2A2P3a1h3*	0.714	0.859	0.847	M3D1A1P1a3h2	0.924	0.745	0.690
M1D2A2P3a2h3*	0.643	0.879	0.839	M3D1A1P2a1h2	0.915	0.715	0.691
M1D2A2P3a3h3*	0.585	0.911	0.875	M3D1A1P2a2h2	0.884	0.752	0.710
M1D2A3P1a1h1	0.949	0.957	0.918	M3D1A1P2a3h2	0.915	0.761	0.725
M1D2A3P1a2h1	0.963	0.980	0.956	M3D1A1P3a1h2	0.912	0.637	0.624
M1D2A3P1a3h1	0.970	0.979	0.971	M3D1A1P3a2h2	0.870	0.768	0.727
M1D2A3P2a1h1	0.923	0.645	0.761	M3D1A1P3a3h2	0.977	0.801	0.771
M1D2A3P2a2h1	0.949	0.948	0.971	M3D1A1P1a1h3	0.885	0.552	0.537
M1D2A3P2a3h1	0.967	0.977	0.980	M3D1A1P1a2h3	0.824	0.592	0.531
M1D2A3P3a1h1	0.858	0.962	0.876	M3D1A1P1a3h3	0.977	0.563	0.595

Table D.2 Critical buckling limit ratios for specimens with single corrosion defect of $d_p/t=0.16$ - continue

Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}	Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}
M1D2A3P3a2h1	0.844	0.972	0.971	M3D1A1P2a1h3	0.857	0.594	0.552
M1D2A3P3a3h1	0.904	0.979	0.973	M3D1A1P2a2h3	0.818	0.656	0.593
M1D2A3P1a1h2	0.831	0.861	0.818	M3D1A1P2a3h3	0.840	0.695	0.638
M1D2A3P1a2h2	0.867	0.903	0.850	M3D1A1P3a1h3	0.855	0.611	0.597
M1D2A3P1a3h2	0.889	0.956	0.924	M3D1A1P3a2h3	0.791	0.669	0.611
M1D2A3P2a1h2	0.830	0.726	0.723	M3D1A1P3a3h3	0.840	0.743	0.697
M1D2A3P2a2h2	0.841	0.982	0.976	M3D1A2P1a1h1	0.968	0.911	0.929
M1D2A3P2a3h2	0.861	0.939	0.914	M3D1A2P1a2h1	0.967	0.904	0.867
M1D2A3P3a1h2	0.671	0.763	0.876	M3D1A2P1a3h1	0.974	0.950	0.848
M1D2A3P3a2h2	0.459	0.846	0.922	M3D1A2P2a1h1	0.969	0.905	0.962
M1D2A3P3a3h2	0.561	0.950	0.960	M3D1A2P2a2h1	0.956	0.846	0.954
M1D2A3P1a1h3	0.761	0.794	0.729	M3D1A2P2a3h1	0.973	0.888	0.955
M1D2A3P1a2h3	0.797	0.920	0.913	M3D1A2P3a1h1	0.966	0.782	0.929
M1D2A3P1a3h3	0.800	0.918	0.857	M3D1A2P3a2h1	0.945	0.963	0.938
M1D2A3P2a1h3	0.735	0.640	0.613	M3D1A2P3a3h1	0.930	0.963	0.940
M1D2A3P2a2h3	0.691	0.795	0.720	M3D1A2P1a1h2	0.903	0.738	0.728
M1D2A3P2a3h3	0.720	0.863	0.804	M3D1A2P1a2h2	0.872	0.783	0.721
M1D2A3P3a1h3	F	F	F	M3D1A2P1a3h2	0.906	0.814	0.760
M1D2A3P3a2h3	F	F	F	M3D1A2P2a1h2	0.892	0.766	0.740
M1D2A3P3a3h3	F	F	F	M3D1A2P2a2h2	0.869	0.791	0.748
M1D3A1P1a1h1	0.970	0.980	0.975	M3D1A2P2a3h2	0.977	0.819	0.784
M1D3A1P1a2h1	0.970	0.977	0.973	M3D1A2P3a1h2	0.888	0.866	0.623
M1D3A1P1a3h1	0.978	0.970	0.980	M3D1A2P3a2h2	0.845	0.815	0.775
M1D3A1P2a1h1	0.970	0.973	0.980	M3D1A2P3a3h2	0.977	0.832	0.798
M1D3A1P2a2h1	0.978	0.977	0.980	M3D1A2P1a1h3	0.839	0.589	0.586
M1D3A1P2a3h1	0.968	0.960	0.970	M3D1A2P1a2h3	0.806	0.667	0.595
M1D3A1P3a1h1*	0.970	0.971	0.975	M3D1A2P1a3h3	0.832	0.741	0.674
M1D3A1P3a2h1*	0.978	0.953	0.967	M3D1A2P2a1h3	0.806	0.649	0.614
M1D3A1P3a3h1*	0.960	0.914	0.906	M3D1A2P2a2h3	0.788	0.704	0.643
M1D3A1P1a1h2	0.956	0.930	0.891	M3D1A2P2a3h3	0.977	0.767	0.711
M1D3A1P1a2h2	0.933	0.938	0.892	M3D1A2P3a1h3	0.802	0.787	0.374
M1D3A1P1a3h2	0.947	0.979	0.979	M3D1A2P3a2h3	0.748	0.698	0.645
M1D3A1P2a1h2	0.911	0.955	0.865	M3D1A2P3a3h3	0.800	0.751	0.702
M1D3A1P2a2h2	0.907	0.910	0.840	M3D1A3P1a1h1	0.971	0.846	0.849
M1D3A1P2a3h2	0.921	0.956	0.961	M3D1A3P1a2h1	0.946	0.922	0.810
M1D3A1P3a1h2*	0.963	0.944	0.939	M3D1A3P1a3h1	0.972	0.860	0.834
M1D3A1P3a2h2*	0.889	0.953	0.948	M3D1A3P2a1h1	0.973	0.832	0.862
M1D3A1P3a3h2*	0.916	0.968	0.951	M3D1A3P2a2h1	0.948	0.745	0.710
M1D3A1P1a1h3	0.918	0.842	0.793	M3D1A3P2a3h1	0.975	0.915	0.871
M1D3A1P1a2h3	0.885	0.854	0.793	M3D1A3P3a1h1	0.963	0.979	0.974

Table D.2 Critical buckling limit ratios for specimens with single corrosion defect of $d_p/t=0.16$ - continue

Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}	Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}
M1D3A1P1a3h3	0.928	0.976	0.978	M3D1A3P3a2h1	0.945	0.891	0.956
M1D3A1P2a1h3	0.810	0.956	0.849	M3D1A3P3a3h1	0.919	0.889	0.952
M1D3A1P2a2h3	0.816	0.902	0.806	M3D1A3P1a1h2	0.893	0.732	0.730
M1D3A1P2a3h3	0.865	0.948	0.897	M3D1A3P1a2h2	0.858	0.771	0.712
M1D3A1P3a1h3*	0.928	0.964	0.956	M3D1A3P1a3h2	0.888	0.845	0.794
M1D3A1P3a2h3*	0.781	0.956	0.949	M3D1A3P2a1h2	0.880	0.773	0.756
M1D3A1P3a3h3*	0.867	0.956	0.947	M3D1A3P2a2h2	0.847	0.788	0.750
M1D3A2P1a1h1	0.947	0.968	0.952	M3D1A3P2a3h2	0.977	0.844	0.814
M1D3A2P1a2h1	0.963	0.977	0.976	M3D1A3P3a1h2	0.881	0.888	0.606
M1D3A2P1a3h1	0.952	0.980	0.978	M3D1A3P3a2h2	0.837	0.810	0.760
M1D3A2P2a1h1	0.973	0.955	0.973	M3D1A3P3a3h2	0.801	0.850	0.801
M1D3A2P2a2h1	0.970	0.978	0.980	M3D1A3P1a1h3	0.828	0.573	0.570
M1D3A2P2a3h1	0.977	0.934	0.937	M3D1A3P1a2h3	0.793	0.785	0.779
M1D3A2P3a1h1*	0.931	0.870	0.918	M3D1A3P1a3h3	0.748	0.775	0.706
M1D3A2P3a2h1*	0.944	0.943	0.957	M3D1A3P2a1h3	0.781	0.672	0.641
M1D3A2P3a3h1*	0.930	0.979	0.967	M3D1A3P2a2h3	0.733	0.585	0.547
M1D3A2P1a1h2	0.890	0.903	0.859	M3D1A3P2a3h3	0.689	0.770	0.719
M1D3A2P1a2h2	0.886	0.937	0.871	M3D1A3P3a1h3	0.798	0.941	0.385
M1D3A2P1a3h2	0.867	0.980	0.924	M3D1A3P3a2h3	0.762	0.837	0.827
M1D3A2P2a1h2	0.878	0.915	0.861	M3D1A3P3a3h3	0.684	0.747	0.677
M1D3A2P2a2h2	0.880	0.937	0.880	M3D2A1P1a1h1	0.972	0.974	0.946
M1D3A2P2a3h2	0.856	0.951	0.946	M3D2A1P1a2h1	0.965	0.939	0.940
M1D3A2P3a1h2*	0.871	0.977	0.969	M3D2A1P1a3h1	0.922	0.759	0.798
M1D3A2P3a2h2*	0.783	0.974	0.950	M3D2A1P2a1h1	0.972	0.956	0.980
M1D3A2P3a3h2*	0.771	0.961	0.956	M3D2A1P2a2h1	0.965	0.964	0.979
M1D3A2P1a1h3	0.852	0.859	0.793	M3D2A1P2a3h1	0.962	0.858	0.837
M1D3A2P1a2h3	0.822	0.898	0.781	M3D2A1P3a1h1	0.978	0.953	0.973
M1D3A2P1a3h3	0.794	0.980	0.887	M3D2A1P3a2h1	0.976	0.925	0.975
M1D3A2P2a1h3	0.788	0.901	0.823	M3D2A1P3a3h1	0.954	0.875	0.872
M1D3A2P2a2h3	0.777	0.918	0.827	M3D2A1P1a1h2	0.942	0.797	0.774
M1D3A2P2a3h3	0.738	0.936	0.931	M3D2A1P1a2h2	0.912	0.843	0.790
M1D3A2P3a1h3*	0.811	0.890	0.911	M3D2A1P1a3h2	0.847	0.768	0.723
M1D3A2P3a2h3*	0.620	0.956	0.951	M3D2A1P2a1h2	0.926	0.788	0.764
M1D3A2P3a3h3*	0.609	0.980	0.959	M3D2A1P2a2h2	0.903	0.861	0.806
M1D3A3P1a1h1	0.935	0.849	0.829	M3D2A1P2a3h2	0.878	0.789	0.742
M1D3A3P1a2h1	0.953	0.980	0.939	M3D2A1P3a1h2	0.914	0.791	0.773
M1D3A3P1a3h1	0.980	0.971	0.974	M3D2A1P3a2h2	0.909	0.871	0.838
M1D3A3P2a1h1	0.955	0.915	0.891	M3D2A1P3a3h2	0.890	0.798	0.766
M1D3A3P2a2h1	0.977	0.928	0.950	M3D2A1P1a1h3	0.900	0.655	0.630
M1D3A3P2a3h1	0.970	0.979	0.980	M3D2A1P1a2h3	0.855	0.713	0.648

Table D.2 Critical buckling limit ratios for specimens with single corrosion defect of $d_p/t=0.16$ - continue

Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}	Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}
M1D3A3P3a1h1	F	F	F	M3D2A1P1a3h3	0.774	0.701	0.640
M1D3A3P3a2h1	F	F	F	M3D2A1P2a1h3	0.871	0.685	0.653
M1D3A3P3a3h1	F	F	F	M3D2A1P2a2h3	0.833	0.767	0.696
M1D3A3P1a1h2	0.873	0.833	0.779	M3D2A1P2a3h3	0.730	0.754	0.694
M1D3A3P1a2h2	0.903	0.932	0.854	M3D2A1P3a1h3	0.832	0.633	0.612
M1D3A3P1a3h2	0.887	0.960	0.955	M3D2A1P3a2h3	0.824	0.742	0.699
M1D3A3P2a1h2	0.821	0.833	0.765	M3D2A1P3a3h3	0.656	0.732	0.687
M1D3A3P2a2h2	0.864	0.919	0.856	M3D2A2P1a1h1	0.945	0.697	0.799
M1D3A3P2a3h2	0.827	0.978	0.978	M3D2A2P1a2h1	0.970	0.917	0.963
M1D3A3P3a1h2	F	F	F	M3D2A2P1a3h1	0.956	0.969	0.967
M1D3A3P3a2h2	F	F	F	M3D2A2P2a1h1	0.944	0.852	0.843
M1D3A3P3a3h2	F	F	F	M3D2A2P2a2h1	0.972	0.912	0.979
M1D3A3P1a1h3	0.828	0.767	0.693	M3D2A2P2a3h1	0.957	0.916	0.973
M1D3A3P1a2h3	0.854	0.946	0.920	M3D2A2P3a1h1	0.963	0.775	0.896
M1D3A3P1a3h3	0.776	0.934	0.929	M3D2A2P3a2h1	0.978	0.958	0.960
M1D3A3P2a1h3	0.689	0.806	0.718	M3D2A2P3a3h1	0.970	0.958	0.948
M1D3A3P2a2h3	0.714	0.748	0.653	M3D2A2P1a1h2	0.888	0.697	0.692
M1D3A3P2a3h3	0.628	0.974	0.975	M3D2A2P1a2h2	0.899	0.821	0.780
M1D3A3P3a1h3	F	F	F	M3D2A2P1a3h2	0.873	0.878	0.829
M1D3A3P3a2h3	F	F	F	M3D2A2P2a1h2	0.868	0.743	0.714
M1D3A3P3a3h3	F	F	F	M3D2A2P2a2h2	0.886	0.850	0.809
M2D1A1P1a1h1	0.960	0.827	0.827	M3D2A2P2a3h2	0.853	0.899	0.864
M2D1A1P1a2h1	0.977	0.758	0.749	M3D2A2P3a1h2	0.841	0.704	0.698
M2D1A1P1a3h1	0.977	0.809	0.789	M3D2A2P3a2h2	0.891	0.851	0.836
M2D1A1P2a1h1	0.951	0.798	0.827	M3D2A2P3a3h2	0.827	0.889	0.859
M2D1A1P2a2h1	0.967	0.763	0.769	M3D2A2P1a1h3	0.830	0.558	0.553
M2D1A1P2a3h1	0.963	0.812	0.797	M3D2A2P1a2h3	0.832	0.695	0.632
M2D1A1P3a1h1	0.941	0.785	0.811	M3D2A2P1a3h3	0.791	0.821	0.738
M2D1A1P3a2h1	0.903	0.744	0.767	M3D2A2P2a1h3	0.792	0.642	0.606
M2D1A1P3a3h1	0.977	0.817	0.804	M3D2A2P2a2h3	0.800	0.764	0.701
M2D1A1P1a1h2	0.933	0.678	0.667	M3D2A2P2a3h3	0.743	0.859	0.801
M2D1A1P1a2h2	0.977	0.671	0.618	M3D2A2P3a1h3	0.713	0.564	0.518
M2D1A1P1a3h2	0.910	0.712	0.661	M3D2A2P3a2h3	0.784	0.728	0.690
M2D1A1P2a1h2	0.910	0.653	0.646	M3D2A2P3a3h3	0.661	0.825	0.758
M2D1A1P2a2h2	0.863	0.679	0.636	M3D2A3P1a1h1	0.932	0.835	0.836
M2D1A1P2a3h2	0.910	0.714	0.674	M3D2A3P1a2h1	0.948	0.979	0.936
M2D1A1P3a1h2	0.884	0.656	0.647	M3D2A3P1a3h1	0.979	0.975	0.964
M2D1A1P3a2h2	0.831	0.688	0.653	M3D2A3P2a1h1	0.919	0.787	0.821
M2D1A1P3a3h2	0.850	0.720	0.690	M3D2A3P2a2h1	0.949	0.947	0.965
M2D1A1P1a1h3	0.893	0.573	0.546	M3D2A3P2a3h1	0.967	0.978	0.980

Table D.2 Critical buckling limit ratios for specimens with single corrosion defect of $d_p/t=0.16$ - continue

Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}	Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}
M2D1A1P1a2h3	0.831	0.585	0.510	M3D2A3P3a1h1	0.915	0.953	0.919
M2D1A1P1a3h3	0.977	0.667	0.590	M3D2A3P3a2h1	0.953	0.964	0.952
M2D1A1P2a1h3	0.858	0.551	0.529	M3D2A3P3a3h1	0.976	0.979	0.970
M2D1A1P2a2h3	0.798	0.593	0.532	M3D2A3P1a1h2	0.863	0.724	0.720
M2D1A1P2a3h3	0.820	0.667	0.608	M3D2A3P1a2h2	0.887	0.835	0.797
M2D1A1P3a1h3	0.818	0.556	0.536	M3D2A3P1a3h2	0.903	0.936	0.893
M2D1A1P3a2h3	0.749	0.603	0.555	M3D2A3P2a1h2	0.835	0.724	0.702
M2D1A1P3a3h3	0.632	0.675	0.631	M3D2A3P2a2h2	0.864	0.978	0.976
M2D1A2P1a1h1	0.962	0.877	0.878	M3D2A3P2a3h2	0.880	0.942	0.918
M2D1A2P1a2h1	0.962	0.828	0.829	M3D2A3P3a1h2	0.790	0.608	0.604
M2D1A2P1a3h1	0.977	0.859	0.848	M3D2A3P3a2h2	0.847	0.825	0.790
M2D1A2P2a1h1	0.957	0.887	0.889	M3D2A3P3a3h2	0.861	0.946	0.909
M2D1A2P2a2h1	0.966	0.809	0.836	M3D2A3P1a1h3	0.807	0.585	0.572
M2D1A2P2a3h1	0.957	0.827	0.850	M3D2A3P1a2h3	0.822	0.870	0.885
M2D1A2P3a1h1	0.943	0.848	0.847	M3D2A3P1a3h3	0.817	0.866	0.784
M2D1A2P3a2h1	0.894	0.815	0.810	M3D2A3P2a1h3	0.752	0.655	0.612
M2D1A2P3a3h1	0.977	0.827	0.810	M3D2A3P2a2h3	0.743	0.761	0.686
M2D1A2P1a1h2	0.904	0.712	0.702	M3D2A3P2a3h3	0.765	0.876	0.826
M2D1A2P1a2h2	0.870	0.726	0.676	M3D2A3P3a1h3	0.681	0.535	0.482
M2D1A2P1a3h2	0.906	0.783	0.729	M3D2A3P3a2h3	0.774	0.935	0.950
M2D1A2P2a1h2	0.881	0.718	0.706	M3D2A3P3a3h3	0.693	0.846	0.780
M2D1A2P2a2h2	0.840	0.727	0.684	M3D3A1P1a1h1	0.970	0.977	0.953
M2D1A2P2a3h2	0.892	0.784	0.745	M3D3A1P1a2h1	0.963	0.957	0.946
M2D1A2P3a1h2	0.840	0.695	0.689	M3D3A1P1a3h1	0.952	0.974	0.978
M2D1A2P3a2h2	0.789	0.731	0.701	M3D3A1P2a1h1	0.970	0.962	0.980
M2D1A2P3a3h2	0.830	0.761	0.726	M3D3A1P2a2h1	0.961	0.969	0.979
M2D1A2P1a1h3	0.844	0.606	0.586	M3D3A1P2a3h1	0.947	0.967	0.956
M2D1A2P1a2h3	0.806	0.642	0.568	M3D3A1P3a1h1	0.972	0.946	0.972
M2D1A2P1a3h3	0.838	0.745	0.662	M3D3A1P3a2h1	0.964	0.872	0.969
M2D1A2P2a1h3	0.802	0.615	0.599	M3D3A1P3a3h1	0.945	0.894	0.951
M2D1A2P2a2h3	0.758	0.649	0.588	M3D3A1P1a1h2	0.932	0.815	0.776
M2D1A2P2a3h3	0.860	0.746	0.687	M3D3A1P1a2h2	0.903	0.841	0.773
M2D1A2P3a1h3	0.736	0.577	0.561	M3D3A1P1a3h2	0.920	0.971	0.977
M2D1A2P3a2h3	0.680	0.639	0.597	M3D3A1P2a1h2	0.915	0.810	0.805
M2D1A2P3a3h3	0.565	0.707	0.654	M3D3A1P2a2h2	0.890	0.884	0.834
M2D1A3P1a1h1	0.966	0.846	0.849	M3D3A1P2a3h2	0.908	0.906	0.911
M2D1A3P1a2h1	0.958	0.863	0.810	M3D3A1P3a1h2	0.901	0.883	0.826
M2D1A3P1a3h1	0.969	0.860	0.834	M3D3A1P3a2h2	0.880	0.873	0.821
M2D1A3P2a1h1	0.961	0.865	0.873	M3D3A1P3a3h2	0.891	0.907	0.844
M2D1A3P2a2h1	0.964	0.644	0.678	M3D3A1P1a1h3	0.882	0.703	0.644

Table D.2 Critical buckling limit ratios for specimens with single corrosion defect of $d_p/t=0.16$ - continue

Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}	Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}
M2D1A3P2a3h1	0.940	0.847	0.835	M3D3A1P1a2h3	0.841	0.725	0.631
M2D1A3P3a1h1	0.929	0.979	0.978	M3D3A1P1a3h3	0.889	0.976	0.976
M2D1A3P3a2h1	0.883	0.824	0.804	M3D3A1P2a1h3	0.852	0.711	0.706
M2D1A3P3a3h1	0.890	0.804	0.769	M3D3A1P2a2h3	0.815	0.803	0.730
M2D1A3P1a1h2	0.889	0.711	0.711	M3D3A1P2a3h3	0.869	0.894	0.847
M2D1A3P1a2h2	0.850	0.727	0.676	M3D3A1P3a1h3	0.820	0.804	0.721
M2D1A3P1a3h2	0.884	0.823	0.769	M3D3A1P3a2h3	0.785	0.750	0.683
M2D1A3P2a1h2	0.862	0.722	0.722	M3D3A1P3a3h3	0.838	0.896	0.859
M2D1A3P2a2h2	0.803	0.721	0.682	M3D3A2P1a1h1	0.956	0.918	0.898
M2D1A3P2a3h2	0.977	0.814	0.781	M3D3A2P1a2h1	0.971	0.969	0.971
M2D1A3P3a1h2	0.817	0.718	0.709	M3D3A2P1a3h1	0.962	0.980	0.975
M2D1A3P3a2h2	0.759	0.718	0.676	M3D3A2P2a1h1	0.945	0.879	0.855
M2D1A3P3a3h2	0.836	0.778	0.720	M3D3A2P2a2h1	0.969	0.930	0.979
M2D1A3P1a1h3	0.827	0.629	0.610	M3D3A2P2a3h1	0.952	0.977	0.976
M2D1A3P1a2h3	0.785	0.776	0.770	M3D3A2P3a1h1	0.946	0.564	0.518
M2D1A3P1a3h3	0.743	0.775	0.696	M3D3A2P3a2h1	0.972	0.962	0.937
M2D1A3P2a1h3	0.767	0.638	0.629	M3D3A2P3a3h1	0.955	0.963	0.953
M2D1A3P2a2h3	0.681	0.502	0.477	M3D3A2P1a1h2	0.908	0.834	0.795
M2D1A3P2a3h3	0.977	0.750	0.698	M3D3A2P1a2h2	0.899	0.914	0.829
M2D1A3P3a1h3	0.708	0.664	0.625	M3D3A2P1a3h2	0.885	0.980	0.906
M2D1A3P3a2h3	0.675	0.807	0.807	M3D3A2P2a1h2	0.889	0.802	0.766
M2D1A3P3a3h3	0.670	0.697	0.622	M3D3A2P2a2h2	0.875	0.892	0.814
M2D2A1P1a1h1	0.974	0.977	0.957	M3D3A2P2a3h2	0.851	0.928	0.923
M2D2A1P1a2h1	0.968	0.963	0.953	M3D3A2P3a1h2	0.871	0.737	0.709
M2D2A1P1a3h1	0.933	0.887	0.858	M3D3A2P3a2h2	0.854	0.922	0.855
M2D2A1P2a1h1	0.973	0.963	0.980	M3D3A2P3a3h2	0.819	0.943	0.940
M2D2A1P2a2h1	0.968	0.969	0.979	M3D3A2P1a1h3	0.863	0.777	0.720
M2D2A1P2a3h1	0.967	0.893	0.871	M3D3A2P1a2h3	0.829	0.869	0.729
M2D2A1P3a1h1	0.974	0.957	0.975	M3D3A2P1a3h3	0.810	0.980	0.867
M2D2A1P3a2h1	0.966	0.943	0.976	M3D3A2P2a1h3	0.828	0.760	0.710
M2D2A1P3a3h1	0.977	0.899	0.883	M3D3A2P2a2h3	0.782	0.852	0.737
M2D2A1P1a1h2	0.946	0.802	0.772	M3D3A2P2a3h3	0.744	0.906	0.901
M2D2A1P1a2h2	0.920	0.853	0.788	M3D3A2P3a1h3	0.795	0.599	0.624
M2D2A1P1a3h2	0.860	0.781	0.719	M3D3A2P3a2h3	0.737	0.880	0.784
M2D2A1P2a1h2	0.931	0.789	0.766	M3D3A2P3a3h3	0.684	0.931	0.923
M2D2A1P2a2h2	0.908	0.863	0.810	M3D3A3P1a1h1	0.939	0.842	0.835
M2D2A1P2a3h2	0.883	0.785	0.737	M3D3A3P1a2h1	0.951	0.980	0.939
M2D2A1P3a1h2	0.915	0.801	0.779	M3D3A3P1a3h1	0.978	0.979	0.973
M2D2A1P3a2h2	0.890	0.873	0.832	M3D3A3P2a1h1	0.923	0.818	0.944
M2D2A1P3a3h2	0.853	0.792	0.757	M3D3A3P2a2h1	0.944	0.458	0.456

Table D.2 Critical buckling limit ratios for specimens with single corrosion defect of $d_p/t=0.16$ - continue

Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}	Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}
M2D2A1P1a1h3	0.905	0.678	0.632	M3D3A3P2a3h1	0.960	0.964	0.980
M2D2A1P1a2h3	0.865	0.745	0.652	M3D3A3P3a1h1	0.893	0.946	0.929
M2D2A1P1a3h3	0.789	0.731	0.642	M3D3A3P3a2h1	0.943	0.964	0.958
M2D2A1P2a1h3	0.878	0.666	0.628	M3D3A3P3a3h1	0.973	0.978	0.966
M2D2A1P2a2h3	0.840	0.754	0.679	M3D3A3P1a1h2	0.876	0.729	0.719
M2D2A1P2a3h3	0.736	0.733	0.665	M3D3A3P1a2h2	0.890	0.900	0.809
M2D2A1P3a1h3	0.847	0.679	0.646	M3D3A3P1a3h2	0.877	0.950	0.945
M2D2A1P3a2h3	0.802	0.766	0.707	M3D3A3P2a1h2	0.856	0.728	0.728
M2D2A1P3a3h3	0.647	0.742	0.694	M3D3A3P2a2h2	0.857	0.898	0.844
M2D2A2P1a1h1	0.953	0.890	0.880	M3D3A3P2a3h2	0.830	0.976	0.977
M2D2A2P1a2h1	0.973	0.962	0.971	M3D3A3P3a1h2	0.814	0.775	0.723
M2D2A2P1a3h1	0.963	0.977	0.973	M3D3A3P3a2h2	0.855	0.912	0.857
M2D2A2P2a1h1	0.948	0.910	0.894	M3D3A3P3a3h2	0.820	0.967	0.941
M2D2A2P2a2h1	0.973	0.942	0.979	M3D3A3P1a1h3	0.827	0.652	0.627
M2D2A2P2a3h1	0.958	0.943	0.975	M3D3A3P1a2h3	0.828	0.929	0.903
M2D2A2P3a1h1	0.934	0.891	0.883	M3D3A3P1a3h3	0.762	0.917	0.912
M2D2A2P3a2h1	0.972	0.964	0.964	M3D3A3P2a1h3	0.791	0.624	0.646
M2D2A2P3a3h1	0.950	0.961	0.954	M3D3A3P2a2h3	0.738	0.643	0.605
M2D2A2P1a1h2	0.895	0.723	0.704	M3D3A3P2a3h3	0.671	0.979	0.974
M2D2A2P1a2h2	0.908	0.844	0.792	M3D3A3P3a1h3	0.730	0.741	0.658
M2D2A2P1a3h2	0.884	0.891	0.836	M3D3A3P3a2h3	0.796	0.961	0.961
M2D2A2P2a1h2	0.873	0.736	0.710	M3D3A3P3a3h3	0.609	0.921	0.941
M2D2A2P2a2h2	0.889	0.847	0.802				

Table D.3 Critical buckling limit ratios for specimens with single corrosion defect of $d_p/t=0.30$

Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}	Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}
M1D1A1P1a1h1	0.959	0.846	0.780	M2D2A2P2a3h2	0.790	0.871	0.773
M1D1A1P1a2h1	0.961	0.885	0.817	M2D2A2P3a1h2	0.675	0.847	0.774
M1D1A1P1a3h1	0.961	0.909	0.840	M2D2A2P3a2h2	0.694	0.904	0.825
M1D1A1P2a1h1	0.933	0.841	0.790	M2D2A2P3a3h2	0.753	0.912	0.907
M1D1A1P2a2h1	0.934	0.861	0.804	M2D2A2P1a1h3	0.649	0.462	0.440
M1D1A1P2a3h1	0.941	0.920	0.857	M2D2A2P1a2h3	0.633	0.473	0.445
M1D1A1P3a1h1	0.837	0.552	0.613	M2D2A2P1a3h3	0.669	0.644	0.574
M1D1A1P3a2h1	0.859	0.781	0.733	M2D2A2P2a1h3	0.592	0.638	0.542
M1D1A1P3a3h1	0.873	0.887	0.806	M2D2A2P2a2h3	0.646	0.712	0.614
M1D1A1P1a1h2	0.903	0.585	0.519	M2D2A2P2a3h3	0.633	0.827	0.695
M1D1A1P1a2h2	0.908	0.706	0.601	M2D2A2P3a1h3*	0.525	0.959	0.845
M1D1A1P1a3h2	0.911	0.764	0.660	M2D2A2P3a2h3*	0.540	0.906	0.901

Table D.3 Critical buckling limit ratios for specimens with single corrosion defect of $d_p/t=0.30$ - continue

Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}	Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}
M1D1A1P2a1h2	0.845	0.619	0.533	M2D2A2P3a3h3*	0.630	0.975	0.943
M1D1A1P2a2h2	0.851	0.670	0.567	M2D2A3P1a1h1	0.888	0.799	0.789
M1D1A1P2a3h2	0.868	0.825	0.690	M2D2A3P1a2h1	0.881	0.811	0.798
M1D1A1P3a1h2	0.751	0.817	0.695	M2D2A3P1a3h1	0.890	0.864	0.845
M1D1A1P3a2h2	0.742	0.835	0.730	M2D2A3P2a1h1	0.883	0.902	0.872
M1D1A1P3a3h2	0.770	0.912	0.803	M2D2A3P2a2h1	0.907	0.932	0.908
M1D1A1P1a1h3	0.831	0.319	0.397	M2D2A3P2a3h1	0.904	0.952	0.928
M1D1A1P1a2h3	0.839	0.371	0.408	M2D2A3P3a1h1	0.797	0.803	0.786
M1D1A1P1a3h3	0.844	0.619	0.495	M2D2A3P3a2h1	0.808	0.862	0.836
M1D1A1P2a1h3	0.770	0.539	0.434	M2D2A3P3a3h1	0.841	0.967	0.926
M1D1A1P2a2h3	0.760	0.565	0.450	M2D2A3P1a1h2	0.733	0.592	0.571
M1D1A1P2a3h3	0.788	0.773	0.601	M2D2A3P1a2h2	0.714	0.618	0.590
M1D1A1P3a1h3*	0.662	0.853	0.690	M2D2A3P1a3h2	0.738	0.733	0.692
M1D1A1P3a2h3*	0.632	0.923	0.785	M2D2A3P2a1h2	0.656	0.669	0.615
M1D1A1P3a3h3*	0.570	0.953	0.842	M2D2A3P2a2h2	0.734	0.791	0.738
M1D1A2P1a1h1	0.947	0.612	0.712	M2D2A3P2a3h2	0.725	0.870	0.803
M1D1A2P1a2h1	0.949	0.509	0.677	M2D2A3P3a1h2	0.550	0.778	0.718
M1D1A2P1a3h1	0.951	0.780	0.805	M2D2A3P3a2h2	0.577	0.846	0.785
M1D1A2P2a1h1	0.922	0.857	0.817	M2D2A3P3a3h2	0.655	0.965	0.907
M1D1A2P2a2h1	0.923	0.875	0.831	M2D2A3P1a1h3	0.566	0.442	0.410
M1D1A2P2a3h1	0.930	0.919	0.872	M2D2A3P1a2h3	0.552	0.461	0.424
M1D1A2P3a1h1	0.777	0.515	0.610	M2D2A3P1a3h3	0.590	0.626	0.569
M1D1A2P3a2h1	0.807	0.787	0.755	M2D2A3P2a1h3	0.498	0.570	0.496
M1D1A2P3a3h1	0.826	0.890	0.825	M2D2A3P2a2h3	0.559	0.674	0.597
M1D1A2P1a1h2	0.866	0.589	0.533	M2D2A3P2a3h3	0.542	0.803	0.699
M1D1A2P1a2h2	0.876	0.485	0.479	M2D2A3P3a1h3*	0.347	0.825	0.739
M1D1A2P1a3h2	0.882	0.769	0.688	M2D2A3P3a2h3*	0.364	0.897	0.807
M1D1A2P2a1h2	0.806	0.639	0.578	M2D2A3P3a3h3*	0.484	0.971	0.915
M1D1A2P2a2h2	0.813	0.692	0.612	M2D3A1P1a1h1	0.893	0.739	0.735
M1D1A2P2a3h2	0.832	0.813	0.715	M2D3A1P1a2h1	0.898	0.774	0.758
M1D1A2P3a1h2	0.667	0.776	0.772	M2D3A1P1a3h1	0.900	0.779	0.765
M1D1A2P3a2h2	0.630	0.841	0.776	M2D3A1P2a1h1	0.902	0.979	0.948
M1D1A2P3a3h2	0.671	0.915	0.839	M2D3A1P2a2h1	0.917	0.979	0.951
M1D1A2P1a1h3	0.771	0.611	0.544	M2D3A1P2a3h1	0.922	0.979	0.956
M1D1A2P1a2h3	0.781	0.369	0.338	M2D3A1P3a1h1	0.914	0.977	0.933
M1D1A2P1a3h3	0.792	0.719	0.607	M2D3A1P3a2h1	0.928	0.978	0.939
M1D1A2P2a1h3	0.698	0.597	0.516	M2D3A1P3a3h1	0.929	0.971	0.965
M1D1A2P2a2h3	0.685	0.620	0.522	M2D3A1P1a1h2	0.763	0.508	0.508
M1D1A2P2a3h3	0.717	0.772	0.650	M2D3A1P1a2h2	0.774	0.577	0.552
M1D1A2P3a1h3*	0.540	0.874	0.769	M2D3A1P1a3h2	0.781	0.586	0.566

Table D.3 Critical buckling limit ratios for specimens with single corrosion defect of $d_p/t=0.30$ - continue

Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}	Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}
M1D1A2P3a2h3*	0.458	0.936	0.852	M2D3A1P2a1h2	0.742	0.785	0.667
M1D1A2P3a3h3*	0.519	0.960	0.891	M2D3A1P2a2h2	0.785	0.802	0.695
M1D1A3P1a1h1	0.929	0.608	0.730	M2D3A1P2a3h2	0.800	0.864	0.743
M1D1A3P1a2h1	0.936	0.509	0.685	M2D3A1P3a1h2*	0.730	0.975	0.855
M1D1A3P1a3h1	0.940	0.786	0.824	M2D3A1P3a2h2*	0.783	0.977	0.872
M1D1A3P2a1h1	0.898	0.876	0.848	M2D3A1P3a3h2*	0.785	0.947	0.942
M1D1A3P2a2h1	0.902	0.890	0.859	M2D3A1P1a1h3	0.665	0.433	0.434
M1D1A3P2a3h1	0.913	0.931	0.897	M2D3A1P1a2h3	0.675	0.492	0.471
M1D1A3P3a1h1	0.621	0.604	0.793	M2D3A1P1a3h3	0.685	0.504	0.488
M1D1A3P3a2h1	0.657	0.802	0.831	M2D3A1P2a1h3	0.619	0.841	0.661
M1D1A3P3a3h1	0.708	0.936	0.889	M2D3A1P2a2h3	0.756	0.858	0.689
M1D1A3P1a1h2	0.802	0.656	0.614	M2D3A1P2a3h3	0.681	0.900	0.737
M1D1A3P1a2h2	0.825	0.564	0.549	M2D3A1P3a1h3*	0.630	1.069	1.064
M1D1A3P1a3h2	0.838	0.810	0.752	M2D3A1P3a2h3*	0.676	1.090	1.084
M1D1A3P2a1h2	0.721	0.687	0.647	M2D3A1P3a3h3*	0.679	1.022	1.017
M1D1A3P2a2h2	0.734	0.725	0.673	M2D3A2P1a1h1	0.857	0.638	0.673
M1D1A3P2a3h2	0.764	0.840	0.772	M2D3A2P1a2h1	0.871	0.787	0.777
M1D1A3P3a1h2	0.320	0.639	0.786	M2D3A2P1a3h1	0.867	0.699	0.720
M1D1A3P3a2h2	0.301	0.818	0.826	M2D3A2P2a1h1	0.879	0.976	0.979
M1D1A3P3a3h2	0.408	0.920	0.887	M2D3A2P2a2h1	0.899	0.977	0.979
M1D1A3P1a1h3	0.646	0.586	0.532	M2D3A2P2a3h1	0.903	0.978	0.979
M1D1A3P1a2h3	0.669	0.405	0.395	M2D3A2P3a1h1	0.887	0.973	0.957
M1D1A3P1a3h3	0.698	0.746	0.670	M2D3A2P3a2h1	0.906	0.977	0.965
M1D1A3P2a1h3	0.568	0.558	0.527	M2D3A2P3a3h1	0.906	0.978	0.977
M1D1A3P2a2h3	0.546	0.560	0.514	M2D3A2P1a1h2	0.689	0.518	0.519
M1D1A3P2a3h3	0.601	0.748	0.662	M2D3A2P1a2h2	0.722	0.720	0.675
M1D1A3P3a1h3	F	F	F	M2D3A2P1a3h2	0.713	0.602	0.589
M1D1A3P3a2h3	F	F	F	M2D3A2P2a1h2	0.664	0.732	0.654
M1D1A3P3a3h3	F	F	F	M2D3A2P2a2h2	0.726	0.818	0.736
M1D2A1P1a1h1	0.935	0.842	0.781	M2D3A2P2a3h2	0.739	0.863	0.777
M1D2A1P1a2h1	0.931	0.838	0.770	M2D3A2P3a1h2*	0.631	0.910	0.835
M1D2A1P1a3h1	0.935	0.869	0.797	M2D3A2P3a2h2*	0.703	0.951	0.884
M1D2A1P2a1h1	0.924	0.878	0.816	M2D3A2P3a3h2*	0.704	0.969	0.963
M1D2A1P2a2h1	0.936	0.905	0.849	M2D3A2P1a1h3	0.554	0.357	0.365
M1D2A1P2a3h1	0.939	0.927	0.865	M2D3A2P1a2h3	0.581	0.499	0.475
M1D2A1P3a1h1	0.866	0.896	0.859	M2D3A2P1a3h3	0.567	0.279	0.333
M1D2A1P3a2h1	0.870	0.917	0.820	M2D3A2P2a1h3*	0.580	1.133	1.127
M1D2A1P3a3h1	0.893	0.894	0.861	M2D3A2P2a2h3*	0.635	1.274	1.267
M1D2A1P1a1h2	0.855	0.692	0.621	M2D3A2P2a3h3*	0.645	1.343	1.336
M1D2A1P1a2h2	0.843	0.682	0.601	M2D3A2P3a1h3*	0.479	0.905	0.900

Table D.3 Critical buckling limit ratios for specimens with single corrosion defect of $d_p/t=0.30$ - continue

Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}	Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}
M1D2A1P1a3h2	0.855	0.747	0.651	M2D3A2P3a2h3*	0.534	0.958	0.953
M1D2A1P2a1h2	0.799	0.752	0.609	M2D3A2P3a3h3*	0.536	0.779	0.975
M1D2A1P2a2h2	0.837	0.811	0.683	M2D3A3P1a1h1	0.814	0.638	0.660
M1D2A1P2a3h2	0.845	0.860	0.721	M2D3A3P1a2h1	0.830	0.783	0.766
M1D2A1P3a1h2*	0.742	0.974	0.969	M2D3A3P1a3h1	0.825	0.696	0.706
M1D2A1P3a2h2*	0.747	0.901	0.896	M2D3A3P2a1h1	0.824	0.825	0.799
M1D2A1P3a3h2*	0.796	0.923	0.918	M2D3A3P2a2h1	0.852	0.882	0.855
M1D2A1P1a1h3	0.755	0.520	0.488	M2D3A3P2a3h1	0.859	0.912	0.881
M1D2A1P1a2h3	0.750	0.504	0.464	M2D3A3P3a1h1	0.849	0.958	0.958
M1D2A1P1a3h3	0.768	0.607	0.532	M2D3A3P3a2h1	0.877	0.970	0.967
M1D2A1P2a1h3*	0.691	0.843	0.655	M2D3A3P3a3h1	0.877	0.981	0.976
M1D2A1P2a2h3*	0.720	0.868	0.698	M2D3A3P1a1h2	0.624	0.518	0.486
M1D2A1P2a3h3*	0.736	0.901	0.734	M2D3A3P1a2h2	0.660	0.715	0.650
M1D2A1P3a1h3*	0.631	0.977	0.974	M2D3A3P1a3h2	0.649	0.597	0.557
M1D2A1P3a2h3*	0.629	0.961	0.967	M2D3A3P2a1h2	0.596	0.667	0.588
M1D2A1P3a3h3*	0.610	0.944	0.938	M2D3A3P2a2h2	0.664	0.782	0.709
M1D2A2P1a1h1	0.914	0.916	0.877	M2D3A3P2a3h2	0.681	0.842	0.764
M1D2A2P1a2h1	0.908	0.914	0.875	M2D3A3P3a1h2	0.481	0.827	0.739
M1D2A2P1a3h1	0.915	0.932	0.894	M2D3A3P3a2h2	0.588	0.908	0.832
M1D2A2P2a1h1	0.900	0.899	0.858	M2D3A3P3a3h2	0.589	0.944	0.939
M1D2A2P2a2h1	0.917	0.940	0.903	M2D3A3P1a1h3	0.475	0.361	0.327
M1D2A2P2a3h1	0.920	0.946	0.906	M2D3A3P1a2h3	0.502	0.500	0.439
M1D2A2P3a1h1*	0.784	0.336	1.247	M2D3A3P1a3h3	0.486	0.288	0.287
M1D2A2P3a2h1*	0.793	0.889	0.868	M2D3A3P2a1h3	0.496	0.961	0.956
M1D2A2P3a3h1*	0.832	0.968	0.869	M2D3A3P2a2h3	0.552	1.156	1.150
M1D2A2P1a1h2	0.780	0.761	0.720	M2D3A3P2a3h3	0.576	1.122	1.116
M1D2A2P1a2h2	0.761	0.755	0.715	M2D3A3P3a1h3*	0.276	0.870	0.748
M1D2A2P1a3h2	0.783	0.810	0.762	M2D3A3P3a2h3*	0.339	0.955	0.843
M1D2A2P2a1h2	0.699	0.751	0.675	M2D3A3P3a3h3*	0.341	0.947	0.942
M1D2A2P2a2h2	0.755	0.866	0.786	M3D1A1P1a1h1	0.955	0.928	0.842
M1D2A2P2a3h2	0.767	0.884	0.794	M3D1A1P1a2h1	0.958	0.880	0.862
M1D2A2P3a1h2*	0.572	1.055	1.049	M3D1A1P1a3h1	0.958	0.952	0.881
M1D2A2P3a2h2*	0.587	0.956	0.951	M3D1A1P2a1h1	0.940	0.901	0.856
M1D2A2P3a3h2*	0.669	0.956	0.951	M3D1A1P2a2h1	0.948	0.916	0.876
M1D2A2P1a1h3	0.645	0.577	0.552	M3D1A1P2a3h1	0.950	0.946	0.902
M1D2A2P1a2h3	0.632	0.558	0.539	M3D1A1P3a1h1	0.912	0.730	0.738
M1D2A2P1a3h3	0.668	0.661	0.618	M3D1A1P3a2h1	0.908	0.838	0.795
M1D2A2P2a1h3*	0.573	0.702	0.605	M3D1A1P3a3h1	0.938	0.929	0.872
M1D2A2P2a2h3*	0.600	0.824	0.718	M3D1A1P1a1h2	0.885	0.644	0.603
M1D2A2P2a3h3*	0.620	0.849	0.728	M3D1A1P1a2h2	0.891	0.723	0.656

Table D.3 Critical buckling limit ratios for specimens with single corrosion defect of $d_p/t=0.30$ - continue

Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}	Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}
M1D2A2P3a1h3*	0.397	0.814	0.783	M3D1A1P1a3h2	0.895	0.790	0.709
M1D2A2P3a2h3*	0.400	1.050	1.045	M3D1A1P2a1h2	0.834	0.696	0.596
M1D2A2P3a3h3*	0.523	1.049	1.044	M3D1A1P2a2h2	0.866	0.747	0.661
M1D2A3P1a1h1	0.884	0.967	0.930	M3D1A1P2a3h2	0.873	0.855	0.739
M1D2A3P1a2h1	0.877	0.969	0.935	M3D1A1P3a1h2	0.816	0.808	0.692
M1D2A3P1a3h1	0.884	0.970	0.942	M3D1A1P3a2h2	0.808	0.797	0.693
M1D2A3P2a1h1	0.868	0.893	0.862	M3D1A1P3a3h2	0.854	0.914	0.811
M1D2A3P2a2h1	0.887	0.942	0.918	M3D1A1P1a1h3	0.789	0.432	0.408
M1D2A3P2a3h1	0.892	0.951	0.926	M3D1A1P1a2h3	0.801	0.506	0.400
M1D2A3P3a1h1	0.490	0.971	0.966	M3D1A1P1a3h3	0.809	0.628	0.535
M1D2A3P3a2h1	0.522	0.867	0.944	M3D1A1P2a1h3	0.733	0.603	0.470
M1D2A3P3a3h1	0.574	0.973	0.970	M3D1A1P2a2h3	0.773	0.643	0.527
M1D2A3P1a1h2	0.723	0.744	0.683	M3D1A1P2a3h3	0.784	0.800	0.639
M1D2A3P1a2h2	0.703	0.777	0.705	M3D1A1P3a1h3	0.713	0.639	0.548
M1D2A3P1a3h2	0.724	0.808	0.750	M3D1A1P3a2h3	0.707	0.796	0.652
M1D2A3P2a1h2	0.627	0.656	0.599	M3D1A1P3a3h3	0.781	0.914	0.787
M1D2A3P2a2h2	0.687	0.839	0.779	M3D1A2P1a1h1	0.947	0.897	0.853
M1D2A3P2a3h2	0.702	0.872	0.804	M3D1A2P1a2h1	0.950	0.932	0.874
M1D2A3P3a1h2	F	F	F	M3D1A2P1a3h1	0.951	0.947	0.895
M1D2A3P3a2h2	F	F	F	M3D1A2P2a1h1	0.934	0.909	0.871
M1D2A3P3a3h2	F	F	F	M3D1A2P2a2h1	0.944	0.924	0.892
M1D2A3P1a1h3	0.579	0.552	0.509	M3D1A2P2a3h1	0.945	0.946	0.913
M1D2A3P1a2h3	0.566	0.599	0.534	M3D1A2P3a1h1	0.899	0.716	0.727
M1D2A3P1a3h3	0.596	0.659	0.607	M3D1A2P3a2h1	0.896	0.842	0.806
M1D2A3P2a1h3	0.446	0.531	0.459	M3D1A2P3a3h1	0.927	0.933	0.889
M1D2A3P2a2h3	0.493	0.742	0.652	M3D1A2P1a1h2	0.855	0.626	0.593
M1D2A3P2a3h3	0.517	0.797	0.692	M3D1A2P1a2h2	0.867	0.708	0.656
M1D2A3P3a1h3	F	F	F	M3D1A2P1a3h2	0.872	0.787	0.722
M1D2A3P3a2h3	F	F	F	M3D1A2P2a1h2	0.806	0.700	0.613
M1D2A3P3a3h3	F	F	F	M3D1A2P2a2h2	0.847	0.757	0.684
M1D3A1P1a1h1	0.910	0.962	0.914	M3D1A2P2a3h2	0.851	0.844	0.756
M1D3A1P1a2h1	0.915	0.961	0.915	M3D1A2P3a1h2	0.781	0.764	0.739
M1D3A1P1a3h1	0.916	0.960	0.916	M3D1A2P3a2h2	0.771	0.797	0.713
M1D3A1P2a1h1	0.912	0.979	0.973	M3D1A2P3a3h2	0.829	0.918	0.840
M1D3A1P2a2h1	0.928	0.979	0.958	M3D1A2P1a1h3	0.745	0.430	0.402
M1D3A1P2a3h1	0.931	0.979	0.956	M3D1A2P1a2h3	0.758	0.444	0.383
M1D3A1P3a1h1*	0.930	0.955	0.966	M3D1A2P1a3h3	0.767	0.650	0.566
M1D3A1P3a2h1*	0.929	0.975	0.971	M3D1A2P2a1h3	0.685	0.608	0.494
M1D3A1P3a3h1*	0.936	0.971	0.977	M3D1A2P2a2h3	0.733	0.654	0.557
M1D3A1P1a1h2	0.809	0.785	0.760	M3D1A2P2a3h3	0.740	0.781	0.658

Table D.3 Critical buckling limit ratios for specimens with single corrosion defect of $d_p/t=0.30$ - continue

Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}	Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}
M1D3A1P1a2h2	0.824	0.776	0.761	M3D1A2P3a1h3	0.653	0.612	0.540
M1D3A1P1a3h2	0.825	0.775	0.764	M3D1A2P3a2h3	0.646	0.791	0.676
M1D3A1P2a1h2*	0.712	0.834	0.829	M3D1A2P3a3h3	0.738	0.916	0.822
M1D3A1P2a2h2*	0.772	0.938	0.832	M3D1A3P1a1h1	0.938	0.867	0.859
M1D3A1P2a3h2*	0.784	0.924	0.818	M3D1A3P1a2h1	0.944	0.908	0.889
M1D3A1P3a1h2*	0.791	0.967	0.948	M3D1A3P1a3h1	0.944	0.955	0.905
M1D3A1P3a2h2*	0.784	0.931	0.923	M3D1A3P2a1h1	0.925	0.919	0.886
M1D3A1P3a3h2*	0.810	0.889	0.898	M3D1A3P2a2h1	0.938	0.932	0.907
M1D3A1P1a1h3	0.701	0.680	0.664	M3D1A3P2a3h1	0.940	0.952	0.928
M1D3A1P1a2h3	0.718	0.651	0.657	M3D1A3P3a1h1	0.881	0.741	0.732
M1D3A1P1a3h3	0.722	0.648	0.662	M3D1A3P3a2h1	0.876	0.850	0.821
M1D3A1P2a1h3*	0.695	0.845	0.841	M3D1A3P3a3h1	0.916	0.942	0.912
M1D3A1P2a2h3*	0.652	0.970	0.843	M3D1A3P1a1h2	0.820	0.623	0.595
M1D3A1P2a3h3*	0.672	0.966	0.830	M3D1A3P1a2h2	0.839	0.738	0.687
M1D3A1P3a1h3*	0.707	0.917	0.901	M3D1A3P1a3h2	0.846	0.801	0.745
M1D3A1P3a2h3*	0.668	0.905	0.900	M3D1A3P2a1h2	0.768	0.710	0.635
M1D3A1P3a3h3*	0.709	0.929	0.924	M3D1A3P2a2h2	0.819	0.769	0.710
M1D3A2P1a1h1	0.837	0.846	0.807	M3D1A3P2a3h2	0.824	0.858	0.789
M1D3A2P1a2h1	0.856	0.900	0.865	M3D1A3P3a1h2	0.731	0.651	0.605
M1D3A2P1a3h1	0.846	0.861	0.830	M3D1A3P3a2h2	0.718	0.802	0.737
M1D3A2P2a1h1	0.894	0.978	0.979	M3D1A3P3a3h2	0.792	0.928	0.875
M1D3A2P2a2h1	0.909	0.978	0.980	M3D1A3P1a1h3	0.686	0.385	0.378
M1D3A2P2a3h1	0.914	0.978	0.980	M3D1A3P1a2h3	0.705	0.466	0.430
M1D3A2P3a1h1	0.861	0.979	0.970	M3D1A3P1a3h3	0.717	0.643	0.575
M1D3A2P3a2h1	0.862	0.980	0.975	M3D1A3P2a1h3	0.618	0.580	0.485
M1D3A2P3a3h1	0.873	0.980	0.979	M3D1A3P2a2h3	0.676	0.621	0.547
M1D3A2P1a1h2	0.812	0.695	0.659	M3D1A3P2a3h3	0.685	0.771	0.673
M1D3A2P1a2h2	0.747	0.810	0.768	M3D1A3P3a1h3	0.567	0.665	0.559
M1D3A2P1a3h2	0.779	0.727	0.704	M3D1A3P3a2h3	0.562	0.692	0.605
M1D3A2P2a1h2	0.659	0.865	0.752	M3D1A3P3a3h3	0.679	0.897	0.818
M1D3A2P2a2h2	0.717	0.885	0.803	M3D2A1P1a1h1	0.923	0.708	0.746
M1D3A2P2a3h2	0.730	0.896	0.814	M3D2A1P1a2h1	0.913	0.705	0.734
M1D3A2P3a1h2*	0.606	0.964	0.942	M3D2A1P1a3h1	0.920	0.781	0.769
M1D3A2P3a2h2*	0.612	0.947	0.951	M3D2A1P2a1h1	0.915	0.885	0.836
M1D3A2P3a3h2*	0.647	0.971	0.975	M3D2A1P2a2h1	0.932	0.910	0.866
M1D3A2P1a1h3	0.575	0.497	0.467	M3D2A1P2a3h1	0.931	0.939	0.886
M1D3A2P1a2h3	0.607	0.587	0.561	M3D2A1P3a1h1	0.903	0.887	0.846
M1D3A2P1a3h3	0.681	0.395	0.434	M3D2A1P3a2h1	0.917	0.880	0.846
M1D3A2P2a1h3*	0.593	1.087	1.081	M3D2A1P3a3h1	0.927	0.916	0.911
M1D3A2P2a2h3*	0.637	1.191	1.184	M3D2A1P1a1h2	0.832	0.613	0.606

Table D.3 Critical buckling limit ratios for specimens with single corrosion defect of $d_p/t=0.30$ - continue

Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}	Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}
M1D3A2P2a3h3*	0.650	1.273	1.266	M3D2A1P1a2h2	0.809	0.606	0.588
M1D3A2P3a1h3*	0.452	1.331	1.324	M3D2A1P1a3h2	0.825	0.711	0.643
M1D3A2P3a2h3*	0.420	1.075	1.069	M3D2A1P2a1h2	0.777	0.720	0.626
M1D3A2P3a3h3*	0.453	0.978	0.973	M3D2A1P2a2h2	0.829	0.790	0.699
M1D3A3P1a1h1	0.823	0.887	0.818	M3D2A1P2a3h2	0.825	0.870	0.750
M1D3A3P1a2h1	0.842	0.927	0.874	M3D2A1P3a1h2	0.757	0.852	0.747
M1D3A3P1a3h1	0.835	0.899	0.842	M3D2A1P3a2h2	0.793	0.845	0.749
M1D3A3P2a1h1	0.841	0.849	0.808	M3D2A1P3a3h2	0.824	0.865	0.860
M1D3A3P2a2h1	0.867	0.912	0.872	M3D2A1P1a1h3	0.716	0.407	0.433
M1D3A3P2a3h1	0.872	0.928	0.891	M3D2A1P1a2h3	0.692	0.397	0.411
M1D3A3P3a1h1	F	F	F	M3D2A1P1a3h3	0.720	0.560	0.490
M1D3A3P3a2h1	F	F	F	M3D2A1P2a1h3	0.664	0.666	0.541
M1D3A3P3a3h1	F	F	F	M3D2A1P2a2h3	0.712	0.727	0.603
M1D3A3P1a1h2	0.673	0.718	0.638	M3D2A1P2a3h3	0.705	0.833	0.670
M1D3A3P1a2h2	0.710	0.828	0.758	M3D2A1P3a1h3*	0.627	0.949	0.799
M1D3A3P1a3h2	0.697	0.751	0.691	M3D2A1P3a2h3*	0.676	0.813	0.836
M1D3A3P2a1h2	0.568	0.721	0.592	M3D2A1P3a3h3*	0.630	0.910	0.906
M1D3A3P2a2h2	0.644	0.846	0.734	M3D2A2P1a1h1	0.906	0.689	0.714
M1D3A3P2a3h2	0.662	0.876	0.778	M3D2A2P1a2h1	0.895	0.686	0.709
M1D3A3P3a1h2	F	F	F	M3D2A2P1a3h1	0.904	0.790	0.777
M1D3A3P3a2h2	F	F	F	M3D2A2P2a1h1	0.902	0.893	0.855
M1D3A3P3a3h2	F	F	F	M3D2A2P2a2h1	0.924	0.917	0.883
M1D3A3P1a1h3	0.502	0.515	0.420	M3D2A2P2a3h1	0.922	0.946	0.908
M1D3A3P1a2h3	0.540	0.617	0.531	M3D2A2P3a1h1	0.885	0.876	0.841
M1D3A3P1a3h3	0.519	0.433	0.395	M3D2A2P3a2h1	0.901	0.885	0.858
M1D3A3P2a1h3	0.462	0.962	0.957	M3D2A2P3a3h1	0.914	0.938	0.933
M1D3A3P2a2h3	0.526	1.135	1.129	M3D2A2P1a1h2	0.794	0.605	0.595
M1D3A3P2a3h3	0.551	1.109	1.103	M3D2A2P1a2h2	0.766	0.598	0.586
M1D3A3P3a1h3	F	F	F	M3D2A2P1a3h2	0.788	0.733	0.684
M1D3A3P3a2h3	F	F	F	M3D2A2P2a1h2	0.726	0.719	0.640
M1D3A3P3a3h3	F	F	F	M3D2A2P2a2h2	0.795	0.792	0.714
M2D1A1P1a1h1	0.956	0.838	0.817	M3D2A2P2a3h2	0.790	0.878	0.782
M2D1A1P1a2h1	0.958	0.856	0.831	M3D2A2P3a1h2	0.698	0.835	0.752
M2D1A1P1a3h1	0.958	0.901	0.864	M3D2A2P3a2h2	0.745	0.847	0.777
M2D1A1P2a1h1	0.929	0.853	0.804	M3D2A2P3a3h2	0.783	0.907	0.902
M2D1A1P2a2h1	0.938	0.882	0.833	M3D2A2P1a1h3	0.650	0.412	0.415
M2D1A1P2a3h1	0.941	0.928	0.871	M3D2A2P1a2h3	0.621	0.392	0.397
M2D1A1P3a1h1	0.883	0.753	0.716	M3D2A2P1a3h3	0.658	0.598	0.544
M2D1A1P3a2h1	0.876	0.780	0.728	M3D2A2P2a1h3	0.598	0.660	0.566
M2D1A1P3a3h1	0.898	0.911	0.831	M3D2A2P2a2h3	0.654	0.722	0.626

Table D.3 Critical buckling limit ratios for specimens with single corrosion defect of $d_p/t=0.30$ - continue

Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}	Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}
M2D1A1P1a1h2	0.891	0.615	0.575	M3D2A2P2a3h3	0.646	0.839	0.715
M2D1A1P1a2h2	0.896	0.660	0.609	M3D2A2P3a1h3*	0.535	0.760	0.756
M2D1A1P1a3h2	0.899	0.777	0.691	M3D2A2P3a2h3*	0.598	0.690	0.826
M2D1A1P2a1h2	0.829	0.628	0.542	M3D2A2P3a3h3*	0.661	0.925	0.920
M2D1A1P2a2h2	0.853	0.708	0.614	M3D2A3P1a1h1	0.886	0.744	0.757
M2D1A1P2a3h2	0.865	0.836	0.708	M3D2A3P1a2h1	0.876	0.756	0.763
M2D1A1P3a1h2	0.784	0.713	0.627	M3D2A3P1a3h1	0.885	0.829	0.823
M2D1A1P3a2h2	0.770	0.745	0.644	M3D2A3P2a1h1	0.888	0.895	0.856
M2D1A1P3a3h2	0.815	0.899	0.780	M3D2A3P2a2h1	0.911	0.927	0.902
M2D1A1P1a1h3	0.804	0.428	0.385	M3D2A3P2a3h1	0.910	0.950	0.923
M2D1A1P1a2h3	0.813	0.497	0.434	M3D2A3P3a1h1	0.839	0.862	0.837
M2D1A1P1a3h3	0.820	0.673	0.555	M3D2A3P3a2h1	0.862	0.873	0.854
M2D1A1P2a1h3	0.738	0.536	0.429	M3D2A3P3a3h1	0.880	0.971	0.941
M2D1A1P2a2h3	0.760	0.605	0.486	M3D2A3P1a1h2	0.744	0.605	0.586
M2D1A1P2a3h3	0.780	0.781	0.613	M3D2A3P1a2h2	0.719	0.622	0.596
M2D1A1P3a1h3*	0.681	0.754	0.628	M3D2A3P1a3h2	0.744	0.738	0.701
M2D1A1P3a2h3*	0.669	0.788	0.645	M3D2A3P2a1h2	0.674	0.693	0.622
M2D1A1P3a3h3*	0.625	0.914	0.781	M3D2A3P2a2h2	0.752	0.803	0.752
M2D1A2P1a1h1	0.945	0.831	0.814	M3D2A3P2a3h2	0.746	0.880	0.815
M2D1A2P1a2h1	0.948	0.857	0.836	M3D2A3P3a1h2	0.607	0.751	0.676
M2D1A2P1a3h1	0.949	0.899	0.870	M3D2A3P3a2h2	0.668	0.772	0.714
M2D1A2P2a1h1	0.920	0.864	0.824	M3D2A3P3a3h2	0.716	0.963	0.897
M2D1A2P2a2h1	0.930	0.893	0.853	M3D2A3P1a1h3	0.583	0.405	0.393
M2D1A2P2a3h1	0.933	0.927	0.884	M3D2A3P1a2h3	0.560	0.413	0.396
M2D1A2P3a1h1	0.858	0.757	0.727	M3D2A3P1a3h3	0.598	0.599	0.556
M2D1A2P3a2h1	0.850	0.786	0.745	M3D2A3P2a1h3	0.496	0.591	0.483
M2D1A2P3a3h1	0.878	0.917	0.856	M3D2A3P2a2h3	0.586	0.688	0.601
M2D1A2P1a1h2	0.857	0.590	0.559	M3D2A3P2a3h3	0.574	0.814	0.706
M2D1A2P1a2h2	0.868	0.659	0.616	M3D2A3P3a1h3*	0.417	0.704	0.635
M2D1A2P1a3h2	0.873	0.769	0.701	M3D2A3P3a2h3*	0.491	0.781	0.693
M2D1A2P2a1h2	0.795	0.633	0.564	M3D2A3P3a3h3*	0.567	0.963	0.891
M2D1A2P2a2h2	0.826	0.720	0.643	M3D3A1P1a1h1	0.877	0.702	0.721
M2D1A2P2a3h2	0.836	0.822	0.726	M3D3A1P1a2h1	0.880	0.731	0.737
M2D1A2P3a1h2	0.729	0.708	0.644	M3D3A1P1a3h1	0.882	0.746	0.749
M2D1A2P3a2h2	0.713	0.743	0.668	M3D3A1P2a1h1	0.887	0.979	0.949
M2D1A2P3a3h2	0.771	0.904	0.816	M3D3A1P2a2h1	0.907	0.979	0.954
M2D1A2P1a1h3	0.755	0.441	0.400	M3D3A1P2a3h1	0.912	0.979	0.958
M2D1A2P1a2h3	0.765	0.494	0.441	M3D3A1P3a1h1	0.915	0.978	0.937
M2D1A2P1a3h3	0.774	0.660	0.567	M3D3A1P3a2h1	0.931	0.977	0.929
M2D1A2P2a1h3	0.682	0.543	0.456	M3D3A1P3a3h1	0.931	0.972	0.967

Table D.3 Critical buckling limit ratios for specimens with single corrosion defect of $d_p/t=0.30$ - continue

Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}	Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}
M2D1A2P2a2h3	0.709	0.618	0.521	M3D3A1P1a1h2	0.743	0.485	0.515
M2D1A2P2a3h3	0.727	0.760	0.633	M3D3A1P1a2h2	0.752	0.539	0.543
M2D1A2P3a1h3*	0.593	0.743	0.650	M3D3A1P1a3h2	0.757	0.564	0.566
M2D1A2P3a2h3*	0.579	0.780	0.674	M3D3A1P2a1h2	0.717	0.758	0.681
M2D1A2P3a3h3*	0.530	0.916	0.819	M3D3A1P2a2h2	0.772	0.817	0.733
M2D1A3P1a1h1	0.934	0.849	0.830	M3D3A1P2a3h2	0.784	0.868	0.766
M2D1A3P1a2h1	0.939	0.879	0.857	M3D3A1P3a1h2	0.717	0.973	0.837
M2D1A3P1a3h1	0.941	0.915	0.890	M3D3A1P3a2h2	0.779	0.970	0.812
M2D1A3P2a1h1	0.905	0.875	0.842	M3D3A1P3a3h2	0.782	0.941	0.936
M2D1A3P2a2h1	0.918	0.903	0.872	M3D3A1P1a1h3	0.640	0.416	0.437
M2D1A3P2a3h1	0.923	0.936	0.903	M3D3A1P1a2h3	0.645	0.454	0.457
M2D1A3P3a1h1	0.817	0.764	0.741	M3D3A1P1a3h3	0.652	0.485	0.485
M2D1A3P3a2h1	0.806	0.793	0.764	M3D3A1P2a1h3	0.590	0.801	0.645
M2D1A3P3a3h1	0.845	0.927	0.885	M3D3A1P2a2h3	0.742	0.855	0.702
M2D1A3P1a1h2	0.816	0.594	0.567	M3D3A1P2a3h3	0.663	0.894	0.739
M2D1A3P1a2h2	0.835	0.682	0.642	M3D3A1P3a1h3*	0.607	0.940	0.922
M2D1A3P1a3h2	0.842	0.788	0.731	M3D3A1P3a2h3*	0.666	0.901	0.896
M2D1A3P2a1h2	0.743	0.645	0.591	M3D3A1P3a3h3*	0.670	0.931	0.917
M2D1A3P2a2h2	0.785	0.734	0.674	M3D3A2P1a1h1	0.854	0.606	0.665
M2D1A3P2a3h2	0.799	0.838	0.764	M3D3A2P1a2h1	0.866	0.749	0.756
M2D1A3P3a1h2	0.638	0.715	0.669	M3D3A2P1a3h1	0.860	0.658	0.702
M2D1A3P3a2h2	0.616	0.751	0.698	M3D3A2P2a1h1	0.890	0.979	0.980
M2D1A3P3a3h2	0.696	0.915	0.856	M3D3A2P2a2h1	0.894	0.976	0.979
M2D1A3P1a1h3	0.685	0.446	0.414	M3D3A2P2a3h1	0.898	0.977	0.979
M2D1A3P1a2h3	0.701	0.512	0.469	M3D3A2P3a1h1	0.898	0.974	0.954
M2D1A3P1a3h3	0.714	0.678	0.603	M3D3A2P3a2h1	0.917	0.975	0.956
M2D1A3P2a1h3	0.595	0.518	0.457	M3D3A2P3a3h1	0.916	0.976	0.977
M2D1A3P2a2h3	0.629	0.590	0.523	M3D3A2P1a1h2	0.699	0.521	0.530
M2D1A3P2a3h3	0.653	0.755	0.657	M3D3A2P1a2h2	0.723	0.696	0.660
M2D1A3P3a1h3*	0.449	0.636	0.581	M3D3A2P1a3h2	0.711	0.585	0.583
M2D1A3P3a2h3*	0.433	0.668	0.606	M3D3A2P2a1h2	0.721	0.614	0.689
M2D1A3P3a3h3*	0.555	0.892	0.815	M3D3A2P2a2h2	0.730	0.786	0.716
M2D2A1P1a1h1	0.928	0.800	0.785	M3D3A2P2a3h2	0.740	0.836	0.755
M2D2A1P1a2h1	0.922	0.801	0.781	M3D3A2P3a1h2	0.650	0.889	0.785
M2D2A1P1a3h1	0.928	0.854	0.817	M3D3A2P3a2h2	0.728	0.909	0.798
M2D2A1P2a1h1	0.920	0.882	0.833	M3D3A2P3a3h2	0.726	0.964	0.959
M2D2A1P2a2h1	0.935	0.911	0.865	M3D3A2P1a1h3	0.561	0.372	0.382
M2D2A1P2a3h1	0.933	0.940	0.886	M3D3A2P1a2h3	0.576	0.464	0.455
M2D2A1P3a1h1	0.884	0.789	0.785	M3D3A2P1a3h3	0.558	0.262	0.328
M2D2A1P3a2h1	0.890	0.867	0.822	M3D3A2P2a1h3*	0.657	0.679	0.647

Table D.3 Critical buckling limit ratios for specimens with single corrosion defect of $d_p/t=0.30$ - continue

Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}	Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}
M2D2A1P3a3h1	0.908	0.888	0.883	M3D3A2P2a2h3*	0.645	0.673	0.623
M2D2A1P1a1h2	0.843	0.615	0.588	M3D3A2P2a3h3*	0.653	0.698	0.677
M2D2A1P1a2h2	0.826	0.617	0.581	M3D3A2P3a1h3*	0.497	0.911	0.784
M2D2A1P1a3h2	0.841	0.725	0.654	M3D3A2P3a2h3*	0.566	0.698	0.887
M2D2A1P2a1h2	0.789	0.695	0.603	M3D3A2P3a3h3*	0.564	0.974	0.969
M2D2A1P2a2h2	0.836	0.779	0.685	M3D3A3P1a1h1	0.823	0.617	0.652
M2D2A1P2a3h2	0.831	0.863	0.739	M3D3A3P1a2h1	0.835	0.749	0.743
M2D2A1P3a1h2	0.757	0.852	0.748	M3D3A3P1a3h1	0.826	0.659	0.684
M2D2A1P3a2h2	0.770	0.905	0.792	M3D3A3P2a1h1	0.823	0.789	0.778
M2D2A1P3a3h2	0.811	0.869	0.864	M3D3A3P2a2h1	0.853	0.885	0.857
M2D2A1P1a1h3	0.728	0.457	0.433	M3D3A3P2a3h1	0.860	0.913	0.885
M2D2A1P1a2h3	0.713	0.459	0.428	M3D3A3P3a1h1	0.879	0.958	0.956
M2D2A1P1a3h3	0.739	0.614	0.528	M3D3A3P3a2h1	0.905	0.964	0.961
M2D2A1P2a1h3	0.684	0.634	0.513	M3D3A3P3a3h1	0.904	0.971	0.976
M2D2A1P2a2h3	0.725	0.711	0.583	M3D3A3P1a1h2	0.644	0.531	0.510
M2D2A1P2a3h3	0.716	0.824	0.656	M3D3A3P1a2h2	0.667	0.694	0.642
M2D2A1P3a1h3*	0.647	0.844	0.840	M3D3A3P1a3h2	0.653	0.582	0.557
M2D2A1P3a2h3*	0.658	0.893	0.889	M3D3A3P2a1h2	0.603	0.608	0.538
M2D2A1P3a3h3*	0.635	0.978	0.924	M3D3A3P2a2h2	0.754	0.795	0.711
M2D2A2P1a1h1	0.915	0.809	0.785	M3D3A3P2a3h2	0.692	0.849	0.772
M2D2A2P1a2h1	0.908	0.815	0.789	M3D3A3P3a1h2	0.565	0.809	0.703
M2D2A2P1a3h1	0.915	0.871	0.835	M3D3A3P3a2h2	0.672	0.854	0.768
M2D2A2P2a1h1	0.905	0.888	0.845	M3D3A3P3a3h2	0.668	0.942	0.937
M2D2A2P2a2h1	0.925	0.916	0.877	M3D3A3P1a1h3	0.495	0.390	0.358
M2D2A2P2a3h1	0.922	0.943	0.900	M3D3A3P1a2h3	0.506	0.473	0.426
M2D2A2P3a1h1	0.853	0.789	0.790	M3D3A3P1a3h3	0.485	0.274	0.288
M2D2A2P3a2h1	0.861	0.871	0.837	M3D3A3P2a1h3	0.514	0.958	0.953
M2D2A2P3a3h1	0.885	0.918	0.913	M3D3A3P2a2h3	0.575	1.149	1.143
M2D2A2P1a1h2	0.801	0.621	0.593	M3D3A3P2a3h3	0.599	1.112	1.106
M2D2A2P1a2h2	0.782	0.635	0.600	M3D3A3P3a1h3*	0.391	0.646	0.598
M2D2A2P1a3h2	0.802	0.751	0.692	M3D3A3P3a2h3*	0.472	0.861	0.694
M2D2A2P2a1h2	0.731	0.707	0.631	M3D3A3P3a3h3*	0.466	0.927	0.922
M2D2A2P2a2h2	0.797	0.789	0.714				

Table D.4 Critical buckling limit ratios for specimens with single corrosion defect of $d_p/t=0.40$

Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}	Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}
M1D1A1P1a1h1	0.949	0.687	0.669	M2D2A2P2a3h2	0.719	0.860	0.742
M1D1A1P1a2h1	0.953	0.814	0.768	M2D2A2P3a1h2*	0.613	0.947	0.849

Table D.4 Critical buckling limit ratios for specimens with single corrosion defect of $d_p/t=0.40$ - continue

Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}	Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}
M1D1A1P1a3h1	0.946	0.848	0.775	M2D2A2P3a2h2*	0.611	0.930	0.925
M1D1A1P2a1h1	0.894	0.651	0.600	M2D2A2P3a3h2*	0.694	0.972	0.967
M1D1A1P2a2h1	0.895	0.694	0.630	M2D2A2P1a1h3	0.568	0.464	0.416
M1D1A1P2a3h1	0.937	0.952	0.866	M2D2A2P1a2h3	0.535	0.390	0.365
M1D1A1P3a1h1	0.831	0.748	0.694	M2D2A2P1a3h3	0.555	0.479	0.435
M1D1A1P3a2h1	0.784	0.759	0.673	M2D2A2P2a1h3*	0.515	0.902	0.897
M1D1A1P3a3h1	0.782	0.821	0.728	M2D2A2P2a2h3*	0.536	0.979	0.793
M1D1A1P1a1h2	0.865	0.514	0.434	M2D2A2P2a3h3*	0.553	0.939	0.767
M1D1A1P1a2h2	0.884	0.618	0.519	M2D2A2P3a1h3*	0.464	0.985	0.980
M1D1A1P1a3h2	0.884	0.746	0.609	M2D2A2P3a2h3*	0.452	1.087	1.082
M1D1A1P2a1h2	0.800	0.560	0.457	M2D2A2P3a3h3*	0.506	1.036	1.030
M1D1A1P2a2h2	0.789	0.580	0.463	M2D2A3P1a1h1	0.864	0.750	0.744
M1D1A1P2a3h2	0.845	0.823	0.670	M2D2A3P1a2h1	0.852	0.796	0.777
M1D1A1P3a1h2*	0.722	0.809	0.709	M2D2A3P1a3h1	0.869	0.877	0.844
M1D1A1P3a2h2*	0.672	0.914	0.780	M2D2A3P2a1h1	0.790	0.705	0.684
M1D1A1P3a3h2*	0.670	0.860	0.856	M2D2A3P2a2h1	0.867	0.871	0.842
M1D1A1P1a1h3	0.779	0.493	0.380	M2D2A3P2a3h1	0.842	0.944	0.897
M1D1A1P1a2h3	0.786	0.385	0.310	M2D2A3P3a1h1	0.695	0.920	0.736
M1D1A1P1a3h3	0.797	0.512	0.396	M2D2A3P3a2h1	0.698	0.828	0.787
M1D1A1P2a1h3	0.709	0.578	0.437	M2D2A3P3a3h1	0.793	0.967	0.962
M1D1A1P2a2h3	0.688	0.605	0.449	M2D2A3P1a1h2	0.675	0.568	0.538
M1D1A1P2a3h3	0.731	0.694	0.520	M2D2A3P1a2h2	0.640	0.575	0.537
M1D1A1P3a1h3*	0.625	0.851	0.846	M2D2A3P1a3h2	0.661	0.675	0.614
M1D1A1P3a2h3*	0.561	0.949	0.944	M2D2A3P2a1h2	0.572	0.723	0.645
M1D1A1P3a3h3*	0.551	1.011	1.006	M2D2A3P2a2h2	0.648	0.732	0.667
M1D1A2P1a1h1	0.928	0.673	0.657	M2D2A3P2a3h2	0.641	0.826	0.745
M1D1A2P1a2h1	0.942	0.857	0.808	M2D2A3P3a1h2*	0.462	0.852	0.777
M1D1A2P1a3h1	0.933	0.879	0.817	M2D2A3P3a2h2*	0.459	0.948	0.867
M1D1A2P2a1h1	0.870	0.666	0.626	M2D2A3P3a3h2*	0.573	0.961	0.956
M1D1A2P2a2h1	0.873	0.711	0.663	M2D2A3P1a1h3	0.474	0.434	0.377
M1D1A2P2a3h1	0.928	0.979	0.914	M2D2A3P1a2h3	0.447	0.381	0.338
M1D1A2P3a1h1	0.763	0.753	0.719	M2D2A3P1a3h3	0.469	0.471	0.410
M1D1A2P3a2h1	0.692	0.765	0.708	M2D2A3P2a1h3	0.395	0.876	0.737
M1D1A2P3a3h1	0.688	0.827	0.768	M2D2A3P2a2h3	0.426	0.698	0.596
M1D1A2P1a1h2	0.811	0.539	0.474	M2D2A3P2a3h3	0.447	0.777	0.661
M1D1A2P1a2h2	0.845	0.683	0.591	M2D2A3P3a1h3*	0.249	0.831	0.874
M1D1A2P1a3h2	0.846	0.764	0.658	M2D2A3P3a2h3*	0.229	0.986	0.981
M1D1A2P2a1h2	0.738	0.609	0.527	M2D2A3P3a3h3*	0.313	0.691	0.996
M1D1A2P2a2h2	0.724	0.645	0.549	M2D3A1P1a1h1	0.878	0.753	0.757
M1D1A2P2a3h2	0.804	0.852	0.737	M2D3A1P1a2h1	0.874	0.737	0.712

Table D.4 Critical buckling limit ratios for specimens with single corrosion defect of $d_p/t=0.40$ - continue

Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}	Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}
M1D1A2P3a1h2*	0.594	0.817	0.755	M2D3A1P1a3h1	0.880	0.804	0.764
M1D1A2P3a2h2*	0.517	0.933	0.853	M2D3A1P2a1h1	0.838	0.731	0.674
M1D1A2P3a3h2*	0.513	0.936	0.931	M2D3A1P2a2h1	0.876	0.835	0.773
M1D1A2P1a1h3	0.681	0.577	0.484	M2D3A1P2a3h1	0.884	0.903	0.824
M1D1A2P1a2h3	0.698	0.547	0.499	M2D3A1P3a1h1	0.820	0.908	0.833
M1D1A2P1a3h3	0.713	0.537	0.454	M2D3A1P3a2h1	0.844	0.918	0.850
M1D1A2P2a1h3*	0.604	0.707	0.584	M2D3A1P3a3h1	0.863	0.925	0.920
M1D1A2P2a2h3*	0.576	0.728	0.596	M2D3A1P1a1h2	0.746	0.539	0.541
M1D1A2P2a3h3*	0.637	0.774	0.637	M2D3A1P1a2h2	0.712	0.523	0.504
M1D1A2P3a1h3*	0.444	0.912	0.907	M2D3A1P1a3h2	0.711	0.502	0.487
M1D1A2P3a2h3*	0.346	1.008	1.003	M2D3A1P2a1h2*	0.691	0.833	0.829
M1D1A2P3a3h3*	0.334	1.079	1.073	M2D3A1P2a2h2*	0.724	0.920	0.749
M1D1A3P1a1h1	0.901	0.694	0.681	M2D3A1P2a3h2*	0.737	0.921	0.754
M1D1A3P1a2h1	0.927	0.906	0.867	M2D3A1P3a1h2*	0.685	0.965	0.960
M1D1A3P1a3h1	0.916	0.941	0.894	M2D3A1P3a2h2*	0.710	0.994	0.989
M1D1A3P2a1h1	0.820	0.694	0.667	M2D3A1P3a3h2*	0.737	1.014	1.009
M1D1A3P2a2h1	0.825	0.741	0.707	M2D3A1P1a1h3	0.535	0.354	0.370
M1D1A3P2a3h1	0.911	0.964	0.959	M2D3A1P1a2h3	0.645	0.601	0.619
M1D1A3P3a1h1	0.591	0.742	0.735	M2D3A1P1a3h3	0.586	0.421	0.407
M1D1A3P3a2h1	0.458	0.749	0.755	M2D3A1P2a1h3*	0.583	1.081	1.075
M1D1A3P3a3h1	0.446	0.816	0.827	M2D3A1P2a2h3*	0.684	1.466	1.458
M1D1A3P1a1h2	0.715	0.580	0.537	M2D3A1P2a3h3*	0.606	0.995	0.990
M1D1A3P1a2h2	0.775	0.802	0.728	M2D3A1P3a1h3*	0.572	1.219	1.213
M1D1A3P1a3h2	0.778	0.834	0.760	M2D3A1P3a2h3*	0.589	1.243	1.237
M1D1A3P2a1h2	0.622	0.609	0.562	M2D3A1P3a3h3*	0.625	1.282	1.275
M1D1A3P2a2h2	0.604	0.628	0.574	M2D3A2P1a1h1	0.847	0.677	0.681
M1D1A3P2a3h2	0.719	0.890	0.819	M2D3A2P1a2h1	0.839	0.758	0.743
M1D1A3P3a1h2	0.258	0.782	0.783	M2D3A2P1a3h1	0.848	0.817	0.787
M1D1A3P3a2h2	F	F	F	M2D3A2P2a1h1	0.787	0.722	0.682
M1D1A3P3a3h2	F	F	F	M2D3A2P2a2h1	0.839	0.840	0.796
M1D1A3P1a1h3	0.558	0.522	0.469	M2D3A2P2a3h1	0.851	0.916	0.855
M1D1A3P1a2h3	0.612	0.567	0.541	M2D3A2P3a1h1	0.759	0.899	0.936
M1D1A3P1a3h3	0.605	0.566	0.509	M2D3A2P3a2h1	0.787	0.912	0.871
M1D1A3P2a1h3	0.457	0.565	0.506	M2D3A2P3a3h1	0.819	0.961	0.956
M1D1A3P2a2h3	0.423	0.566	0.502	M2D3A2P1a1h2	0.680	0.601	0.614
M1D1A3P2a3h3	0.492	0.718	0.642	M2D3A2P1a2h2	0.639	0.659	0.639
M1D1A3P3a1h3	F	F	F	M2D3A2P1a3h2	0.625	0.511	0.497
M1D1A3P3a2h3	F	F	F	M2D3A2P2a1h2*	0.599	0.949	0.802
M1D1A3P3a3h3	F	F	F	M2D3A2P2a2h2*	0.642	0.855	0.741
M1D2A1P1a1h1	0.906	0.723	0.678	M2D3A2P2a3h2*	0.658	0.875	0.760

Table D.4 Critical buckling limit ratios for specimens with single corrosion defect of $d_p/t=0.40$ - continue

Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}	Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}
M1D2A1P1a2h1	0.910	0.847	0.765	M2D3A2P3a1h2*	0.569	0.933	0.928
M1D2A1P1a3h1	0.922	0.938	0.833	M2D3A2P3a2h2*	0.602	0.992	0.987
M1D2A1P2a1h1	0.871	0.697	0.625	M2D3A2P3a3h2*	0.640	1.039	1.034
M1D2A1P2a2h1	0.896	0.785	0.710	M2D3A2P1a1h3	0.427	0.253	0.252
M1D2A1P2a3h1	0.908	0.936	0.822	M2D3A2P1a2h3	0.556	0.469	0.460
M1D2A1P3a1h1	0.816	0.801	0.751	M2D3A2P1a3h3	0.483	0.430	0.402
M1D2A1P3a2h1	0.793	0.904	0.821	M2D3A2P2a1h3*	0.466	0.981	0.976
M1D2A1P3a3h1	0.840	0.940	0.935	M2D3A2P2a2h3*	0.481	0.946	0.941
M1D2A1P1a1h2	0.787	0.656	0.578	M2D3A2P2a3h3*	0.494	0.894	0.889
M1D2A1P1a2h2	0.802	0.677	0.594	M2D3A2P3a1h3*	0.414	0.953	0.948
M1D2A1P1a3h2	0.835	0.915	0.764	M2D3A2P3a2h3*	0.436	1.175	1.169
M1D2A1P2a1h2*	0.746	0.947	0.746	M2D3A2P3a3h3*	0.493	1.279	1.272
M1D2A1P2a2h2*	0.756	0.980	0.767	M2D3A3P1a1h1	0.804	0.701	0.688
M1D2A1P2a3h2*	0.793	0.957	0.762	M2D3A3P1a2h1	0.790	0.749	0.722
M1D2A1P3a1h2*	0.700	0.873	0.868	M2D3A3P1a3h1	0.805	0.825	0.798
M1D2A1P3a2h2*	0.675	0.924	0.912	M2D3A3P2a1h1	0.743	0.715	0.672
M1D2A1P3a3h2*	0.714	0.941	0.929	M2D3A3P2a2h1	0.804	0.832	0.798
M1D2A1P1a1h3	0.684	0.838	0.677	M2D3A3P2a3h1	0.816	0.919	0.875
M1D2A1P1a2h3	0.662	0.429	0.404	M2D3A3P3a1h1*	0.676	0.830	0.808
M1D2A1P1a3h3	0.685	0.536	0.482	M2D3A3P3a2h1*	0.709	0.877	0.830
M1D2A1P2a1h3*	0.639	0.928	0.923	M2D3A3P3a3h1*	0.762	0.947	0.942
M1D2A1P2a2h3*	0.649	0.934	0.929	M2D3A3P1a1h2	0.612	0.548	0.498
M1D2A1P2a3h3*	0.667	0.885	0.881	M2D3A3P1a2h2	0.566	0.529	0.488
M1D2A1P3a1h3*	0.590	1.075	1.069	M2D3A3P1a3h2	0.550	0.506	0.456
M1D2A1P3a2h3*	0.552	1.251	1.245	M2D3A3P2a1h2	0.511	0.830	0.708
M1D2A1P3a3h3*	0.579	1.514	1.506	M2D3A3P2a2h2	0.568	0.778	0.674
M1D2A2P1a1h1	0.854	0.768	0.749	M2D3A3P2a3h2	0.586	0.821	0.718
M1D2A2P1a2h1	0.871	0.935	0.885	M2D3A3P3a1h2*	0.383	0.922	0.816
M1D2A2P1a3h1	0.894	0.960	0.955	M2D3A3P3a2h2*	0.434	0.911	0.906
M1D2A2P2a1h1	0.803	0.721	0.655	M2D3A3P3a3h2*	0.490	0.996	0.991
M1D2A2P2a2h1	0.846	0.817	0.768	M2D3A3P1a1h3	0.341	0.317	0.250
M1D2A2P2a3h1	0.868	0.906	0.902	M2D3A3P1a2h3	0.450	0.527	538.980
M1D2A2P3a1h1*	0.701	0.791	0.772	M2D3A3P1a3h3	0.386	0.438	0.369
M1D2A2P3a2h1*	0.662	0.889	0.861	M2D3A3P2a1h3	0.337	0.813	0.809
M1D2A2P3a3h1*	0.741	1.008	1.003	M2D3A3P2a2h3	0.355	0.869	0.710
M1D2A2P1a1h2	0.683	0.698	0.652	M2D3A3P2a3h3	0.376	0.851	0.698
M1D2A2P1a2h2	0.712	0.797	0.732	M2D3A3P3a1h3*	0.132	0.937	0.932
M1D2A2P1a3h2	0.767	0.823	0.799	M2D3A3P3a2h3*	0.165	1.047	1.042
M1D2A2P2a1h2*	0.633	0.853	0.743	M2D3A3P3a3h3*	0.263	1.223	1.217
M1D2A2P2a2h2*	0.646	0.910	0.793	M3D1A1P1a1h1	0.942	0.756	0.747

Table D.4 Critical buckling limit ratios for specimens with single corrosion defect of $d_p/t=0.40$ - continue

Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}	Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}
M1D2A2P2a3h2*	0.693	0.939	0.821	M3D1A1P1a2h1	0.944	0.827	0.797
M1D2A2P3a1h2*	0.511	0.920	0.872	M3D1A1P1a3h1	0.938	0.865	0.815
M1D2A2P3a2h2*	0.472	1.045	1.039	M3D1A1P2a1h1	0.904	0.742	0.695
M1D2A2P3a3h2*	0.532	1.281	1.274	M3D1A1P2a2h1	0.929	0.879	0.816
M1D2A2P1a1h3	0.559	0.773	0.681	M3D1A1P2a3h1	0.925	0.947	0.856
M1D2A2P1a2h3	0.547	0.462	0.440	M3D1A1P3a1h1	0.884	0.781	0.729
M1D2A2P1a3h3	0.583	0.549	0.523	M3D1A1P3a2h1	0.874	0.798	0.723
M1D2A2P2a1h3*	0.500	0.940	0.807	M3D1A1P3a3h1	0.932	0.927	0.922
M1D2A2P2a2h3*	0.511	0.978	0.826	M3D1A1P1a1h2	0.851	0.609	0.556
M1D2A2P2a3h3*	0.541	0.905	0.772	M3D1A1P1a2h2	0.853	0.639	0.576
M1D2A2P3a1h3*	0.338	1.015	1.010	M3D1A1P1a3h2	0.865	0.761	0.667
M1D2A2P3a2h3*	0.276	1.200	1.193	M3D1A1P2a1h2	0.801	0.680	0.569
M1D2A2P3a3h3*	0.315	1.543	1.535	M3D1A1P2a2h2	0.820	0.705	0.592
M1D2A3P1a1h1	0.807	0.760	0.728	M3D1A1P2a3h2	0.830	0.827	0.683
M1D2A3P1a2h1	0.831	0.961	0.909	M3D1A1P3a1h2	0.775	0.800	0.679
M1D2A3P1a3h1	0.857	0.821	0.819	M3D1A1P3a2h2	0.752	0.837	0.693
M1D2A3P2a1h1	0.751	0.657	0.626	M3D1A1P3a3h2	0.800	0.930	0.781
M1D2A3P2a2h1	0.802	0.792	0.756	M3D1A1P1a1h3	0.743	0.581	0.479
M1D2A3P2a3h1	0.826	0.952	0.903	M3D1A1P1a2h3	0.725	0.569	0.492
M1D2A3P3a1h1*	0.359	0.760	0.750	M3D1A1P1a3h3	0.752	0.537	0.456
M1D2A3P3a2h1*	0.267	0.852	0.875	M3D1A1P2a1h3	0.694	0.726	0.556
M1D2A3P3a3h1*	0.464	1.125	1.119	M3D1A1P2a2h3	0.699	0.681	0.521
M1D2A3P1a1h2	0.613	0.643	0.584	M3D1A1P2a3h3	0.712	0.709	0.545
M1D2A3P1a2h2	0.651	0.659	0.595	M3D1A1P3a1h3*	0.673	0.939	0.746
M1D2A3P1a3h2	0.709	0.672	0.607	M3D1A1P3a2h3*	0.638	0.788	0.784
M1D2A3P2a1h2	0.536	0.688	0.608	M3D1A1P3a3h3*	0.680	0.973	0.770
M1D2A3P2a2h2	0.552	0.759	0.672	M3D1A2P1a1h1	0.928	0.750	0.742
M1D2A3P2a3h2	0.614	0.862	0.773	M3D1A2P1a2h1	0.934	0.835	0.808
M1D2A3P3a1h2	F	F	F	M3D1A2P1a3h1	0.927	0.878	0.833
M1D2A3P3a2h2	F	F	F	M3D1A2P2a1h1	0.891	0.751	0.712
M1D2A3P3a3h2	F	F	F	M3D1A2P2a2h1	0.922	0.890	0.836
M1D2A3P1a1h3	0.459	0.551	0.473	M3D1A2P2a3h1	0.917	0.960	0.883
M1D2A3P1a2h3	0.460	0.484	0.419	M3D1A2P3a1h1	0.865	0.784	0.741
M1D2A3P1a3h3	0.479	0.448	0.534	M3D1A2P3a2h1	0.853	0.803	0.740
M1D2A3P2a1h3*	0.351	0.674	0.572	M3D1A2P3a3h1	0.925	0.947	0.942
M1D2A3P2a2h3*	0.364	0.723	0.618	M3D1A2P1a1h2	0.814	0.593	0.550
M1D2A3P2a3h3*	0.410	0.760	0.653	M3D1A2P1a2h2	0.822	0.654	0.594
M1D2A3P3a1h3	F	F	F	M3D1A2P1a3h2	0.837	0.761	0.681
M1D2A3P3a2h3	F	F	F	M3D1A2P2a1h2	0.766	0.684	0.592
M1D2A3P3a3h3	F	F	F	M3D1A2P2a2h2	0.791	0.715	0.619

Table D.4 Critical buckling limit ratios for specimens with single corrosion defect of $d_p/t=0.40$ - continue

Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}	Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}
M1D3A1P1a1h1	0.891	0.856	0.832	M3D1A2P2a3h2	0.804	0.838	0.718
M1D3A1P1a2h1	0.900	0.977	0.972	M3D1A2P3a1h2	0.730	0.794	0.698
M1D3A1P1a3h1	0.910	0.916	0.899	M3D1A2P3a2h2	0.703	0.833	0.718
M1D3A1P2a1h1	0.799	0.934	0.818	M3D1A2P3a3h2	0.762	0.931	0.812
M1D3A1P2a2h1	0.902	0.967	0.884	M3D1A2P1a1h3	0.678	0.568	0.486
M1D3A1P2a3h1	0.864	0.931	0.926	M3D1A2P1a2h3	0.689	0.526	0.513
M1D3A1P3a1h1*	0.813	0.955	0.950	M3D1A2P1a3h3	0.703	0.541	0.470
M1D3A1P3a2h1*	0.814	1.040	1.034	M3D1A2P2a1h3	0.636	0.730	0.589
M1D3A1P3a3h1*	0.905	1.154	1.148	M3D1A2P2a2h3	0.643	0.688	0.553
M1D3A1P1a1h2	0.801	0.951	0.944	M3D1A2P2a3h3	0.660	0.722	0.584
M1D3A1P1a2h2	0.767	0.944	0.923	M3D1A2P3a1h3*	0.603	0.925	0.773
M1D3A1P1a3h2	0.818	0.966	0.952	M3D1A2P3a2h3*	0.560	0.969	0.815
M1D3A1P2a1h2*	0.695	1.007	1.002	M3D1A2P3a3h3*	0.612	0.967	0.806
M1D3A1P2a2h2*	0.726	0.991	0.986	M3D1A3P1a1h1	0.909	0.743	0.737
M1D3A1P2a3h2*	0.736	0.984	0.979	M3D1A3P1a2h1	0.923	0.847	0.823
M1D3A1P3a1h2*	0.684	1.199	1.192	M3D1A3P1a3h1	0.916	0.899	0.859
M1D3A1P3a2h2*	0.684	1.327	1.320	M3D1A3P2a1h1	0.874	0.760	0.726
M1D3A1P3a3h2*	0.790	1.558	1.550	M3D1A3P2a2h1	0.911	0.900	0.858
M1D3A1P1a1h3	0.592	0.459	0.489	M3D1A3P2a3h1	0.906	0.973	0.912
M1D3A1P1a2h3	0.626	0.603	0.595	M3D1A3P3a1h1	0.837	0.791	0.757
M1D3A1P1a3h3	0.699	1.988	1.977	M3D1A3P3a2h1	0.824	0.805	0.761
M1D3A1P2a1h3*	0.595	1.265	1.258	M3D1A3P3a3h1	0.914	0.974	0.968
M1D3A1P2a2h3*	0.610	1.221	1.214	M3D1A3P1a1h2	0.771	0.592	0.557
M1D3A1P2a3h3*	0.617	1.188	1.182	M3D1A3P1a2h2	0.786	0.673	0.621
M1D3A1P3a1h3*	0.570	1.473	1.465	M3D1A3P1a3h2	0.804	0.777	0.711
M1D3A1P3a2h3*	0.555	1.630	1.622	M3D1A3P2a1h2	0.719	0.693	0.618
M1D3A1P3a3h3*	0.645	2.010	2.000	M3D1A3P2a2h2	0.750	0.727	0.650
M1D3A2P1a1h1	0.813	0.773	0.756	M3D1A3P2a3h2	0.767	0.852	0.754
M1D3A2P1a2h1	0.831	0.926	0.921	M3D1A3P3a1h2*	0.666	0.793	0.719
M1D3A2P1a3h1	0.844	0.924	0.919	M3D1A3P3a2h2*	0.633	0.828	0.741
M1D3A2P2a1h1*	0.747	0.826	0.748	M3D1A3P3a3h2*	0.708	0.938	0.847
M1D3A2P2a2h1*	0.870	0.958	0.911	M3D1A3P1a1h3	0.607	0.531	0.478
M1D3A2P2a3h1*	0.817	0.930	0.925	M3D1A3P1a2h3	0.648	0.559	0.526
M1D3A2P3a1h1	0.667	0.850	0.767	M3D1A3P1a3h3	0.647	0.575	0.511
M1D3A2P3a2h1	0.666	0.953	0.906	M3D1A3P2a1h3	0.561	0.722	0.611
M1D3A2P3a3h1	0.811	0.929	0.916	M3D1A3P2a2h3	0.570	0.684	0.579
M1D3A2P1a1h2	0.713	0.928	0.919	M3D1A3P2a3h3	0.596	0.750	0.635
M1D3A2P1a2h2	0.717	0.924	0.919	M3D1A3P3a1h3*	0.507	0.896	0.784
M1D3A2P1a3h2	0.736	0.915	0.914	M3D1A3P3a2h3*	0.456	0.935	0.810
M1D3A2P2a1h2*	0.612	0.872	0.867	M3D1A3P3a3h3*	0.520	0.953	0.833

Table D.4 Critical buckling limit ratios for specimens with single corrosion defect of $d_p/t=0.40$ - continue

Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}	Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}
M1D3A2P2a2h2*	0.650	0.880	0.875	M3D2A1P1a1h1	0.911	0.761	0.753
M1D3A2P2a3h2*	0.661	0.909	0.904	M3D2A1P1a2h1	0.896	0.765	0.745
M1D3A2P3a1h2*	0.464	0.885	0.881	M3D2A1P1a3h1	0.905	0.853	0.815
M1D3A2P3a2h2*	0.458	1.116	1.110	M3D2A1P2a1h1	0.869	0.737	0.688
M1D3A2P3a3h2*	0.615	1.484	1.476	M3D2A1P2a2h1	0.901	0.845	0.787
M1D3A2P1a1h3	0.483	0.424	0.400	M3D2A1P2a3h1	0.900	0.923	0.841
M1D3A2P1a2h3	0.507	0.546	0.499	M3D2A1P3a1h1	0.848	0.892	0.736
M1D3A2P1a3h3	0.587	0.576	0.529	M3D2A1P3a2h1	0.868	0.862	0.804
M1D3A2P2a1h3*	0.471	1.042	1.037	M3D2A1P3a3h1	0.885	0.976	0.893
M1D3A2P2a2h3*	0.494	1.006	1.000	M3D2A1P1a1h2	0.795	0.611	0.577
M1D3A2P2a3h3*	0.515	1.021	1.016	M3D2A1P1a2h2	0.760	0.549	0.509
M1D3A2P3a1h3*	0.269	0.989	0.984	M3D2A1P1a3h2	0.771	0.634	0.589
M1D3A2P3a2h3*	0.236	1.290	1.283	M3D2A1P2a1h2	0.728	0.861	0.701
M1D3A2P3a3h3*	0.367	1.863	1.853	M3D2A1P2a2h2	0.770	0.791	0.666
M1D3A3P1a1h1	0.788	0.772	0.710	M3D2A1P2a3h2	0.772	0.837	0.699
M1D3A3P1a2h1	0.819	0.975	0.970	M3D2A1P3a1h2*	0.721	0.850	0.845
M1D3A3P1a3h1	0.831	0.958	0.953	M3D2A1P3a2h2*	0.732	0.879	0.874
M1D3A3P2a1h1	0.694	0.782	0.685	M3D2A1P3a3h2*	0.757	0.880	0.875
M1D3A3P2a2h1	0.838	0.938	0.870	M3D2A1P1a1h3	0.670	0.473	0.444
M1D3A3P2a3h1	0.776	0.927	0.922	M3D2A1P1a2h3	0.606	0.385	0.372
M1D3A3P3a1h1	F	F	F	M3D2A1P1a3h3	0.620	0.456	0.424
M1D3A3P3a2h1	F	F	F	M3D2A1P2a1h3*	0.614	0.921	0.916
M1D3A3P3a3h1	F	F	F	M3D2A1P2a2h3*	0.626	0.872	0.867
M1D3A3P1a1h2	0.648	0.564	0.482	M3D2A1P2a3h3*	0.642	0.796	0.791
M1D3A3P1a2h2	0.604	0.775	0.712	M3D2A1P3a1h3*	0.608	1.041	1.036
M1D3A3P1a3h2	0.696	0.674	0.671	M3D2A1P3a2h3*	0.613	1.073	1.067
M1D3A3P2a1h2	0.500	0.848	0.709	M3D2A1P3a3h3*	0.627	0.420	1.002
M1D3A3P2a2h2	0.557	0.873	0.740	M3D2A2P1a1h1	0.891	0.749	0.732
M1D3A3P2a3h2	0.574	0.978	0.849	M3D2A2P1a2h1	0.876	0.776	0.757
M1D3A3P3a1h2	F	F	F	M3D2A2P1a3h1	0.889	0.860	0.825
M1D3A3P3a2h2	F	F	F	M3D2A2P2a1h1	0.844	0.743	0.671
M1D3A3P3a3h2	F	F	F	M3D2A2P2a2h1	0.884	0.850	0.799
M1D3A3P1a1h3	0.367	0.356	0.253	M3D2A2P2a3h1	0.883	0.928	0.861
M1D3A3P1a2h3	0.411	0.575	0.455	M3D2A2P3a1h1	0.814	0.815	0.751
M1D3A3P1a3h3	0.493	0.390	0.389	M3D2A2P3a2h1	0.841	0.860	0.816
M1D3A3P2a1h3	0.283	0.974	0.787	M3D2A2P3a3h1	0.862	0.935	0.930
M1D3A3P2a2h3	0.334	0.871	0.696	M3D2A2P1a1h2	0.744	0.610	0.579
M1D3A3P2a3h3	0.338	0.968	0.796	M3D2A2P1a2h2	0.710	0.571	0.509
M1D3A3P3a1h3	F	F	F	M3D2A2P1a3h2	0.722	0.640	0.597
M1D3A3P3a2h3	F	F	F	M3D2A2P2a1h2	0.669	0.840	0.718

Table D.4 Critical buckling limit ratios for specimens with single corrosion defect of $d_p/t=0.40$ - continue

Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}	Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}
M1D3A3P3a3h3	F	F	F	M3D2A2P2a2h2	0.721	0.790	0.688
M2D1A1P1a1h1	0.944	0.732	0.722	M3D2A2P2a3h2	0.725	0.837	0.725
M2D1A1P1a2h1	0.947	0.816	0.785	M3D2A2P3a1h2*	0.652	0.975	0.853
M2D1A1P1a3h1	0.940	0.850	0.797	M3D2A2P3a2h2*	0.667	0.893	0.889
M2D1A1P2a1h1	0.893	0.694	0.644	M3D2A2P3a3h2*	0.700	0.903	0.899
M2D1A1P2a2h1	0.908	0.784	0.721	M3D2A2P1a1h3	0.595	0.461	0.434
M2D1A1P2a3h1	0.920	0.909	0.821	M3D2A2P1a2h3	0.526	0.386	0.366
M2D1A1P3a1h1	0.854	0.727	0.675	M3D2A2P1a3h3	0.538	0.468	0.430
M2D1A1P3a2h1	0.831	0.740	0.659	M3D2A2P2a1h3*	0.529	0.993	0.988
M2D1A1P3a3h1	0.863	0.848	0.768	M3D2A2P2a2h3*	0.547	0.865	0.860
M2D1A1P1a1h2	0.859	0.567	0.515	M3D2A2P2a3h3*	0.562	0.950	0.767
M2D1A1P1a2h2	0.864	0.628	0.558	M3D2A2P3a1h3*	0.511	1.018	1.013
M2D1A1P1a3h2	0.872	0.744	0.643	M3D2A2P3a2h3*	0.516	1.060	1.055
M2D1A1P2a1h2	0.793	0.623	0.517	M3D2A2P3a3h3*	0.537	1.003	0.997
M2D1A1P2a2h2	0.798	0.635	0.525	M3D2A3P1a1h1	0.870	0.772	0.765
M2D1A1P2a3h2	0.827	0.770	0.635	M3D2A3P1a2h1	0.853	0.798	0.780
M2D1A1P3a1h2*	0.746	0.756	0.646	M3D2A3P1a3h1	0.868	0.885	0.842
M2D1A1P3a2h2*	0.714	0.820	0.683	M3D2A3P2a1h1	0.812	0.728	0.705
M2D1A1P3a3h2*	0.738	0.903	0.752	M3D2A3P2a2h1	0.863	0.865	0.833
M2D1A1P1a1h3	0.751	0.526	0.429	M3D2A3P2a3h1	0.859	0.936	0.884
M2D1A1P1a2h3	0.735	0.357	0.309	M3D2A3P3a1h1	0.754	0.772	0.734
M2D1A1P1a3h3	0.769	0.541	0.445	M3D2A3P3a2h1	0.788	0.835	0.796
M2D1A1P2a1h3	0.692	0.642	0.490	M3D2A3P3a3h1	0.814	0.974	0.915
M2D1A1P2a2h3	0.684	0.643	0.483	M3D2A3P1a1h2	0.688	0.617	0.577
M2D1A1P2a3h3	0.715	0.661	0.504	M3D2A3P1a2h2	0.651	0.573	0.540
M2D1A1P3a1h3*	0.648	0.896	0.724	M3D2A3P1a3h2	0.667	0.662	0.612
M2D1A1P3a2h3*	0.603	0.965	0.779	M3D2A3P2a1h2	0.602	0.763	0.669
M2D1A1P3a3h3*	0.623	0.819	0.815	M3D2A3P2a2h2	0.660	0.772	0.695
M2D1A2P1a1h1	0.925	0.709	0.703	M3D2A3P2a3h2	0.663	0.823	0.731
M2D1A2P1a2h1	0.934	0.820	0.792	M3D2A3P3a1h2*	0.556	0.874	0.782
M2D1A2P1a3h1	0.927	0.860	0.815	M3D2A3P3a2h2*	0.573	0.925	0.831
M2D1A2P2a1h1	0.875	0.704	0.663	M3D2A3P3a3h2*	0.616	0.965	0.875
M2D1A2P2a2h1	0.894	0.797	0.745	M3D2A3P1a1h3	0.518	0.456	0.416
M2D1A2P2a3h1	0.909	0.926	0.854	M3D2A3P1a2h3	0.449	0.392	0.352
M2D1A2P3a1h1	0.821	0.731	0.691	M3D2A3P1a3h3	0.469	0.472	0.413
M2D1A2P3a2h1	0.793	0.744	0.680	M3D2A3P2a1h3	0.436	0.859	0.855
M2D1A2P3a3h1	0.834	0.854	0.794	M3D2A3P2a2h3	0.458	0.839	0.709
M2D1A2P1a1h2	0.817	0.543	0.503	M3D2A3P2a3h3	0.476	0.794	0.663
M2D1A2P1a2h2	0.829	0.636	0.576	M3D2A3P3a1h3*	0.380	0.893	0.889
M2D1A2P1a3h2	0.840	0.736	0.655	M3D2A3P3a2h3*	0.387	0.942	0.937

Table D.4 Critical buckling limit ratios for specimens with single corrosion defect of $d_p/t=0.40$ - continue

Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}	Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}
M2D1A2P2a1h2	0.751	0.627	0.543	M3D2A3P3a3h3*	0.418	0.910	0.905
M2D1A2P2a2h2	0.758	0.645	0.556	M3D3A1P1a1h1	0.861	0.692	0.700
M2D1A2P2a3h2	0.794	0.786	0.676	M3D3A1P1a2h1	0.858	0.726	0.718
M2D1A2P3a1h2*	0.680	0.748	0.666	M3D3A1P1a3h1	0.863	0.741	0.732
M2D1A2P3a2h2*	0.639	0.811	0.710	M3D3A1P2a1h1	0.831	0.746	0.716
M2D1A2P3a3h2*	0.670	0.897	0.786	M3D3A1P2a2h1	0.860	0.829	0.789
M2D1A2P1a1h3	0.680	0.519	0.441	M3D3A1P2a3h1	0.876	0.879	0.833
M2D1A2P1a2h3	0.688	0.568	0.562	M3D3A1P3a1h1	0.812	0.838	0.768
M2D1A2P1a3h3	0.710	0.532	0.455	M3D3A1P3a2h1	0.874	0.883	0.837
M2D1A2P2a1h3	0.622	0.656	0.533	M3D3A1P3a3h1	0.852	0.950	0.867
M2D1A2P2a2h3	0.613	0.662	0.531	M3D3A1P1a1h2	0.708	0.523	0.493
M2D1A2P2a3h3	0.656	0.684	0.556	M3D3A1P1a2h2	0.665	0.470	0.470
M2D1A2P3a1h3*	0.549	0.875	0.750	M3D3A1P1a3h2	0.680	0.489	0.489
M2D1A2P3a2h3*	0.492	0.946	0.815	M3D3A1P2a1h2*	0.681	0.847	0.842
M2D1A2P3a3h3*	0.518	0.858	0.853	M3D3A1P2a2h2*	0.704	0.947	0.784
M2D1A3P1a1h1	0.904	0.712	0.704	M3D3A1P2a3h2*	0.722	0.874	0.744
M2D1A3P1a2h1	0.921	0.839	0.814	M3D3A1P3a1h2*	0.683	0.947	0.942
M2D1A3P1a3h1	0.913	0.892	0.851	M3D3A1P3a2h2*	0.721	0.902	0.897
M2D1A3P2a1h1	0.848	0.714	0.681	M3D3A1P3a3h2*	0.722	0.934	0.929
M2D1A3P2a2h1	0.873	0.809	0.769	M3D3A1P1a1h3	0.511	0.312	0.330
M2D1A3P2a3h1	0.893	0.940	0.886	M3D3A1P1a2h3	0.539	0.393	0.380
M2D1A3P3a1h1	0.766	0.736	0.706	M3D3A1P1a3h3	0.563	0.446	0.428
M2D1A3P3a2h1	0.728	0.744	0.704	M3D3A1P2a1h3*	0.573	1.137	1.131
M2D1A3P3a3h1	0.785	0.861	0.819	M3D3A1P2a2h3*	0.668	1.579	1.571
M2D1A3P1a1h2	0.765	0.549	0.516	M3D3A1P2a3h3*	0.589	1.036	1.031
M2D1A3P1a2h2	0.787	0.669	0.616	M3D3A1P3a1h3*	0.572	1.195	1.188
M2D1A3P1a3h2	0.800	0.757	0.690	M3D3A1P3a2h3*	0.590	1.153	1.147
M2D1A3P2a1h2	0.685	0.646	0.580	M3D3A1P3a3h3*	0.598	1.137	1.131
M2D1A3P2a2h2	0.695	0.663	0.594	M3D3A2P1a1h1	0.842	0.672	0.688
M2D1A3P2a3h2	0.744	0.804	0.720	M3D3A2P1a2h1	0.836	0.749	0.742
M2D1A3P3a1h2*	0.569	0.748	0.692	M3D3A2P1a3h1	0.843	0.761	0.753
M2D1A3P3a2h2*	0.514	0.803	0.736	M3D3A2P2a1h1	0.799	0.663	0.650
M2D1A3P3a3h2*	0.557	0.900	0.827	M3D3A2P2a2h1	0.832	0.781	0.749
M2D1A3P1a1h3	0.588	0.531	0.470	M3D3A2P2a3h1	0.852	0.791	0.762
M2D1A3P1a2h3	0.633	0.519	0.511	M3D3A2P3a1h1	0.767	0.827	0.747
M2D1A3P1a3h3	0.630	0.545	0.484	M3D3A2P3a2h1	0.843	0.870	0.822
M2D1A3P2a1h3	0.519	0.647	0.558	M3D3A2P3a3h1	0.822	0.961	0.899
M2D1A3P2a2h3	0.509	0.641	0.549	M3D3A2P1a1h2	0.661	0.519	0.522
M2D1A3P2a3h3	0.565	0.702	0.605	M3D3A2P1a2h2	0.594	0.482	0.474
M2D1A3P3a1h3*	0.392	0.835	0.754	M3D3A2P1a3h2	0.616	0.503	0.495

Table D.4 Critical buckling limit ratios for specimens with single corrosion defect of $d_p/t=0.40$ - continue

Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}	Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}
M2D1A3P3a2h3*	0.316	0.896	0.805	M3D3A2P2a1h2	0.611	0.874	0.747
M2D1A3P3a3h3*	0.351	0.964	0.870	M3D3A2P2a2h2	0.725	0.826	0.811
M2D2A1P1a1h1	0.918	0.764	0.753	M3D3A2P2a3h2	0.663	0.755	0.672
M2D2A1P1a2h1	0.905	0.784	0.746	M3D3A2P3a1h2*	0.604	0.915	0.911
M2D2A1P1a3h1	0.914	0.871	0.820	M3D3A2P3a2h2*	0.653	0.873	0.869
M2D2A1P2a1h1	0.870	0.724	0.675	M3D3A2P3a3h2*	0.654	0.928	0.923
M2D2A1P2a2h1	0.913	0.850	0.796	M3D3A2P1a1h3	0.422	0.220	0.230
M2D2A1P2a3h1	0.899	0.920	0.831	M3D3A2P1a2h3	0.451	0.417	0.387
M2D2A1P3a1h1	0.832	0.750	0.741	M3D3A2P1a3h3	0.478	0.430	0.403
M2D2A1P3a2h1	0.833	0.854	0.782	M3D3A2P2a1h3*	0.479	0.979	0.974
M2D2A1P3a3h1	0.881	0.917	0.914	M3D3A2P2a2h3*	0.486	0.977	0.972
M2D2A1P1a1h2	0.806	0.571	0.536	M3D3A2P2a3h3*	0.500	0.869	0.865
M2D2A1P1a2h2	0.776	0.564	0.512	M3D3A2P3a1h3*	0.463	1.136	1.130
M2D2A1P1a3h2	0.791	0.660	0.589	M3D3A2P3a2h3*	0.489	1.067	1.062
M2D2A1P2a1h2	0.737	0.817	0.663	M3D3A2P3a3h3*	0.499	1.078	1.072
M2D2A1P2a2h2	0.783	0.747	0.632	M3D3A3P1a1h1	0.808	0.722	0.713
M2D2A1P2a3h2	0.780	0.845	0.696	M3D3A3P1a2h1	0.797	0.754	0.736
M2D2A1P3a1h2*	0.712	0.967	0.822	M3D3A3P1a3h1	0.808	0.773	0.759
M2D2A1P3a2h2*	0.710	0.893	0.889	M3D3A3P2a1h1	0.758	0.735	0.695
M2D2A1P3a3h2*	0.769	0.919	0.914	M3D3A3P2a2h1	0.800	0.834	0.793
M2D2A1P1a1h3	0.666	0.450	0.400	M3D3A3P2a3h1	0.822	0.888	0.840
M2D2A1P1a2h3	0.632	0.381	0.353	M3D3A3P3a1h1	0.714	0.770	0.712
M2D2A1P1a3h3	0.703	0.447	0.439	M3D3A3P3a2h1	0.814	0.880	0.835
M2D2A1P2a1h3*	0.623	0.843	0.838	M3D3A3P3a3h1	0.783	0.953	0.896
M2D2A1P2a2h3*	0.639	0.790	0.786	M3D3A3P1a1h2	0.614	0.653	0.625
M2D2A1P2a3h3*	0.653	0.768	0.764	M3D3A3P1a2h2	0.526	0.484	0.441
M2D2A1P3a1h3*	0.602	0.993	0.988	M3D3A3P1a3h2	0.547	0.507	0.469
M2D2A1P3a2h3*	0.594	1.075	1.069	M3D3A3P2a1h2	0.538	0.881	0.742
M2D2A1P3a3h3*	0.632	1.019	1.013	M3D3A3P2a2h2	0.675	0.921	0.774
M2D2A2P1a1h1	0.900	0.780	0.764	M3D3A3P2a3h2	0.617	0.861	0.751
M2D2A2P1a2h1	0.887	0.811	0.779	M3D3A3P3a1h2*	0.505	0.957	0.824
M2D2A2P1a3h1	0.899	0.898	0.851	M3D3A3P3a2h2*	0.571	0.923	0.801
M2D2A2P2a1h1	0.840	0.726	0.650	M3D3A3P3a3h2*	0.576	0.893	0.888
M2D2A2P2a2h1	0.897	0.856	0.811	M3D3A3P1a1h3	0.349	0.328	0.267
M2D2A2P2a3h1	0.878	0.929	0.859	M3D3A3P1a2h3	0.372	0.423	0.348
M2D2A2P3a1h1	0.780	0.751	0.771	M3D3A3P1a3h3	0.392	0.434	0.365
M2D2A2P3a2h1	0.783	0.849	0.805	M3D3A3P2a1h3*	0.374	0.938	0.933
M2D2A2P3a3h1	0.850	0.925	0.969	M3D3A3P2a2h3*	0.528	1.494	1.486
M2D2A2P1a1h2	0.752	0.593	0.557	M3D3A3P2a3h3*	0.400	0.802	0.798
M2D2A2P1a2h2	0.716	0.584	0.545	M3D3A3P3a1h3*	0.317	0.978	0.973

Table D.4 Critical buckling limit ratios for specimens with single corrosion defect of $d_p/t=0.40$ - continue

Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}	Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}
M2D2A2P1a3h2	0.736	0.685	0.615	M3D3A3P3a2h3*	0.356	0.930	0.925
M2D2A2P2a1h2	0.661	0.821	0.703	M3D3A3P3a3h3*	0.369	0.969	0.964
M2D2A2P2a2h2	0.725	0.763	0.670				

Table D.5 Critical buckling limit ratios for specimens with two corrosion defects of $d_p/t = d_s/t = 0.16$

Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}	Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}
M1D1A1P1a1h1	0.971	0.954	0.964	M2D2A2P2a3h2	0.886	0.804	0.774
M1D1A1P1a2h1	0.973	0.973	0.972	M2D2A2P3a1h2	0.873	0.915	0.878
M1D1A1P1a3h1	0.972	0.964	0.969	M2D2A2P3a2h2	0.848	0.873	0.839
M1D1A1P2a1h1	0.963	0.937	0.913	M2D2A2P3a3h2	0.861	0.858	0.835
M1D1A1P2a2h1	0.955	0.899	0.877	M2D2A2P1a1h3	0.783	0.621	0.599
M1D1A1P2a3h1	0.960	0.911	0.895	M2D2A2P1a2h3	0.821	0.712	0.674
M1D1A1P3a1h1	0.945	0.955	0.930	M2D2A2P1a3h3	0.834	0.701	0.678
M1D1A1P3a2h1	0.938	0.909	0.891	M2D2A2P2a1h3	0.772	0.775	0.695
M1D1A1P3a3h1	0.939	0.905	0.892	M2D2A2P2a2h3	0.812	0.715	0.670
M1D1A1P1a1h2	0.940	0.708	0.664	M2D2A2P2a3h3	0.805	0.727	0.679
M1D1A1P1a2h2	0.951	0.845	0.835	M2D2A2P3a1h3	0.792	0.902	0.845
M1D1A1P1a3h2	0.947	0.810	0.770	M2D2A2P3a2h3	0.747	0.851	0.794
M1D1A1P2a1h2	0.930	0.853	0.790	M2D2A2P3a3h3	0.771	0.834	0.788
M1D1A1P2a2h2	0.906	0.737	0.689	M2D2A3P1a1h1	0.942	0.924	0.913
M1D1A1P2a3h2	0.921	0.775	0.740	M2D2A3P1a2h1	0.950	0.937	0.927
M1D1A1P3a1h2	0.879	0.927	0.866	M2D2A3P1a3h1	0.952	0.936	0.929
M1D1A1P3a2h2	0.861	0.827	0.777	M2D2A3P2a1h1	0.960	0.966	0.958
M1D1A1P3a3h2	0.863	0.818	0.779	M2D2A3P2a2h1	0.964	0.961	0.955
M1D1A1P1a1h3	0.898	0.511	0.488	M2D2A3P2a3h1	0.964	0.962	0.956
M1D1A1P1a2h3	0.921	0.611	0.587	M2D2A3P3a1h1	0.937	0.965	0.957
M1D1A1P1a3h3	0.913	0.586	0.566	M2D2A3P3a2h1	0.926	0.955	0.947
M1D1A1P2a1h3	0.896	0.807	0.715	M2D2A3P3a3h1	0.932	0.952	0.945
M1D1A1P2a2h3	0.857	0.650	0.575	M2D2A3P1a1h2	0.827	0.725	0.706
M1D1A1P2a3h3	0.881	0.701	0.645	M2D2A3P1a2h2	0.857	0.785	0.764
M1D1A1P3a1h3	0.815	0.923	0.844	M2D2A3P1a3h2	0.867	0.781	0.771
M1D1A1P3a2h3	0.787	0.817	0.735	M2D2A3P2a1h2	0.829	0.849	0.815
M1D1A1P3a3h3	0.789	0.807	0.739	M2D2A3P2a2h2	0.857	0.807	0.788
M1D1A2P1a1h1	0.970	0.940	0.974	M2D2A3P2a3h2	0.852	0.815	0.794
M1D1A2P1a2h1	0.972	0.930	0.975	M2D2A3P3a1h2	0.824	0.909	0.881
M1D1A2P1a3h1	0.972	0.940	0.960	M2D2A3P3a2h2	0.788	0.865	0.839
M1D1A2P2a1h1	0.960	0.920	0.930	M2D2A3P3a3h2	0.808	0.851	0.831
M1D1A2P2a2h1	0.950	0.911	0.894	M2D2A3P1a1h3	0.709	0.606	0.586

Table D.5 Critical buckling limit ratios for specimens with two corrosion defects of $d_p/t = d_s/t = 0.16$ - continue

Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}	Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}
M1D1A2P2a3h1	0.956	0.923	0.911	M2D2A3P1a2h3	0.762	0.694	0.669
M1D1A2P3a1h1	0.932	0.910	0.942	M2D2A3P1a3h3	0.780	0.688	0.679
M1D1A2P3a2h1	0.924	0.917	0.904	M2D2A3P2a1h3	0.698	0.778	0.720
M1D1A2P3a3h1	0.924	0.911	0.901	M2D2A3P2a2h3	0.751	0.713	0.678
M1D1A2P1a1h2	0.922	0.719	0.681	M2D2A3P2a3h3	0.742	0.725	0.688
M1D1A2P1a2h2	0.936	0.753	0.736	M2D2A3P3a1h3	0.710	0.886	0.843
M1D1A2P1a3h2	0.934	0.814	0.779	M2D2A3P3a2h3	0.646	0.829	0.783
M1D1A2P2a1h2	0.917	0.871	0.824	M2D2A3P3a3h3	0.681	0.811	0.772
M1D1A2P2a2h2	0.886	0.750	0.713	M2D3A1P1a1h1	0.937	0.858	0.851
M1D1A2P2a3h2	0.905	0.793	0.765	M2D3A1P1a2h1	0.940	0.864	0.857
M1D1A2P3a1h2	0.833	0.929	0.892	M2D3A1P1a3h1	0.943	0.857	0.857
M1D1A2P3a2h2	0.810	0.834	0.802	M2D3A1P2a1h1	0.954	0.940	0.915
M1D1A2P3a3h2	0.810	0.821	0.795	M2D3A1P2a2h1	0.958	0.920	0.910
M1D1A2P1a1h3	0.864	0.690	0.610	M2D3A1P2a3h1	0.958	0.923	0.914
M1D1A2P1a2h3	0.892	0.637	0.601	M2D3A1P3a1h1	0.963	0.974	0.969
M1D1A2P1a3h3	0.887	0.728	0.668	M2D3A1P3a2h1	0.964	0.971	0.968
M1D1A2P2a1h3	0.872	0.831	0.762	M2D3A1P3a3h1	0.964	0.971	0.968
M1D1A2P2a2h3	0.820	0.667	0.608	M2D3A1P1a1h2	0.867	0.715	0.697
M1D1A2P2a3h3	0.853	0.725	0.681	M2D3A1P1a2h2	0.875	0.726	0.711
M1D1A2P3a1h3	0.737	0.926	0.879	M2D3A1P1a3h2	0.882	0.711	0.709
M1D1A2P3a2h3	0.698	0.827	0.776	M2D3A1P2a1h2	0.871	0.853	0.772
M1D1A2P3a3h3	0.698	0.813	0.768	M2D3A1P2a2h2	0.887	0.790	0.757
M1D1A3P1a1h1	0.969	0.960	0.940	M2D3A1P2a3h2	0.890	0.800	0.768
M1D1A3P1a2h1	0.972	0.940	0.930	M2D3A1P3a1h2	0.875	0.910	0.856
M1D1A3P1a3h1	0.972	0.950	0.940	M2D3A1P3a2h2	0.886	0.874	0.846
M1D1A3P2a1h1	0.954	0.956	0.946	M2D3A1P3a3h2	0.883	0.873	0.843
M1D1A3P2a2h1	0.940	0.923	0.912	M2D3A1P1a1h3	0.802	0.644	0.612
M1D1A3P2a3h1	0.949	0.934	0.926	M2D3A1P1a2h3	0.814	0.659	0.629
M1D1A3P3a1h1	0.899	0.966	0.969	M2D3A1P1a3h3	0.826	0.640	0.627
M1D1A3P3a2h1	0.882	0.931	0.940	M2D3A1P2a1h3	0.786	0.800	0.668
M1D1A3P3a3h1	0.884	0.928	0.939	M2D3A1P2a2h3	0.815	0.710	0.646
M1D1A3P1a1h2	0.896	0.763	0.733	M2D3A1P2a3h3	0.820	0.724	0.663
M1D1A3P1a2h2	0.915	0.767	0.753	M2D3A1P3a1h3	0.782	0.893	0.801
M1D1A3P1a3h2	0.915	0.843	0.817	M2D3A1P3a2h3	0.803	0.848	0.787
M1D1A3P2a1h2	0.892	0.892	0.861	M2D3A1P3a3h3	0.797	0.847	0.782
M1D1A3P2a2h2	0.846	0.771	0.745	M2D3A2P1a1h1	0.925	0.875	0.870
M1D1A3P2a3h2	0.875	0.812	0.792	M2D3A2P1a2h1	0.929	0.880	0.875
M1D1A3P3a1h2	0.715	0.943	0.950	M2D3A2P1a3h1	0.933	0.871	0.870
M1D1A3P3a2h2	0.661	0.846	0.869	M2D3A2P2a1h1	0.947	0.936	0.924
M1D1A3P3a3h2	0.666	0.839	0.865	M2D3A2P2a2h1	0.952	0.923	0.918

Table D.5 Critical buckling limit ratios for specimens with two corrosion defects of $d_p/t = d_s/t = 0.16$ - continue

Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}	Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}
M1D1A3P1a1h3	0.808	0.700	0.610	M2D3A2P2a3h1	0.953	0.925	0.918
M1D1A3P1a2h3	0.847	0.662	0.636	M2D3A2P3a1h1	0.956	0.973	0.973
M1D1A3P1a3h3	0.847	0.776	0.732	M2D3A2P3a2h1	0.958	0.970	0.972
M1D1A3P2a1h3	0.824	0.861	0.818	M2D3A2P3a3h1	0.957	0.968	0.971
M1D1A3P2a2h3	0.743	0.700	0.660	M2D3A2P1a1h2	0.831	0.734	0.722
M1D1A3P2a3h3	0.795	0.754	0.724	M2D3A2P1a2h2	0.841	0.744	0.733
M1D1A3P3a1h3	0.537	0.936	0.940	M2D3A2P1a3h2	0.851	0.723	0.721
M1D1A3P3a2h3	0.446	0.821	0.832	M2D3A2P2a1h2	0.828	0.839	0.792
M1D1A3P3a3h3	0.455	0.812	0.827	M2D3A2P2a2h2	0.854	0.797	0.772
M1D2A1P1a1h1	0.963	0.940	0.949	M2D3A2P2a3h2	0.858	0.801	0.771
M1D2A1P1a2h1	0.968	0.930	0.955	M2D3A2P3a1h2	0.831	0.919	0.889
M1D2A1P1a3h1	0.969	0.940	0.953	M2D3A2P3a2h2	0.846	0.889	0.873
M1D2A1P2a1h1	0.968	0.930	0.963	M2D3A2P3a3h2	0.841	0.877	0.861
M1D2A1P2a2h1	0.970	0.940	0.964	M2D3A2P1a1h3	0.741	0.663	0.641
M1D2A1P2a3h1	0.970	0.940	0.964	M2D3A2P1a2h3	0.758	0.676	0.657
M1D2A1P3a1h1	0.956	0.950	0.940	M2D3A2P1a3h3	0.773	0.650	0.640
M1D2A1P3a2h1	0.940	0.952	0.933	M2D3A2P2a1h3	0.713	0.778	0.706
M1D2A1P3a3h1	0.948	0.949	0.936	M2D3A2P2a2h3	0.758	0.718	0.677
M1D2A1P1a1h2	0.895	0.783	0.707	M2D3A2P2a3h3	0.765	0.724	0.676
M1D2A1P1a2h2	0.917	0.825	0.757	M2D3A2P3a1h3	0.703	0.885	0.824
M1D2A1P1a3h2	0.923	0.792	0.744	M2D3A2P3a2h3	0.730	0.839	0.796
M1D2A1P2a1h2	0.902	0.821	0.739	M2D3A2P3a3h3	0.720	0.820	0.775
M1D2A1P2a2h2	0.916	0.795	0.750	M2D3A3P1a1h1	0.905	0.875	0.865
M1D2A1P2a3h2	0.916	0.785	0.747	M2D3A3P1a2h1	0.910	0.879	0.870
M1D2A1P3a1h2*	0.910	1.071	1.012	M2D3A3P1a3h1	0.914	0.872	0.867
M1D2A1P3a2h2*	0.864	0.905	0.855	M2D3A3P2a1h1	0.937	0.945	0.941
M1D2A1P3a3h2*	0.885	0.896	0.863	M2D3A3P2a2h1	0.944	0.937	0.938
M1D2A1P1a1h3	0.827	0.685	0.591	M2D3A3P2a3h1	0.945	0.938	0.938
M1D2A1P1a2h3	0.866	0.748	0.663	M2D3A3P3a1h1	0.949	0.970	0.959
M1D2A1P1a3h3	0.877	0.699	0.644	M2D3A3P3a2h1	0.951	0.966	0.954
M1D2A1P2a1h3	0.827	0.778	0.636	M2D3A3P3a3h1	0.950	0.966	0.955
M1D2A1P2a2h3	0.855	0.744	0.652	M2D3A3P1a1h2	0.783	0.734	0.709
M1D2A1P2a3h3	0.854	0.731	0.648	M2D3A3P1a2h2	0.795	0.742	0.721
M1D2A1P3a1h3*	0.862	1.046	1.016	M2D3A3P1a3h2	0.807	0.726	0.714
M1D2A1P3a2h3*	0.784	0.926	0.842	M2D3A3P2a1h2	0.788	0.828	0.788
M1D2A1P3a3h3*	0.820	0.919	0.851	M2D3A3P2a2h2	0.818	0.796	0.774
M1D2A2P1a1h1	0.960	0.960	0.930	M2D3A3P2a3h2	0.822	0.801	0.772
M1D2A2P1a2h1	0.966	0.960	0.940	M2D3A3P3a1h2	0.770	0.901	0.860
M1D2A2P1a3h1	0.967	0.960	0.950	M2D3A3P3a2h2	0.787	0.867	0.832
M1D2A2P2a1h1	0.965	0.940	0.972	M2D3A3P3a3h2	0.781	0.869	0.839

Table D.5 Critical buckling limit ratios for specimens with two corrosion defects of $d_p/t = d_s/t = 0.16$ - continue

Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}	Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}
M1D2A2P2a2h1	0.966	0.940	0.971	M2D3A3P1a1h3	0.679	0.663	0.618
M1D2A2P2a3h1	0.967	0.950	0.970	M2D3A3P1a2h3	0.698	0.674	0.634
M1D2A2P3a1h1	0.940	0.960	0.920	M2D3A3P1a3h3	0.716	0.653	0.624
M1D2A2P3a2h1	0.916	0.964	0.957	M2D3A3P2a1h3	0.650	0.759	0.686
M1D2A2P3a3h1	0.928	0.962	0.957	M2D3A3P2a2h3	0.703	0.712	0.665
M1D2A2P1a1h2	0.841	0.845	0.806	M2D3A3P2a3h3	0.710	0.719	0.662
M1D2A2P1a2h2	0.881	0.873	0.841	M2D3A3P3a1h3	0.592	0.866	0.797
M1D2A2P1a3h2	0.892	0.853	0.831	M2D3A3P3a2h3	0.622	0.817	0.754
M1D2A2P2a1h2	0.871	0.861	0.811	M2D3A3P3a3h3	0.612	0.819	0.766
M1D2A2P2a2h2	0.881	0.840	0.801	M3D1A1P1a1h1	0.971	0.970	0.959
M1D2A2P2a3h2	0.884	0.814	0.784	M3D1A1P1a2h1	0.974	0.970	0.971
M1D2A2P3a1h2*	0.859	1.074	1.047	M3D1A1P1a3h1	0.973	0.970	0.966
M1D2A2P3a2h2*	0.784	0.915	0.893	M3D1A1P2a1h1	0.971	0.950	0.961
M1D2A2P3a3h2*	0.820	0.908	0.894	M3D1A1P2a2h1	0.970	0.975	0.960
M1D2A2P1a1h3	0.726	0.754	0.703	M3D1A1P2a3h1	0.971	0.975	0.960
M1D2A2P1a2h3	0.798	0.801	0.759	M3D1A1P3a1h1	0.970	0.950	0.966
M1D2A2P1a3h3	0.818	0.767	0.742	M3D1A1P3a2h1	0.962	0.967	0.949
M1D2A2P2a1h3	0.757	0.822	0.744	M3D1A1P3a3h1	0.967	0.968	0.955
M1D2A2P2a2h3	0.777	0.794	0.730	M3D1A1P1a1h2	0.930	0.749	0.723
M1D2A2P2a3h3	0.784	0.759	0.706	M3D1A1P1a2h2	0.947	0.923	0.868
M1D2A2P3a1h3*	0.776	1.063	1.055	M3D1A1P1a3h2	0.941	0.841	0.809
M1D2A2P3a2h3*	0.649	0.922	0.882	M3D1A1P2a1h2	0.924	0.855	0.794
M1D2A2P3a3h3*	0.711	0.916	0.883	M3D1A1P2a2h2	0.922	0.826	0.784
M1D2A3P1a1h1	0.956	0.970	0.950	M3D1A1P2a3h2	0.926	0.813	0.782
M1D2A3P1a2h1	0.962	0.970	0.950	M3D1A1P3a1h2	0.936	0.957	0.904
M1D2A3P1a3h1	0.964	0.970	0.950	M3D1A1P3a2h2	0.902	0.855	0.805
M1D2A3P2a1h1	0.961	0.940	0.940	M3D1A1P3a3h2	0.920	0.870	0.838
M1D2A3P2a2h1	0.962	0.950	0.960	M3D1A1P1a1h3	0.873	0.560	0.470
M1D2A3P2a3h1	0.963	0.940	0.940	M3D1A1P1a2h3	0.909	0.806	0.741
M1D2A3P3a1h1	0.910	0.978	0.910	M3D1A1P1a3h3	0.896	0.580	0.615
M1D2A3P3a2h1	0.841	0.971	0.970	M3D1A1P2a1h3	0.875	0.784	0.687
M1D2A3P3a3h1	0.865	0.971	0.960	M3D1A1P2a2h3	0.872	0.739	0.670
M1D2A3P1a1h2	0.798	0.866	0.818	M3D1A1P2a3h3	0.879	0.719	0.668
M1D2A3P1a2h2	0.839	0.883	0.838	M3D1A1P3a1h3	0.902	0.947	0.866
M1D2A3P1a3h2	0.854	0.877	0.849	M3D1A1P3a2h3	0.840	0.795	0.717
M1D2A3P2a1h2	0.832	0.852	0.823	M3D1A1P3a3h3	0.874	0.818	0.765
M1D2A3P2a2h2	0.840	0.842	0.822	M3D1A2P1a1h1	0.972	0.960	0.960
M1D2A3P2a3h2	0.844	0.809	0.790	M3D1A2P1a2h1	0.974	0.970	0.950
M1D2A3P3a1h2	0.712	0.928	0.947	M3D1A2P1a3h1	0.974	0.970	0.940
M1D2A3P3a2h2	0.452	0.873	0.935	M3D1A2P2a1h1	0.970	0.950	0.969

Table D.5 Critical buckling limit ratios for specimens with two corrosion defects of $d_p/t = d_s/t = 0.16$ - continue

Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}	Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}
M1D2A3P3a3h2	0.543	0.869	0.940	M3D1A2P2a2h1	0.970	0.940	0.968
M1D2A3P1a1h3	0.673	0.780	0.716	M3D1A2P2a3h1	0.971	0.950	0.968
M1D2A3P1a2h3	0.742	0.809	0.749	M3D1A2P3a1h1	0.969	0.950	0.972
M1D2A3P1a3h3	0.768	0.799	0.767	M3D1A2P3a2h1	0.961	0.972	0.957
M1D2A3P2a1h3	0.697	0.780	0.716	M3D1A2P3a3h1	0.965	0.973	0.962
M1D2A3P2a2h3	0.713	0.765	0.714	M3D1A2P1a1h2	0.914	0.752	0.729
M1D2A3P2a3h3	0.721	0.714	0.660	M3D1A2P1a2h2	0.935	0.904	0.861
M1D2A3P3a1h3	F	F	F	M3D1A2P1a3h2	0.929	0.841	0.814
M1D2A3P3a2h3	F	F	F	M3D1A2P2a1h2	0.914	0.864	0.812
M1D2A3P3a3h3	F	F	F	M3D1A2P2a2h2	0.912	0.834	0.798
M1D3A1P1a1h1	0.957	0.970	0.950	M3D1A2P2a3h2	0.917	0.824	0.798
M1D3A1P1a2h1	0.960	0.960	0.950	M3D1A2P3a1h2	0.928	0.964	0.920
M1D3A1P1a3h1	0.961	0.960	0.940	M3D1A2P3a2h2	0.887	0.860	0.819
M1D3A1P2a1h1	0.967	0.960	0.961	M3D1A2P3a3h2	0.910	0.877	0.850
M1D3A1P2a2h1	0.970	0.963	0.949	M3D1A2P1a1h3	0.843	0.540	0.464
M1D3A1P2a3h1	0.970	0.965	0.954	M3D1A2P1a2h3	0.887	0.790	0.736
M1D3A1P3a1h1*	0.978	1.106	1.129	M3D1A2P1a3h3	0.874	0.631	0.639
M1D3A1P3a2h1*	0.977	1.075	1.065	M3D1A2P2a1h3	0.856	0.794	0.711
M1D3A1P3a3h1*	0.977	0.995	0.958	M3D1A2P2a2h3	0.852	0.747	0.688
M1D3A1P1a1h2	0.883	0.896	0.859	M3D1A2P2a3h3	0.861	0.731	0.688
M1D3A1P1a2h2	0.894	0.894	0.863	M3D1A2P3a1h3	0.886	0.956	0.889
M1D3A1P1a3h2	0.900	0.869	0.850	M3D1A2P3a2h3	0.812	0.799	0.734
M1D3A1P2a1h2	0.860	0.960	0.859	M3D1A2P3a3h3	0.853	0.826	0.782
M1D3A1P2a2h2	0.893	0.846	0.789	M3D1A3P1a1h1	0.973	0.960	0.950
M1D3A1P2a3h2	0.894	0.863	0.817	M3D1A3P1a2h1	0.976	0.970	0.950
M1D3A1P3a1h2*	0.931	1.097	1.056	M3D1A3P1a3h1	0.975	0.970	0.960
M1D3A1P3a2h2*	0.894	1.069	1.023	M3D1A3P2a1h1	0.970	0.940	0.930
M1D3A1P3a3h2*	0.906	0.994	0.969	M3D1A3P2a2h1	0.969	0.950	0.930
M1D3A1P1a1h3	0.828	0.808	0.781	M3D1A3P2a3h1	0.970	0.960	0.940
M1D3A1P1a2h3	0.845	0.804	0.789	M3D1A3P3a1h1	0.968	0.970	0.940
M1D3A1P1a3h3	0.854	0.753	0.767	M3D1A3P3a2h1	0.958	0.940	0.969
M1D3A1P2a1h3	0.739	0.963	0.854	M3D1A3P3a3h1	0.964	0.950	0.971
M1D3A1P2a2h3	0.805	0.869	0.780	M3D1A3P1a1h2	0.898	0.766	0.743
M1D3A1P2a3h3	0.808	0.883	0.809	M3D1A3P1a2h2	0.923	0.904	0.869
M1D3A1P3a1h3*	0.878	1.208	1.121	M3D1A3P1a3h2	0.918	0.850	0.826
M1D3A1P3a2h3*	0.799	1.152	1.060	M3D1A3P2a1h2	0.902	0.874	0.832
M1D3A1P3a3h3*	0.825	1.008	0.959	M3D1A3P2a2h2	0.899	0.843	0.813
M1D3A2P1a1h1	0.915	0.955	0.934	M3D1A3P2a3h2	0.905	0.834	0.811
M1D3A2P1a2h1	0.921	0.947	0.928	M3D1A3P3a1h2	0.916	0.973	0.940
M1D3A2P1a3h1	0.922	0.945	0.927	M3D1A3P3a2h2	0.865	0.867	0.834

Table D.5 Critical buckling limit ratios for specimens with two corrosion defects of $d_p/t = d_s/t = 0.16$ - continue

Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}	Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}
M1D3A2P2a1h1	0.967	0.950	0.973	M3D1A3P3a3h2	0.894	0.887	0.865
M1D3A2P2a2h1	0.970	0.974	0.972	M3D1A3P1a1h3	0.809	0.550	0.481
M1D3A2P2a3h1	0.971	0.973	0.972	M3D1A3P1a2h3	0.862	0.791	0.747
M1D3A2P3a1h1*	0.946	0.915	0.977	M3D1A3P1a3h3	0.850	0.656	0.655
M1D3A2P3a2h1*	0.931	1.010	0.960	M3D1A3P2a1h3	0.830	0.807	0.738
M1D3A2P3a3h1*	0.936	1.126	1.037	M3D1A3P2a2h3	0.825	0.757	0.707
M1D3A2P1a1h2	0.814	0.850	0.814	M3D1A3P2a3h3	0.837	0.742	0.705
M1D3A2P1a2h2	0.828	0.808	0.793	M3D1A3P3a1h3	0.863	0.969	0.918
M1D3A2P1a3h2	0.832	0.802	0.789	M3D1A3P3a2h3	0.770	0.806	0.755
M1D3A2P2a1h2	0.817	0.909	0.849	M3D1A3P3a3h3	0.823	0.836	0.802
M1D3A2P2a2h2	0.856	0.850	0.821	M3D2A1P1a1h1	0.951	0.897	0.888
M1D3A2P2a3h2	0.858	0.848	0.823	M3D2A1P1a2h1	0.957	0.918	0.910
M1D3A2P3a1h2*	0.848	1.009	0.984	M3D2A1P1a3h1	0.959	0.916	0.911
M1D3A2P3a2h2*	0.787	0.967	0.942	M3D2A1P2a1h1	0.962	0.944	0.931
M1D3A2P3a3h2*	0.810	0.915	0.897	M3D2A1P2a2h1	0.966	0.934	0.929
M1D3A2P1a1h3	0.735	0.793	0.744	M3D2A1P2a3h1	0.966	0.938	0.933
M1D3A2P1a2h3	0.755	0.734	0.713	M3D2A1P3a1h1	0.971	0.960	0.930
M1D3A2P1a3h3	0.761	0.724	0.707	M3D2A1P3a2h1	0.971	0.940	0.930
M1D3A2P2a1h3	0.682	0.894	0.800	M3D2A1P3a3h1	0.971	0.940	0.930
M1D3A2P2a2h3	0.754	0.823	0.762	M3D2A1P1a1h2	0.882	0.707	0.696
M1D3A2P2a3h3	0.757	0.820	0.764	M3D2A1P1a2h2	0.901	0.779	0.764
M1D3A2P3a1h3*	0.746	0.943	0.940	M3D2A1P1a3h2	0.908	0.772	0.768
M1D3A2P3a2h3*	0.638	0.997	0.946	M3D2A1P2a1h2	0.884	0.828	0.761
M1D3A2P3a3h3*	0.678	1.064	0.906	M3D2A1P2a2h2	0.903	0.789	0.755
M1D3A3P1a1h1	0.901	0.874	0.856	M3D2A1P2a3h2	0.902	0.803	0.770
M1D3A3P1a2h1	0.911	0.862	0.856	M3D2A1P3a1h2	0.899	0.904	0.853
M1D3A3P1a3h1	0.915	0.864	0.858	M3D2A1P3a2h2	0.902	0.867	0.831
M1D3A3P2a1h1	0.967	0.960	0.950	M3D2A1P3a3h2	0.901	0.857	0.828
M1D3A3P2a2h1	0.970	0.950	0.940	M3D2A1P1a1h3	0.813	0.534	0.537
M1D3A3P2a3h1	0.970	0.900	0.960	M3D2A1P1a2h3	0.846	0.651	0.642
M1D3A3P3a1h1	F	F	F	M3D2A1P1a3h3	0.857	0.640	0.648
M1D3A3P3a2h1	F	F	F	M3D2A1P2a1h3	0.805	0.774	0.678
M1D3A3P3a3h1	F	F	F	M3D2A1P2a2h3	0.841	0.720	0.669
M1D3A3P1a1h2	0.785	0.842	0.784	M3D2A1P2a3h3	0.839	0.739	0.689
M1D3A3P1a2h2	0.810	0.826	0.785	M3D2A1P3a1h3	0.824	0.881	0.796
M1D3A3P1a3h2	0.819	0.828	0.788	M3D2A1P3a2h3	0.830	0.833	0.764
M1D3A3P2a1h2	0.775	0.891	0.821	M3D2A1P3a3h3	0.829	0.821	0.760
M1D3A3P2a2h2	0.825	0.845	0.789	M3D2A2P1a1h1	0.946	0.901	0.893
M1D3A3P2a3h2	0.822	0.851	0.808	M3D2A2P1a2h1	0.952	0.918	0.909
M1D3A3P3a1h2	F	F	F	M3D2A2P1a3h1	0.954	0.917	0.910

Table D.5 Critical buckling limit ratios for specimens with two corrosion defects of $d_p/t = d_s/t = 0.16$ - continue

Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}	Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}
M1D3A3P3a2h2	F	F	F	M3D2A2P2a1h1	0.962	0.951	0.942
M1D3A3P3a3h2	F	F	F	M3D2A2P2a2h1	0.965	0.943	0.940
M1D3A3P1a1h3	0.689	0.784	0.707	M3D2A2P2a3h1	0.965	0.946	0.943
M1D3A3P1a2h3	0.727	0.762	0.707	M3D2A2P3a1h1	0.969	0.950	0.960
M1D3A3P1a3h3	0.740	0.765	0.713	M3D2A2P3a2h1	0.969	0.950	0.940
M1D3A3P2a1h3	0.598	0.864	0.759	M3D2A2P3a3h1	0.969	0.950	0.940
M1D3A3P2a2h3	0.691	0.804	0.714	M3D2A2P1a1h2	0.859	0.722	0.710
M1D3A3P2a3h3	0.686	0.812	0.741	M3D2A2P1a2h2	0.880	0.777	0.759
M1D3A3P3a1h3	F	F	F	M3D2A2P1a3h2	0.889	0.772	0.764
M1D3A3P3a2h3	F	F	F	M3D2A2P2a1h2	0.864	0.841	0.788
M1D3A3P3a3h3	F	F	F	M3D2A2P2a2h2	0.887	0.801	0.777
M2D1A1P1a1h1	0.969	0.960	0.940	M3D2A2P2a3h2	0.887	0.814	0.789
M2D1A1P1a2h1	0.972	0.960	0.950	M3D2A2P3a1h2	0.879	0.908	0.870
M2D1A1P1a3h1	0.971	0.960	0.950	M3D2A2P3a2h2	0.884	0.860	0.840
M2D1A1P2a1h1	0.961	0.935	0.912	M3D2A2P3a3h2	0.882	0.862	0.838
M2D1A1P2a2h1	0.958	0.921	0.900	M3D2A2P1a1h3	0.775	0.564	0.566
M2D1A1P2a3h1	0.960	0.921	0.905	M3D2A2P1a2h3	0.811	0.653	0.641
M2D1A1P3a1h1	0.957	0.940	0.947	M3D2A2P1a3h3	0.826	0.646	0.648
M2D1A1P3a2h1	0.940	0.894	0.874	M3D2A2P2a1h3	0.769	0.782	0.698
M2D1A1P3a3h1	0.947	0.900	0.888	M3D2A2P2a2h3	0.810	0.725	0.682
M2D1A1P1a1h2	0.933	0.730	0.703	M3D2A2P2a3h3	0.810	0.743	0.699
M2D1A1P1a2h2	0.948	0.910	0.853	M3D2A2P3a1h3	0.780	0.893	0.822
M2D1A1P1a3h2	0.942	0.822	0.792	M3D2A2P3a2h3	0.790	0.835	0.779
M2D1A1P2a1h2	0.919	0.826	0.765	M3D2A2P3a3h3	0.787	0.837	0.776
M2D1A1P2a2h2	0.909	0.776	0.730	M3D2A3P1a1h1	0.939	0.918	0.910
M2D1A1P2a3h2	0.917	0.777	0.743	M3D2A3P1a2h1	0.947	0.934	0.926
M2D1A1P3a1h2	0.918	0.971	0.909	M3D2A3P1a3h1	0.949	0.931	0.925
M2D1A1P3a2h2	0.875	0.808	0.754	M3D2A3P2a1h1	0.959	0.957	0.951
M2D1A1P3a3h2	0.891	0.820	0.783	M3D2A3P2a2h1	0.963	0.949	0.946
M2D1A1P1a1h3	0.882	0.580	0.480	M3D2A3P2a3h1	0.963	0.951	0.949
M2D1A1P1a2h3	0.912	0.803	0.730	M3D2A3P3a1h1	0.951	0.967	0.956
M2D1A1P1a3h3	0.901	0.680	0.610	M3D2A3P3a2h1	0.951	0.961	0.950
M2D1A1P2a1h3	0.876	0.762	0.671	M3D2A3P3a3h1	0.952	0.961	0.951
M2D1A1P2a2h3	0.859	0.692	0.621	M3D2A3P1a1h2	0.829	0.734	0.720
M2D1A1P2a3h3	0.873	0.693	0.641	M3D2A3P1a2h2	0.859	0.797	0.780
M2D1A1P3a1h3	0.879	0.968	0.884	M3D2A3P1a3h2	0.868	0.786	0.776
M2D1A1P3a2h3	0.809	0.756	0.677	M3D2A3P2a1h2	0.837	0.851	0.810
M2D1A1P3a3h3	0.836	0.771	0.715	M3D2A3P2a2h2	0.863	0.807	0.787
M2D1A2P1a1h1	0.968	0.950	0.940	M3D2A3P2a3h2	0.864	0.821	0.800
M2D1A2P1a2h1	0.972	0.960	0.940	M3D2A3P3a1h2	0.834	0.891	0.861

Table D.5 Critical buckling limit ratios for specimens with two corrosion defects of $d_p/t = d_s/t = 0.16$ - continue

Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}	Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}
M2D1A2P1a3h1	0.971	0.940	0.940	M3D2A3P3a2h2	0.838	0.856	0.832
M2D1A2P2a1h1	0.958	0.943	0.925	M3D2A3P3a3h2	0.839	0.853	0.835
M2D1A2P2a2h1	0.954	0.929	0.913	M3D2A3P1a1h3	0.717	0.555	0.551
M2D1A2P2a3h1	0.957	0.930	0.917	M3D2A3P1a2h3	0.768	0.664	0.650
M2D1A2P3a1h1	0.952	0.960	0.959	M3D2A3P1a3h3	0.785	0.646	0.642
M2D1A2P3a2h1	0.933	0.904	0.888	M3D2A3P2a1h3	0.716	0.789	0.715
M2D1A2P3a3h1	0.940	0.916	0.904	M3D2A3P2a2h3	0.765	0.725	0.679
M2D1A2P1a1h2	0.915	0.728	0.703	M3D2A3P2a3h3	0.766	0.744	0.700
M2D1A2P1a2h2	0.934	0.882	0.840	M3D2A3P3a1h3	0.717	0.860	0.806
M2D1A2P1a3h2	0.929	0.815	0.791	M3D2A3P3a2h3	0.724	0.812	0.763
M2D1A2P2a1h2	0.906	0.838	0.788	M3D2A3P3a3h3	0.726	0.809	0.768
M2D1A2P2a2h2	0.894	0.785	0.748	M3D3A1P1a1h1	0.922	0.830	0.831
M2D1A2P2a3h2	0.905	0.790	0.762	M3D3A1P1a2h1	0.926	0.825	0.832
M2D1A2P3a1h2	0.901	0.940	0.931	M3D3A1P1a3h1	0.929	0.823	0.834
M2D1A2P3a2h2	0.848	0.799	0.761	M3D3A1P2a1h1	0.945	0.927	0.926
M2D1A2P3a3h2	0.869	0.828	0.799	M3D3A1P2a2h1	0.950	0.910	0.921
M2D1A2P1a1h3	0.848	0.560	0.463	M3D3A1P2a3h1	0.950	0.911	0.921
M2D1A2P1a2h3	0.887	0.775	0.719	M3D3A1P3a1h1	0.961	0.968	0.956
M2D1A2P1a3h3	0.876	0.636	0.626	M3D3A1P3a2h1	0.963	0.947	0.945
M2D1A2P2a1h3	0.853	0.775	0.700	M3D3A1P3a3h1	0.963	0.951	0.948
M2D1A2P2a2h3	0.832	0.700	0.641	M3D3A1P1a1h2	0.851	0.705	0.702
M2D1A2P2a3h3	0.851	0.707	0.662	M3D3A1P1a2h2	0.858	0.697	0.703
M2D1A2P3a1h3	0.851	0.930	0.917	M3D3A1P1a3h2	0.866	0.693	0.707
M2D1A2P3a2h3	0.763	0.761	0.699	M3D3A1P2a1h2	0.857	0.842	0.796
M2D1A2P3a3h3	0.798	0.796	0.748	M3D3A1P2a2h2	0.875	0.796	0.781
M2D1A3P1a1h1	0.969	0.960	0.950	M3D3A1P2a3h2	0.877	0.797	0.782
M2D1A3P1a2h1	0.972	0.960	0.950	M3D3A1P3a1h2	0.869	0.930	0.869
M2D1A3P1a3h1	0.971	0.970	0.960	M3D3A1P3a2h2	0.885	0.847	0.823
M2D1A3P2a1h1	0.954	0.949	0.935	M3D3A1P3a3h2	0.881	0.862	0.832
M2D1A3P2a2h1	0.949	0.937	0.924	M3D3A1P1a1h3	0.788	0.634	0.623
M2D1A3P2a3h1	0.953	0.939	0.927	M3D3A1P1a2h3	0.799	0.624	0.624
M2D1A3P3a1h1	0.944	0.960	0.968	M3D3A1P1a3h3	0.811	0.619	0.630
M2D1A3P3a2h1	0.919	0.910	0.899	M3D3A1P2a1h3	0.772	0.792	0.716
M2D1A3P3a3h1	0.929	0.922	0.913	M3D3A1P2a2h3	0.803	0.730	0.693
M2D1A3P1a1h2	0.895	0.748	0.725	M3D3A1P2a3h3	0.805	0.732	0.695
M2D1A3P1a2h2	0.919	0.888	0.854	M3D3A1P3a1h3	0.774	0.913	0.818
M2D1A3P1a3h2	0.914	0.829	0.806	M3D3A1P3a2h3	0.803	0.802	0.750
M2D1A3P2a1h2	0.888	0.848	0.809	M3D3A1P3a3h3	0.797	0.821	0.765
M2D1A3P2a2h2	0.872	0.795	0.764	M3D3A2P1a1h1	0.921	0.851	0.848
M2D1A3P2a3h2	0.886	0.801	0.777	M3D3A2P1a2h1	0.925	0.843	0.845

Table D.5 Critical buckling limit ratios for specimens with two corrosion defects of $d_p/t = d_s/t = 0.16$ - continue

Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}	Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}
M2D1A3P3a1h2	0.874	0.960	0.951	M3D3A2P1a3h1	0.929	0.841	0.847
M2D1A3P3a2h2	0.803	0.806	0.778	M3D3A2P2a1h1	0.937	0.861	0.852
M2D1A3P3a3h2	0.832	0.835	0.813	M3D3A2P2a2h1	0.943	0.818	0.836
M2D1A3P1a1h3	0.808	0.610	0.530	M3D3A2P2a3h1	0.944	0.817	0.836
M2D1A3P1a2h3	0.857	0.782	0.736	M3D3A2P3a1h1	0.959	0.927	0.931
M2D1A3P1a3h3	0.847	0.657	0.643	M3D3A2P3a2h1	0.960	0.947	0.943
M2D1A3P2a1h3	0.820	0.788	0.729	M3D3A2P3a3h1	0.960	0.951	0.946
M2D1A3P2a2h3	0.792	0.710	0.663	M3D3A2P1a1h2	0.829	0.732	0.727
M2D1A3P2a3h3	0.817	0.720	0.683	M3D3A2P1a2h2	0.839	0.717	0.721
M2D1A3P3a1h3	0.805	0.890	0.943	M3D3A2P1a3h2	0.848	0.713	0.724
M2D1A3P3a2h3	0.686	0.770	0.725	M3D3A2P2a1h2	0.828	0.786	0.744
M2D1A3P3a3h3	0.734	0.805	0.770	M3D3A2P2a2h2	0.850	0.717	0.715
M2D2A1P1a1h1	0.958	0.943	0.918	M3D3A2P2a3h2	0.853	0.716	0.715
M2D2A1P1a2h1	0.962	0.954	0.933	M3D3A2P3a1h2	0.852	0.884	0.842
M2D2A1P1a3h1	0.963	0.953	0.934	M3D3A2P3a2h2	0.858	0.845	0.822
M2D2A1P2a1h1	0.965	0.955	0.943	M3D3A2P3a3h2	0.855	0.863	0.839
M2D2A1P2a2h1	0.968	0.948	0.943	M3D3A2P1a1h3	0.749	0.667	0.651
M2D2A1P2a3h1	0.968	0.950	0.944	M3D3A2P1a2h3	0.763	0.648	0.643
M2D2A1P3a1h1	0.956	0.963	0.945	M3D3A2P1a3h3	0.778	0.642	0.647
M2D2A1P3a2h1	0.951	0.953	0.936	M3D3A2P2a1h3	0.721	0.740	0.671
M2D2A1P3a3h1	0.954	0.949	0.935	M3D3A2P2a2h3	0.759	0.654	0.633
M2D2A1P1a1h2	0.892	0.714	0.693	M3D3A2P2a3h3	0.764	0.653	0.633
M2D2A1P1a2h2	0.910	0.793	0.762	M3D3A2P3a1h3	0.743	0.823	0.774
M2D2A1P1a3h2	0.915	0.785	0.765	M3D3A2P3a2h3	0.755	0.796	0.751
M2D2A1P2a1h2	0.892	0.829	0.763	M3D3A2P3a3h3	0.749	0.820	0.775
M2D2A1P2a2h2	0.908	0.791	0.761	M3D3A3P1a1h1	0.905	0.868	0.861
M2D2A1P2a3h2	0.905	0.799	0.766	M3D3A3P1a2h1	0.908	0.858	0.856
M2D2A1P3a1h2	0.900	0.908	0.857	M3D3A3P1a3h1	0.913	0.855	0.856
M2D2A1P3a2h2	0.881	0.869	0.825	M3D3A3P2a1h1	0.935	0.930	0.968
M2D2A1P3a3h2	0.891	0.853	0.822	M3D3A3P2a2h1	0.936	0.919	0.913
M2D2A1P1a1h3	0.825	0.566	0.540	M3D3A3P2a3h1	0.938	0.919	0.913
M2D2A1P1a2h3	0.857	0.690	0.646	M3D3A3P3a1h1	0.951	0.967	0.959
M2D2A1P1a3h3	0.866	0.677	0.650	M3D3A3P3a2h1	0.955	0.953	0.949
M2D2A1P2a1h3	0.817	0.761	0.655	M3D3A3P3a3h1	0.955	0.953	0.945
M2D2A1P2a2h3	0.848	0.705	0.651	M3D3A3P1a1h2	0.793	0.745	0.726
M2D2A1P2a3h3	0.842	0.717	0.660	M3D3A3P1a2h2	0.802	0.725	0.715
M2D2A1P3a1h3	0.840	0.894	0.813	M3D3A3P1a3h2	0.813	0.718	0.714
M2D2A1P3a2h3	0.809	0.848	0.770	M3D3A3P2a1h2	0.816	0.827	0.794
M2D2A1P3a3h3	0.825	0.828	0.765	M3D3A3P2a2h2	0.819	0.799	0.771
M2D2A2P1a1h1	0.954	0.955	0.932	M3D3A3P2a3h2	0.825	0.800	0.773

Table D.5 Critical buckling limit ratios for specimens with two corrosion defects of $d_p/t = d_s/t = 0.16$ - continue

Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}	Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}
M2D2A2P1a2h1	0.959	0.962	0.941	M3D3A3P3a1h2	0.801	0.916	0.867
M2D2A2P1a3h1	0.961	0.961	0.942	M3D3A3P3a2h2	0.825	0.843	0.814
M2D2A2P2a1h1	0.964	0.964	0.956	M3D3A3P3a3h2	0.824	0.844	0.794
M2D2A2P2a2h1	0.967	0.959	0.954	M3D3A3P1a1h3	0.699	0.678	0.644
M2D2A2P2a3h1	0.966	0.960	0.955	M3D3A3P1a2h3	0.712	0.652	0.629
M2D2A2P3a1h1	0.950	0.967	0.957	M3D3A3P1a3h3	0.729	0.643	0.627
M2D2A2P3a2h1	0.943	0.958	0.949	M3D3A3P2a1h3	0.711	0.742	0.698
M2D2A2P3a3h1	0.946	0.955	0.948	M3D3A3P2a2h3	0.716	0.725	0.675
M2D2A2P1a1h2	0.869	0.746	0.721	M3D3A3P2a3h3	0.727	0.726	0.679
M2D2A2P1a2h2	0.891	0.806	0.772	M3D3A3P3a1h3	0.650	0.888	0.808
M2D2A2P1a3h2	0.898	0.798	0.775	M3D3A3P3a2h3	0.695	0.783	0.725
M2D2A2P2a1h2	0.869	0.837	0.785	M3D3A3P3a3h3	0.692	0.784	0.695
M2D2A2P2a2h2	0.890	0.796	0.768				

Table D.6 Critical buckling limit ratios for specimens with two corrosion defects of $d_p/t = d_s/t = 0.30$

Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}	Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}
M1D1A1P1a1h1	0.956	0.949	0.861	M2D2A2P2a3h2	0.804	0.723	0.672
M1D1A1P1a2h1	0.961	0.961	0.896	M2D2A2P3a1h2	0.756	0.898	0.831
M1D1A1P1a3h1	0.960	0.955	0.884	M2D2A2P3a2h2	0.730	0.913	0.842
M1D1A1P2a1h1	0.935	0.837	0.787	M2D2A2P3a3h2	0.755	0.827	0.780
M1D1A1P2a2h1	0.924	0.785	0.746	M2D2A2P1a1h3	0.630	0.495	0.455
M1D1A1P2a3h1	0.932	0.793	0.767	M2D2A2P1a2h3	0.678	0.560	0.519
M1D1A1P3a1h1	0.886	0.869	0.812	M2D2A2P1a3h3	0.699	0.538	0.514
M1D1A1P3a2h1	0.880	0.816	0.777	M2D2A2P2a1h3	0.617	0.751	0.633
M1D1A1P3a3h1	0.875	0.746	0.743	M2D2A2P2a2h3	0.666	0.651	0.575
M1D1A1P1a1h2	0.901	0.637	0.552	M2D2A2P2a3h3	0.667	0.655	0.579
M1D1A1P1a2h2	0.918	0.774	0.677	M2D2A2P3a1h3*	0.622	0.994	0.876
M1D1A1P1a3h2	0.915	0.699	0.637	M2D2A2P3a2h3*	0.581	0.992	0.883
M1D1A1P2a1h2	0.875	0.736	0.637	M2D2A2P3a3h3*	0.620	1.007	0.840
M1D1A1P2a2h2	0.852	0.646	0.565	M2D2A3P1a1h1	0.890	0.843	0.822
M1D1A1P2a3h2	0.869	0.660	0.602	M2D2A3P1a2h1	0.900	0.857	0.838
M1D1A1P3a1h2	0.789	0.886	0.789	M2D2A3P1a3h1	0.906	0.851	0.834
M1D1A1P3a2h2	0.776	0.841	0.750	M2D2A3P2a1h1	0.892	0.902	0.881
M1D1A1P3a3h2	0.767	0.780	0.711	M2D2A3P2a2h1	0.903	0.872	0.859
M1D1A1P1a1h3	0.831	0.470	0.468	M2D2A3P2a3h1	0.903	0.876	0.863
M1D1A1P1a2h3	0.862	0.573	0.547	M2D2A3P3a1h1	0.836	0.878	0.857
M1D1A1P1a3h3	0.856	0.563	0.489	M2D2A3P3a2h1	0.819	0.887	0.864
M1D1A1P2a1h3	0.810	0.692	0.558	M2D2A3P3a3h1	0.834	0.819	0.820

Table D.6 Critical buckling limit ratios for specimens with two corrosion defects of $d_p/t = d_s/t = 0.30$ - continue

Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}	Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}
M1D1A1P2a2h3	0.772	0.585	0.479	M2D2A3P1a1h2	0.718	0.653	0.621
M1D1A1P2a3h3	0.800	0.602	0.515	M2D2A3P1a2h2	0.748	0.686	0.658
M1D1A1P3a1h3*	0.689	0.939	0.820	M2D2A3P1a3h2	0.764	0.672	0.650
M1D1A1P3a2h3*	0.668	0.919	0.787	M2D2A3P2a1h2	0.707	0.790	0.731
M1D1A1P3a3h3*	0.654	0.893	0.754	M2D2A3P2a2h2	0.741	0.716	0.678
M1D1A2P1a1h1	0.945	0.847	0.817	M2D2A3P2a3h2	0.742	0.725	0.688
M1D1A2P1a2h1	0.951	0.834	0.818	M2D2A3P3a1h2	0.660	0.869	0.818
M1D1A2P1a3h1	0.951	0.866	0.843	M2D2A3P3a2h2	0.623	0.880	0.827
M1D1A2P2a1h1	0.923	0.853	0.814	M2D2A3P3a3h2	0.657	0.807	0.769
M1D1A2P2a2h1	0.910	0.799	0.768	M2D2A3P1a1h3	0.547	0.497	0.451
M1D1A2P2a3h1	0.920	0.806	0.785	M2D2A3P1a2h3	0.596	0.546	0.505
M1D1A2P3a1h1	0.847	0.876	0.838	M2D2A3P1a3h3	0.623	0.524	0.493
M1D1A2P3a2h1	0.838	0.825	0.799	M2D2A3P2a1h3	0.546	0.728	0.641
M1D1A2P3a3h1	0.831	0.744	0.744	M2D2A3P2a2h3	0.580	0.630	0.568
M1D1A2P1a1h2	0.868	0.664	0.592	M2D2A3P2a3h3	0.583	0.642	0.582
M1D1A2P1a2h2	0.889	0.631	0.595	M2D2A3P3a1h3*	0.476	0.910	0.828
M1D1A2P1a3h2	0.889	0.709	0.656	M2D2A3P3a2h3*	0.418	0.916	0.835
M1D1A2P2a1h2	0.845	0.759	0.685	M2D2A3P3a3h3*	0.471	0.870	0.781
M1D1A2P2a2h2	0.814	0.666	0.603	M2D3A1P1a1h1	0.903	0.808	0.786
M1D1A2P2a3h2	0.838	0.679	0.633	M2D3A1P1a2h1	0.905	0.789	0.775
M1D1A2P3a1h2	0.700	0.893	0.834	M2D3A1P1a3h1	0.909	0.779	0.772
M1D1A2P3a2h2	0.682	0.850	0.794	M2D3A1P2a1h1	0.909	0.893	0.839
M1D1A2P3a3h2	0.667	0.782	0.737	M2D3A1P2a2h1	0.917	0.838	0.814
M1D1A2P1a1h3	0.772	0.660	0.580	M2D3A1P2a3h1	0.919	0.842	0.822
M1D1A2P1a2h3	0.811	0.559	0.495	M2D3A1P3a1h1	0.901	0.932	0.875
M1D1A2P1a3h3	0.811	0.652	0.571	M2D3A1P3a2h1	0.906	0.904	0.873
M1D1A2P2a1h3	0.753	0.739	0.638	M2D3A1P3a3h1	0.907	0.822	0.846
M1D1A2P2a2h3	0.701	0.636	0.544	M2D3A1P1a1h2	0.786	0.640	0.602
M1D1A2P2a3h3	0.741	0.651	0.579	M2D3A1P1a2h2	0.789	0.600	0.580
M1D1A2P3a1h3*	0.543	0.950	0.881	M2D3A1P1a3h2	0.799	0.582	0.575
M1D1A2P3a2h3*	0.515	0.935	0.854	M2D3A1P2a1h2	0.782	0.822	0.702
M1D1A2P3a3h3*	0.492	0.912	0.815	M2D3A1P2a2h2	0.804	0.723	0.653
M1D1A3P1a1h1	0.929	0.881	0.858	M2D3A1P2a3h2	0.811	0.730	0.669
M1D1A3P1a2h1	0.939	0.850	0.838	M2D3A1P3a1h2*	0.782	0.948	0.848
M1D1A3P1a3h1	0.941	0.888	0.871	M2D3A1P3a2h2*	0.794	0.929	0.845
M1D1A3P2a1h1	0.901	0.872	0.846	M2D3A1P3a3h2*	0.798	0.874	0.811
M1D1A3P2a2h1	0.883	0.816	0.795	M2D3A1P1a1h3	0.690	0.570	0.523
M1D1A3P2a3h1	0.899	0.823	0.806	M2D3A1P1a2h3	0.696	0.522	0.497
M1D1A3P3a1h1	0.747	0.900	0.919	M2D3A1P1a3h3	0.711	0.500	0.491
M1D1A3P3a2h1	0.718	0.839	0.861	M2D3A1P2a1h3	0.647	0.817	0.661

Table D.6 Critical buckling limit ratios for specimens with two corrosion defects of $d_p/t = d_s/t = 0.30$ - continue

Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}	Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}
M1D1A3P3a3h1	0.717	0.850	0.813	M2D3A1P2a2h3	0.684	0.715	0.605
M1D1A3P1a1h2	0.811	0.737	0.684	M2D3A1P2a3h3	0.695	0.722	0.623
M1D1A3P1a2h2	0.844	0.662	0.635	M2D3A1P3a1h3*	0.658	1.051	0.936
M1D1A3P1a3h2	0.849	0.756	0.715	M2D3A1P3a2h3*	0.678	1.093	0.935
M1D1A3P2a1h2	0.781	0.795	0.747	M2D3A1P3a3h3*	0.684	1.215	0.923
M1D1A3P2a2h2	0.735	0.699	0.658	M2D3A2P1a1h1	0.879	0.817	0.801
M1D1A3P2a3h2	0.774	0.711	0.678	M2D3A2P1a2h1	0.882	0.806	0.796
M1D1A3P3a1h2	0.468	0.895	0.907	M2D3A2P1a3h1	0.888	0.796	0.791
M1D1A3P3a2h2	0.404	0.830	0.839	M2D3A2P2a1h1	0.882	0.878	0.844
M1D1A3P3a3h2	0.403	0.771	0.783	M2D3A2P2a2h1	0.895	0.838	0.819
M1D1A3P1a1h3	0.655	0.680	0.609	M2D3A2P2a3h1	0.897	0.840	0.823
M1D1A3P1a2h3	0.718	0.588	0.546	M2D3A2P3a1h1	0.867	0.924	0.896
M1D1A3P1a3h3	0.729	0.703	0.647	M2D3A2P3a2h1	0.874	0.913	0.896
M1D1A3P2a1h3	0.650	0.748	0.686	M2D3A2P3a3h1	0.876	0.856	0.865
M1D1A3P2a2h3	0.573	0.628	0.574	M2D3A2P1a1h2	0.715	0.638	0.614
M1D1A3P2a3h3	0.639	0.642	0.598	M2D3A2P1a2h2	0.725	0.616	0.603
M1D1A3P3a1h3	F	F	F	M2D3A2P1a3h2	0.740	0.594	0.592
M1D1A3P3a2h3	F	F	F	M2D3A2P2a1h2	0.706	0.793	0.713
M1D1A3P3a3h3	F	F	F	M2D3A2P2a2h2	0.743	0.720	0.665
M1D2A1P1a1h1	0.934	0.882	0.818	M2D3A2P2a3h2	0.750	0.722	0.672
M1D2A1P1a2h1	0.941	0.891	0.832	M2D3A2P3a1h2*	0.701	0.927	0.863
M1D2A1P1a3h1	0.943	0.875	0.819	M2D3A2P3a2h2*	0.717	0.916	0.862
M1D2A1P2a1h1	0.930	0.884	0.827	M2D3A2P3a3h2*	0.723	0.861	0.819
M1D2A1P2a2h1	0.934	0.839	0.808	M2D3A2P1a1h3	0.594	0.563	0.525
M1D2A1P2a3h1	0.939	0.812	0.800	M2D3A2P1a2h3	0.609	0.536	0.511
M1D2A1P3a1h1	0.891	0.930	0.892	M2D3A2P1a3h3	0.629	0.509	0.498
M1D2A1P3a2h1	0.877	0.930	0.847	M2D3A2P2a1h3*	0.535	0.750	0.641
M1D2A1P3a3h1	0.888	0.940	0.771	M2D3A2P2a2h3*	0.596	0.660	0.580
M1D2A1P1a1h2	0.840	0.712	0.627	M2D3A2P2a3h3*	0.606	0.663	0.589
M1D2A1P1a2h2	0.861	0.737	0.657	M2D3A2P3a1h3*	0.534	1.010	0.916
M1D2A1P1a3h2	0.868	0.692	0.630	M2D3A2P3a2h3*	0.560	1.016	0.916
M1D2A1P2a1h2	0.828	0.827	0.687	M2D3A2P3a3h3*	0.569	1.046	0.893
M1D2A1P2a2h2	0.842	0.754	0.650	M2D3A3P1a1h1	0.839	0.814	0.793
M1D2A1P2a3h2	0.855	0.711	0.636	M2D3A3P1a2h1	0.846	0.807	0.790
M1D2A1P3a1h2*	0.804	1.081	0.971	M2D3A3P1a3h1	0.853	0.797	0.785
M1D2A1P3a2h2*	0.776	1.005	0.905	M2D3A3P2a1h1	0.855	0.889	0.853
M1D2A1P3a3h2*	0.798	0.929	0.862	M2D3A3P2a2h1	0.868	0.839	0.821
M1D2A1P1a1h3	0.741	0.541	0.486	M2D3A3P2a3h1	0.871	0.838	0.822
M1D2A1P1a2h3	0.778	0.582	0.528	M2D3A3P3a1h1	0.822	0.911	0.880
M1D2A1P1a3h3	0.788	0.508	0.490	M2D3A3P3a2h1	0.830	0.908	0.884

Table D.6 Critical buckling limit ratios for specimens with two corrosion defects of $d_p/t = d_s/t = 0.30$ - continue

Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}	Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}
M1D2A1P2a1h3*	0.712	0.885	0.707	M2D3A3P3a3h1	0.833	0.869	0.857
M1D2A1P2a2h3*	0.736	0.840	0.673	M2D3A3P1a1h2	0.648	0.631	0.584
M1D2A1P2a3h3*	0.759	0.814	0.660	M2D3A3P1a2h2	0.665	0.616	0.577
M1D2A1P3a1h3*	0.706	1.843	0.986	M2D3A3P1a3h2	0.680	0.596	0.566
M1D2A1P3a2h3*	0.662	1.194	1.035	M2D3A3P2a1h2	0.655	0.812	0.730
M1D2A1P3a3h3*	0.695	0.539	1.066	M2D3A3P2a2h2	0.689	0.718	0.667
M1D2A2P1a1h1	0.913	0.938	0.904	M2D3A3P2a3h2	0.697	0.717	0.670
M1D2A2P1a2h1	0.923	0.941	0.910	M2D3A3P3a1h2	0.584	0.885	0.810
M1D2A2P1a3h1	0.927	0.934	0.904	M2D3A3P3a2h2	0.603	0.882	0.816
M1D2A2P2a1h1	0.909	0.902	0.865	M2D3A3P3a3h2	0.611	0.828	0.769
M1D2A2P2a2h1	0.914	0.900	0.868	M2D3A3P1a1h3	0.509	0.553	0.484
M1D2A2P2a3h1	0.920	0.863	0.843	M2D3A3P1a2h3	0.532	0.534	0.475
M1D2A2P3a1h1*	0.828	0.633	1.153	M2D3A3P1a3h3	0.553	0.509	0.461
M1D2A2P3a2h1*	0.806	0.909	0.890	M2D3A3P2a1h3	0.463	0.728	0.642
M1D2A2P3a3h1*	0.824	1.140	0.706	M2D3A3P2a2h3	0.518	0.644	0.556
M1D2A2P1a1h2	0.760	0.784	0.734	M2D3A3P2a3h3	0.530	0.643	0.560
M1D2A2P1a2h2	0.792	0.799	0.756	M2D3A3P3a1h3*	0.340	0.944	0.837
M1D2A2P1a3h2	0.805	0.762	0.735	M2D3A3P3a2h3*	0.371	0.943	0.843
M1D2A2P2a1h2	0.748	0.828	0.747	M2D3A3P3a3h3*	0.383	0.922	0.804
M1D2A2P2a2h2	0.762	0.824	0.753	M3D1A1P1a1h1	0.952	0.968	0.898
M1D2A2P2a3h2	0.783	0.753	0.703	M3D1A1P1a2h1	0.958	0.960	0.919
M1D2A2P3a1h2*	0.681	1.081	1.030	M3D1A1P1a3h1	0.957	0.970	0.912
M1D2A2P3a2h2*	0.637	1.001	0.954	M3D1A1P2a1h1	0.941	0.899	0.854
M1D2A2P3a3h2*	0.672	0.933	0.900	M3D1A1P2a2h1	0.941	0.875	0.842
M1D2A2P1a1h3	0.626	0.602	0.564	M3D1A1P2a3h1	0.944	0.873	0.846
M1D2A2P1a2h3	0.677	0.631	0.600	M3D1A1P3a1h1	0.935	0.915	0.869
M1D2A2P1a3h3	0.698	0.560	0.565	M3D1A1P3a2h1	0.921	0.863	0.828
M1D2A2P2a1h3*	0.599	0.794	0.683	M3D1A1P3a3h1	0.929	0.851	0.833
M1D2A2P2a2h3*	0.623	0.788	0.690	M3D1A1P1a1h2	0.882	0.688	0.630
M1D2A2P2a3h3*	0.656	0.701	0.626	M3D1A1P1a2h2	0.903	0.787	0.721
M1D2A2P3a1h3*	0.521	1.739	0.828	M3D1A1P1a3h2	0.900	0.733	0.689
M1D2A2P3a2h3*	0.454	1.135	1.059	M3D1A1P2a1h2	0.866	0.788	0.685
M1D2A2P3a3h3*	0.509	0.631	1.220	M3D1A1P2a2h2	0.867	0.729	0.659
M1D2A3P1a1h1	0.886	0.970	0.939	M3D1A1P2a3h2	0.874	0.723	0.666
M1D2A3P1a2h1	0.897	0.972	0.945	M3D1A1P3a1h2	0.868	0.881	0.787
M1D2A3P1a3h1	0.901	0.969	0.939	M3D1A1P3a2h2	0.832	0.804	0.716
M1D2A3P2a1h1	0.878	0.893	0.872	M3D1A1P3a3h2	0.852	0.785	0.723
M1D2A3P2a2h1	0.882	0.894	0.876	M3D1A1P1a1h3	0.789	0.557	0.477
M1D2A3P2a3h1	0.891	0.870	0.859	M3D1A1P1a2h3	0.830	0.663	0.541
M1D2A3P3a1h1	0.595	0.975	0.971	M3D1A1P1a3h3	0.824	0.573	0.530

Table D.6 Critical buckling limit ratios for specimens with two corrosion defects of $d_p/t = d_s/t = 0.30$ - continue

Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}	Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}
M1D2A3P3a2h1	0.552	0.891	0.951	M3D1A1P2a1h3	0.780	0.734	0.586
M1D2A3P3a3h1	0.552	0.891	0.951	M3D1A1P2a2h3	0.784	0.659	0.552
M1D2A3P1a1h2	0.707	0.781	0.719	M3D1A1P2a3h3	0.796	0.652	0.562
M1D2A3P1a2h2	0.738	0.815	0.753	M3D1A1P3a1h3	0.794	0.870	0.742
M1D2A3P1a3h2	0.751	0.766	0.717	M3D1A1P3a2h3	0.735	0.783	0.655
M1D2A3P2a1h2	0.683	0.782	0.720	M3D1A1P3a3h3	0.769	0.762	0.664
M1D2A3P2a2h2	0.695	0.784	0.729	M3D1A2P1a1h1	0.945	0.950	0.903
M1D2A3P2a3h2	0.721	0.728	0.689	M3D1A2P1a2h1	0.952	0.965	0.923
M1D2A3P3a1h2	F	F	F	M3D1A2P1a3h1	0.951	0.961	0.914
M1D2A3P3a2h2	F	F	F	M3D1A2P2a1h1	0.935	0.907	0.869
M1D2A3P3a3h2	F	F	F	M3D1A2P2a2h1	0.936	0.884	0.855
M1D2A3P1a1h3	0.560	0.596	0.543	M3D1A2P2a3h1	0.938	0.882	0.859
M1D2A3P1a2h3	0.609	0.661	0.599	M3D1A2P3a1h1	0.927	0.921	0.883
M1D2A3P1a3h3	0.628	0.567	0.539	M3D1A2P3a2h1	0.911	0.869	0.840
M1D2A3P2a1h3	0.499	0.704	0.615	M3D1A2P3a3h1	0.921	0.858	0.842
M1D2A3P2a2h3	0.518	0.708	0.628	M3D1A2P1a1h2	0.857	0.694	0.644
M1D2A3P2a3h3	0.560	0.630	0.571	M3D1A2P1a2h2	0.881	0.788	0.731
M1D2A3P3a1h3	F	F	F	M3D1A2P1a3h2	0.879	0.732	0.693
M1D2A3P3a2h3	F	F	F	M3D1A2P2a1h2	0.845	0.798	0.711
M1D2A3P3a3h3	F	F	F	M3D1A2P2a2h2	0.847	0.737	0.677
M1D3A1P1a1h1	0.918	0.967	0.928	M3D1A2P2a3h2	0.856	0.734	0.686
M1D3A1P1a2h1	0.921	0.962	0.920	M3D1A2P3a1h2	0.845	0.888	0.811
M1D3A1P1a3h1	0.923	0.960	0.918	M3D1A2P3a2h2	0.802	0.808	0.736
M1D3A1P2a1h1	0.918	0.900	0.950	M3D1A2P3a3h2	0.827	0.791	0.739
M1D3A1P2a2h1	0.928	0.887	0.855	M3D1A2P1a1h3	0.746	0.503	0.450
M1D3A1P2a3h1	0.929	0.795	0.824	M3D1A2P1a2h3	0.792	0.611	0.529
M1D3A1P3a1h1*	0.920	1.069	1.029	M3D1A2P1a3h3	0.789	0.566	0.527
M1D3A1P3a2h1*	0.907	1.066	1.026	M3D1A2P2a1h3	0.742	0.746	0.622
M1D3A1P3a3h1*	0.917	1.011	0.990	M3D1A2P2a2h3	0.746	0.669	0.577
M1D3A1P1a1h2	0.827	0.840	0.804	M3D1A2P2a3h3	0.762	0.664	0.589
M1D3A1P1a2h2	0.835	0.788	0.775	M3D1A2P3a1h3	0.754	0.876	0.773
M1D3A1P1a3h2	0.839	0.773	0.769	M3D1A2P3a2h3	0.682	0.785	0.681
M1D3A1P2a1h2*	0.757	0.999	0.846	M3D1A2P3a3h3	0.724	0.766	0.685
M1D3A1P2a2h2*	0.792	0.919	0.810	M3D1A3P1a1h1	0.938	0.950	0.921
M1D3A1P2a3h2*	0.796	0.859	0.768	M3D1A3P1a2h1	0.946	0.960	0.936
M1D3A1P3a1h2*	0.830	1.290	1.178	M3D1A3P1a3h1	0.945	0.968	0.928
M1D3A1P3a2h2*	0.795	1.279	1.165	M3D1A3P2a1h1	0.927	0.916	0.885
M1D3A1P3a3h2*	0.821	1.088	1.021	M3D1A3P2a2h1	0.928	0.893	0.869
M1D3A1P1a1h3	0.723	0.755	0.716	M3D1A3P2a3h1	0.932	0.891	0.871
M1D3A1P1a2h3	0.736	0.671	0.673	M3D1A3P3a1h1	0.916	0.929	0.899

Table D.6 Critical buckling limit ratios for specimens with two corrosion defects of $d_p/t = d_s/t = 0.30$ - continue

Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}	Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}
M1D3A1P1a3h3	0.745	0.645	0.664	M3D1A3P3a2h1	0.896	0.877	0.853
M1D3A1P2a1h3*	0.623	0.987	0.841	M3D1A3P3a3h1	0.908	0.868	0.854
M1D3A1P2a2h3*	0.680	0.958	0.804	M3D1A3P1a1h2	0.828	0.712	0.668
M1D3A1P2a3h3*	0.686	0.936	0.760	M3D1A3P1a2h2	0.856	0.795	0.746
M1D3A1P3a1h3*	0.729	1.578	1.402	M3D1A3P1a3h2	0.856	0.744	0.708
M1D3A1P3a2h3*	0.671	1.556	1.372	M3D1A3P2a1h2	0.817	0.810	0.739
M1D3A1P3a3h3*	0.714	1.188	1.066	M3D1A3P2a2h2	0.820	0.748	0.697
M1D3A2P1a1h1	0.863	0.916	0.879	M3D1A3P2a3h2	0.831	0.745	0.703
M1D3A2P1a2h1	0.869	0.908	0.876	M3D1A3P3a1h2	0.812	0.898	0.839
M1D3A2P1a3h1	0.871	0.902	0.871	M3D1A3P3a2h2	0.758	0.815	0.758
M1D3A2P2a1h1	0.897	0.928	0.894	M3D1A3P3a3h2	0.790	0.800	0.759
M1D3A2P2a2h1	0.906	0.888	0.875	M3D1A3P1a1h3	0.694	0.527	0.481
M1D3A2P2a3h1	0.909	0.869	0.864	M3D1A3P1a2h3	0.748	0.629	0.572
M1D3A2P3a1h1	0.835	0.971	0.942	M3D1A3P1a3h3	0.746	0.581	0.545
M1D3A2P3a2h1	0.810	0.972	0.951	M3D1A3P2a1h3	0.690	0.760	0.659
M1D3A2P3a3h1	0.829	0.964	0.954	M3D1A3P2a2h3	0.695	0.679	0.603
M1D3A2P1a1h2	0.736	0.769	0.725	M3D1A3P2a3h3	0.715	0.675	0.611
M1D3A2P1a2h2	0.749	0.742	0.718	M3D1A3P3a1h3	0.697	0.883	0.805
M1D3A2P1a3h2	0.754	0.722	0.706	M3D1A3P3a2h3	0.608	0.785	0.705
M1D3A2P2a1h2	0.702	0.893	0.793	M3D1A3P3a3h3	0.661	0.768	0.706
M1D3A2P2a2h2	0.734	0.828	0.752	M3D2A1P1a1h1	0.921	0.787	0.790
M1D3A2P2a3h2	0.742	0.795	0.728	M3D2A1P1a2h1	0.927	0.808	0.807
M1D3A2P3a1h2*	0.681	1.130	1.072	M3D2A1P1a3h1	0.931	0.792	0.794
M1D3A2P3a2h2*	0.631	1.112	1.052	M3D2A1P2a1h1	0.922	0.890	0.845
M1D3A2P3a3h2*	0.670	0.973	0.933	M3D2A1P2a2h1	0.930	0.848	0.830
M1D3A2P1a1h3	0.613	0.657	0.601	M3D2A1P2a3h1	0.931	0.852	0.833
M1D3A2P1a2h3	0.633	0.618	0.591	M3D2A1P3a1h1	0.920	0.925	0.882
M1D3A2P1a3h3	0.641	0.587	0.573	M3D2A1P3a2h1	0.921	0.901	0.869
M1D3A2P2a1h3*	0.549	0.879	0.747	M3D2A1P3a3h1	0.924	0.873	0.858
M1D3A2P2a2h3*	0.598	0.803	0.695	M3D2A1P1a1h2	0.814	0.639	0.612
M1D3A2P2a3h3*	0.611	0.765	0.666	M3D2A1P1a2h2	0.831	0.675	0.646
M1D3A2P3a1h3*	0.510	1.331	1.254	M3D2A1P1a3h2	0.841	0.648	0.622
M1D3A2P3a2h3*	0.452	1.289	1.193	M3D2A1P2a1h2	0.810	0.806	0.700
M1D3A2P3a3h3*	0.492	0.963	0.841	M3D2A1P2a2h2	0.834	0.725	0.668
M1D3A3P1a1h1	0.847	0.935	0.885	M3D2A1P2a3h2	0.836	0.733	0.674
M1D3A3P1a2h1	0.857	0.933	0.886	M3D2A1P3a1h2	0.815	0.893	0.797
M1D3A3P1a3h1	0.861	0.928	0.882	M3D2A1P3a2h2	0.816	0.857	0.774
M1D3A3P2a1h1	0.868	0.903	0.859	M3D2A1P3a3h2	0.825	0.812	0.753
M1D3A3P2a2h1	0.881	0.882	0.842	M3D2A1P1a1h3	0.699	0.433	0.430
M1D3A3P2a3h1	0.883	0.871	0.838	M3D2A1P1a2h3	0.727	0.492	0.481

Table D.6 Critical buckling limit ratios for specimens with two corrosion defects of $d_p/t = d_s/t = 0.30$ - continue

Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}	Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}
M1D3A3P3a1h1	F	F	F	M3D2A1P1a3h3	0.745	0.448	0.444
M1D3A3P3a2h1	F	F	F	M3D2A1P2a1h3	0.687	0.763	0.612
M1D3A3P3a3h1	F	F	F	M3D2A1P2a2h3	0.728	0.663	0.570
M1D3A3P1a1h2	0.693	0.782	0.706	M3D2A1P2a3h3	0.731	0.672	0.577
M1D3A3P1a2h2	0.715	0.772	0.709	M3D2A1P3a1h3*	0.703	0.940	0.802
M1D3A3P1a3h2	0.724	0.750	0.697	M3D2A1P3a2h3*	0.704	0.923	0.780
M1D3A3P2a1h2	0.631	0.841	0.733	M3D2A1P3a3h3*	0.718	0.902	0.760
M1D3A3P2a2h2	0.671	0.802	0.696	M3D2A2P1a1h1	0.905	0.788	0.783
M1D3A3P2a3h2	0.679	0.782	0.690	M3D2A2P1a2h1	0.913	0.805	0.800
M1D3A3P3a1h2	F	F	F	M3D2A2P1a3h1	0.918	0.799	0.801
M1D3A3P3a2h2	F	F	F	M3D2A2P2a1h1	0.911	0.896	0.862
M1D3A3P3a3h2	F	F	F	M3D2A2P2a2h1	0.921	0.855	0.839
M1D3A3P1a1h3	0.534	0.659	0.555	M3D2A2P2a3h1	0.922	0.862	0.847
M1D3A3P1a2h3	0.568	0.643	0.561	M3D2A2P3a1h1	0.906	0.924	0.890
M1D3A3P1a3h3	0.582	0.608	0.542	M3D2A2P3a2h1	0.907	0.906	0.882
M1D3A3P2a1h3	0.427	0.799	0.656	M3D2A2P3a3h1	0.910	0.874	0.863
M1D3A3P2a2h3	0.490	0.748	0.608	M3D2A2P1a1h2	0.775	0.645	0.616
M1D3A3P2a3h3	0.502	0.722	0.600	M3D2A2P1a2h2	0.796	0.673	0.647
M1D3A3P3a1h3	F	F	F	M3D2A2P1a3h2	0.809	0.664	0.648
M1D3A3P3a2h3	F	F	F	M3D2A2P2a1h2	0.771	0.807	0.720
M1D3A3P3a3h3	F	F	F	M3D2A2P2a2h2	0.801	0.724	0.669
M2D1A1P1a1h1	0.953	0.947	0.883	M3D2A2P2a3h2	0.804	0.738	0.685
M2D1A1P1a2h1	0.958	0.955	0.903	M3D2A2P3a1h2	0.773	0.891	0.815
M2D1A1P1a3h1	0.957	0.952	0.900	M3D2A2P3a2h2	0.775	0.863	0.800
M2D1A1P2a1h1	0.931	0.850	0.801	M3D2A2P3a3h2	0.785	0.813	0.767
M2D1A1P2a2h1	0.928	0.820	0.784	M3D2A2P1a1h3	0.631	0.448	0.431
M2D1A1P2a3h1	0.933	0.818	0.791	M3D2A2P1a2h3	0.667	0.493	0.478
M2D1A1P3a1h1	0.916	0.921	0.859	M3D2A2P1a3h3	0.689	0.478	0.479
M2D1A1P3a2h1	0.894	0.815	0.773	M3D2A2P2a1h3	0.623	0.766	0.652
M2D1A1P3a3h1	0.900	0.806	0.777	M3D2A2P2a2h3	0.674	0.663	0.588
M2D1A1P1a1h2	0.888	0.663	0.604	M3D2A2P2a3h3	0.679	0.681	0.608
M2D1A1P1a2h2	0.907	0.740	0.683	M3D2A2P3a1h3*	0.630	0.919	0.807
M2D1A1P1a3h2	0.904	0.716	0.670	M3D2A2P3a2h3*	0.633	0.899	0.791
M2D1A1P2a1h2	0.862	0.742	0.644	M3D2A2P3a3h3*	0.651	0.865	0.755
M2D1A1P2a2h2	0.854	0.687	0.612	M3D2A3P1a1h1	0.888	0.802	0.796
M2D1A1P2a3h2	0.866	0.682	0.626	M3D2A3P1a2h1	0.896	0.817	0.811
M2D1A1P3a1h2	0.846	0.826	0.744	M3D2A3P1a3h1	0.902	0.811	0.810
M2D1A1P3a2h2	0.800	0.754	0.671	M3D2A3P2a1h1	0.896	0.895	0.867
M2D1A1P3a3h2	0.813	0.742	0.676	M3D2A3P2a2h1	0.908	0.861	0.848
M2D1A1P1a1h3	0.804	0.554	0.457	M3D2A3P2a3h1	0.909	0.867	0.854

Table D.6 Critical buckling limit ratios for specimens with two corrosion defects of $d_p/t = d_s/t = 0.30$ - continue

Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}	Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}
M2D1A1P1a2h3	0.840	0.657	0.567	M3D2A3P3a1h1	0.869	0.912	0.889
M2D1A1P1a3h3	0.834	0.625	0.550	M3D2A3P3a2h1	0.870	0.896	0.879
M2D1A1P2a1h3	0.784	0.690	0.554	M3D2A3P3a3h1	0.875	0.874	0.866
M2D1A1P2a2h3	0.772	0.623	0.513	M3D2A3P1a1h2	0.729	0.664	0.634
M2D1A1P2a3h3	0.792	0.617	0.530	M3D2A3P1a2h2	0.752	0.689	0.663
M2D1A1P3a1h3*	0.772	0.907	0.786	M3D2A3P1a3h2	0.769	0.679	0.661
M2D1A1P3a2h3*	0.701	0.774	0.648	M3D2A3P2a1h2	0.722	0.805	0.736
M2D1A1P3a3h3*	0.721	0.763	0.654	M3D2A3P2a2h2	0.758	0.734	0.695
M2D1A2P1a1h1	0.943	0.926	0.879	M3D2A3P2a3h2	0.762	0.747	0.708
M2D1A2P1a2h1	0.950	0.942	0.903	M3D2A3P3a1h2	0.702	0.854	0.792
M2D1A2P1a3h1	0.950	0.934	0.894	M3D2A3P3a2h2	0.704	0.825	0.771
M2D1A2P2a1h1	0.921	0.861	0.821	M3D2A3P3a3h2	0.717	0.785	0.743
M2D1A2P2a2h1	0.918	0.831	0.800	M3D2A3P1a1h3	0.564	0.464	0.435
M2D1A2P2a3h1	0.924	0.830	0.807	M3D2A3P1a2h3	0.603	0.506	0.481
M2D1A2P3a1h1	0.900	0.930	0.883	M3D2A3P1a3h3	0.630	0.489	0.478
M2D1A2P3a2h1	0.873	0.824	0.791	M3D2A3P2a1h3	0.544	0.741	0.632
M2D1A2P3a3h1	0.881	0.816	0.792	M3D2A3P2a2h3	0.606	0.646	0.573
M2D1A2P1a1h2	0.859	0.665	0.615	M3D2A3P2a3h3	0.612	0.663	0.591
M2D1A2P1a2h2	0.882	0.754	0.700	M3D2A3P3a1h3*	0.532	0.855	0.763
M2D1A2P1a3h2	0.880	0.709	0.670	M3D2A3P3a2h3*	0.534	0.827	0.739
M2D1A2P2a1h2	0.836	0.755	0.675	M3D2A3P3a3h3*	0.556	0.787	0.707
M2D1A2P2a2h2	0.827	0.697	0.635	M3D3A1P1a1h1	0.889	0.782	0.775
M2D1A2P2a3h2	0.842	0.695	0.647	M3D3A1P1a2h1	0.889	0.749	0.756
M2D1A2P3a1h2	0.810	0.864	0.744	M3D3A1P1a3h1	0.893	0.746	0.757
M2D1A2P3a2h2	0.752	0.758	0.695	M3D3A1P2a1h1	0.895	0.871	0.841
M2D1A2P3a3h2	0.768	0.747	0.696	M3D3A1P2a2h1	0.907	0.838	0.832
M2D1A2P1a1h3	0.756	0.513	0.448	M3D3A1P2a3h1	0.909	0.834	0.834
M2D1A2P1a2h3	0.798	0.645	0.573	M3D3A1P3a1h1	0.902	0.945	0.885
M2D1A2P1a3h3	0.795	0.578	0.528	M3D3A1P3a2h1	0.910	0.865	0.847
M2D1A2P2a1h3	0.740	0.705	0.594	M3D3A1P3a3h1	0.911	0.875	0.858
M2D1A2P2a2h3	0.724	0.634	0.543	M3D3A1P1a1h2	0.768	0.624	0.607
M2D1A2P2a3h3	0.750	0.631	0.559	M3D3A1P1a2h2	0.768	0.565	0.572
M2D1A2P3a1h3*	0.713	0.913	0.825	M3D3A1P1a3h2	0.777	0.560	0.575
M2D1A2P3a2h3*	0.623	0.773	0.679	M3D3A1P2a1h2	0.761	0.800	0.714
M2D1A2P3a3h3*	0.648	0.763	0.680	M3D3A1P2a2h2	0.792	0.746	0.696
M2D1A3P1a1h1	0.934	0.945	0.907	M3D3A1P2a3h2	0.796	0.740	0.699
M2D1A3P1a2h1	0.942	0.952	0.921	M3D3A1P3a1h2	0.771	0.937	0.829
M2D1A3P1a3h1	0.942	0.949	0.917	M3D3A1P3a2h2	0.790	0.841	0.770
M2D1A3P2a1h1	0.908	0.871	0.840	M3D3A1P3a3h2	0.795	0.852	0.787
M2D1A3P2a2h1	0.903	0.840	0.815	M3D3A1P1a1h3	0.667	0.557	0.526

Table D.6 Critical buckling limit ratios for specimens with two corrosion defects of $d_p/t = d_s/t = 0.30$ - continue

Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}	Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}
M2D1A3P2a3h1	0.911	0.839	0.819	M3D3A1P1a2h3	0.668	0.486	0.484
M2D1A3P3a1h1	0.874	0.934	0.902	M3D3A1P1a3h3	0.681	0.481	0.488
M2D1A3P3a2h1	0.839	0.832	0.807	M3D3A1P2a1h3	0.620	0.771	0.645
M2D1A3P3a3h1	0.849	0.823	0.804	M3D3A1P2a2h3	0.671	0.708	0.622
M2D1A3P1a1h2	0.824	0.690	0.646	M3D3A1P2a3h3	0.678	0.702	0.626
M2D1A3P1a2h2	0.853	0.752	0.710	M3D3A1P3a1h3*	0.637	0.971	0.858
M2D1A3P1a3h2	0.852	0.726	0.691	M3D3A1P3a2h3*	0.669	0.952	0.809
M2D1A3P2a1h2	0.798	0.769	0.708	M3D3A1P3a3h3*	0.676	0.954	0.824
M2D1A3P2a2h2	0.786	0.709	0.660	M3D3A2P1a1h1	0.877	0.802	0.796
M2D1A3P2a3h2	0.807	0.707	0.667	M3D3A2P1a2h1	0.878	0.771	0.777
M2D1A3P3a1h2	0.749	0.914	0.863	M3D3A2P1a3h1	0.882	0.769	0.778
M2D1A3P3a2h2	0.671	0.768	0.722	M3D3A2P2a1h1	0.893	0.961	0.975
M2D1A3P3a3h2	0.694	0.755	0.717	M3D3A2P2a2h1	0.890	0.754	0.760
M2D1A3P1a1h3	0.693	0.573	0.511	M3D3A2P2a3h1	0.892	0.749	0.760
M2D1A3P1a2h3	0.745	0.661	0.601	M3D3A2P3a1h1	0.880	0.929	0.885
M2D1A3P1a3h3	0.743	0.623	0.575	M3D3A2P3a2h1	0.889	0.863	0.843
M2D1A3P2a1h3	0.672	0.726	0.641	M3D3A2P3a3h1	0.890	0.870	0.853
M2D1A3P2a2h3	0.651	0.653	0.582	M3D3A2P1a1h2	0.724	0.640	0.622
M2D1A3P2a3h3	0.686	0.651	0.592	M3D3A2P1a2h2	0.726	0.582	0.584
M2D1A3P3a1h3*	0.616	0.874	0.814	M3D3A2P1a3h2	0.738	0.577	0.586
M2D1A3P3a2h3*	0.493	0.769	0.706	M3D3A2P2a1h2	0.755	0.704	0.742
M2D1A3P3a3h3*	0.529	0.757	0.701	M3D3A2P2a2h2	0.746	0.669	0.639
M2D2A1P1a1h1	0.927	0.852	0.821	M3D3A2P2a3h2	0.751	0.662	0.639
M2D2A1P1a2h1	0.934	0.868	0.840	M3D3A2P3a1h2	0.716	0.911	0.823
M2D2A1P1a3h1	0.937	0.861	0.837	M3D3A2P3a2h2	0.741	0.821	0.755
M2D2A1P2a1h1	0.926	0.887	0.843	M3D3A2P3a3h2	0.744	0.830	0.772
M2D2A1P2a2h1	0.933	0.849	0.829	M3D3A2P1a1h3	0.600	0.573	0.538
M2D2A1P2a3h1	0.933	0.853	0.833	M3D3A2P1a2h3	0.604	0.504	0.492
M2D2A1P3a1h1	0.905	0.867	0.838	M3D3A2P1a3h3	0.621	0.498	0.494
M2D2A1P3a2h1	0.896	0.891	0.849	M3D3A2P2a1h3*	0.621	1.151	0.970
M2D2A1P3a3h1	0.904	0.779	0.809	M3D3A2P2a2h3*	0.607	0.606	0.549
M2D2A1P1a1h2	0.826	0.641	0.594	M3D3A2P2a3h3*	0.614	0.598	0.549
M2D2A1P1a2h2	0.846	0.684	0.640	M3D3A2P3a1h3*	0.550	0.931	0.824
M2D2A1P1a3h2	0.855	0.666	0.633	M3D3A2P3a2h3*	0.590	0.866	0.756
M2D2A1P2a1h2	0.820	0.789	0.682	M3D3A2P3a3h3*	0.595	0.873	0.773
M2D2A1P2a2h2	0.841	0.711	0.652	M3D3A3P1a1h1	0.847	0.804	0.788
M2D2A1P2a3h2	0.842	0.719	0.660	M3D3A3P1a2h1	0.850	0.777	0.769
M2D2A1P3a1h2	0.815	0.893	0.798	M3D3A3P1a3h1	0.854	0.773	0.769
M2D2A1P3a2h2	0.796	0.911	0.812	M3D3A3P2a1h1	0.854	0.868	0.838
M2D2A1P3a3h2	0.813	0.825	0.761	M3D3A3P2a2h1	0.869	0.843	0.823

Table D.6 Critical buckling limit ratios for specimens with two corrosion defects of $d_p/t = d_s/t = 0.30$ - continue

Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}	Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}
M2D2A1P1a1h3	0.712	0.481	0.430	M3D3A3P2a3h1	0.872	0.841	0.829
M2D2A1P1a2h3	0.746	0.544	0.496	M3D3A3P3a1h1	0.859	0.910	0.870
M2D2A1P1a3h3	0.762	0.517	0.486	M3D3A3P3a2h1	0.871	0.868	0.848
M2D2A1P2a1h3	0.705	0.741	0.588	M3D3A3P3a3h1	0.872	0.871	0.854
M2D2A1P2a2h3	0.740	0.643	0.548	M3D3A3P1a1h2	0.666	0.641	0.603
M2D2A1P2a3h3	0.741	0.653	0.559	M3D3A3P1a2h2	0.672	0.588	0.567
M2D2A1P3a1h3*	0.718	1.021	0.842	M3D3A3P1a3h2	0.684	0.581	0.566
M2D2A1P3a2h3*	0.688	1.012	0.853	M3D3A3P2a1h2	0.661	0.780	0.698
M2D2A1P3a3h3*	0.714	1.052	0.814	M3D3A3P2a2h2	0.699	0.735	0.669
M2D2A2P1a1h1	0.914	0.867	0.836	M3D3A3P2a3h2	0.707	0.730	0.681
M2D2A2P1a2h1	0.923	0.882	0.853	M3D3A3P3a1h2	0.651	0.874	0.785
M2D2A2P1a3h1	0.927	0.876	0.852	M3D3A3P3a2h2	0.684	0.809	0.745
M2D2A2P2a1h1	0.913	0.891	0.852	M3D3A3P3a3h2	0.686	0.815	0.756
M2D2A2P2a2h1	0.922	0.852	0.831	M3D3A3P1a1h3	0.528	0.573	0.508
M2D2A2P2a3h1	0.922	0.854	0.832	M3D3A3P1a2h3	0.536	0.509	0.463
M2D2A2P3a1h1	0.881	0.877	0.857	M3D3A3P1a3h3	0.552	0.500	0.462
M2D2A2P3a2h1	0.869	0.895	0.865	M3D3A3P2a1h3	0.483	0.723	0.612
M2D2A2P3a3h1	0.880	0.788	0.814	M3D3A3P2a2h3	0.543	0.666	0.574
M2D2A2P1a1h2	0.783	0.659	0.614	M3D3A3P2a3h3	0.555	0.660	0.589
M2D2A2P1a2h2	0.810	0.702	0.659	M3D3A3P3a1h3*	0.444	0.871	0.744
M2D2A2P1a3h2	0.822	0.687	0.656	M3D3A3P3a2h3*	0.497	0.804	0.695
M2D2A2P2a1h2	0.775	0.799	0.713	M3D3A3P3a3h3*	0.500	0.810	0.708
M2D2A2P2a2h2	0.803	0.720	0.669				

Table D.7 Critical buckling limit ratios for specimens with two corrosion defects of $d_p/t = d_s/t = 0.40$

Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}	Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}
M1D1A1P1a1h1	0.945	0.905	0.808	M2D2A2P2a3h2	0.739	0.697	0.632
M1D1A1P1a2h1	0.952	0.926	0.845	M2D2A2P3a1h2*	0.682	0.970	0.878
M1D1A1P1a3h1	0.951	0.910	0.831	M2D2A2P3a2h2*	0.656	1.035	0.931
M1D1A1P2a1h1	0.916	0.778	0.715	M2D2A2P3a3h2*	0.685	0.887	0.818
M1D1A1P2a2h1	0.903	0.726	0.674	M2D2A2P1a1h3	0.538	0.454	0.422
M1D1A1P2a3h1	0.911	0.710	0.680	M2D2A2P1a2h3	0.575	0.453	0.419
M1D1A1P3a1h1	0.839	0.796	0.733	M2D2A2P1a3h3	0.605	0.417	0.417
M1D1A1P3a2h1	0.834	0.790	0.732	M2D2A2P2a1h3*	0.522	0.839	0.701
M1D1A1P3a3h1	0.822	0.777	0.674	M2D2A2P2a2h3*	0.566	0.740	0.623
M1D1A1P1a1h2	0.875	0.630	0.518	M2D2A2P2a3h3*	0.576	0.740	0.627
M1D1A1P1a2h2	0.895	0.730	0.617	M2D2A2P3a1h3*	0.531	0.940	1.107
M1D1A1P1a3h2	0.893	0.656	0.580	M2D2A2P3a2h3*	0.493	1.192	1.041

Table D.7 Critical buckling limit ratios for specimens with two corrosion defects of $d_p/t = d_s/t = 0.40$ - continue

Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}	Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}
M1D1A1P2a1h2	0.841	0.692	0.576	M2D2A2P3a3h3*	0.536	0.625	1.181
M1D1A1P2a2h2	0.812	0.619	0.513	M2D2A3P1a1h1	0.866	0.839	0.819
M1D1A1P2a3h2	0.829	0.596	0.522	M2D2A3P1a2h1	0.874	0.843	0.822
M1D1A1P3a1h2*	0.729	0.909	0.789	M2D2A3P1a3h1	0.881	0.834	0.818
M1D1A1P3a2h2*	0.720	0.907	0.788	M2D2A3P2a1h1	0.848	0.867	0.830
M1D1A1P3a3h2*	0.699	0.842	0.743	M2D2A3P2a2h1	0.860	0.815	0.794
M1D1A1P1a1h3	0.771	0.565	0.433	M2D2A3P2a3h1	0.862	0.817	0.796
M1D1A1P1a2h3	0.811	0.612	0.471	M2D2A3P3a1h1	0.756	0.860	0.728
M1D1A1P1a3h3	0.806	0.504	0.419	M2D2A3P3a2h1	0.736	0.871	0.837
M1D1A1P2a1h3	0.758	0.662	0.516	M2D2A3P3a3h1	0.756	0.854	0.733
M1D1A1P2a2h3	0.711	0.580	0.444	M2D2A3P1a1h2	0.648	0.624	0.578
M1D1A1P2a3h3	0.739	0.554	0.455	M2D2A3P1a2h2	0.671	0.636	0.586
M1D1A1P3a1h3*	0.612	1.090	0.920	M2D2A3P1a3h2	0.691	0.612	0.575
M1D1A1P3a2h3*	0.599	1.093	0.920	M2D2A3P2a1h2	0.627	0.771	0.696
M1D1A1P3a3h3*	0.569	1.193	0.906	M2D2A3P2a2h2	0.657	0.676	0.627
M1D1A2P1a1h1	0.929	0.815	0.772	M2D2A3P2a3h2	0.663	0.678	0.630
M1D1A2P1a2h1	0.938	0.775	0.754	M2D2A3P3a1h2*	0.558	0.910	0.843
M1D1A2P1a3h1	0.938	0.814	0.785	M2D2A3P3a2h2*	0.520	0.974	0.902
M1D1A2P2a1h1	0.901	0.793	0.745	M2D2A3P3a3h2*	0.559	0.843	0.791
M1D1A2P2a2h1	0.883	0.741	0.701	M2D2A3P1a1h3	0.449	0.425	0.387
M1D1A2P2a3h1	0.894	0.718	0.695	M2D2A3P1a2h3	0.487	0.444	0.399
M1D1A2P3a1h1	0.777	0.808	0.765	M2D2A3P1a3h3	0.519	0.406	0.382
M1D1A2P3a2h1	0.771	0.799	0.762	M2D2A3P2a1h3	0.416	0.744	0.635
M1D1A2P3a3h1	0.754	0.766	0.656	M2D2A3P2a2h3	0.464	0.636	0.551
M1D1A2P1a1h2	0.832	0.650	0.579	M2D2A3P2a3h3	0.474	0.638	0.555
M1D1A2P1a2h2	0.858	0.595	0.546	M2D2A3P3a1h3*	0.346	2.240	0.978
M1D1A2P1a3h2	0.859	0.670	0.605	M2D2A3P3a2h3*	0.289	1.081	0.979
M1D1A2P2a1h2	0.799	0.723	0.634	M2D2A3P3a3h3*	0.347	3.458	0.978
M1D1A2P2a2h2	0.759	0.652	0.570	M2D3A1P1a1h1	0.888	0.439	0.382
M1D1A2P2a3h2	0.784	0.619	0.561	M2D3A1P1a2h1	0.883	0.460	0.438
M1D1A2P3a1h2*	0.607	0.922	0.849	M2D3A1P1a3h1	0.893	0.394	0.363
M1D1A2P3a2h2*	0.596	0.919	0.847	M2D3A1P2a1h1	0.877	0.953	0.831
M1D1A2P3a3h2*	0.564	0.844	0.782	M2D3A1P2a2h1	0.888	0.793	0.760
M1D1A2P1a1h3	0.694	0.610	0.574	M2D3A1P2a3h1	0.891	0.781	0.757
M1D1A2P1a2h3	0.744	0.540	0.541	M2D3A1P3a1h1	0.852	0.941	0.753
M1D1A2P1a3h3	0.746	0.630	0.601	M2D3A1P3a2h1	0.859	0.931	0.872
M1D1A2P2a1h3*	0.676	0.745	0.631	M2D3A1P3a3h1	0.864	0.939	0.791
M1D1A2P2a2h3*	0.609	0.680	0.565	M2D3A1P1a1h2	0.720	0.537	0.510
M1D1A2P2a3h3*	0.651	0.650	0.557	M2D3A1P1a2h2	0.707	0.528	0.579
M1D1A2P3a1h3*	0.427	1.087	0.989	M2D3A1P1a3h2	0.733	0.482	0.484

Table D.7 Critical buckling limit ratios for specimens with two corrosion defects of $d_p/t = d_s/t = 0.40$ - continue

Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}	Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}
M1D1A2P3a2h3*	0.410	1.093	0.989	M2D3A1P2a1h2*	0.716	0.950	0.767
M1D1A2P3a3h3*	0.362	1.233	0.994	M2D3A1P2a2h2*	0.745	0.776	0.665
M1D1A3P1a1h1	0.907	0.861	0.827	M2D3A1P2a3h2*	0.751	0.763	0.661
M1D1A3P1a2h1	0.920	0.795	0.779	M2D3A1P3a1h2*	0.729	1.069	0.924
M1D1A3P1a3h1	0.922	0.843	0.820	M2D3A1P3a2h2*	0.743	1.093	0.954
M1D1A3P2a1h1	0.866	0.821	0.788	M2D3A1P3a3h2*	0.752	0.959	0.861
M1D1A3P2a2h1	0.842	0.765	0.737	M2D3A1P1a1h3	0.622	0.229	0.203
M1D1A3P2a3h1	0.859	0.750	0.730	M2D3A1P1a2h3	0.604	0.204	0.201
M1D1A3P3a1h1	0.647	0.880	0.968	M2D3A1P1a3h3	0.640	0.205	0.192
M1D1A3P3a2h1	0.590	0.806	0.825	M2D3A1P2a1h3*	0.563	1.013	0.936
M1D1A3P3a3h1	0.590	0.806	0.825	M2D3A1P2a2h3*	0.608	1.211	0.916
M1D1A3P1a1h2	0.756	0.720	0.692	M2D3A1P2a3h3*	0.617	1.226	0.915
M1D1A3P1a2h2	0.794	0.636	0.600	M2D3A1P3a1h3*	0.598	1.299	1.326
M1D1A3P1a3h2	0.803	0.725	0.677	M2D3A1P3a2h3*	0.619	1.383	1.144
M1D1A3P2a1h2	0.708	0.752	0.698	M2D3A1P3a3h3*	0.632	0.906	1.724
M1D1A3P2a2h2	0.652	0.672	0.622	M2D3A2P1a1h1	0.863	0.884	0.846
M1D1A3P2a3h2	0.691	0.650	0.612	M2D3A2P1a2h1	0.854	0.779	0.763
M1D1A3P3a1h2	0.305	0.898	0.903	M2D3A2P1a3h1	0.858	0.771	0.760
M1D1A3P3a2h2	F	F	F	M2D3A2P2a1h1	0.845	0.905	0.836
M1D1A3P3a3h2	F	F	F	M2D3A2P2a2h1	0.859	0.799	0.774
M1D1A3P1a1h3	0.564	0.674	0.589	M2D3A2P2a3h1	0.862	0.792	0.773
M1D1A3P1a2h3	0.635	0.618	0.519	M2D3A2P3a1h1	0.799	0.955	0.808
M1D1A3P1a3h3	0.651	0.628	0.569	M2D3A2P3a2h1	0.807	0.930	0.895
M1D1A3P2a1h3	0.547	0.664	0.620	M2D3A2P3a3h1	0.814	0.817	0.800
M1D1A3P2a2h3	0.459	0.584	0.523	M2D3A2P1a1h2	0.664	0.534	0.485
M1D1A3P2a3h3	0.521	0.555	0.510	M2D3A2P1a2h2	0.639	0.510	0.500
M1D1A3P3a1h3	F	F	F	M2D3A2P1a3h2	0.653	0.492	0.493
M1D1A3P3a2h3	F	F	F	M2D3A2P2a1h2*	0.632	0.879	0.756
M1D1A3P3a3h3	F	F	F	M2D3A2P2a2h2*	0.666	0.738	0.659
M1D2A1P1a1h1	0.918	0.808	0.750	M2D3A2P2a3h2*	0.675	0.728	0.657
M1D2A1P1a2h1	0.925	0.801	0.750	M2D3A2P3a1h2*	0.630	1.020	0.928
M1D2A1P1a3h1	0.928	0.772	0.732	M2D3A2P3a2h2*	0.646	1.059	0.971
M1D2A1P2a1h1	0.900	0.864	0.759	M2D3A2P3a3h2*	0.658	0.931	0.868
M1D2A1P2a2h1	0.905	0.807	0.743	M2D3A2P1a1h3	0.550	0.410	0.423
M1D2A1P2a3h1	0.911	0.643	0.684	M2D3A2P1a2h3	0.517	0.413	0.400
M1D2A1P3a1h1	0.839	0.907	0.804	M2D3A2P1a3h3	0.535	0.392	0.391
M1D2A1P3a2h1	0.830	0.913	0.846	M2D3A2P2a1h3*	0.451	0.964	0.837
M1D2A1P3a3h1	0.840	0.938	0.965	M2D3A2P2a2h3*	0.503	0.940	0.776
M1D2A1P1a1h2	0.802	0.687	0.602	M2D3A2P2a3h3*	0.517	0.939	0.775
M1D2A1P1a2h2	0.822	0.676	0.602	M2D3A2P3a1h3*	0.454	1.123	1.754

Table D.7 Critical buckling limit ratios for specimens with two corrosion defects of $d_p/t = d_s/t = 0.40$ - continue

Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}	Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}
M1D2A1P1a3h2	0.828	0.626	0.571	M2D3A2P3a2h3*	0.477	1.269	1.120
M1D2A1P2a1h2*	0.777	0.895	0.715	M2D3A2P3a3h3*	0.497	0.803	2.635
M1D2A1P2a2h2*	0.788	0.853	0.696	M2D3A3P1a1h1	0.809	0.795	0.766
M1D2A1P2a3h2*	0.805	0.733	0.625	M2D3A3P1a2h1	0.811	0.779	0.755
M1D2A1P3a1h2*	0.736	1.180	1.033	M2D3A3P1a3h1	0.816	0.771	0.750
M1D2A1P3a2h2*	0.721	1.164	1.021	M2D3A3P2a1h1	0.808	0.864	0.819
M1D2A1P3a3h2*	0.737	1.096	0.985	M2D3A3P2a2h1	0.826	0.799	0.778
M1D2A1P1a1h3	0.659	0.477	0.434	M2D3A3P2a3h1	0.828	0.795	0.774
M1D2A1P1a2h3	0.696	0.458	0.434	M2D3A3P3a1h1*	0.728	1.049	0.746
M1D2A1P1a3h3	0.707	0.372	0.390	M2D3A3P3a2h1*	0.736	0.914	0.871
M1D2A1P2a1h3*	0.650	1.067	0.855	M2D3A3P3a3h1*	0.745	1.217	0.664
M1D2A1P2a2h3*	0.668	1.109	0.846	M2D3A3P1a1h2	0.566	0.548	0.492
M1D2A1P2a3h3*	0.696	1.231	0.813	M2D3A3P1a2h2	0.571	0.512	0.467
M1D2A1P3a1h3*	0.614	1.491	1.317	M2D3A3P1a3h2	0.584	0.493	0.457
M1D2A1P3a2h3*	0.590	1.450	1.236	M2D3A3P2a1h2	0.556	0.798	0.691
M1D2A1P3a3h3*	0.615	1.277	1.009	M2D3A3P2a2h2	0.599	0.695	0.619
M1D2A2P1a1h1	0.884	0.840	0.816	M2D3A3P2a3h2	0.606	0.689	0.612
M1D2A2P1a2h1	0.895	0.859	0.836	M2D3A3P3a1h2*	0.478	0.952	0.858
M1D2A2P1a3h1	0.899	0.805	0.792	M2D3A3P3a2h2*	0.495	1.007	0.923
M1D2A2P2a1h1	0.857	0.801	0.765	M2D3A3P3a3h2*	0.513	0.884	0.814
M1D2A2P2a2h1	0.862	0.829	0.786	M2D3A3P1a1h3	0.410	0.459	0.382
M1D2A2P2a3h1	0.872	0.647	0.697	M2D3A3P1a2h3	0.417	0.416	0.351
M1D2A2P3a1h1*	0.740	0.940	0.906	M2D3A3P1a3h3	0.435	0.392	0.339
M1D2A2P3a2h1*	0.725	0.941	0.908	M2D3A3P2a1h3	0.328	0.789	0.643
M1D2A2P3a3h1*	0.741	0.960	0.954	M2D3A3P2a2h3	0.394	0.682	0.559
M1D2A2P1a1h2	0.705	0.739	0.687	M2D3A3P2a3h3	0.404	0.676	0.551
M1D2A2P1a2h2	0.737	0.771	0.723	M2D3A3P3a1h3*	0.209	0.777	1.144
M1D2A2P1a3h2	0.747	0.679	0.646	M2D3A3P3a2h3*	0.235	1.175	1.057
M1D2A2P2a1h2*	0.676	0.852	0.749	M2D3A3P3a3h3*	0.262	0.281	1.203
M1D2A2P2a2h2*	0.686	0.872	0.771	M3D1A1P1a1h1	0.939	0.922	0.854
M1D2A2P2a3h2*	0.711	0.742	0.676	M3D1A1P1a2h1	0.946	0.934	0.874
M1D2A2P3a1h2*	0.571	1.159	1.090	M3D1A1P1a3h1	0.946	0.924	0.864
M1D2A2P3a2h2*	0.546	1.156	1.087	M3D1A1P2a1h1	0.923	0.871	0.807
M1D2A2P3a3h2*	0.573	1.071	1.019	M3D1A1P2a2h1	0.921	0.822	0.778
M1D2A2P1a1h3	0.525	0.429	0.407	M3D1A1P2a3h1	0.927	0.812	0.781
M1D2A2P1a2h3	0.576	0.429	0.419	M3D1A1P3a1h1	0.910	0.870	0.807
M1D2A2P1a3h3	0.595	0.447	0.415	M3D1A1P3a2h1	0.891	0.826	0.772
M1D2A2P2a1h3*	0.521	0.889	0.749	M3D1A1P3a3h1	0.898	0.756	0.749
M1D2A2P2a2h3*	0.537	0.903	0.771	M3D1A1P1a1h2	0.851	0.679	0.602
M1D2A2P2a3h3*	0.574	0.811	0.677	M3D1A1P1a2h2	0.873	0.741	0.663

Table D.7 Critical buckling limit ratios for specimens with two corrosion defects of $d_p/t = d_s/t = 0.40$ - continue

Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}	Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}
M1D2A2P3a1h3*	0.376	1.372	1.272	M3D1A1P1a3h2	0.872	0.688	0.634
M1D2A2P3a2h3*	0.339	1.366	1.264	M3D1A1P2a1h2	0.830	0.780	0.653
M1D2A2P3a3h3*	0.379	1.180	1.083	M3D1A1P2a2h2	0.826	0.690	0.598
M1D2A3P1a1h1	0.846	0.960	0.925	M3D1A1P2a3h2	0.839	0.672	0.603
M1D2A3P1a2h1	0.863	0.960	0.935	M3D1A1P3a1h2	0.825	0.874	0.754
M1D2A3P1a3h1	0.867	0.960	0.927	M3D1A1P3a2h2	0.782	0.831	0.708
M1D2A3P2a1h1	0.816	0.799	0.775	M3D1A1P3a3h2	0.799	0.764	0.678
M1D2A3P2a2h1	0.819	0.821	0.796	M3D1A1P1a1h3	0.717	0.396	0.346
M1D2A3P2a3h1	0.832	0.748	0.747	M3D1A1P1a2h3	0.763	0.416	0.348
M1D2A3P3a1h1*	0.383	0.919	0.981	M3D1A1P1a3h3	0.760	0.415	0.399
M1D2A3P3a2h1*	0.383	0.919	0.981	M3D1A1P2a1h3	0.723	0.742	0.573
M1D2A3P3a3h1*	0.383	0.919	0.981	M3D1A1P2a2h3	0.715	0.635	0.505
M1D2A3P1a1h2	0.640	0.702	0.642	M3D1A1P2a3h3	0.738	0.615	0.512
M1D2A3P1a2h2	0.684	0.765	0.704	M3D1A1P3a1h3*	0.733	0.920	0.760
M1D2A3P1a3h2	0.693	0.698	0.654	M3D1A1P3a2h3*	0.665	0.896	0.715
M1D2A3P2a1h2	0.591	0.746	0.666	M3D1A1P3a3h3*	0.692	0.859	0.686
M1D2A3P2a2h2	0.598	0.774	0.697	M3D1A2P1a1h1	0.929	0.920	0.865
M1D2A3P2a3h2	0.629	0.679	0.623	M3D1A2P1a2h1	0.937	0.930	0.882
M1D2A3P3a1h2	F	F	F	M3D1A2P1a3h1	0.937	0.920	0.871
M1D2A3P3a2h2	F	F	F	M3D1A2P2a1h1	0.914	0.879	0.826
M1D2A3P3a3h2	F	F	F	M3D1A2P2a2h1	0.912	0.831	0.793
M1D2A3P1a1h3	F	F	F	M3D1A2P2a3h1	0.918	0.822	0.794
M1D2A3P1a2h3	F	F	F	M3D1A2P3a1h1	0.897	0.878	0.825
M1D2A3P1a3h3	F	F	F	M3D1A2P3a2h1	0.874	0.831	0.786
M1D2A3P2a1h3*	0.391	0.681	0.578	M3D1A2P3a3h1	0.883	0.765	0.757
M1D2A3P2a2h3*	0.401	0.718	0.619	M3D1A2P1a1h2	0.820	0.688	0.619
M1D2A3P2a3h3*	0.449	0.596	0.524	M3D1A2P1a2h2	0.846	0.738	0.672
M1D2A3P3a1h3	F	F	F	M3D1A2P1a3h2	0.846	0.689	0.640
M1D2A3P3a2h3	F	F	F	M3D1A2P2a1h2	0.803	0.789	0.683
M1D2A3P3a3h3	F	F	F	M3D1A2P2a2h2	0.798	0.699	0.620
M1D3A1P1a1h1	0.907	0.967	0.927	M3D1A2P2a3h2	0.815	0.682	0.622
M1D3A1P1a2h1	0.909	0.961	0.914	M3D1A2P3a1h2	0.792	0.879	0.781
M1D3A1P1a3h1	0.911	0.960	0.912	M3D1A2P3a2h2	0.740	0.832	0.732
M1D3A1P2a1h1	0.872	0.868	0.935	M3D1A2P3a3h2	0.761	0.765	0.695
M1D3A1P2a2h1	0.881	0.919	0.843	M3D1A2P1a1h3	0.663	0.418	0.366
M1D3A1P2a3h1	0.884	0.970	0.745	M3D1A2P1a2h3	0.714	0.515	0.457
M1D3A1P3a1h1*	0.866	1.153	1.075	M3D1A2P1a3h3	0.713	0.419	0.402
M1D3A1P3a2h1*	0.855	1.150	1.073	M3D1A2P2a1h3	0.672	0.753	0.612
M1D3A1P3a3h1*	0.874	1.074	1.028	M3D1A2P2a2h3	0.663	0.645	0.535
M1D3A1P1a1h2	0.770	0.780	0.749	M3D1A2P2a3h3	0.692	0.625	0.537

Table D.7 Critical buckling limit ratios for specimens with two corrosion defects of $d_p/t = d_s/t = 0.40$ - continue

Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}	Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}
M1D3A1P1a2h2	0.776	0.680	0.690	M3D1A2P3a1h3*	0.679	0.917	0.791
M1D3A1P1a3h2	0.782	0.665	0.683	M3D1A2P3a2h3*	0.596	0.887	0.744
M1D3A1P2a1h2*	0.714	1.167	0.955	M3D1A2P3a3h3*	0.630	0.846	0.708
M1D3A1P2a2h2*	0.736	1.082	0.904	M3D1A3P1a1h1	0.918	0.931	0.884
M1D3A1P2a3h2*	0.742	0.997	0.849	M3D1A3P1a2h1	0.928	0.938	0.897
M1D3A1P3a1h2*	0.757	1.545	1.373	M3D1A3P1a3h1	0.928	0.929	0.887
M1D3A1P3a2h2*	0.736	1.536	1.365	M3D1A3P2a1h1	0.902	0.888	0.844
M1D3A1P3a3h2*	0.773	1.287	1.179	M3D1A3P2a2h1	0.900	0.840	0.808
M1D3A1P1a1h3	0.633	0.644	0.651	M3D1A3P2a3h1	0.907	0.832	0.808
M1D3A1P1a2h3	0.642	0.555	0.568	M3D1A3P3a1h1	0.878	0.888	0.846
M1D3A1P1a3h3	0.652	0.533	0.557	M3D1A3P3a2h1	0.850	0.839	0.804
M1D3A1P2a1h3*	0.588	1.755	1.020	M3D1A3P3a3h1	0.862	0.777	0.770
M1D3A1P2a2h3*	0.620	1.402	1.101	M3D1A3P1a1h2	0.784	0.709	0.649
M1D3A1P2a3h3*	0.629	1.052	1.188	M3D1A3P1a2h2	0.814	0.751	0.695
M1D3A1P3a1h3*	0.630	1.923	1.671	M3D1A3P1a3h2	0.815	0.703	0.660
M1D3A1P3a2h3*	0.596	1.909	1.657	M3D1A3P2a1h2	0.765	0.801	0.714
M1D3A1P3a3h3*	0.655	1.493	1.330	M3D1A3P2a2h2	0.759	0.709	0.644
M1D3A2P1a1h1	0.838	0.910	0.869	M3D1A3P2a3h2	0.780	0.694	0.643
M1D3A2P1a2h1	0.844	0.892	0.854	M3D1A3P3a1h2*	0.745	0.886	0.812
M1D3A2P1a3h1	0.846	0.887	0.850	M3D1A3P3a2h2*	0.681	0.836	0.759
M1D3A2P2a1h1*	0.830	0.965	0.871	M3D1A3P3a3h2*	0.708	0.771	0.716
M1D3A2P2a2h1*	0.843	0.895	0.851	M3D1A3P1a1h3	0.594	0.536	0.551
M1D3A2P2a3h1*	0.845	0.789	0.806	M3D1A3P1a2h3	0.653	0.574	0.513
M1D3A2P3a1h1	0.745	1.027	0.986	M3D1A3P1a3h3	0.655	0.550	0.500
M1D3A2P3a2h1	0.726	1.028	0.986	M3D1A3P2a1h3	0.605	0.761	0.647
M1D3A2P3a3h1	0.757	1.003	0.983	M3D1A3P2a2h3	0.594	0.649	0.559
M1D3A2P1a1h2	0.667	0.711	0.664	M3D1A3P2a3h3	0.631	0.630	0.559
M1D3A2P1a2h2	0.681	0.639	0.621	M3D1A3P3a1h3*	0.603	0.904	0.810
M1D3A2P1a3h2	0.685	0.621	0.611	M3D1A3P3a2h3*	0.500	0.864	0.757
M1D3A2P2a1h2*	0.639	0.969	0.840	M3D1A3P3a3h3*	0.544	0.812	0.714
M1D3A2P2a2h2*	0.668	0.920	0.814	M3D2A1P1a1h1	0.906	0.784	0.778
M1D3A2P2a3h2*	0.673	0.844	0.755	M3D2A1P1a2h1	0.909	0.776	0.770
M1D3A2P3a1h2*	0.568	1.314	1.229	M3D2A1P1a3h1	0.913	0.769	0.774
M1D3A2P3a2h2*	0.535	1.318	1.230	M3D2A1P2a1h1	0.901	0.886	0.820
M1D3A2P3a3h2*	0.588	1.145	1.086	M3D2A1P2a2h1	0.908	0.811	0.782
M1D3A2P1a1h3	0.512	0.631	0.559	M3D2A1P2a3h1	0.910	0.815	0.787
M1D3A2P1a2h3	0.533	0.539	0.502	M3D2A1P3a1h1	0.881	0.840	0.811
M1D3A2P1a3h3	0.539	0.515	0.488	M3D2A1P3a2h1	0.880	0.884	0.832
M1D3A2P2a1h3*	0.466	0.990	0.888	M3D2A1P3a3h1	0.886	0.781	0.762
M1D3A2P2a2h3*	0.510	1.035	0.871	M3D2A1P1a1h2	0.767	0.604	0.566

Table D.7 Critical buckling limit ratios for specimens with two corrosion defects of $d_p/t = d_s/t = 0.40$ - continue

Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}	Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}
M1D3A2P2a3h3*	0.517	1.104	0.833	M3D2A1P1a2h2	0.778	0.588	0.550
M1D3A2P3a1h3*	0.349	1.581	1.461	M3D2A1P1a3h2	0.788	0.575	0.558
M1D3A2P3a2h3*	0.298	1.589	1.463	M3D2A1P2a1h2	0.759	0.822	0.684
M1D3A2P3a3h3*	0.380	1.276	1.184	M3D2A1P2a2h2	0.781	0.696	0.615
M1D3A3P1a1h1	0.845	1.008	0.977	M3D2A1P2a3h2	0.785	0.702	0.624
M1D3A3P1a2h1	0.831	0.921	0.866	M3D2A1P3a1h2*	0.762	0.953	0.817
M1D3A3P1a3h1	0.834	0.918	0.863	M3D2A1P3a2h2*	0.759	0.975	0.837
M1D3A3P2a1h1	0.795	0.901	0.838	M3D2A1P3a3h2*	0.772	0.861	0.767
M1D3A3P2a2h1	0.808	0.889	0.835	M3D2A1P1a1h3	0.619	0.423	0.415
M1D3A3P2a3h1	0.813	0.846	0.798	M3D2A1P1a2h3	0.636	0.399	0.392
M1D3A3P3a1h1	F	F	F	M3D2A1P1a3h3	0.654	0.381	0.404
M1D3A3P3a2h1	F	F	F	M3D2A1P2a1h3*	0.610	0.902	0.723
M1D3A3P3a3h1	F	F	F	M3D2A1P2a2h3*	0.646	0.840	0.663
M1D3A3P1a1h2	0.668	0.701	0.628	M3D2A1P2a3h3*	0.654	0.843	0.671
M1D3A3P1a2h2	0.635	0.669	0.598	M3D2A1P3a1h3*	0.641	2.288	0.987
M1D3A3P1a3h2	0.642	0.652	0.589	M3D2A1P3a2h3*	0.637	1.229	0.986
M1D3A3P2a1h2	0.543	0.855	0.726	M3D2A1P3a3h3*	0.657	1.210	0.989
M1D3A3P2a2h2	0.576	0.836	0.720	M3D2A2P1a1h1	0.887	0.780	0.767
M1D3A3P2a3h2	0.586	0.768	0.654	M3D2A2P1a2h1	0.891	0.775	0.766
M1D3A3P3a1h2	F	F	F	M3D2A2P1a3h1	0.897	0.768	0.763
M1D3A3P3a2h2	F	F	F	M3D2A2P2a1h1	0.884	0.881	0.827
M1D3A3P3a3h2	F	F	F	M3D2A2P2a2h1	0.893	0.816	0.791
M1D3A3P1a1h3	0.496	0.594	0.477	M3D2A2P2a3h1	0.896	0.821	0.797
M1D3A3P1a2h3	0.445	0.565	0.458	M3D2A2P3a1h1	0.856	0.770	0.809
M1D3A3P1a3h3	0.455	0.543	0.444	M3D2A2P3a2h1	0.855	0.877	0.834
M1D3A3P2a1h3	0.305	0.841	0.671	M3D2A2P3a3h1	0.862	0.820	0.736
M1D3A3P2a2h3	0.356	0.819	0.663	M3D2A2P1a1h2	0.717	0.610	0.573
M1D3A3P2a3h3	0.372	0.743	0.583	M3D2A2P1a2h2	0.730	0.600	0.572
M1D3A3P3a1h3	F	F	F	M3D2A2P1a3h2	0.746	0.587	0.565
M1D3A3P3a2h3	F	F	F	M3D2A2P2a1h2	0.709	0.811	0.699
M1D3A3P3a3h3	F	F	F	M3D2A2P2a2h2	0.735	0.699	0.633
M2D1A1P1a1h1	0.940	0.912	0.841	M3D2A2P2a3h2	0.742	0.707	0.644
M2D1A1P1a2h1	0.947	0.921	0.859	M3D2A2P3a1h2*	0.704	0.938	0.835
M2D1A1P1a3h1	0.947	0.917	0.856	M3D2A2P3a2h2*	0.702	0.960	0.856
M2D1A1P2a1h1	0.913	0.817	0.752	M3D2A2P3a3h2*	0.719	0.847	0.774
M2D1A1P2a2h1	0.907	0.771	0.722	M3D2A2P1a1h3	0.538	0.415	0.388
M2D1A1P2a3h1	0.914	0.753	0.723	M3D2A2P1a2h3	0.560	0.400	0.386
M2D1A1P3a1h1	0.882	0.874	0.785	M3D2A2P1a3h3	0.587	0.380	0.376
M2D1A1P3a2h1	0.858	0.770	0.713	M3D2A2P2a1h3*	0.526	0.837	0.688
M2D1A1P3a3h1	0.862	0.699	0.686	M3D2A2P2a2h3*	0.570	0.742	0.621

Table D.7 Critical buckling limit ratios for specimens with two corrosion defects of $d_p/t = d_s/t = 0.40$ - continue

Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}	Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}
M2D1A1P1a1h2	0.859	0.650	0.571	M3D2A2P2a3h3*	0.582	0.749	0.632
M2D1A1P1a2h2	0.881	0.692	0.624	M3D2A2P3a1h3*	0.552	1.347	0.985
M2D1A1P1a3h2	0.879	0.673	0.616	M3D2A2P3a2h3*	0.548	1.160	0.984
M2D1A1P2a1h2	0.827	0.725	0.606	M3D2A2P3a3h3*	0.574	2.149	0.987
M2D1A1P2a2h2	0.812	0.653	0.555	M3D2A3P1a1h1	0.865	0.792	0.778
M2D1A1P2a3h2	0.830	0.625	0.557	M3D2A3P1a2h1	0.870	0.786	0.776
M2D1A1P3a1h2*	0.794	0.893	0.767	M3D2A3P1a3h1	0.875	0.781	0.775
M2D1A1P3a2h2*	0.748	0.808	0.688	M3D2A3P2a1h1	0.864	0.882	0.845
M2D1A1P3a3h2*	0.755	0.750	0.659	M3D2A3P2a2h1	0.874	0.824	0.804
M2D1A1P1a1h3	0.744	0.484	0.383	M3D2A3P2a3h1	0.877	0.832	0.815
M2D1A1P1a2h3	0.785	0.547	0.460	M3D2A3P3a1h1	0.808	0.829	0.803
M2D1A1P1a3h3	0.782	0.517	0.448	M3D2A3P3a2h1	0.804	0.859	0.822
M2D1A1P2a1h3	0.729	0.693	0.536	M3D2A3P3a3h1	0.814	0.716	0.753
M2D1A1P2a2h3	0.705	0.611	0.476	M3D2A3P1a1h2	0.663	0.628	0.587
M2D1A1P2a3h3	0.734	0.580	0.479	M3D2A3P1a2h2	0.677	0.618	0.584
M2D1A1P3a1h3*	0.702	0.938	0.794	M3D2A3P1a3h2	0.691	0.608	0.582
M2D1A1P3a2h3*	0.633	0.898	0.725	M3D2A3P2a1h2	0.648	0.796	0.710
M2D1A1P3a3h3*	0.643	0.870	0.700	M3D2A3P2a2h2	0.678	0.686	0.628
M2D1A2P1a1h1	0.928	0.894	0.840	M3D2A3P2a3h2	0.687	0.702	0.651
M2D1A2P1a2h1	0.936	0.909	0.861	M3D2A3P3a1h2*	0.622	0.877	0.796
M2D1A2P1a3h1	0.936	0.897	0.851	M3D2A3P3a2h2*	0.615	0.897	0.816
M2D1A2P2a1h1	0.900	0.828	0.775	M3D2A3P3a3h2*	0.636	0.800	0.743
M2D1A2P2a2h1	0.893	0.782	0.741	M3D2A3P1a1h3	0.466	0.427	0.381
M2D1A2P2a3h1	0.902	0.765	0.739	M3D2A3P1a2h3	0.488	0.410	0.377
M2D1A2P3a1h1	0.858	0.886	0.815	M3D2A3P1a3h3	0.511	0.395	0.373
M2D1A2P3a2h1	0.828	0.776	0.732	M3D2A3P2a1h3	0.443	0.763	0.643
M2D1A2P3a3h1	0.832	0.704	0.693	M3D2A3P2a2h3	0.492	0.633	0.540
M2D1A2P1a1h2	0.824	0.656	0.588	M3D2A3P2a3h3	0.506	0.652	0.569
M2D1A2P1a2h2	0.849	0.714	0.649	M3D2A3P3a1h3*	0.437	1.022	0.874
M2D1A2P1a3h2	0.848	0.667	0.619	M3D2A3P3a2h3*	0.427	1.014	0.886
M2D1A2P2a1h2	0.793	0.736	0.640	M3D2A3P3a3h3*	0.459	1.054	0.844
M2D1A2P2a2h2	0.776	0.663	0.583	M3D3A1P1a1h1	0.869	0.748	0.740
M2D1A2P2a3h2	0.798	0.637	0.580	M3D3A1P1a2h1	0.866	0.716	0.720
M2D1A2P3a1h2*	0.744	0.900	0.806	M3D3A1P1a3h1	0.871	0.726	0.729
M2D1A2P3a2h2*	0.685	0.807	0.718	M3D3A1P2a1h1	0.873	0.915	0.825
M2D1A2P3a3h2*	0.693	0.746	0.677	M3D3A1P2a2h1	0.880	0.804	0.788
M2D1A2P1a1h3	0.685	0.448	0.378	M3D3A1P2a3h1	0.883	0.730	0.756
M2D1A2P1a2h3	0.732	0.544	0.471	M3D3A1P3a1h1	0.860	0.866	0.881
M2D1A2P1a3h3	0.731	0.467	0.426	M3D3A1P3a2h1	0.870	0.855	0.820
M2D1A2P2a1h3	0.671	0.707	0.581	M3D3A1P3a3h1	0.873	0.687	0.801

Table D.7 Critical buckling limit ratios for specimens with two corrosion defects of $d_p/t = d_s/t = 0.40$ - continue

Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}	Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}
M2D1A2P2a2h3	0.641	0.625	0.515	M3D3A1P1a1h2	0.694	0.525	0.516
M2D1A2P2a3h3	0.678	0.595	0.511	M3D3A1P1a2h2	0.688	0.462	0.476
M2D1A2P3a1h3*	0.622	0.936	0.832	M3D3A1P1a3h2	0.700	0.481	0.494
M2D1A2P3a2h3*	0.534	0.885	0.758	M3D3A1P2a1h2*	0.707	0.923	0.772
M2D1A2P3a3h3*	0.545	0.851	0.724	M3D3A1P2a2h2*	0.726	0.827	0.723
M2D1A3P1a1h1	0.913	0.913	0.869	M3D3A1P2a3h2*	0.732	0.762	0.679
M2D1A3P1a2h1	0.924	0.923	0.884	M3D3A1P3a1h2*	0.715	1.051	0.891
M2D1A3P1a3h1	0.924	0.913	0.874	M3D3A1P3a2h2*	0.737	0.957	0.837
M2D1A3P2a1h1	0.880	0.839	0.797	M3D3A1P3a3h2*	0.743	0.926	0.819
M2D1A3P2a2h1	0.871	0.793	0.759	M3D3A1P1a1h3	0.592	0.505	0.472
M2D1A3P2a3h1	0.883	0.775	0.753	M3D3A1P1a2h3	0.584	0.439	0.429
M2D1A3P3a1h1	0.817	0.894	0.843	M3D3A1P1a3h3	0.600	0.459	0.448
M2D1A3P3a2h1	0.777	0.784	0.751	M3D3A1P2a1h3*	0.565	1.080	0.963
M2D1A3P3a3h1	0.783	0.714	0.703	M3D3A1P2a2h3*	0.594	1.252	0.959
M2D1A3P1a1h2	0.780	0.686	0.628	M3D3A1P2a3h3*	0.604	1.367	0.956
M2D1A3P1a2h2	0.811	0.732	0.677	M3D3A1P3a1h3*	0.578	1.120	1.002
M2D1A3P1a3h2	0.812	0.687	0.644	M3D3A1P3a2h3*	0.610	1.255	1.015
M2D1A3P2a1h2	0.742	0.752	0.677	M3D3A1P3a3h3*	0.620	1.628	1.019
M2D1A3P2a2h2	0.720	0.677	0.614	M3D3A2P1a1h1	0.860	0.940	0.883
M2D1A3P2a3h2	0.749	0.650	0.603	M3D3A2P1a2h1	0.849	0.736	0.739
M2D1A3P3a1h2*	0.658	0.907	0.843	M3D3A2P1a3h1	0.853	0.736	0.741
M2D1A3P3a2h2*	0.578	0.812	0.752	M3D3A2P2a1h1	0.832	0.834	0.771
M2D1A3P3a3h2*	0.589	0.753	0.704	M3D3A2P2a2h1	0.847	0.723	0.710
M2D1A3P1a1h3	0.600	0.472	0.417	M3D3A2P2a3h1	0.850	0.714	0.707
M2D1A3P1a2h3	0.659	0.552	0.495	M3D3A2P3a1h1	0.831	0.806	0.873
M2D1A3P1a3h3	0.660	0.474	0.442	M3D3A2P3a2h1	0.842	0.848	0.818
M2D1A3P2a1h3	0.581	0.718	0.624	M3D3A2P3a3h1	0.845	0.801	0.807
M2D1A3P2a2h3	0.544	0.632	0.550	M3D3A2P1a1h2	0.663	0.541	0.511
M2D1A3P2a3h3	0.593	0.600	0.537	M3D3A2P1a2h2	0.632	0.478	0.482
M2D1A3P3a1h3*	0.493	0.925	0.857	M3D3A2P1a3h2	0.644	0.478	0.487
M2D1A3P3a2h3*	0.429	0.855	0.774	M3D3A2P2a1h2	0.635	0.809	0.704
M2D1A3P3a3h3*	0.390	0.810	0.731	M3D3A2P2a2h2	0.672	0.679	0.624
M2D2A1P1a1h1	0.912	0.848	0.807	M3D3A2P2a3h2	0.678	0.669	0.620
M2D2A1P1a2h1	0.917	0.849	0.811	M3D3A2P3a1h2*	0.648	0.993	0.870
M2D2A1P1a3h1	0.922	0.844	0.812	M3D3A2P3a2h2*	0.672	0.913	0.815
M2D2A1P2a1h1	0.902	0.869	0.801	M3D3A2P3a3h2*	0.680	0.888	0.803
M2D2A1P2a2h1	0.909	0.798	0.766	M3D3A2P1a1h3	0.543	0.452	0.449
M2D2A1P2a3h1	0.910	0.798	0.769	M3D3A2P1a2h3	0.500	0.422	0.404
M2D2A1P3a1h1	0.864	0.901	0.728	M3D3A2P1a3h3	0.517	0.422	0.410
M2D2A1P3a2h1	0.854	0.887	0.820	M3D3A2P2a1h3*	0.450	0.979	0.842

Table D.7 Critical buckling limit ratios for specimens with two corrosion defects of $d_p/t = d_s/t = 0.40$ - continue

Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}	Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}
M2D2A1P3a3h1	0.864	0.898	0.750	M3D3A2P2a2h3*	0.506	0.978	0.801
M2D2A1P1a1h2	0.781	0.613	0.554	M3D3A2P2a3h3*	0.515	0.978	0.799
M2D2A1P1a2h2	0.798	0.615	0.564	M3D3A2P3a1h3*	0.476	0.952	0.960
M2D2A1P1a3h2	0.810	0.600	0.566	M3D3A2P3a2h3*	0.513	1.121	0.950
M2D2A1P2a1h2	0.770	0.801	0.663	M3D3A2P3a3h3*	0.525	1.172	0.948
M2D2A1P2a2h2	0.790	0.685	0.602	M3D3A3P1a1h1	0.816	0.772	0.754
M2D2A1P2a3h2	0.793	0.685	0.607	M3D3A3P1a2h1	0.815	0.744	0.734
M2D2A1P3a1h2*	0.762	0.969	0.837	M3D3A3P1a3h1	0.820	0.744	0.736
M2D2A1P3a2h2*	0.743	1.039	0.889	M3D3A3P2a1h1	0.838	0.798	0.751
M2D2A1P3a3h2*	0.763	0.888	0.792	M3D3A3P2a2h1	0.828	0.807	0.779
M2D2A1P1a1h3	0.634	0.433	0.386	M3D3A3P2a3h1	0.833	0.787	0.769
M2D2A1P1a2h3	0.663	0.436	0.400	M3D3A3P3a1h1	0.791	0.914	0.834
M2D2A1P1a3h3	0.684	0.415	0.403	M3D3A3P3a2h1	0.805	0.843	0.808
M2D2A1P2a1h3*	0.629	0.871	0.688	M3D3A3P3a3h1	0.808	0.807	0.785
M2D2A1P2a2h3*	0.661	0.801	0.631	M3D3A3P1a1h2	0.570	0.542	0.497
M2D2A1P2a3h3*	0.668	0.801	0.636	M3D3A3P1a2h2	0.568	0.483	0.453
M2D2A1P3a1h3*	0.652	0.931	1.032	M3D3A3P1a3h2	0.581	0.482	0.457
M2D2A1P3a2h3*	0.623	1.240	1.013	M3D3A3P2a1h2	0.636	0.690	0.597
M2D2A1P3a3h3*	0.653	0.572	1.048	M3D3A3P2a2h2	0.610	0.734	0.650
M2D2A2P1a1h1	0.895	0.857	0.817	M3D3A3P2a3h2	0.623	0.706	0.633
M2D2A2P1a2h1	0.902	0.857	0.816	M3D3A3P3a1h2*	0.565	0.928	0.808
M2D2A2P1a3h1	0.908	0.849	0.815	M3D3A3P3a2h2*	0.596	0.871	0.778
M2D2A2P2a1h1	0.882	0.876	0.818	M3D3A3P3a3h2*	0.602	0.842	0.751
M2D2A2P2a2h1	0.892	0.803	0.773	M3D3A3P1a1h3	0.423	0.492	0.417
M2D2A2P2a3h1	0.894	0.802	0.775	M3D3A3P1a2h3	0.421	0.426	0.366
M2D2A2P3a1h1	0.824	0.997	0.688	M3D3A3P1a3h3	0.438	0.425	0.370
M2D2A2P3a2h1	0.811	0.889	0.841	M3D3A3P2a1h3*	0.463	0.741	0.528
M2D2A2P3a3h1	0.826	1.133	0.519	M3D3A3P2a2h3*	0.424	0.694	0.562
M2D2A2P1a1h2	0.724	0.641	0.588	M3D3A3P2a3h3*	0.443	0.661	0.540
M2D2A2P1a2h2	0.745	0.640	0.586	M3D3A3P3a1h3*	0.338	0.984	0.859
M2D2A2P1a3h2	0.763	0.617	0.584	M3D3A3P3a2h3*	0.387	0.988	0.837
M2D2A2P2a1h2	0.707	0.814	0.705	M3D3A3P3a3h3*	0.395	0.990	0.819
M2D2A2P2a2h2	0.733	0.698	0.628				

Table D.8 Critical buckling limit ratios for specimens with two corrosion defects of $d_p/t = 0.3$, $d_s/t = 0.20$

Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}	Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}
M1D1A1P1a1h1	0.958	0.766	0.745	M2D2A2P2a2h3	0.649	0.679	0.589
M1D1A1P1a1h2	0.900	0.572	0.505	M2D2A2P2a3h1	0.912	0.894	0.854

Table D.8 Critical buckling limit ratios for specimens with two corrosion defects of $d_p/t = 0.3$, $d_s/t = 0.20$ - continue

Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}	Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}
M1D1A1P1a1h3	0.830	0.514	0.411	M2D2A2P2a3h2	0.793	0.784	0.710
M1D1A1P1a2h1	0.963	0.860	0.833	M2D2A2P2a3h3	0.655	0.725	0.627
M1D1A1P1a2h2	0.916	0.696	0.616	M2D2A2P3a1h1	0.853	0.836	0.807
M1D1A1P1a2h3	0.853	0.578	0.468	M2D2A2P3a1h2	0.688	0.809	0.786
M1D1A1P1a3h1	0.958	0.876	0.830	M2D2A2P3a1h3*	0.543	0.990	0.873
M1D1A1P1a3h2	0.912	0.726	0.637	M2D2A2P3a2h1	0.865	0.883	0.850
M1D1A1P1a3h3	0.851	0.612	0.496	M2D2A2P3a2h2	0.710	0.863	0.828
M1D1A1P2a1h1	0.924	0.763	0.720	M2D2A2P3a2h3*	0.555	1.010	0.892
M1D1A1P2a1h2	0.841	0.591	0.505	M2D2A2P3a3h1	0.889	0.924	0.895
M1D1A1P2a1h3	0.759	0.563	0.439	M2D2A2P3a3h2	0.758	0.890	0.868
M1D1A1P2a2h1	0.924	0.790	0.743	M2D2A2P3a3h3*	0.594	0.940	0.841
M1D1A1P2a2h2	0.845	0.632	0.539	M2D2A3P1a1h1	0.886	0.791	0.784
M1D1A1P2a2h3	0.758	0.568	0.442	M2D2A3P1a1h2	0.721	0.618	0.588
M1D1A1P2a3h1	0.942	0.887	0.843	M2D2A3P1a1h3	0.562	0.512	0.462
M1D1A1P2a3h2	0.872	0.722	0.636	M2D2A3P1a2h1	0.892	0.836	0.822
M1D1A1P2a3h3	0.796	0.636	0.517	M2D2A3P1a2h2	0.727	0.649	0.621
M1D1A1P3a1h1	0.876	0.812	0.769	M2D2A3P1a2h3	0.563	0.484	0.446
M1D1A1P3a1h2	0.769	0.783	0.699	M2D2A3P1a3h1	0.903	0.856	0.843
M1D1A1P3a1h3*	0.673	0.868	0.744	M2D2A3P1a3h2	0.750	0.696	0.666
M1D1A1P3a2h1	0.858	0.798	0.747	M2D2A3P1a3h3	0.598	0.555	0.512
M1D1A1P3a2h2	0.747	0.769	0.720	M2D2A3P2a1h1	0.856	0.811	0.787
M1D1A1P3a2h3*	0.640	0.927	0.786	M2D2A3P2a1h2	0.667	0.693	0.638
M1D1A1P3a3h1	0.868	0.837	0.788	M2D2A3P2a1h3	0.500	0.655	0.570
M1D1A1P3a3h2*	0.769	0.904	0.801	M2D2A3P2a2h1	0.901	0.879	0.860
M1D1A1P3a3h3*	0.652	0.967	0.824	M2D2A3P2a2h2	0.730	0.740	0.695
M1D1A2P1a1h1	0.943	0.751	0.734	M2D2A3P2a2h3	0.563	0.648	0.576
M1D1A2P1a1h2	0.860	0.570	0.517	M2D2A3P2a3h1	0.889	0.909	0.882
M1D1A2P1a1h3	0.757	0.563	0.480	M2D2A3P2a3h2	0.729	0.783	0.730
M1D1A2P1a2h1	0.953	0.841	0.823	M2D2A3P2a3h3	0.568	0.702	0.627
M1D1A2P1a2h2	0.888	0.702	0.638	M2D2A3P3a1h1	0.797	0.826	0.801
M1D1A2P1a2h3	0.798	0.604	0.518	M2D2A3P3a1h2	0.569	0.798	0.739
M1D1A2P1a3h1	0.949	0.897	0.857	M2D2A3P3a1h3*	0.367	0.861	0.774
M1D1A2P1a3h2	0.884	0.739	0.667	M2D2A3P3a2h1	0.814	0.875	0.849
M1D1A2P1a3h3	0.799	0.634	0.544	M2D2A3P3a2h2	0.598	0.857	0.800
M1D1A2P2a1h1	0.910	0.779	0.745	M2D2A3P3a2h3*	0.384	0.902	0.815
M1D1A2P2a1h2	0.798	0.615	0.549	M2D2A3P3a3h1	0.849	0.920	0.898
M1D1A2P2a1h3	0.677	0.557	0.532	M2D2A3P3a3h2	0.666	0.883	0.872
M1D1A2P2a2h1	0.910	0.805	0.770	M2D2A3P3a3h3*	0.438	0.874	0.798
M1D1A2P2a2h2	0.804	0.655	0.585	M2D3A1P1a1h1	0.902	0.754	0.747
M1D1A2P2a2h3	0.676	0.648	0.544	M2D3A1P1a1h2	0.778	0.569	0.552

Table D.8 Critical buckling limit ratios for specimens with two corrosion defects of $d_p/t = 0.3$, $d_s/t = 0.20$ - continue

Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}	Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}
M1D1A2P2a3h1	0.934	0.909	0.876	M2D3A1P1a1h3	0.676	0.469	0.457
M1D1A2P2a3h2	0.842	0.746	0.681	M2D3A1P1a2h1	0.900	0.770	0.757
M1D1A2P2a3h3	0.738	0.678	0.586	M2D3A1P1a2h2	0.778	0.582	0.563
M1D1A2P3a1h1	0.831	0.818	0.790	M2D3A1P1a2h3	0.679	0.490	0.471
M1D1A2P3a1h2	0.669	0.790	0.738	M2D3A1P1a3h1	0.906	0.794	0.779
M1D1A2P3a1h3*	0.518	0.886	0.810	M2D3A1P1a3h2	0.789	0.608	0.584
M1D1A2P3a2h1	0.805	0.805	0.773	M2D3A1P1a3h3	0.691	0.493	0.477
M1D1A2P3a2h2	0.635	0.799	0.768	M2D3A1P2a1h1	0.887	0.793	0.754
M1D1A2P3a2h3*	0.468	0.943	0.857	M2D3A1P2a1h2	0.749	0.785	0.670
M1D1A2P3a3h1	0.819	0.842	0.811	M2D3A1P2a1h3*	0.630	1.172	0.892
M1D1A2P3a3h2*	0.673	0.919	0.855	M2D3A1P2a2h1	0.908	0.838	0.795
M1D1A2P3a3h3*	0.488	0.979	0.892	M2D3A1P2a2h2	0.789	0.759	0.671
M1D1A3P1a1h1	0.924	0.769	0.756	M2D3A1P2a2h3	0.664	0.733	0.640
M1D1A3P1a1h2	0.790	0.625	0.587	M2D3A1P2a3h1	0.914	0.878	0.835
M1D1A3P1a1h3	0.646	0.567	0.515	M2D3A1P2a3h2	0.800	0.771	0.681
M1D1A3P1a2h1	0.941	0.857	0.843	M2D3A1P2a3h3	0.676	0.755	0.625
M1D1A3P1a2h2	0.844	0.756	0.709	M2D3A1P3a1h1	0.876	0.877	0.831
M1D1A3P1a2h3	0.706	0.651	0.593	M2D3A1P3a1h2*	0.753	1.021	0.893
M1D1A3P1a3h1	0.939	0.939	0.908	M2D3A1P3a1h3*	0.642	1.320	1.094
M1D1A3P1a3h2	0.840	0.795	0.742	M2D3A1P3a2h1	0.910	0.947	0.930
M1D1A3P1a3h3	0.708	0.675	0.616	M2D3A1P3a2h2*	0.788	1.019	0.904
M1D1A3P2a1h1	0.881	0.798	0.775	M2D3A1P3a2h3*	0.667	1.224	1.027
M1D1A3P2a1h2	0.706	0.644	0.603	M2D3A1P3a3h1	0.904	0.954	0.906
M1D1A3P2a1h3	0.545	0.592	0.536	M2D3A1P3a3h2*	0.797	1.025	0.914
M1D1A3P2a2h1	0.883	0.824	0.800	M2D3A1P3a3h3*	0.682	1.240	1.045
M1D1A3P2a2h2	0.718	0.687	0.643	M2D3A2P1a1h1	0.877	0.767	0.766
M1D1A3P2a2h3	0.544	0.601	0.544	M2D3A2P1a1h2	0.707	0.583	0.572
M1D1A3P2a3h1	0.918	0.928	0.906	M2D3A2P1a1h3	0.584	0.480	0.463
M1D1A3P2a3h2	0.780	0.783	0.739	M2D3A2P1a2h1	0.875	0.785	0.776
M1D1A3P2a3h3	0.624	0.699	0.643	M2D3A2P1a2h2	0.710	0.595	0.582
M1D1A3P3a1h1	0.715	0.829	0.825	M2D3A2P1a2h3	0.588	0.503	0.481
M1D1A3P3a1h2	0.408	0.779	0.786	M2D3A2P1a3h1	0.883	0.809	0.798
M1D1A3P3a1h3	F	F	F	M2D3A2P1a3h2	0.724	0.621	0.604
M1D1A3P3a2h1	0.662	0.817	0.825	M2D3A2P1a3h3	0.602	0.504	0.487
M1D1A3P3a2h2	0.331	0.802	0.806	M2D3A2P2a1h1	0.857	0.798	0.771
M1D1A3P3a2h3	F	F	F	M2D3A2P2a1h2	0.673	0.745	0.667
M1D1A3P3a3h1	F	F	F	M2D3A2P2a1h3*	0.529	0.891	0.741
M1D1A3P3a3h2	F	F	F	M2D3A2P2a2h1	0.888	0.847	0.822
M1D1A3P3a3h3	F	F	F	M2D3A2P2a2h2	0.723	0.751	0.687
M1D2A1P1a1h1	0.928	0.788	0.743	M2D3A2P2a2h3*	0.577	0.713	0.615

Table D.8 Critical buckling limit ratios for specimens with two corrosion defects of $d_p/t = 0.3$, $d_s/t = 0.20$ - continue

Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}	Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}
M1D2A1P1a1h2	0.829	0.651	0.586	M2D3A2P2a3h1	0.895	0.882	0.853
M1D2A1P1a1h3	0.745	0.585	0.522	M2D3A2P2a3h2	0.737	0.771	0.705
M1D2A1P1a2h1	0.934	0.862	0.800	M2D3A2P2a3h3*	0.590	0.702	0.606
M1D2A1P1a2h2	0.846	0.701	0.625	M2D3A2P3a1h1	0.836	0.885	0.857
M1D2A1P1a2h3	0.752	0.528	0.487	M2D3A2P3a1h2*	0.668	0.982	0.901
M1D2A1P1a3h1	0.942	0.904	0.845	M2D3A2P3a1h3*	0.516	1.169	1.034
M1D2A1P1a3h2	0.860	0.755	0.667	M2D3A2P3a2h1	0.882	0.958	0.964
M1D2A1P1a3h3	0.775	0.617	0.551	M2D3A2P3a2h2*	0.712	1.006	0.934
M1D2A1P2a1h1	0.913	0.772	0.721	M2D3A2P3a2h3*	0.548	1.113	0.993
M1D2A1P2a1h2	0.793	0.713	0.663	M2D3A2P3a3h1	0.876	0.967	0.937
M1D2A1P2a1h3*	0.694	0.995	0.768	M2D3A2P3a3h2*	0.726	1.022	0.950
M1D2A1P2a2h1	0.936	0.865	0.818	M2D3A2P3a3h3*	0.572	1.162	1.039
M1D2A1P2a2h2	0.829	0.788	0.663	M2D3A3P1a1h1	0.841	0.765	0.756
M1D2A1P2a2h3*	0.716	0.960	0.748	M2D3A3P1a1h2	0.644	0.579	0.540
M1D2A1P2a3h1	0.933	0.894	0.837	M2D3A3P1a1h3	0.506	0.478	0.421
M1D2A1P2a3h2	0.845	0.798	0.681	M2D3A3P1a2h1	0.837	0.784	0.765
M1D2A1P2a3h3*	0.737	0.848	0.676	M2D3A3P1a2h2	0.648	0.596	0.555
M1D2A1P3a1h1	0.873	0.848	0.806	M2D3A3P1a2h3	0.508	0.499	0.439
M1D2A1P3a1h2*	0.754	0.924	0.826	M2D3A3P1a3h1	0.849	0.812	0.795
M1D2A1P3a1h3*	0.646	1.160	0.998	M2D3A3P1a3h2	0.663	0.624	0.583
M1D2A1P3a2h1	0.865	0.884	0.832	M2D3A3P1a3h3	0.524	0.504	0.449
M1D2A1P3a2h2*	0.753	1.009	0.896	M2D3A3P2a1h1	0.821	0.788	0.760
M1D2A1P3a2h3*	0.636	1.244	1.066	M2D3A3P2a1h2	0.607	0.694	0.615
M1D2A1P3a3h1	0.905	0.960	0.920	M2D3A3P2a1h3	0.429	0.685	0.565
M1D2A1P3a3h2*	0.800	1.048	0.949	M2D3A3P2a2h1	0.861	0.852	0.833
M1D2A1P3a3h3*	0.687	1.252	1.089	M2D3A3P2a2h2	0.666	0.734	0.664
M1D2A2P1a1h1	0.899	0.831	0.810	M2D3A3P2a2h3	0.493	0.676	0.572
M1D2A2P1a1h2	0.738	0.700	0.663	M2D3A3P2a3h1	0.868	0.875	0.841
M1D2A2P1a1h3	0.631	0.593	0.550	M2D3A3P2a3h2	0.683	0.762	0.701
M1D2A2P1a2h1	0.911	0.913	0.881	M2D3A3P2a3h3	0.509	0.666	0.557
M1D2A2P1a2h2	0.772	0.785	0.739	M2D3A3P3a1h1	0.784	0.869	0.824
M1D2A2P1a2h3	0.644	0.573	0.545	M2D3A3P3a1h2	0.543	0.854	0.825
M1D2A2P1a3h1	0.926	0.962	0.928	M2D3A3P3a1h3*	0.308	1.023	0.899
M1D2A2P1a3h2	0.790	0.830	0.774	M2D3A3P3a2h1	0.847	0.964	0.949
M1D2A2P1a3h3	0.676	0.672	0.631	M2D3A3P3a2h2	0.601	0.967	0.891
M1D2A2P2a1h1	0.877	0.797	0.762	M2D3A3P3a2h3*	0.357	1.009	0.898
M1D2A2P2a1h2	0.693	0.790	0.703	M2D3A3P3a3h1	0.838	0.960	0.924
M1D2A2P2a1h3*	0.574	0.795	0.686	M2D3A3P3a3h2	0.623	0.891	0.918
M1D2A2P2a2h1	0.916	0.892	0.860	M2D3A3P3a3h3*	0.392	1.081	0.974
M1D2A2P2a2h2	0.745	0.822	0.744	M3D1A1P1a1h1	0.952	0.808	0.797

Table D.8 Critical buckling limit ratios for specimens with two corrosion defects of $d_p/t = 0.3$, $d_s/t = 0.20$ - continue

Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}	Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}
M1D2A2P2a2h3*	0.601	0.804	0.699	M3D1A1P1a1h2	0.885	0.660	0.616
M1D2A2P2a3h1	0.912	0.914	0.873	M3D1A1P1a1h3	0.803	0.591	0.514
M1D2A2P2a3h2	0.767	0.840	0.763	M3D1A1P1a2h1	0.959	0.928	0.892
M1D2A2P2a3h3*	0.628	0.788	0.690	M3D1A1P1a2h2	0.897	0.728	0.672
M1D2A2P3a1h1*	0.796	0.856	0.839	M3D1A1P1a2h3	0.810	0.546	0.486
M1D2A2P3a1h2*	0.598	0.892	0.846	M3D1A1P1a3h1	0.953	0.889	0.858
M1D2A2P3a1h3*	0.427	1.036	0.963	M3D1A1P1a3h2	0.897	0.749	0.689
M1D2A2P3a2h1*	0.785	0.893	0.871	M3D1A1P1a3h3	0.820	0.609	0.534
M1D2A2P3a2h2*	0.598	0.990	0.937	M3D1A1P2a1h1	0.932	0.824	0.785
M1D2A2P3a2h3*	0.412	1.133	1.051	M3D1A1P2a1h2	0.845	0.700	0.611
M1D2A2P3a3h1*	0.855	0.971	0.953	M3D1A1P2a1h3	0.757	0.690	0.553
M1D2A2P3a3h2*	0.675	1.056	1.010	M3D1A1P2a2h1	0.944	0.889	0.852
M1D2A2P3a3h3*	0.493	1.224	1.145	M3D1A1P2a2h2	0.867	0.745	0.662
M1D2A3P1a1h1	0.863	0.850	0.821	M3D1A1P2a2h3	0.779	0.659	0.542
M1D2A3P1a1h2	0.679	0.661	0.605	M3D1A1P2a3h1	0.944	0.911	0.866
M1D2A3P1a1h3	0.552	0.586	0.515	M3D1A1P2a3h2	0.870	0.777	0.689
M1D2A3P1a2h1	0.883	0.959	0.927	M3D1A1P2a3h3	0.786	0.691	0.572
M1D2A3P1a2h2	0.720	0.788	0.717	M3D1A1P3a1h1	0.922	0.859	0.820
M1D2A3P1a2h3	0.574	0.606	0.544	M3D1A1P3a1h2	0.822	0.775	0.682
M1D2A3P1a3h1	0.902	0.967	0.971	M3D1A1P3a1h3	0.727	0.756	0.671
M1D2A3P1a3h2	0.738	0.835	0.769	M3D1A1P3a2h1	0.918	0.865	0.822
M1D2A3P1a3h3	0.608	0.693	0.623	M3D1A1P3a2h2	0.819	0.788	0.691
M1D2A3P2a1h1	0.839	0.781	0.762	M3D1A1P3a2h3	0.717	0.764	0.651
M1D2A3P2a1h2	0.615	0.693	0.622	M3D1A1P3a3h1	0.946	0.955	0.919
M1D2A3P2a1h3	0.460	0.640	0.553	M3D1A1P3a3h2	0.855	0.847	0.761
M1D2A3P2a2h1	0.887	0.898	0.882	M3D1A1P3a3h3	0.758	0.797	0.672
M1D2A3P2a2h2	0.677	0.769	0.705	M3D1A2P1a1h1	0.942	0.801	0.792
M1D2A3P2a2h3	0.495	0.685	0.597	M3D1A2P1a1h2	0.858	0.657	0.618
M1D2A3P2a3h1	0.882	0.921	0.899	M3D1A2P1a1h3	0.760	0.594	0.527
M1D2A3P2a3h2	0.705	0.811	0.752	M3D1A2P1a2h1	0.952	0.921	0.891
M1D2A3P2a3h3	0.532	0.729	0.646	M3D1A2P1a2h2	0.874	0.726	0.679
M1D2A3P3a1h1	0.593	0.839	0.834	M3D1A2P1a2h3	0.769	0.544	0.490
M1D2A3P3a1h2	F	F	F	M3D1A2P1a3h1	0.946	0.898	0.869
M1D2A3P3a1h3	F	F	F	M3D1A2P1a3h2	0.875	0.749	0.696
M1D2A3P3a2h1	0.536	0.874	0.907	M3D1A2P1a3h3	0.782	0.608	0.543
M1D2A3P3a2h2	F	F	F	M3D1A2P2a1h1	0.925	0.834	0.801
M1D2A3P3a2h3	F	F	F	M3D1A2P2a1h2	0.820	0.707	0.631
M1D2A3P3a3h1	0.666	0.958	1.041	M3D1A2P2a1h3	0.714	0.696	0.582
M1D2A3P3a3h2	F	F	F	M3D1A2P2a2h1	0.939	0.898	0.868
M1D2A3P3a3h3	F	F	F	M3D1A2P2a2h2	0.847	0.755	0.684

Table D.8 Critical buckling limit ratios for specimens with two corrosion defects of $d_p/t = 0.3$, $d_s/t = 0.20$ - continue

Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}	Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}
M1D3A1P1a1h1	0.908	0.905	0.877	M3D1A2P2a2h3	0.740	0.671	0.572
M1D3A1P1a1h2	0.815	0.790	0.768	M3D1A2P2a3h1	0.940	0.923	0.886
M1D3A1P1a1h3	0.710	0.679	0.666	M3D1A2P2a3h2	0.851	0.791	0.715
M1D3A1P1a2h1	0.915	0.950	0.909	M3D1A2P2a3h3	0.750	0.704	0.603
M1D3A1P1a2h2	0.822	0.795	0.773	M3D1A2P3a1h1	0.912	0.866	0.832
M1D3A1P1a2h3	0.725	0.704	0.688	M3D1A2P3a1h2	0.789	0.776	0.701
M1D3A1P1a3h1	0.925	0.923	0.944	M3D1A2P3a1h3	0.671	0.750	0.695
M1D3A1P1a3h2	0.830	0.795	0.779	M3D1A2P3a2h1	0.907	0.871	0.835
M1D3A1P1a3h3	0.735	0.695	0.687	M3D1A2P3a2h2	0.786	0.792	0.713
M1D3A1P2a1h1	0.863	0.865	0.795	M3D1A2P3a2h3	0.659	0.793	0.678
M1D3A1P2a1h2*	0.732	1.065	0.888	M3D1A2P3a3h1	0.941	0.965	0.936
M1D3A1P2a1h3*	0.641	1.326	1.051	M3D1A2P3a3h2	0.831	0.856	0.785
M1D3A1P2a2h1	0.926	0.913	0.869	M3D1A2P3a3h3	0.711	0.805	0.703
M1D3A1P2a2h2*	0.779	0.945	0.816	M3D1A3P1a1h1	0.931	0.807	0.797
M1D3A1P2a2h3*	0.665	1.092	0.892	M3D1A3P1a1h2	0.828	0.667	0.632
M1D3A1P2a3h1	0.915	0.959	0.892	M3D1A3P1a1h3	0.708	0.611	0.553
M1D3A1P2a3h2*	0.784	1.002	0.861	M3D1A3P1a2h1	0.946	0.926	0.902
M1D3A1P2a3h3*	0.674	1.086	0.888	M3D1A3P1a2h2	0.848	0.736	0.695
M1D3A1P3a1h1*	0.883	0.961	0.920	M3D1A3P1a2h3	0.720	0.554	0.509
M1D3A1P3a1h2*	0.744	1.187	1.073	M3D1A3P1a3h1	0.939	0.915	0.888
M1D3A1P3a1h3*	0.629	1.500	1.315	M3D1A3P1a3h2	0.850	0.760	0.715
M1D3A1P3a2h1*	0.897	1.041	0.994	M3D1A3P1a3h3	0.736	0.617	0.561
M1D3A1P3a2h2*	0.771	1.276	1.153	M3D1A3P2a1h1	0.915	0.844	0.816
M1D3A1P3a2h3*	0.646	1.587	1.389	M3D1A3P2a1h2	0.786	0.717	0.655
M1D3A1P3a3h1*	0.924	1.062	1.024	M3D1A3P2a1h3	0.655	0.703	0.611
M1D3A1P3a3h2*	0.813	1.217	1.117	M3D1A3P2a2h1	0.932	0.907	0.882
M1D3A1P3a3h3*	0.688	1.486	1.316	M3D1A3P2a2h2	0.820	0.766	0.708
M1D3A2P1a1h1	0.833	0.825	0.799	M3D1A3P2a2h3	0.688	0.682	0.600
M1D3A2P1a1h2	0.710	0.725	0.678	M3D1A3P2a3h1	0.933	0.934	0.904
M1D3A2P1a1h3	0.604	0.624	0.582	M3D1A3P2a3h2	0.825	0.804	0.742
M1D3A2P1a2h1	0.851	0.881	0.848	M3D1A3P2a3h3	0.700	0.717	0.633
M1D3A2P1a2h2	0.731	0.743	0.710	M3D1A3P3a1h1	0.898	0.874	0.848
M1D3A2P1a2h3	0.639	0.727	0.701	M3D1A3P3a1h2	0.741	0.781	0.722
M1D3A2P1a3h1	0.869	0.929	0.891	M3D1A3P3a1h3	0.593	0.772	0.715
M1D3A2P1a3h2	0.745	0.783	0.745	M3D1A3P3a2h1	0.891	0.880	0.851
M1D3A2P1a3h3	0.631	0.652	0.616	M3D1A3P3a2h2	0.739	0.798	0.736
M1D3A2P2a1h1	0.822	0.809	0.762	M3D1A3P3a2h3	0.579	0.787	0.699
M1D3A2P2a1h2	0.664	0.774	0.751	M3D1A3P3a3h1	0.934	0.976	0.952
M1D3A2P2a1h3*	0.542	0.970	0.822	M3D1A3P3a3h2	0.795	0.867	0.812
M1D3A2P2a2h1	0.902	0.907	0.886	M3D1A3P3a3h3	0.644	0.813	0.734

Table D.8 Critical buckling limit ratios for specimens with two corrosion defects of $d_p/t = 0.3$, $d_s/t = 0.20$ - continue

Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}	Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}
M1D3A2P2a2h2	0.725	0.863	0.778	M3D2A1P1a1h1	0.919	0.790	0.786
M1D3A2P2a2h3*	0.582	0.833	0.716	M3D2A1P1a1h2	0.822	0.631	0.606
M1D3A2P2a3h1	0.886	0.950	0.913	M3D2A1P1a1h3	0.718	0.526	0.497
M1D3A2P2a3h2	0.724	0.907	0.808	M3D2A1P1a2h1	0.921	0.815	0.804
M1D3A2P2a3h3*	0.594	0.897	0.771	M3D2A1P1a2h2	0.818	0.626	0.602
M1D3A2P3a1h1	0.775	0.860	0.836	M3D2A1P1a2h3	0.706	0.486	0.467
M1D3A2P3a1h2*	0.560	0.946	0.884	M3D2A1P1a3h1	0.928	0.849	0.835
M1D3A2P3a1h3*	0.372	1.085	0.992	M3D2A1P1a3h2	0.832	0.667	0.628
M1D3A2P3a2h1	0.797	0.946	0.920	M3D2A1P1a3h3	0.727	0.548	0.516
M1D3A2P3a2h2*	0.599	1.075	1.010	M3D2A1P2a1h1	0.905	0.803	0.763
M1D3A2P3a2h3*	0.396	1.244	1.144	M3D2A1P2a1h2	0.789	0.726	0.635
M1D3A2P3a3h1	0.841	0.951	0.961	M3D2A1P2a1h3	0.676	0.675	0.624
M1D3A2P3a3h2*	0.662	1.078	1.024	M3D2A1P2a2h1	0.926	0.855	0.827
M1D3A2P3a3h3*	0.463	1.252	1.163	M3D2A1P2a2h2	0.823	0.742	0.662
M1D3A3P1a1h1	0.813	0.837	0.784	M3D2A1P2a2h3	0.712	0.708	0.591
M1D3A3P1a1h2	0.668	0.757	0.666	M3D2A1P2a3h1	0.925	0.892	0.851
M1D3A3P1a1h3	0.533	0.657	0.558	M3D2A1P2a3h2	0.828	0.778	0.690
M1D3A3P1a2h1	0.838	0.907	0.858	M3D2A1P2a3h3	0.720	0.708	0.594
M1D3A3P1a2h2	0.695	0.774	0.703	M3D2A1P3a1h1	0.898	0.843	0.805
M1D3A3P1a2h3	0.547	0.669	0.575	M3D2A1P3a1h2	0.776	0.828	0.763
M1D3A3P1a3h1	0.857	0.956	0.905	M3D2A1P3a1h3*	0.668	1.058	0.866
M1D3A3P1a3h2	0.712	0.810	0.737	M3D2A1P3a2h1	0.921	0.907	0.871
M1D3A3P1a3h3	0.565	0.674	0.585	M3D2A1P3a2h2	0.806	0.865	0.772
M1D3A3P2a1h1	0.791	0.810	0.753	M3D2A1P3a2h3*	0.689	0.976	0.811
M1D3A3P2a1h2	0.582	0.787	0.665	M3D2A1P3a3h1	0.920	0.931	0.890
M1D3A3P2a1h3	0.405	0.788	0.638	M3D2A1P3a3h2	0.816	0.881	0.791
M1D3A3P2a2h1	0.885	0.908	0.865	M3D2A1P3a3h3*	0.702	0.936	0.788
M1D3A3P2a2h2	0.670	0.839	0.740	M3D2A2P1a1h1	0.902	0.785	0.779
M1D3A3P2a2h3	0.473	0.762	0.611	M3D2A2P1a1h2	0.781	0.636	0.611
M1D3A3P2a3h1	0.862	0.950	0.896	M3D2A2P1a1h3	0.656	0.530	0.500
M1D3A3P2a3h2	0.664	0.896	0.797	M3D2A2P1a2h1	0.907	0.824	0.810
M1D3A3P2a3h3	0.477	0.839	0.704	M3D2A2P1a2h2	0.781	0.639	0.617
M1D3A3P3a1h1	F	F	F	M3D2A2P1a2h3	0.643	0.489	0.468
M1D3A3P3a1h2	F	F	F	M3D2A2P1a3h1	0.915	0.844	0.826
M1D3A3P3a1h3	F	F	F	M3D2A2P1a3h2	0.798	0.680	0.652
M1D3A3P3a2h1	F	F	F	M3D2A2P1a3h3	0.668	0.549	0.518
M1D3A3P3a2h2	F	F	F	M3D2A2P2a1h1	0.889	0.808	0.772
M1D3A3P3a2h3	F	F	F	M3D2A2P2a1h2	0.744	0.723	0.647
M1D3A3P3a3h1	F	F	F	M3D2A2P2a1h3	0.607	0.712	0.616
M1D3A3P3a3h2	F	F	F	M3D2A2P2a2h1	0.916	0.861	0.838

Table D.8 Critical buckling limit ratios for specimens with two corrosion defects of $d_p/t = 0.3$, $d_s/t = 0.20$ - continue

Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}	Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}
M1D3A3P3a3h3	F	F	F	M3D2A2P2a2h2	0.787	0.753	0.688
M2D1A1P1a1h1	0.954	0.789	0.778	M3D2A2P2a2h3	0.652	0.706	0.608
M2D1A1P1a1h2	0.890	0.624	0.580	M3D2A2P2a3h1	0.915	0.899	0.866
M2D1A1P1a1h3	0.813	0.550	0.473	M3D2A2P2a3h2	0.793	0.789	0.714
M2D1A1P1a2h1	0.959	0.918	0.879	M3D2A2P2a3h3	0.662	0.719	0.623
M2D1A1P1a2h2	0.903	0.707	0.651	M3D2A2P3a1h1	0.879	0.849	0.823
M2D1A1P1a2h3	0.825	0.548	0.478	M3D2A2P3a1h2	0.724	0.850	0.769
M2D1A1P1a3h1	0.954	0.875	0.843	M3D2A2P3a1h3*	0.587	0.994	0.855
M2D1A1P1a3h2	0.901	0.736	0.673	M3D2A2P3a2h1	0.908	0.909	0.878
M2D1A1P1a3h3	0.831	0.607	0.525	M3D2A2P3a2h2	0.762	0.863	0.792
M2D1A1P2a1h1	0.922	0.783	0.741	M3D2A2P3a2h3*	0.614	0.928	0.807
M2D1A1P2a1h2	0.836	0.648	0.560	M3D2A2P3a3h1	0.906	0.936	0.902
M2D1A1P2a1h3	0.751	0.621	0.496	M3D2A2P3a3h2	0.774	0.879	0.807
M2D1A1P2a2h1	0.930	0.832	0.789	M3D2A2P3a3h3*	0.632	0.909	0.798
M2D1A1P2a2h2	0.851	0.693	0.606	M3D2A3P1a1h1	0.882	0.796	0.789
M2D1A1P2a2h3	0.763	0.610	0.492	M3D2A3P1a1h2	0.733	0.650	0.625
M2D1A1P2a3h1	0.937	0.877	0.831	M3D2A3P1a1h3	0.588	0.534	0.494
M2D1A1P2a3h2	0.863	0.731	0.646	M3D2A3P1a2h1	0.890	0.837	0.821
M2D1A1P2a3h3	0.782	0.637	0.526	M3D2A3P1a2h2	0.734	0.650	0.624
M2D1A1P3a1h1	0.896	0.806	0.762	M3D2A3P1a2h3	0.576	0.498	0.465
M2D1A1P3a1h2	0.793	0.736	0.647	M3D2A3P1a3h1	0.903	0.869	0.855
M2D1A1P3a1h3*	0.699	0.778	0.646	M3D2A3P1a3h2	0.755	0.699	0.671
M2D1A1P3a2h1	0.885	0.801	0.752	M3D2A3P1a3h3	0.604	0.562	0.524
M2D1A1P3a2h2	0.782	0.751	0.655	M3D2A3P2a1h1	0.868	0.821	0.797
M2D1A1P3a2h3*	0.680	0.789	0.649	M3D2A3P2a1h2	0.690	0.706	0.644
M2D1A1P3a3h1	0.912	0.876	0.834	M3D2A3P2a1h3	0.534	0.675	0.582
M2D1A1P3a3h2	0.814	0.814	0.722	M3D2A3P2a2h1	0.900	0.865	0.845
M2D1A1P3a3h3*	0.714	0.822	0.688	M3D2A3P2a2h2	0.741	0.745	0.689
M2D1A2P1a1h1	0.941	0.774	0.766	M3D2A3P2a2h3	0.587	0.677	0.596
M2D1A2P1a1h2	0.860	0.615	0.578	M3D2A3P2a3h1	0.898	0.904	0.878
M2D1A2P1a1h3	0.760	0.532	0.472	M3D2A3P2a3h2	0.749	0.788	0.724
M2D1A2P1a2h1	0.951	0.906	0.876	M3D2A3P2a3h3	0.595	0.704	0.623
M2D1A2P1a2h2	0.877	0.697	0.651	M3D2A3P3a1h1	0.835	0.828	0.802
M2D1A2P1a2h3	0.780	0.543	0.484	M3D2A3P3a1h2	0.644	0.797	0.732
M2D1A2P1a3h1	0.945	0.880	0.852	M3D2A3P3a1h3*	0.478	0.863	0.759
M2D1A2P1a3h2	0.876	0.728	0.676	M3D2A3P3a2h1	0.872	0.897	0.875
M2D1A2P1a3h3	0.788	0.602	0.535	M3D2A3P3a2h2	0.690	0.827	0.770
M2D1A2P2a1h1	0.911	0.794	0.759	M3D2A3P3a2h3*	0.513	0.832	0.739
M2D1A2P2a1h2	0.805	0.655	0.585	M3D2A3P3a3h1	0.870	0.927	0.905
M2D1A2P2a1h3	0.698	0.628	0.527	M3D2A3P3a3h2	0.705	0.851	0.793

Table D.8 Critical buckling limit ratios for specimens with two corrosion defects of $d_p/t = 0.3$, $d_s/t = 0.20$ - continue

Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}	Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}
M2D1A2P2a2h1	0.920	0.846	0.810	M3D2A3P3a3h3*	0.534	0.838	0.748
M2D1A2P2a2h2	0.824	0.704	0.632	M3D3A1P1a1h1	0.889	0.755	0.758
M2D1A2P2a2h3	0.713	0.622	0.526	M3D3A1P1a1h2	0.758	0.563	0.565
M2D1A2P2a3h1	0.929	0.893	0.856	M3D3A1P1a1h3	0.652	0.464	0.464
M2D1A2P2a3h2	0.839	0.746	0.676	M3D3A1P1a2h1	0.884	0.744	0.749
M2D1A2P2a3h3	0.737	0.651	0.559	M3D3A1P1a2h2	0.763	0.563	0.571
M2D1A2P3a1h1	0.875	0.815	0.781	M3D3A1P1a2h3	0.653	0.480	0.475
M2D1A2P3a1h2	0.742	0.736	0.669	M3D3A1P1a3h1	0.891	0.762	0.766
M2D1A2P3a1h3*	0.618	0.768	0.671	M3D3A1P1a3h2	0.767	0.572	0.575
M2D1A2P3a2h1	0.863	0.811	0.772	M3D3A1P1a3h3	0.664	0.490	0.486
M2D1A2P3a2h2	0.729	0.754	0.681	M3D3A1P2a1h1	0.880	0.802	0.785
M2D1A2P3a2h3*	0.594	0.784	0.680	M3D3A1P2a1h2	0.738	0.773	0.684
M2D1A2P3a3h1	0.896	0.886	0.854	M3D3A1P2a1h3*	0.621	1.139	0.889
M2D1A2P3a3h2	0.770	0.822	0.752	M3D3A1P2a2h1	0.897	0.839	0.824
M2D1A2P3a3h3*	0.640	0.826	0.725	M3D3A1P2a2h2	0.774	0.772	0.703
M2D1A3P1a1h1	0.927	0.784	0.775	M3D3A1P2a2h3	0.658	0.746	0.665
M2D1A3P1a1h2	0.823	0.630	0.597	M3D3A1P2a3h1	0.905	0.862	0.846
M2D1A3P1a1h3	0.690	0.552	0.503	M3D3A1P2a3h2	0.787	0.777	0.714
M2D1A3P1a2h1	0.943	0.915	0.890	M3D3A1P2a3h3	0.669	0.707	0.616
M2D1A3P1a2h2	0.846	0.714	0.674	M3D3A1P3a1h1	0.870	0.842	0.798
M2D1A3P1a2h3	0.721	0.560	0.512	M3D3A1P3a1h2*	0.736	0.949	0.825
M2D1A3P1a3h1	0.936	0.904	0.877	M3D3A1P3a1h3*	0.625	1.248	1.010
M2D1A3P1a3h2	0.846	0.746	0.701	M3D3A1P3a2h1	0.908	0.885	0.860
M2D1A3P1a3h3	0.733	0.620	0.564	M3D3A1P3a2h2	0.777	0.871	0.782
M2D1A3P2a1h1	0.894	0.805	0.777	M3D3A1P3a2h3*	0.651	1.069	0.887
M2D1A3P2a1h2	0.756	0.668	0.612	M3D3A1P3a3h1	0.901	0.926	0.886
M2D1A3P2a1h3	0.615	0.650	0.572	M3D3A1P3a3h2	0.782	0.909	0.808
M2D1A3P2a2h1	0.906	0.856	0.827	M3D3A1P3a3h3*	0.661	1.063	0.886
M2D1A3P2a2h2	0.783	0.717	0.661	M3D3A2P1a1h1	0.876	0.771	0.770
M2D1A3P2a2h3	0.636	0.643	0.569	M3D3A2P1a1h2	0.708	0.571	0.570
M2D1A3P2a3h1	0.918	0.906	0.877	M3D3A2P1a1h3	0.584	0.475	0.464
M2D1A3P2a3h2	0.802	0.761	0.706	M3D3A2P1a2h1	0.870	0.765	0.768
M2D1A3P2a3h3	0.669	0.671	0.599	M3D3A2P1a2h2	0.711	0.575	0.574
M2D1A3P3a1h1	0.841	0.822	0.797	M3D3A2P1a2h3	0.587	0.494	0.479
M2D1A3P3a1h2	0.656	0.745	0.697	M3D3A2P1a3h1	0.879	0.781	0.783
M2D1A3P3a1h3*	0.486	0.752	0.688	M3D3A2P1a3h2	0.724	0.591	0.589
M2D1A3P3a2h1	0.824	0.818	0.791	M3D3A2P1a3h3	0.598	0.501	0.488
M2D1A3P3a2h2	0.639	0.763	0.712	M3D3A2P2a1h1	0.857	0.720	0.714
M2D1A3P3a2h3*	0.455	0.766	0.697	M3D3A2P2a1h2	0.682	0.675	0.612
M2D1A3P3a3h1	0.869	0.894	0.871	M3D3A2P2a1h3*	0.540	0.773	0.655

Table D.8 Critical buckling limit ratios for specimens with two corrosion defects of $d_p/t = 0.3$, $d_s/t = 0.20$ - continue

Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}	Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}
M2D1A3P3a3h2	0.696	0.833	0.784	M3D3A2P2a2h1	0.878	0.755	0.752
M2D1A3P3a3h3*	0.517	0.831	0.763	M3D3A2P2a2h2	0.725	0.683	0.639
M2D2A1P1a1h1	0.926	0.794	0.781	M3D3A2P2a2h3*	0.580	0.634	0.562
M2D2A1P1a1h2	0.832	0.620	0.583	M3D3A2P2a3h1	0.887	0.774	0.771
M2D2A1P1a1h3	0.727	0.517	0.467	M3D3A2P2a3h2	0.740	0.695	0.657
M2D2A1P1a2h1	0.928	0.834	0.809	M3D3A2P2a3h3*	0.599	0.624	0.560
M2D2A1P1a2h2	0.833	0.644	0.602	M3D3A2P3a1h1	0.843	0.842	0.812
M2D2A1P1a2h3	0.722	0.481	0.444	M3D3A2P3a1h2*	0.672	0.889	0.793
M2D2A1P1a3h1	0.935	0.867	0.840	M3D3A2P3a1h3*	0.532	1.091	0.922
M2D2A1P1a3h2	0.848	0.691	0.643	M3D3A2P3a2h1	0.890	0.885	0.865
M2D2A1P1a3h3	0.748	0.552	0.502	M3D3A2P3a2h2	0.726	0.847	0.770
M2D2A1P2a1h1	0.907	0.795	0.755	M3D3A2P3a2h3*	0.569	0.934	0.804
M2D2A1P2a1h2	0.796	0.713	0.618	M3D3A2P3a3h1	0.880	0.926	0.894
M2D2A1P2a1h3	0.686	0.675	0.615	M3D3A2P3a3h2	0.729	0.899	0.820
M2D2A1P2a2h1	0.932	0.862	0.833	M3D3A2P3a3h3*	0.581	0.964	0.832
M2D2A1P2a2h2	0.834	0.733	0.655	M3D3A3P1a1h1	0.846	0.777	0.770
M2D2A1P2a2h3	0.727	0.678	0.563	M3D3A3P1a1h2	0.655	0.581	0.554
M2D2A1P2a3h1	0.925	0.890	0.844	M3D3A3P1a1h3	0.514	0.478	0.432
M2D2A1P2a3h2	0.834	0.777	0.686	M3D3A3P1a2h1	0.843	0.778	0.770
M2D2A1P2a3h3	0.731	0.720	0.594	M3D3A3P1a2h2	0.655	0.580	0.554
M2D2A1P3a1h1	0.884	0.831	0.790	M3D3A3P1a2h3	0.517	0.498	0.449
M2D2A1P3a1h2	0.766	0.772	0.758	M3D3A3P1a3h1	0.852	0.793	0.786
M2D2A1P3a1h3*	0.660	1.039	0.863	M3D3A3P1a3h2	0.669	0.597	0.573
M2D2A1P3a2h1	0.893	0.879	0.833	M3D3A3P1a3h3	0.533	0.511	0.464
M2D2A1P3a2h2	0.782	0.902	0.794	M3D3A3P2a1h1	0.829	0.805	0.778
M2D2A1P3a2h3*	0.669	1.051	0.874	M3D3A3P2a1h2	0.630	0.713	0.635
M2D2A1P3a3h1	0.910	0.915	0.874	M3D3A3P2a1h3	0.464	0.695	0.567
M2D2A1P3a3h2	0.813	0.898	0.830	M3D3A3P2a2h1	0.855	0.848	0.823
M2D2A1P3a3h3*	0.696	0.957	0.812	M3D3A3P2a2h2	0.678	0.753	0.685
M2D2A2P1a1h1	0.913	0.805	0.787	M3D3A3P2a2h3	0.515	0.723	0.608
M2D2A2P1a1h2	0.789	0.638	0.602	M3D3A3P2a3h1	0.866	0.867	0.841
M2D2A2P1a1h3	0.647	0.539	0.493	M3D3A3P2a3h2	0.688	0.766	0.697
M2D2A2P1a2h1	0.916	0.849	0.820	M3D3A3P2a3h3	0.536	0.677	0.578
M2D2A2P1a2h2	0.793	0.665	0.626	M3D3A3P3a1h1	0.807	0.834	0.798
M2D2A2P1a2h3	0.644	0.493	0.461	M3D3A3P3a1h2	0.596	0.836	0.742
M2D2A2P1a3h1	0.925	0.879	0.849	M3D3A3P3a1h3*	0.414	0.945	0.800
M2D2A2P1a3h2	0.811	0.713	0.669	M3D3A3P3a2h1	0.862	0.882	0.854
M2D2A2P1a3h3	0.679	0.567	0.525	M3D3A3P3a2h2	0.663	0.827	0.753
M2D2A2P2a1h1	0.889	0.799	0.765	M3D3A3P3a2h3*	0.468	0.833	0.704
M2D2A2P2a1h2	0.741	0.725	0.648	M3D3A3P3a3h1	0.851	0.910	0.869

Table D.8 Critical buckling limit ratios for specimens with two corrosion defects of $d_p/t = 0.3$, $d_s/t = 0.20$ - continue

Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}	Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}
M2D2A2P2a1h3	0.596	0.706	0.630	M3D3A3P3a3h2	0.669	0.865	0.775
M2D2A2P2a2h1	0.921	0.866	0.839	M3D3A3P3a3h3*	0.481	0.887	0.758
M2D2A2P2a2h2	0.794	0.738	0.673				

Table D.9 Critical buckling limit ratios for specimens with two corrosion defects of $d_p/t = 0.40$, $d_s/t = 0.10$

Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}	Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}
M1D1A1P1a1h1	0.948	0.698	0.674	M2D2A2P2a2h3*	0.542	0.966	0.788
M1D1A1P1a1h2	0.867	0.520	0.437	M2D2A2P2a3h1	0.880	0.919	0.853
M1D1A1P1a1h3	0.777	0.491	0.378	M2D2A2P2a3h2	0.722	0.847	0.735
M1D1A1P1a2h1	0.953	0.831	0.777	M2D2A2P2a3h3*	0.556	0.923	0.758
M1D1A1P1a2h2	0.885	0.635	0.531	M2D2A2P3a1h1	0.781	0.800	0.757
M1D1A1P1a2h3	0.788	0.420	0.330	M2D2A2P3a1h2*	0.614	0.952	0.853
M1D1A1P1a3h1	0.947	0.848	0.775	M2D2A2P3a1h3*	0.465	1.151	1.001
M1D1A1P1a3h2	0.886	0.746	0.609	M2D2A2P3a2h1	0.785	0.856	0.805
M1D1A1P1a3h3	0.799	0.512	0.396	M2D2A2P3a2h2*	0.615	1.039	0.925
M1D1A1P2a1h1	0.894	0.660	0.607	M2D2A2P3a2h3*	0.456	1.249	1.082
M1D1A1P2a1h2	0.801	0.569	0.464	M2D2A2P3a3h1	0.845	0.953	0.901
M1D1A1P2a1h3	0.710	0.524	0.441	M2D2A2P3a3h2*	0.685	1.049	0.945
M1D1A1P2a2h1	0.896	0.700	0.636	M2D2A2P3a3h3*	0.512	1.208	1.053
M1D1A1P2a2h2	0.791	0.588	0.470	M2D2A3P1a1h1	0.864	0.750	0.744
M1D1A1P2a2h3	0.690	0.580	0.448	M2D2A3P1a1h2	0.660	0.547	0.517
M1D1A1P2a3h1	0.932	0.921	0.841	M2D2A3P1a1h3	0.469	0.434	0.377
M1D1A1P2a3h2	0.842	0.794	0.650	M2D2A3P1a2h1	0.854	0.796	0.777
M1D1A1P2a3h3	0.732	0.676	0.511	M2D2A3P1a2h2	0.642	0.571	0.532
M1D1A1P3a1h1	0.831	0.750	0.696	M2D2A3P1a2h3	0.449	0.381	0.338
M1D1A1P3a1h2*	0.722	0.814	0.713	M2D2A3P1a3h1	0.870	0.872	0.844
M1D1A1P3a1h3*	0.625	1.003	0.849	M2D2A3P1a3h2	0.665	0.668	0.619
M1D1A1P3a2h1	0.788	0.759	0.685	M2D2A3P1a3h3	0.476	0.464	0.410
M1D1A1P3a2h2*	0.676	0.914	0.782	M2D2A3P2a1h1	0.791	0.730	0.701
M1D1A1P3a2h3*	0.563	1.126	0.940	M2D2A3P2a1h2	0.573	0.731	0.651
M1D1A1P3a3h1	0.789	0.807	0.724	M2D2A3P2a1h3*	0.395	0.856	0.725
M1D1A1P3a3h2*	0.675	0.997	0.849	M2D2A3P2a2h1	0.866	0.866	0.836
M1D1A1P3a3h3*	0.554	1.204	0.999	M2D2A3P2a2h2	0.652	0.727	0.662
M1D1A2P1a1h1	0.928	0.678	0.659	M2D2A3P2a2h3	0.434	0.692	0.590
M1D1A2P1a1h2	0.811	0.543	0.476	M2D2A3P2a3h1	0.844	0.934	0.890
M1D1A2P1a1h3	0.681	0.532	0.466	M2D2A3P2a3h2	0.644	0.815	0.738
M1D1A2P1a2h1	0.941	0.846	0.802	M2D2A3P2a3h3	0.451	0.766	0.654
M1D1A2P1a2h2	0.846	0.671	0.585	M2D2A3P3a1h1	0.696	0.773	0.735

Table D.9 Critical buckling limit ratios for specimens with two corrosion defects of $d_p/t = 0.40$, $d_s/t = 0.10$ - continue

Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}	Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}
M1D1A2P1a2h3	0.703	0.574	0.477	M2D2A3P3a1h2*	0.465	0.859	0.783
M1D1A2P1a3h1	0.934	0.879	0.817	M2D2A3P3a1h3*	0.251	0.990	0.884
M1D1A2P1a3h2	0.849	0.764	0.658	M2D2A3P3a2h1	0.701	0.830	0.790
M1D1A2P1a3h3	0.719	0.537	0.454	M2D2A3P3a2h2*	0.464	0.949	0.869
M1D1A2P2a1h1	0.871	0.674	0.633	M2D2A3P3a2h3*	0.234	1.093	0.981
M1D1A2P2a1h2	0.740	0.617	0.533	M2D2A3P3a3h1	0.786	0.946	0.910
M1D1A2P2a1h3*	0.606	0.710	0.587	M2D2A3P3a3h2*	0.563	1.002	0.930
M1D1A2P2a2h1	0.873	0.717	0.668	M2D2A3P3a3h3*	0.320	1.097	0.993
M1D1A2P2a2h2	0.726	0.646	0.552	M2D3A1P1a1h1	0.880	0.704	0.697
M1D1A2P2a2h3*	0.578	0.718	0.591	M2D3A1P1a1h2	0.738	0.590	0.578
M1D1A2P2a3h1	0.921	0.949	0.890	M2D3A1P1a1h3	0.552	0.335	0.343
M1D1A2P2a3h2	0.800	0.825	0.718	M2D3A1P1a2h1	0.875	0.739	0.717
M1D1A2P2a3h3	0.640	0.760	0.628	M2D3A1P1a2h2	0.712	0.577	0.541
M1D1A2P3a1h1	0.763	0.756	0.722	M2D3A1P1a2h3	0.644	0.493	0.398
M1D1A2P3a1h2*	0.594	0.823	0.760	M2D3A1P1a3h1	0.881	0.804	0.764
M1D1A2P3a1h3*	0.443	1.004	0.912	M2D3A1P1a3h2	0.712	0.534	0.508
M1D1A2P3a2h1	0.699	0.765	0.719	M2D3A1P1a3h3	0.589	0.421	0.407
M1D1A2P3a2h2*	0.523	0.933	0.852	M2D3A1P2a1h1	0.839	0.731	0.674
M1D1A2P3a2h3*	0.351	1.109	1.000	M2D3A1P2a1h2*	0.692	1.053	0.829
M1D1A2P3a3h1	0.701	0.814	0.763	M2D3A1P2a1h3*	0.583	1.462	1.075
M1D1A2P3a3h2*	0.523	1.014	0.924	M2D3A1P2a2h1	0.878	0.829	0.771
M1D1A2P3a3h3*	0.340	1.188	1.069	M2D3A1P2a2h2*	0.727	0.899	0.736
M1D1A3P1a1h1	0.901	0.699	0.684	M2D3A1P2a2h3*	0.672	1.871	1.372
M1D1A3P1a1h2	0.715	0.585	0.540	M2D3A1P2a3h1	0.884	0.896	0.820
M1D1A3P1a1h3	0.558	0.527	0.472	M2D3A1P2a3h2*	0.735	0.913	0.749
M1D1A3P1a2h1	0.927	0.887	0.853	M2D3A1P2a3h3*	0.606	1.322	0.986
M1D1A3P1a2h2	0.777	0.773	0.709	M2D3A1P3a1h1	0.821	0.908	0.833
M1D1A3P1a2h3	0.615	0.611	0.577	M2D3A1P3a1h2*	0.687	1.128	0.961
M1D1A3P1a3h1	0.917	0.941	0.894	M2D3A1P3a1h3*	0.573	1.489	1.213
M1D1A3P1a3h2	0.783	0.834	0.760	M2D3A1P3a2h1	0.846	0.919	0.851
M1D1A3P1a3h3	0.614	0.566	0.509	M2D3A1P3a2h2*	0.714	1.155	0.987
M1D1A3P2a1h1	0.821	0.702	0.674	M2D3A1P3a2h3*	0.592	1.508	1.230
M1D1A3P2a1h2	0.624	0.618	0.569	M2D3A1P3a3h1	0.863	0.947	0.920
M1D1A3P2a1h3	0.458	0.573	0.512	M2D3A1P3a3h2*	0.747	1.209	1.034
M1D1A3P2a2h1	0.826	0.746	0.713	M2D3A1P3a3h3*	0.626	1.562	1.275
M1D1A3P2a2h2	0.608	0.637	0.583	M2D3A2P1a1h1	0.850	0.718	0.715
M1D1A3P2a2h3	0.426	0.569	0.506	M2D3A2P1a1h2	0.669	0.567	0.544
M1D1A3P2a3h1	0.900	0.974	0.936	M2D3A2P1a1h3	0.452	0.343	0.329
M1D1A3P2a3h2	0.713	0.865	0.798	M2D3A2P1a2h1	0.842	0.758	0.743
M1D1A3P2a3h3	0.497	0.701	0.628	M2D3A2P1a2h2	0.640	0.601	0.566

Table D.9 Critical buckling limit ratios for specimens with two corrosion defects of $d_p/t = 0.40$, $d_s/t = 0.10$ - continue

Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}	Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}
M1D1A3P3a1h1	0.593	0.755	0.748	M2D3A2P1a2h3	0.548	0.523	0.429
M1D1A3P3a1h2*	0.259	0.789	0.790	M2D3A2P1a3h1	0.849	0.817	0.787
M1D1A3P3a1h3	F	F	F	M2D3A2P1a3h2	0.628	0.546	0.522
M1D1A3P3a2h1	0.469	0.761	0.769	M2D3A2P1a3h3	0.488	0.430	0.402
M1D1A3P3a2h2	F	F	F	M2D3A2P2a1h1	0.788	0.722	0.682
M1D1A3P3a2h3	F	F	F	M2D3A2P2a1h2*	0.600	0.951	0.804
M1D1A3P3a3h1	0.473	0.815	0.827	M2D3A2P2a1h3*	0.466	1.215	0.976
M1D1A3P3a3h2	F	F	F	M2D3A2P2a2h1	0.843	0.833	0.792
M1D1A3P3a3h3	F	F	F	M2D3A2P2a2h2*	0.651	0.835	0.726
M1D2A1P1a1h1	0.908	0.723	0.678	M2D3A2P2a2h3*	0.485	1.122	0.910
M1D2A1P1a1h2	0.790	0.656	0.578	M2D3A2P2a3h1	0.852	0.902	0.847
M1D2A1P1a1h3	0.679	0.559	0.477	M2D3A2P2a3h2	0.659	0.859	0.750
M1D2A1P1a2h1	0.910	0.847	0.763	M2D3A2P2a3h3*	0.496	1.080	0.878
M1D2A1P1a2h2	0.803	0.677	0.595	M2D3A2P3a1h1	0.760	0.899	0.850
M1D2A1P1a2h3	0.663	0.429	0.407	M2D3A2P3a1h2*	0.571	1.034	0.931
M1D2A1P1a3h1	0.923	0.938	0.833	M2D3A2P3a1h3*	0.415	1.271	1.109
M1D2A1P1a3h2	0.834	0.915	0.764	M2D3A2P3a2h1	0.789	0.913	0.872
M1D2A1P1a3h3	0.690	0.536	0.482	M2D3A2P3a2h2*	0.607	1.091	0.986
M1D2A1P2a1h1	0.871	0.697	0.625	M2D3A2P3a2h3*	0.441	1.332	1.166
M1D2A1P2a1h2*	0.746	0.947	0.746	M2D3A2P3a3h1	0.818	0.944	0.956
M1D2A1P2a1h3*	0.639	1.228	0.923	M2D3A2P3a3h2*	0.658	1.184	1.073
M1D2A1P2a2h1	0.898	0.786	0.710	M2D3A2P3a3h3*	0.494	1.449	1.272
M1D2A1P2a2h2*	0.762	0.971	0.766	M2D3A3P1a1h1	0.805	0.717	0.702
M1D2A1P2a2h3*	0.653	1.233	0.927	M2D3A3P1a1h2	0.600	0.547	0.499
M1D2A1P2a3h1	0.908	0.905	0.806	M2D3A3P1a1h3	0.355	0.341	0.273
M1D2A1P2a3h2*	0.793	0.933	0.746	M2D3A3P1a2h1	0.794	0.752	0.725
M1D2A1P2a3h3*	0.668	1.151	0.873	M2D3A3P1a2h2	0.568	0.603	0.571
M1D2A1P3a1h1	0.817	0.822	0.761	M2D3A3P1a2h3	0.443	0.537	0.442
M1D2A1P3a1h2*	0.701	1.029	0.901	M2D3A3P1a3h1	0.807	0.825	0.789
M1D2A1P3a1h3*	0.591	1.315	1.119	M2D3A3P1a3h2	0.558	0.549	0.491
M1D2A1P3a2h1	0.797	0.904	0.822	M2D3A3P1a3h3	0.397	0.438	0.363
M1D2A1P3a2h2*	0.679	1.180	1.020	M2D3A3P2a1h1	0.745	0.715	0.672
M1D2A1P3a2h3*	0.555	1.473	1.244	M2D3A3P2a1h2*	0.512	0.835	0.713
M1D2A1P3a3h1	0.840	0.945	0.940	M2D3A3P2a1h3*	0.337	0.989	0.809
M1D2A1P3a3h2*	0.719	1.340	1.163	M2D3A3P2a2h1	0.808	0.832	0.798
M1D2A1P3a3h3*	0.586	1.688	1.428	M2D3A3P2a2h2	0.575	0.786	0.685
M1D2A2P1a1h1	0.860	0.768	0.749	M2D3A3P2a2h3*	0.363	0.869	0.710
M1D2A2P1a1h2	0.687	0.698	0.652	M2D3A3P2a3h1	0.818	0.904	0.862
M1D2A2P1a1h3	0.552	0.673	0.581	M2D3A3P2a3h2	0.588	0.805	0.704
M1D2A2P1a2h1	0.873	0.935	0.885	M2D3A3P2a3h3	0.379	0.769	0.678

Table D.9 Critical buckling limit ratios for specimens with two corrosion defects of $d_p/t = 0.40$, $d_s/t = 0.10$ - continue

Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}	Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}
M1D2A2P1a2h2	0.714	0.797	0.732	M2D3A3P3a1h1*	0.677	0.864	0.801
M1D2A2P1a2h3	0.549	0.462	0.440	M2D3A3P3a1h2*	0.386	0.927	0.821
M1D2A2P1a3h1	0.895	0.944	0.955	M2D3A3P3a1h3*	0.134	1.095	0.956
M1D2A2P1a3h2	0.763	0.796	0.777	M2D3A3P3a2h1*	0.712	0.884	0.833
M1D2A2P1a3h3	0.586	0.619	0.597	M2D3A3P3a2h2*	0.441	1.007	0.908
M1D2A2P2a1h1	0.804	0.721	0.677	M2D3A3P3a2h3*	0.173	1.178	1.043
M1D2A2P2a1h2*	0.634	0.853	0.744	M2D3A3P3a3h1*	0.758	0.995	0.942
M1D2A2P2a1h3*	0.500	0.940	0.795	M2D3A3P3a3h2*	0.521	1.135	1.040
M1D2A2P2a2h1	0.849	0.818	0.768	M2D3A3P3a3h3*	0.263	1.349	1.217
M1D2A2P2a2h2*	0.654	0.908	0.792	M3D1A1P1a1h1	0.942	0.764	0.750
M1D2A2P2a2h3*	0.516	0.974	0.825	M3D1A1P1a1h2	0.851	0.613	0.558
M1D2A2P2a3h1	0.869	0.956	0.888	M3D1A1P1a1h3	0.738	0.572	0.474
M1D2A2P2a3h2	0.695	0.924	0.811	M3D1A1P1a2h1	0.944	0.843	0.807
M1D2A2P2a3h3	0.544	0.898	0.766	M3D1A1P1a2h2	0.854	0.655	0.587
M1D2A2P3a1h1*	0.702	0.821	0.794	M3D1A1P1a2h3	0.729	0.494	0.467
M1D2A2P3a1h2*	0.513	0.968	0.908	M3D1A1P1a3h1	0.939	0.865	0.815
M1D2A2P3a1h3*	0.339	1.141	1.053	M3D1A1P1a3h2	0.867	0.761	0.667
M1D2A2P3a2h1*	0.668	0.898	0.861	M3D1A1P1a3h3	0.754	0.537	0.456
M1D2A2P3a2h2*	0.478	1.114	1.039	M3D1A1P2a1h1	0.905	0.751	0.701
M1D2A2P3a2h3*	0.282	1.296	1.193	M3D1A1P2a1h2	0.801	0.687	0.574
M1D2A2P3a3h1*	0.741	1.034	0.995	M3D1A1P2a1h3	0.694	0.628	0.557
M1D2A2P3a3h2*	0.540	1.320	1.236	M3D1A1P2a2h1	0.929	0.868	0.811
M1D2A2P3a3h3*	0.328	1.589	1.467	M3D1A1P2a2h2	0.820	0.702	0.593
M1D2A3P1a1h1	0.815	0.760	0.728	M3D1A1P2a2h3	0.700	0.672	0.518
M1D2A3P1a1h2	0.619	0.643	0.584	M3D1A1P2a3h1	0.925	0.929	0.846
M1D2A3P1a1h3	0.455	0.551	0.473	M3D1A1P2a3h2	0.832	0.807	0.672
M1D2A3P1a2h1	0.833	0.961	0.909	M3D1A1P2a3h3	0.717	0.697	0.540
M1D2A3P1a2h2	0.654	0.777	0.706	M3D1A1P3a1h1	0.884	0.786	0.732
M1D2A3P1a2h3	0.464	0.484	0.419	M3D1A1P3a1h2	0.775	0.763	0.682
M1D2A3P1a3h1	0.859	0.931	0.928	M3D1A1P3a1h3*	0.673	0.938	0.746
M1D2A3P1a3h2	0.707	0.744	0.712	M3D1A1P3a2h1	0.875	0.798	0.733
M1D2A3P1a3h3	0.485	0.617	0.534	M3D1A1P3a2h2	0.754	0.752	0.696
M1D2A3P2a1h1	0.753	0.678	0.644	M3D1A1P3a2h3*	0.640	0.985	0.770
M1D2A3P2a1h2	0.537	0.697	0.615	M3D1A1P3a3h1	0.926	0.980	0.911
M1D2A3P2a1h3*	0.352	0.675	0.573	M3D1A1P3a3h2	0.800	0.919	0.774
M1D2A3P2a2h1	0.805	0.795	0.762	M3D1A1P3a3h3*	0.682	0.965	0.764
M1D2A3P2a2h2	0.561	0.760	0.676	M3D1A2P1a1h1	0.928	0.756	0.744
M1D2A3P2a2h3*	0.371	0.723	0.618	M3D1A2P1a1h2	0.814	0.596	0.551
M1D2A3P2a3h1	0.827	0.936	0.893	M3D1A2P1a1h3	0.678	0.563	0.483
M1D2A3P2a3h2	0.616	0.847	0.763	M3D1A2P1a2h1	0.934	0.848	0.817

Table D.9 Critical buckling limit ratios for specimens with two corrosion defects of $d_p/t = 0.40$, $d_s/t = 0.10$ - continue

Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}	Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}
M1D2A3P2a3h3	0.414	0.747	0.644	M3D1A2P1a2h2	0.824	0.665	0.603
M1D2A3P3a1h1*	0.360	0.778	0.773	M3D1A2P1a2h3	0.691	0.538	0.510
M1D2A3P3a1h2	F	F	F	M3D1A2P1a3h1	0.929	0.878	0.833
M1D2A3P3a1h3	F	F	F	M3D1A2P1a3h2	0.839	0.761	0.681
M1D2A3P3a2h1*	0.277	0.855	0.882	M3D1A2P1a3h3	0.705	0.541	0.470
M1D2A3P3a2h2	F	F	F	M3D1A2P2a1h1	0.892	0.760	0.718
M1D2A3P3a2h3	F	F	F	M3D1A2P2a1h2	0.767	0.691	0.597
M1D2A3P3a3h1*	0.448	1.023	1.098	M3D1A2P2a1h3	0.637	0.682	0.590
M1D2A3P3a3h2	F	F	F	M3D1A2P2a2h1	0.921	0.878	0.830
M1D2A3P3a3h3	F	F	F	M3D1A2P2a2h2	0.791	0.712	0.619
M1D3A1P1a1h1	0.894	0.874	0.847	M3D1A2P2a2h3	0.645	0.679	0.551
M1D3A1P1a1h2	0.795	0.730	0.690	M3D1A2P2a3h1	0.917	0.944	0.874
M1D3A1P1a1h3	0.600	0.496	0.515	M3D1A2P2a3h2	0.806	0.821	0.707
M1D3A1P1a2h1	0.900	0.947	0.960	M3D1A2P2a3h3	0.667	0.711	0.579
M1D3A1P1a2h2	0.767	0.812	0.792	M3D1A2P3a1h1	0.865	0.790	0.745
M1D3A1P1a2h3	0.626	0.599	0.589	M3D1A2P3a1h2	0.730	0.769	0.702
M1D3A1P1a3h1	0.910	0.960	0.912	M3D1A2P3a1h3*	0.604	0.925	0.774
M1D3A1P1a3h2	0.816	0.665	0.683	M3D1A2P3a2h1	0.855	0.803	0.749
M1D3A1P1a3h3	0.696	0.533	0.557	M3D1A2P3a2h2	0.706	0.783	0.721
M1D3A1P2a1h1	0.801	0.934	0.818	M3D1A2P3a2h3*	0.563	0.969	0.801
M1D3A1P2a1h2*	0.696	1.240	1.002	M3D1A2P3a3h1	0.917	0.953	0.933
M1D3A1P2a1h3*	0.595	1.639	1.258	M3D1A2P3a3h2	0.762	0.923	0.806
M1D3A1P2a2h1	0.899	0.960	0.878	M3D1A2P3a3h3*	0.616	0.961	0.801
M1D3A1P2a2h2*	0.727	1.187	0.973	M3D1A3P1a1h1	0.909	0.749	0.740
M1D3A1P2a2h3*	0.612	1.547	1.196	M3D1A3P1a1h2	0.771	0.596	0.559
M1D3A1P2a3h1	0.864	0.945	0.915	M3D1A3P1a1h3	0.607	0.562	0.496
M1D3A1P2a3h2*	0.736	1.183	0.971	M3D1A3P1a2h1	0.924	0.863	0.834
M1D3A1P2a3h3*	0.617	1.525	1.182	M3D1A3P1a2h2	0.789	0.686	0.632
M1D3A1P3a1h1*	0.814	1.018	0.950	M3D1A3P1a2h3	0.648	0.594	0.565
M1D3A1P3a1h2*	0.687	1.343	1.192	M3D1A3P1a3h1	0.918	0.899	0.859
M1D3A1P3a1h3*	0.572	1.688	1.465	M3D1A3P1a3h2	0.806	0.777	0.711
M1D3A1P3a2h1*	0.818	1.123	1.037	M3D1A3P1a3h3	0.649	0.575	0.511
M1D3A1P3a2h2*	0.690	1.500	1.323	M3D1A3P2a1h1	0.874	0.768	0.733
M1D3A1P3a2h3*	0.560	1.882	1.624	M3D1A3P2a1h2	0.720	0.700	0.623
M1D3A1P3a3h1*	0.899	1.225	1.148	M3D1A3P2a1h3	0.562	0.685	0.613
M1D3A1P3a3h2*	0.786	1.748	1.550	M3D1A3P2a2h1	0.911	0.888	0.849
M1D3A1P3a3h3*	0.647	2.318	2.000	M3D1A3P2a2h2	0.751	0.724	0.649
M1D3A2P1a1h1	0.818	0.800	0.779	M3D1A3P2a2h3	0.572	0.677	0.576
M1D3A2P1a1h2	0.703	0.620	0.590	M3D1A3P2a3h1	0.906	0.958	0.901
M1D3A2P1a1h3	0.488	0.465	0.433	M3D1A3P2a3h2	0.769	0.835	0.742

Table D.9 Critical buckling limit ratios for specimens with two corrosion defects of $d_p/t = 0.40$, $d_s/t = 0.10$ - continue

Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}	Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}
M1D3A2P1a2h1	0.834	0.941	0.921	M3D1A3P2a3h3	0.603	0.738	0.627
M1D3A2P1a2h2	0.710	0.877	0.919	M3D1A3P3a1h1	0.838	0.797	0.762
M1D3A2P1a2h3	0.512	0.546	0.499	M3D1A3P3a1h2*	0.667	0.799	0.725
M1D3A2P1a3h1	0.844	0.887	0.850	M3D1A3P3a1h3*	0.508	0.897	0.786
M1D3A2P1a3h2	0.730	0.621	0.611	M3D1A3P3a2h1	0.826	0.811	0.770
M1D3A2P1a3h3	0.583	0.515	0.488	M3D1A3P3a2h2*	0.637	0.830	0.744
M1D3A2P2a1h1*	0.749	0.826	0.748	M3D1A3P3a2h3*	0.459	0.921	0.800
M1D3A2P2a1h2*	0.613	1.008	0.867	M3D1A3P3a3h1	0.905	0.934	0.960
M1D3A2P2a1h3*	0.471	1.253	1.037	M3D1A3P3a3h2*	0.708	0.930	0.842
M1D3A2P2a2h1*	0.864	0.948	0.900	M3D1A3P3a3h3*	0.525	0.946	0.827
M1D3A2P2a2h2*	0.653	0.990	0.864	M3D2A1P1a1h1	0.910	0.761	0.753
M1D3A2P2a2h3*	0.497	1.172	0.976	M3D2A1P1a1h2	0.790	0.611	0.577
M1D3A2P2a3h1*	0.819	0.989	0.913	M3D2A1P1a1h3	0.660	0.473	0.444
M1D3A2P2a3h2*	0.662	1.019	0.890	M3D2A1P1a2h1	0.896	0.765	0.748
M1D3A2P2a3h3*	0.515	1.194	0.998	M3D2A1P1a2h2	0.760	0.549	0.513
M1D3A2P3a1h1	0.670	0.850	0.811	M3D2A1P1a2h3	0.607	0.385	0.374
M1D3A2P3a1h2*	0.467	1.029	0.951	M3D2A1P1a3h1	0.907	0.853	0.815
M1D3A2P3a1h3*	0.271	1.186	1.079	M3D2A1P1a3h2	0.775	0.634	0.589
M1D3A2P3a2h1	0.673	0.957	0.911	M3D2A1P1a3h3	0.626	0.456	0.424
M1D3A2P3a2h2*	0.467	1.207	1.117	M3D2A1P2a1h1	0.869	0.737	0.688
M1D3A2P3a2h3*	0.243	1.417	1.294	M3D2A1P2a1h2	0.729	0.721	0.661
M1D3A2P3a3h1*	0.800	1.131	1.092	M3D2A1P2a1h3*	0.614	1.242	0.916
M1D3A2P3a3h2*	0.610	1.573	1.476	M3D2A1P2a2h1	0.902	0.843	0.787
M1D3A2P3a3h3*	0.370	2.001	1.853	M3D2A1P2a2h2	0.772	0.784	0.665
M1D3A3P1a1h1	0.799	0.811	0.757	M3D2A1P2a2h3*	0.630	1.155	0.862
M1D3A3P1a1h2	0.652	0.650	0.570	M3D2A1P2a3h1	0.900	0.911	0.835
M1D3A3P1a1h3	0.393	0.492	0.378	M3D2A1P2a3h2	0.773	0.823	0.690
M1D3A3P1a2h1	0.821	0.911	0.960	M3D2A1P2a3h3*	0.642	1.021	0.777
M1D3A3P1a2h2	0.611	0.796	0.784	M3D2A1P3a1h1	0.848	0.809	0.751
M1D3A3P1a2h3	0.418	0.574	0.455	M3D2A1P3a1h2*	0.722	1.000	0.840
M1D3A3P1a3h1	0.831	0.918	0.863	M3D2A1P3a1h3*	0.609	1.295	1.026
M1D3A3P1a3h2	0.684	0.652	0.589	M3D2A1P3a2h1	0.869	0.864	0.805
M1D3A3P1a3h3	0.485	0.543	0.444	M3D2A1P3a2h2*	0.734	1.041	0.873
M1D3A3P2a1h1	0.697	0.782	0.685	M3D2A1P3a2h3*	0.615	1.347	1.064
M1D3A3P2a1h2*	0.501	0.848	0.709	M3D2A1P3a3h1	0.885	0.950	0.873
M1D3A3P2a1h3*	0.284	0.974	0.787	M3D2A1P3a3h2*	0.760	1.010	0.858
M1D3A3P2a2h1	0.832	0.938	0.870	M3D2A1P3a3h3*	0.633	1.256	1.000
M1D3A3P2a2h2	0.561	0.873	0.740	M3D2A2P1a1h1	0.890	0.749	0.732
M1D3A3P2a2h3	0.339	0.871	0.696	M3D2A2P1a1h2	0.738	0.610	0.579
M1D3A3P2a3h1	0.780	0.926	0.906	M3D2A2P1a1h3	0.584	0.461	0.434

Table D.9 Critical buckling limit ratios for specimens with two corrosion defects of $d_p/t = 0.40$, $d_s/t = 0.10$ - continue

Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}	Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}
M1D3A3P2a3h2	0.576	0.953	0.823	M3D2A2P1a2h1	0.877	0.776	0.757
M1D3A3P2a3h3	0.342	0.941	0.767	M3D2A2P1a2h2	0.711	0.571	0.509
M1D3A3P3a1h1	F	F	F	M3D2A2P1a2h3	0.528	0.386	0.366
M1D3A3P3a1h2	F	F	F	M3D2A2P1a3h1	0.891	0.860	0.825
M1D3A3P3a1h3	F	F	F	M3D2A2P1a3h2	0.727	0.640	0.597
M1D3A3P3a2h1	F	F	F	M3D2A2P1a3h3	0.548	0.468	0.430
M1D3A3P3a2h2	F	F	F	M3D2A2P2a1h1	0.845	0.743	0.702
M1D3A3P3a2h3	F	F	F	M3D2A2P2a1h2	0.670	0.740	0.694
M1D3A3P3a3h1	F	F	F	M3D2A2P2a1h3*	0.529	1.175	0.928
M1D3A3P3a3h2	F	F	F	M3D2A2P2a2h1	0.886	0.848	0.799
M1D3A3P3a3h3	F	F	F	M3D2A2P2a2h2	0.724	0.785	0.686
M2D1A1P1a1h1	0.944	0.741	0.726	M3D2A2P2a2h3*	0.551	1.069	0.854
M2D1A1P1a1h2	0.858	0.571	0.517	M3D2A2P2a3h1	0.884	0.920	0.857
M2D1A1P1a1h3	0.750	0.524	0.427	M3D2A2P2a3h2	0.727	0.827	0.719
M2D1A1P1a2h1	0.947	0.832	0.794	M3D2A2P2a3h3*	0.564	0.935	0.758
M2D1A1P1a2h2	0.865	0.638	0.566	M3D2A2P3a1h1	0.815	0.806	0.761
M2D1A1P1a2h3	0.740	0.386	0.327	M3D2A2P3a1h2*	0.654	0.968	0.850
M2D1A1P1a3h1	0.941	0.850	0.797	M3D2A2P3a1h3*	0.512	1.201	1.008
M2D1A1P1a3h2	0.874	0.750	0.650	M3D2A2P3a2h1	0.842	0.863	0.816
M2D1A1P1a3h3	0.772	0.541	0.445	M3D2A2P3a2h2*	0.670	1.012	0.889
M2D1A1P2a1h1	0.893	0.702	0.650	M3D2A2P3a2h3*	0.519	1.258	1.055
M2D1A1P2a1h2	0.794	0.630	0.522	M3D2A2P3a3h1	0.862	0.958	0.901
M2D1A1P2a1h3	0.692	0.615	0.492	M3D2A2P3a3h2*	0.704	0.996	0.880
M2D1A1P2a2h1	0.908	0.781	0.721	M3D2A2P3a3h3*	0.544	1.181	0.996
M2D1A1P2a2h2	0.799	0.640	0.529	M3D2A3P1a1h1	0.869	0.772	0.765
M2D1A1P2a2h3	0.686	0.637	0.482	M3D2A3P1a1h2	0.683	0.617	0.577
M2D1A1P2a3h1	0.919	0.889	0.808	M3D2A3P1a1h3	0.507	0.456	0.416
M2D1A1P2a3h2	0.827	0.752	0.624	M3D2A3P1a2h1	0.854	0.798	0.780
M2D1A1P2a3h3	0.719	0.651	0.501	M3D2A3P1a2h2	0.652	0.573	0.540
M2D1A1P3a1h1	0.854	0.735	0.680	M3D2A3P1a2h3	0.452	0.392	0.352
M2D1A1P3a1h2*	0.746	0.763	0.651	M3D2A3P1a3h1	0.869	0.873	0.842
M2D1A1P3a1h3*	0.648	0.898	0.727	M3D2A3P1a3h2	0.670	0.656	0.612
M2D1A1P3a2h1	0.833	0.740	0.670	M3D2A3P1a3h3	0.474	0.463	0.413
M2D1A1P3a2h2*	0.717	0.821	0.684	M3D2A3P2a1h1	0.813	0.751	0.722
M2D1A1P3a2h3*	0.605	0.965	0.768	M3D2A3P2a1h2	0.602	0.748	0.674
M2D1A1P3a3h1	0.863	0.838	0.763	M3D2A3P2a1h3*	0.436	1.002	0.829
M2D1A1P3a3h2*	0.741	0.893	0.746	M3D2A3P2a2h1	0.865	0.862	0.829
M2D1A1P3a3h3*	0.626	1.014	0.807	M3D2A3P2a2h2	0.664	0.765	0.686
M2D1A2P1a1h1	0.925	0.715	0.706	M3D2A3P2a2h3	0.464	0.761	0.687
M2D1A2P1a1h2	0.816	0.547	0.505	M3D2A3P2a3h1	0.861	0.928	0.879

Table D.9 Critical buckling limit ratios for specimens with two corrosion defects of $d_p/t = 0.40$, $d_s/t = 0.10$ - continue

Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}	Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}
M2D1A2P1a1h3	0.680	0.516	0.439	M3D2A3P2a3h2	0.666	0.813	0.726
M2D1A2P1a2h1	0.934	0.832	0.800	M3D2A3P2a3h3	0.480	0.782	0.657
M2D1A2P1a2h2	0.831	0.647	0.584	M3D2A3P3a1h1	0.756	0.778	0.741
M2D1A2P1a2h3	0.692	0.529	0.478	M3D2A3P3a1h2*	0.557	0.874	0.784
M2D1A2P1a3h1	0.928	0.860	0.815	M3D2A3P3a1h3*	0.382	1.024	0.887
M2D1A2P1a3h2	0.842	0.743	0.662	M3D2A3P3a2h1	0.789	0.836	0.798
M2D1A2P1a3h3	0.714	0.532	0.455	M3D2A3P3a2h2*	0.577	0.923	0.830
M2D1A2P2a1h1	0.876	0.712	0.669	M3D2A3P3a2h3*	0.390	1.078	0.933
M2D1A2P2a1h2	0.751	0.634	0.548	M3D2A3P3a3h1	0.814	0.936	0.889
M2D1A2P2a1h3	0.623	0.630	0.535	M3D2A3P3a3h2*	0.620	0.941	0.855
M2D1A2P2a2h1	0.894	0.794	0.744	M3D2A3P3a3h3*	0.426	1.028	0.896
M2D1A2P2a2h2	0.759	0.649	0.560	M3D3A1P1a1h1	0.863	0.701	0.707
M2D1A2P2a2h3	0.616	0.614	0.529	M3D3A1P1a1h2	0.705	0.644	0.592
M2D1A2P2a3h1	0.908	0.908	0.842	M3D3A1P1a1h3	0.527	0.342	0.353
M2D1A2P2a3h2	0.795	0.769	0.666	M3D3A1P1a2h1	0.858	0.725	0.719
M2D1A2P2a3h3	0.661	0.674	0.551	M3D3A1P1a2h2	0.665	0.469	0.471
M2D1A2P3a1h1	0.822	0.740	0.697	M3D3A1P1a2h3	0.539	0.397	0.390
M2D1A2P3a1h2*	0.680	0.756	0.674	M3D3A1P1a3h1	0.864	0.741	0.732
M2D1A2P3a1h3*	0.550	0.878	0.754	M3D3A1P1a3h2	0.681	0.489	0.489
M2D1A2P3a2h1	0.796	0.744	0.691	M3D3A1P1a3h3	0.565	0.446	0.428
M2D1A2P3a2h2*	0.642	0.814	0.713	M3D3A1P2a1h1	0.833	0.746	0.716
M2D1A2P3a2h3*	0.495	0.946	0.803	M3D3A1P2a1h2*	0.682	1.044	0.842
M2D1A2P3a3h1	0.834	0.846	0.789	M3D3A1P2a1h3*	0.573	1.527	1.131
M2D1A2P3a3h2*	0.675	0.889	0.781	M3D3A1P2a2h1	0.863	0.825	0.789
M2D1A2P3a3h3*	0.523	0.996	0.847	M3D3A1P2a2h2*	0.707	0.929	0.774
M2D1A3P1a1h1	0.904	0.718	0.708	M3D3A1P2a2h3*	0.656	2.004	1.473
M2D1A3P1a1h2	0.764	0.554	0.519	M3D3A1P2a3h1	0.876	0.871	0.828
M2D1A3P1a1h3	0.588	0.529	0.469	M3D3A1P2a3h2	0.722	0.867	0.740
M2D1A3P1a2h1	0.921	0.853	0.824	M3D3A1P2a3h3*	0.589	1.363	1.026
M2D1A3P1a2h2	0.790	0.680	0.625	M3D3A1P3a1h1	0.814	0.838	0.768
M2D1A3P1a2h3	0.636	0.499	0.458	M3D3A1P3a1h2*	0.684	1.133	0.942
M2D1A3P1a3h1	0.915	0.892	0.851	M3D3A1P3a1h3*	0.573	1.512	1.188
M2D1A3P1a3h2	0.803	0.762	0.696	M3D3A1P3a2h1	0.874	0.881	0.836
M2D1A3P1a3h3	0.636	0.545	0.484	M3D3A1P3a2h2*	0.722	1.048	0.893
M2D1A3P2a1h1	0.848	0.722	0.687	M3D3A1P3a2h3*	0.592	1.438	1.138
M2D1A3P2a1h2	0.686	0.653	0.585	M3D3A1P3a3h1	0.856	0.950	0.867
M2D1A3P2a1h3	0.520	0.651	0.561	M3D3A1P3a3h2*	0.726	1.102	0.929
M2D1A3P2a2h1	0.873	0.806	0.767	M3D3A1P3a3h3*	0.602	1.426	1.131
M2D1A3P2a2h2	0.697	0.668	0.598	M3D3A2P1a1h1	0.846	0.725	0.728
M2D1A3P2a2h3	0.511	0.640	0.549	M3D3A2P1a1h2	0.661	0.593	0.575

Table D.9 Critical buckling limit ratios for specimens with two corrosion defects of $d_p/t = 0.40$, $d_s/t = 0.10$ - continue

Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}	Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}
M2D1A3P2a3h1	0.891	0.923	0.872	M3D3A2P1a1h3	0.446	0.351	0.337
M2D1A3P2a3h2	0.746	0.788	0.708	M3D3A2P1a2h1	0.838	0.749	0.742
M2D1A3P2a3h3	0.571	0.692	0.598	M3D3A2P1a2h2	0.601	0.482	0.474
M2D1A3P3a1h1	0.767	0.746	0.714	M3D3A2P1a2h3	0.461	0.417	0.387
M2D1A3P3a1h2*	0.570	0.757	0.700	M3D3A2P1a3h1	0.844	0.761	0.753
M2D1A3P3a1h3*	0.394	0.840	0.760	M3D3A2P1a3h2	0.619	0.503	0.495
M2D1A3P3a2h1	0.732	0.752	0.713	M3D3A2P1a3h3	0.482	0.430	0.403
M2D1A3P3a2h2*	0.519	0.807	0.740	M3D3A2P2a1h1	0.800	0.663	0.650
M2D1A3P3a2h3*	0.321	0.888	0.798	M3D3A2P2a1h2*	0.611	0.874	0.747
M2D1A3P3a3h1	0.784	0.854	0.814	M3D3A2P2a1h3*	0.478	1.217	0.974
M2D1A3P3a3h2*	0.563	0.893	0.822	M3D3A2P2a2h1	0.835	0.771	0.742
M2D1A3P3a3h3*	0.359	0.957	0.863	M3D3A2P2a2h2*	0.714	1.255	1.057
M2D2A1P1a1h1	0.916	0.764	0.753	M3D3A2P2a2h3*	0.490	1.168	0.940
M2D2A1P1a1h2	0.796	0.560	0.521	M3D3A2P2a3h1	0.852	0.782	0.756
M2D2A1P1a1h3	0.660	0.450	0.400	M3D3A2P2a3h2	0.664	0.745	0.667
M2D2A1P1a2h1	0.906	0.784	0.752	M3D3A2P2a3h3*	0.501	1.056	0.858
M2D2A1P1a2h2	0.777	0.560	0.517	M3D3A2P3a1h1	0.769	0.827	0.772
M2D2A1P1a2h3	0.633	0.381	0.357	M3D3A2P3a1h2*	0.605	1.045	0.902
M2D2A1P1a3h1	0.916	0.871	0.820	M3D3A2P3a1h3*	0.463	1.323	1.096
M2D2A1P1a3h2	0.796	0.666	0.596	M3D3A2P3a2h1	0.843	0.868	0.822
M2D2A1P1a3h3	0.699	0.528	0.477	M3D3A2P3a2h2*	0.655	0.986	0.866
M2D2A1P2a1h1	0.871	0.724	0.675	M3D3A2P3a2h3*	0.492	1.264	1.055
M2D2A1P2a1h2	0.738	0.722	0.667	M3D3A2P3a3h1	0.827	0.961	0.899
M2D2A1P2a1h3*	0.623	1.126	0.838	M3D3A2P3a3h2*	0.659	1.056	0.923
M2D2A1P2a2h1	0.912	0.847	0.796	M3D3A2P3a3h3*	0.504	1.283	1.072
M2D2A1P2a2h2	0.785	0.743	0.631	M3D3A3P1a1h1	0.810	0.731	0.721
M2D2A1P2a2h3*	0.644	1.038	0.782	M3D3A3P1a1h2	0.605	0.577	0.541
M2D2A1P2a3h1	0.900	0.907	0.824	M3D3A3P1a1h3	0.364	0.355	0.293
M2D2A1P2a3h2	0.780	0.828	0.686	M3D3A3P1a2h1	0.801	0.754	0.735
M2D2A1P2a3h3*	0.653	0.986	0.749	M3D3A3P1a2h2	0.534	0.484	0.442
M2D2A1P3a1h1	0.832	0.800	0.738	M3D3A3P1a2h3	0.382	0.423	0.350
M2D2A1P3a1h2*	0.713	0.971	0.826	M3D3A3P1a3h1	0.811	0.773	0.755
M2D2A1P3a1h3*	0.604	1.229	0.997	M3D3A3P1a3h2	0.555	0.507	0.466
M2D2A1P3a2h1	0.835	0.856	0.783	M3D3A3P1a3h3	0.402	0.434	0.366
M2D2A1P3a2h2*	0.713	1.054	0.889	M3D3A3P2a1h1	0.760	0.735	0.695
M2D2A1P3a2h3*	0.597	1.323	1.067	M3D3A3P2a1h2*	0.541	0.881	0.742
M2D2A1P3a3h1	0.878	0.945	0.872	M3D3A3P2a1h3*	0.376	1.169	0.933
M2D2A1P3a3h2*	0.763	1.045	0.895	M3D3A3P2a2h1	0.806	0.834	0.793
M2D2A1P3a3h3*	0.636	1.252	1.019	M3D3A3P2a2h2*	0.661	1.340	1.141
M2D2A2P1a1h1	0.899	0.780	0.764	M3D3A3P2a2h3*	0.506	1.819	1.486

Table D.9 Critical buckling limit ratios for specimens with two corrosion defects of $d_p/t = 0.40$, $d_s/t = 0.10$ - continue

Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}	Model	M_{lc}/M_{lp}	$\varepsilon_{lc}/\varepsilon_{lp}$	Φ_{lc}/Φ_{lp}
M2D2A2P1a1h2	0.738	0.576	0.543	M3D3A3P2a3h1	0.824	0.876	0.831
M2D2A2P1a1h3	0.562	0.464	0.416	M3D3A3P2a3h2	0.618	0.842	0.736
M2D2A2P1a2h1	0.888	0.811	0.779	M3D3A3P2a3h3*	0.405	0.951	0.763
M2D2A2P1a2h2	0.718	0.582	0.543	M3D3A3P3a1h1	0.717	0.792	0.726
M2D2A2P1a2h3	0.537	0.390	0.365	M3D3A3P3a1h2*	0.507	0.953	0.822
M2D2A2P1a3h1	0.901	0.898	0.851	M3D3A3P3a1h3*	0.318	1.149	0.960
M2D2A2P1a3h2	0.742	0.685	0.624	M3D3A3P3a2h1	0.813	0.873	0.833
M2D2A2P1a3h3	0.565	0.479	0.435	M3D3A3P3a2h2*	0.574	0.913	0.799
M2D2A2P2a1h1	0.841	0.726	0.684	M3D3A3P3a2h3*	0.360	1.090	0.917
M2D2A2P2a1h2	0.662	0.727	0.708	M3D3A3P3a3h1	0.788	0.953	0.896
M2D2A2P2a1h3*	0.516	1.062	0.858	M3D3A3P3a3h2*	0.581	1.008	0.888
M2D2A2P2a2h1	0.896	0.853	0.810	M3D3A3P3a3h3*	0.374	1.143	0.964
M2D2A2P2a2h2	0.727	0.759	0.669				