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Post Yield Behaviour of Transversely Loaded Icebreaking Ship Hull Structures

by

David Toscano

A thesis submitted to the
Faculty of Graduate Studies and Research
in partial fulfilment of the requirements
for the degree of
Master of Engineering

Department of Civil and Environmental Engineering
Carleton University
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**Post Yield Behaviour of Transversely
Loaded Icebreaking Ship Hull Structures**

submitted by
David Toscano, B.Eng.

in partial fulfilment of the requirements for
the degree of Master of Engineering

for Chairman, Department of Civil and Environmental Engineering

Thesis Supervisor

External Examiner

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Ottawa, Ontario, Canada

May, 1995

Abstract

The proposed Arctic Shipping Pollution Prevention Regulations (ASPPR) have adopted a Limit States Design format for the structural design of icebreaker hull plating and stiffening members. The proposed regulations now explicitly recognize the contribution of membrane behaviour in the design of the hull plate but the behaviour of the stiffening elements attached to the plate in the post-yield region is not fully understood. Analytical methods and experimental verification are needed to describe this complex behaviour. The objectives of this study were to experimentally verify the results of a nonlinear finite element analysis of this structure type, to observe the behaviour of transverse flat bar stiffening members in the post-yield region, and to comment on the applicability of the corresponding ASPPR design equations.

Two large scale midbody hull panels, each measuring 2600 mm by 5000 mm, were tested under transverse loads which modelled the design ice load pattern. The panels were fully fixed to a horizontal reaction frame. The first test panel was designed to be compliant with the proposed rules. The second test panel ventured outside of the rules in order to observe the behaviour of the main frames with large unsupported lengths and slenderness ratios ranging from 9.76 to 29.92.

Load-deflection curves and strain distributions are presented along with the

corresponding finite element results.

The nonlinear finite element analysis can be used to accurately predict the behaviour of the structure. The tripping failure mode for flat bar main frames was not critical. Local buckling was the governing failure mode. A realistic representation of the local buckling failure mode is achieved through the use of a linearly varying stress distribution that includes the effect of residual stresses.

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D_{ph}	Design parameter for determining P_{av} for longitudinal framing.
D_{pt}	Design parameter for determining P_{av} for transverse framing.
E	Modulus of Elasticity.
E_{st}	Strain hardening modulus.
E_t	Tangent Modulus of Elasticity.
E_v	Vertical load distribution factor.
F	Shear load distribution factor.
F_s	Maximum shear force.
F_y	Yield stress.
G	Shear Modulus.
G_l	Longitudinal load distribution factor.
H	Shear strength factor.
H_p	Horizontal length of the design ice load.
I_y	Moment of inertia about the y-axis.
I_p	Polar moment of inertia with reference to the enforced centre of rotation.
J	Saint Venant's Torsional Constant.
J_s	Shear strength factor.
k	Factor for boundary conditions.
k_ϕ	Rotational rigidity provided to the stiffener by the hull plate.
l	Unsupported span of the stiffener.
L	Plate span.
L_B	Frame length for bending calculation.

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List of Symbols

a	Distance from the enforced centre of rotation to the shear centre.
A	Maximum shear factor.
A_f	Factor for hull area.
A_s	Stiffener area.
A_w	Web area.
A_{wl}	Web area of longitudinal framing member.
A_{wt}	Web area of transverse framing member.
b	Stiffener web depth.
b_e	Hull plate effective width.
B	Factor to obtain maximum moment.
C	Ship class factor for minimum design provisions.
C_a	Corrosion and wear allowance.
C_E	Enforced axis of rotation.
C_f	Factor for ship class.
C_w	Warping constant.
D	Constant.
D_p	Design pressure for the shell plating.

D_{ph}	Design parameter for determining P_{av} for longitudinal framing.
D_{pt}	Design parameter for determining P_{av} for transverse framing.
E	Modulus of Elasticity.
E_{st}	Strain hardening modulus.
E_t	Tangent Modulus of Elasticity.
E_v	Vertical load distribution factor.
F	Shear load distribution factor.
F_s	Maximum shear force.
F_y	Yield stress.
G	Shear Modulus.
G_l	Longitudinal load distribution factor.
H	Shear strength factor.
H_p	Horizontal length of the design ice load.
I_v	Moment of inertia about the y-axis.
I_p	Polar moment of inertia with reference to the enforced centre of rotation.
J	Saint Venant's Torsional Constant.
J_s	Shear strength factor.
k	Factor for boundary conditions.
k_ϕ	Rotational rigidity provided to the stiffener by the hull plate.
l	Unsupported span of the stiffener.
L	Plate span.
L_B	Frame length for bending calculation.

L_s	Effective shear span taking into account effective brackets.
M	Applied moment.
M_{cr}	Lateral-torsional buckling moment.
n	Number of half waves in longitudinal direction.
N	Frame tilt factor.
O, O'	Location of centroid.
O_f	Framing orientation factor.
P	Shaft power.
P_{σ}	Design pressure for framing members.
Q	Load sharing factor.
q_c	Pressure required to cause hinges in a strip of plate one unit wide.
R	Load sharing factor.
S	Frame spacing.
S_c, S_c'	Location of the shear centre.
t	Stiffener web thickness.
t_f	Flange thickness.
t_{hull}	Hull plate thickness.
t_p	Plate thickness.
t_w	Web frame or stringer web thickness.
U	Area and transition factor.
V	Flexural stress factor.
V_p	Vertical height of the design ice load.

x,y	Co-ordinate axes.
y_o	Distance from shear centre to centroid.
z	Distance along longitudinal axis.
Z_{long}	Section modulus of longitudinal framing member.
Z_p	Provided frame plastic section modulus.
Z_r	Required frame plastic section modulus.
Z_{tran}	Section modulus of transverse framing member.
β	Angle of twist.
β''	Second derivative of angle β .
β^{IV}	Fourth derivative of angle β .
Δ	Ship displacement.
δ	Angle between the stiffener web and the hull plate.
ϵ_f	Strain at fracture.
ϵ_u	Ultimate strain.
ϵ_y	Yield strain.
ϵ_{st}	Strain at onset of strain hardening
ν	Poisson's ratio.
ν_p	Inelastic value of Poisson's ratio.
ξ,η	Co-ordinate axes.
σ	Critical tripping stress.
σ_1	Primary applied stress.
σ_c	Ultimate buckling stress.

σ_{ce}	Elastic buckling stress for a long plate.
σ_{cr}	Elastic critical stress of a long plate
σ_{el}	Elastic torsional buckling stress.
σ_f	Stress at fracture.
σ_p	Proportional limit.
σ_{sy}	Static yield stress.
σ_{tr}	Average buckling stress of a stiffened plate.
σ_u	Ultimate stress.
σ_y	Yield stress.
σ_{yl}	Lower yield stress.
σ_{yu}	Upper yield stress.
τ	Factor in tangent-modulus theory of inelastic buckling.
τ_y	Shear stress at yield.
Ω	Acute angle between the chord of the waterline and the line of the first level of framing supporting the hull plate.

Chapter 1

Introduction

1.1 General

In 1972, the Arctic Shipping Pollution Prevention Regulations (ASPPR) were published. Their purpose was

"to see that the Arctic waters adjacent to the mainland and islands of the Canadian Arctic are navigated only in a manner that takes cognizance of the preservation of the peculiar ecological balance that now exists in the water, ice and land areas of the Canadian Arctic".

Inherent in those regulations and their desire to minimize the risk of pollution in the waters of the Canadian Arctic were the structural design rules for Canadian Arctic Class ship structures. These design rules are mainly empirical in nature and are based on past experience and ship performance and take into account how Arctic shipping might evolve. These rules provided simplified and easy-to-use formulas in order to determine the scantlings, or structural dimensions, of a ship structure.

From a structural engineering viewpoint, the drawbacks of this kind of "rulebook" approach are:

1. it is not a limit states design format, where failure modes are explicitly recognized and design for. Design rules describing various failure modes which can occur in a structure don't exist. These failure modes can be quite complex and are in many cases interrelated. By not designing for these specific failure modes and using the simplified techniques, there is no measure of reliability and probability of failure. This leads to an inefficient and costly design.
2. there are limitations that are placed on the use of these formulas. In order to determine those easy-to-use rules, simplifications and limitations were imposed. The danger of unknowingly applying a standard, time-honoured method to a design application which is outside its limits of validity can be disastrous.

Because of these drawbacks and environmental concerns, the 1972 ASPPR were restructured to a limit states format which is now incorporated in the Proposed Equivalent Standards for the Construction of Arctic Class Ships. Ship structural design has now evolved to a safer, more efficient method which is based entirely on structural theory to achieve an optimum structure.

As a result of testing and analysis conducted in the mid 1980's by Ratzlaff and Kennedy (1985,1986), the Standards now recognize the strength reserve resulting from allowing the hull to deform (ie. membrane behaviour). However, the performance of basic stiffening elements attached to the plate in this post yield region is not completely understood. Analytical studies have been conducted by Transport Canada (Martec, 1994)

and have given rise to further research work required to establish analytical methods that can describe this complex behaviour. These methods required experimental verification.

Hence the objectives of this study are:

1. to describe the post-yield behaviour of a typical icebreaking ship hull structure subjected to transverse loads;
2. to verify the results of a nonlinear finite element analysis (FEA) of this type of structure through comparison with experimental data;
3. to study the strength and stability of transverse flat bar stiffening members.

1.2 Scope

To accomplish the objectives, two large scale stiffened plate panels, measuring 2600 mm by 5000 mm, were tested with a five point load system transverse to the structure which approximated the design ice load. The test was conducted beyond the design load and well into the plastic region until failure occurred by rupture of the plate. The loads were applied quasi-statically with each test lasting approximately one week. The panels were fully fixed, through the use of full penetration groove and fillet welds, on all four sides to a horizontal reaction frame.

The initial test panel was designed to be ASPPR compliant. This test was used not only as a verification for the FEA but provided a basis in which the applicability of the proposed design rules and the stability behaviour of the flat bar main frames could be studied. For the second test, the two basic parameters which govern the tripping and local buckling design rules for the main frames were varied from the first test. The

section depth to thickness (b/t) ratios of the flat bar stiffeners were varied from 9.76 to 29.92 and the unsupported span to thickness (l/t) ratios were varied from 89.68 to 179.35. The b/t and l/t ratios for the first test panel were 11.34 and 77.13 respectively. One main frame in the second test panel was canted at a 15° angle to the vertical. This second test provided a range of parameters over which the stability of the stiffeners could be compared.

As part of this work, the test results were analyzed and compared to the corresponding results of an inelastic large deformation FEA. Within the limitations of the tests conducted, conclusions are presented with respect to the applicability of the ASPPR design rules for tripping to the stability of the main frames.

1.3 Outline

A review of the existing literature upon which the proposed structural design rules for Canadian Arctic Class ship structures are based is presented in Chapter 2. The experimental program, which incorporates the test panel designs, test set-up, instrumentation, experimental method and the ancillary tests, is presented in Chapter 3. The test results, which include geometric and material properties, a brief discussion of the FEA, a general description of the overall behaviour of the test panels, general load deflection curves for the stiffening elements, steel strain distributions and comparisons with the results from the FEA, as well as the discussion are presented in Chapter 4. A summary, conclusions, recommendations, along with a discussion of possible future work are presented in Chapter 5.

Chapter 2

Literature Review

2.1 General Behaviour of Ice Breaking Ship Structures

Typical ice breaking ship structures consist of an outer hull plate stiffened with an interior grillage consisting of longitudinal and transverse framing in order to resist ice loads. This system spans longitudinally between bulkheads and transversely between decks.

Icebreaking ships consist of highly redundant structural systems and are therefore quite complex. At high load levels, the structure responds in a series of collapse mechanisms. Various structural elements fail and load is redistributed to other members because of the redundant nature of the structure.

The structural system is designed to avoid rupture of the hull plate. Related to this is the stability of the framing members. If the members are excessively stable and strong, then the plastic membrane response of the plate is limited to a small area bounded by the members, which could result in the plate reaching the ultimate tensile strain and rupture occurring. If the members are very unstable, then the strength of the plate will not be

used efficiently and excessive deformations will occur under relatively low load levels. An important design consideration is to provide a balance of these two conditions.

Kennedy and Bond (1995) describe the general behaviour of an icebreaking ship structure in response to loading up until ultimate as a progression of failure. At moderate load levels, the ice belt produces high local loading in the hull plating between the longitudinal stiffeners. The ice loads are resisted elastically in flexure by the structural system. As the load increases, plastic hinges form at the long edge of the panel defined by the transverse frames and longitudinals. This results in plastic plate deformations and a visible bulge in the icebelt region. At this point, the yielded frames must remain stable in order to allow for the benefit of local plastic deformations and energy absorption to occur. If the frames become unstable, the load is distributed to adjacent structure and the damage is spread. Higher load levels result in primarily elastic plastic flexural-membrane action response of the structural system. Membrane action takes over at a deflection which is approximately equal to the hull plate thickness. Plastic zones still only occur along the edges. With further increase in load, flexural yielding occurs at the plate midspan and a central hinge forms. A full collapse mechanism has now formed and deflections increase markedly. The flexural capacity of the plate has now been exceeded and with increased loading, the structure responds with elastic-plastic membrane behaviour. The plastic zones continue to spread inward from the plate edges and outward from the plate centre. At this point, it is desirable for the framing members to trip or buckle after significant plastic deformations have occurred (Class 1 or 2 behaviour) allowing redistribution of the load to a larger plastic membrane area which in turn allows

the plate to develop its full membrane strength before rupture.

2.2 Proposed Structural Design Rules for the Construction of Canadian Arctic Class Ship Structures

Since the first edition of the structural design rules for Canadian Arctic Class ship structures was published in 1972, a better understanding of the behaviour of these types of structures has emerged through direct experience of ice strengthened ships working in the Arctic and through theoretical and experimental research. The ASPPR 1972 are generally empirically based as the behaviour of these statically indeterminate structures is very complex and the mechanics are not well understood or defined and this is borne out through the damage histories of early icebreakers.

2.2.1 Background for the Proposed Design Rule for the Hull Plating

Chiu, Haciski, and Hirsimaki (1981) reviewed the performance of U.S. Coast Guard icebreakers. Past icebelt damage sustained by the icebreakers indicated that an imbalance existed between the strength of the framing and that of the plating. The observed failures could be attributed to failures in the framing due to underdesign or inadequate lateral support. Deformations in the plating only occurred over areas supported by several frames and were always associated with failures in the framing. There has not been any evidence of visible local damage between the frames such as permanent plastic deformation of the plate (development of yield line mechanism).

By reviewing the past damage experiences of other vessels such as the M.V.

Arctic, Kigoriak, Robert Lemeur, Kalvik, Louis S. St. Laurent, Polar Sea, and the Manhattan, the ASPPR Subcommittee recommended the use of lower shell thickness and higher framing strength.

The new design approach for the shell thickness considers the plastic behaviour of ductile steel. By allowing an acceptable amount of plastic deformation, or permanent set, in the plate between frames, significant weight savings for the plate can be achieved.

Analysis and design for steel plates has been studied extensively by many authors. A review of the work of Timoshenko (1940), Clarkson (1956), Young (1959), Hooke and Rawlings (1969), Hooke (1970), and Kennedy and Hafez (1984) is given in Ratzlaff and Kennedy (1985). Their work considers the elastic and inelastic behaviour of transversely loaded plates with rigid boundary conditions. Through this work, it was realized that membrane stresses increase the load carrying capacity of a steel plate up to twenty times over and above the flexural collapse load. This ultimate load corresponded to a maximum deflection of up to thirty times the thickness of the plate. Therefore, failure was defined in terms of a serviceability limit instead of an ultimate strength limit.

These ideas are important when looking at the philosophy behind the proposed rules. When a ship is operated under the conditions given by its Class, the design load occurs approximately one time per year. This results in acceptable permanent set but not rupture of the hull plate, which could lead to disastrous consequences. Even in the event of an extreme overload situation (1 in 100 year event) there is reserve capacity in the plate in terms of membrane capacity, large deformations and energy absorption capability.

The design condition adopted by the ASPPR Subcommittee for the hull plate is

that of a steel plate forming plastic hinges at its supports due to flexure. This condition represents an 82% increase in strength from the condition of first yield at the plate edges without significant permanent deflection being experienced. From the derivation in Ratzlaff and Kennedy (1986), the pressure required to cause edge hinges in a strip of plate one unit wide is given by Equation 2.1 as,

$$q_c = \frac{3\sigma_y}{1-\nu_p^2} \left(\frac{t_p}{L}\right)^2 \quad (2.1)$$

where, q_c = critical pressure required to cause edge hinges to form (MPa)
 σ_y = yield stress (MPa)
 ν_p = inelastic value of Poissons ratio
 t_p = plate thickness (mm)
 L = span of the plate (mm)

Substituting for $\nu_p = 0.5$, taking L to be the frame spacing S , using $0.75D_p$ as the pressure and solving for the plate thickness using the appropriate symbols ($\sigma_y=F_y$), the equation shown in Equation 2.2, which is equivalent to the design equation in Section 12.1 of the Proposed Equivalent Standards for the Construction of Arctic Class Ships (Standards, 1993), is obtained.

$$t_p = S \left(\frac{0.75D_p}{4F_y} \right)^{1/2} + C_a \quad (2.2)$$

where, D_p = design pressure for the shell plating (MPa) (see Appendix A)
 C_a = corrosion and wear allowance, either 0 or 2 mm depending on if a high impact resistant coating is applied to the exterior of the hull

The factor 0.75 applied to the design plate pressure, D_p , is obtained from the Baltic Rules and is used to account for the greater ductility in the plate than in the frames.

The combination of restricting the failure to the development of plastic hinges at the

plate edges and reducing the design plate pressure leads to a design plate thickness which is the same as if the plate was designed for a collapse mechanism which also involves the formation of a plastic hinge at midspan where,

$$q_c = \frac{4\sigma_y}{1-\nu_p^2} \left(\frac{t_p}{L}\right)^2 \quad (2.3)$$

2.2.2 Background for the Proposed Design Rules for the Framing Members

ASPPR 1972 required that a minimum elastic section modulus be provided for the design of framing members. This rule was based on the assumption that bending would be critical and that yield of the section constituted failure. The review of past damage to the framing members in icebreakers indicates that this is not the case and that there are more types of failure modes than previously presumed. The proposed regulations explicitly recognize that shear, tripping or flexural torsional buckling, local buckling, and fracture failures may also occur and that they need be designed for.

2.2.2.1 Design for Shear

The shear capacity of framing members is provided by the web, where the shear area (web area) required is given by,

$$A_w = \frac{F_s}{\tau_y} \quad (2.4)$$

where, A_w = web area (mm²)
 F_s = maximum shear force (N)
 τ_y = shear stress at yield (MPa)

The maximum shear force, F_s , occurs when the ice load is near the support of the frame and is given as a function of factors incorporating the hull area, ship class, and loading parameters. Given in Sections 18.2 and 19.2 in the ASPPR (1993), for transverse and longitudinal framing members and expressed in terms of required web area these are,

$$A_{wt} = \frac{A_f C_f H P_{av} S V_p A R}{F_y} \quad (2.5)$$

$$A_{wl} = \frac{A_f C_f P_{av} E_v J_s Q L_s S F}{F_y} \quad (2.6)$$

where, A_{wt} = web area of transverse framing member (mm²)
 A_{wl} = web area of longitudinal framing member (mm²)
 A_f = factor for hull area (see Appendix A)
 C_f = factor for ship class (see Appendix A)
 H, J_s = shear strength factor
 = 1/0.66 for sturdy flanged sections
 = 1/0.58 for all other sections (including flat bars)
 P_{av} = design pressure (MPa) (see Appendix A)
 S = frame spacing (mm)
 V_p = vertical height of the design ice load (mm)
 = 0.125 H_p
 H_p = horizontal length of the design ice load (mm)
 = 2.15 $\sqrt{(\Delta^{0.9} + \Delta^{0.68} P^{0.33})}$
 Δ = ship displacement (tonnes x 10³)
 P = shaft power (MegaWatts)
 A = maximum shear factor (see Appendix A)
 R = load sharing factor = 0.83
 E_v = vertical load distribution factor
 = (2-S)/ V_p for $V_p > S$
 = V_p/S for $V_p < S$

- Q = load sharing factor
 = the greater of 0.7 and $(0.64+0.058V_p/S)$ when $V_p/S < 4.5$
 = the lesser of 1.0 and $(0.855+0.01V_p/S)$ when $V_p/S \geq 4.5$
 L_s = effective shear span taking into account effective brackets (mm)
 F = shear load distribution factor
 = 0.55 when $H_p \geq L_s$
 = $(H_p/L_s) - (H_p^2/2.22L_s^2)$ when $H_p < L_s$
 F_y = yield stress (MPa)

but not less than,

$$A_{wt} = \frac{A_f C H P_{av} S V_p A R}{F_y} \quad (2.7)$$

$$A_{wt} = \frac{A_f C P_{av} E_v J_s Q L_s S F}{F_y} \quad (2.8)$$

where, C = 1.0 for ship category CAC1, CAC2, and CAC3
 = 0.8 for ship category CAC4

V_p = 750 mm

H_p = 6000 mm

The shear strength factors of $1/0.58$ for flat bars and $1/0.66$ for sturdy flanged sections is based on the von Mises Huber-Hencky yield criterion, $\tau_y = F_y/\sqrt{3}$, and the ability of stocky sections (not subject to web distortions) to achieve full shear yield with strain hardening, CISC (1992).

2.2.2.2 Design for Flexure

The bending strength of the framing members assuming Class 1 or Class 2 behaviour, is defined as the plastic capacity of the flange, web and hull plate (overall member stability, tripping is considered elsewhere) with the required plastic section modulus given as,

$$Z_r = \frac{M}{\sigma_y} \quad (2.9)$$

where, Z_r = required plastic section modulus (mm^3)
 M = maximum moment ($\text{N}\cdot\text{mm}$)

The maximum moment on the member occurs when the ice load is centred on the frame. Given in sections 18.2 and 19.2 in the ASPPR (1993), for transverse and longitudinal framing members and expressed in terms of the required plastic section modulus, these are,

$$Z_{tran} = \frac{A_f C_f P_{av} S L_B B R}{24F_y} \quad (2.10)$$

$$Z_{long} = \frac{A_f C_f P_{av} E_v Q S L_B^2 G_l}{16F_y} \quad (2.11)$$

where, Z_{tran} = section modulus of transverse framing member (mm^3)
 Z_{long} = section modulus of longitudinal framing member (mm^3)
 L_B = frame length for bending calculation (mm)
 B = factor to obtain maximum moment (mm)
 $= V_p(3-V_p/L_B)$ when $V_p \leq L_B$
 $= L_B(3-L_B/V_p)$ when $V_p > L_B$
 G_l = longitudinal load distribution factor
 $= 1.1$ when $H_p > L_B$
 $= 2(H_p/L_B - H_p^2/2.22L_B^2)$

but not less than,

$$Z_{tran} = \frac{A_f C P_{av} S L_B B R}{24F_y} \quad (2.12)$$

$$Z_{long} = \frac{A_f C P_{av} E_v Q S L_B^2 G_l}{16F_y} \quad (2.13)$$

where, $C = 1.0$ for ship category CAC1, CAC2, and CAC3
 $= 0.8$ for ship category CAC4
 $V_p = 750$ mm
 $H_p = 6000$ mm

2.2.2.3 Design for Tripping

Tripping of stiffening members attached to a plate is a special case of the problem of buckling of columns by torsion and flexure with an enforced axis of rotation, as shown in Figure 2.1. The hull plate prevents the stiffener from moving laterally except by rotation about its toe. The fundamental differential equation for this problem, given in Equation 2.14, was derived using the theorem of stationary potential energy, Bleich (1952).

$$E\tau(a^2I_y + C_w)\beta^{IV} + (\sigma I_p - G\tau J)\beta'' = 0 \quad (2.14)$$

where, E = Modulus of Elasticity (MPa)
 G = Shear Modulus (MPa)
 $\tau = E_p/E$
 E_t = Tangent Modulus of Elasticity (MPa)
 a = distance from the enforced centre of rotation to the shear centre (mm)
 I_y = moment of inertia about the y-axis (mm⁴)
 I_p = the polar moment of inertia with reference to the enforced centre of rotation (mm⁴)
 J = Saint Venant's Torsional Constant (mm⁴)
 β = angle of twist (radians)
 C_w = warping constant (mm⁶)
 σ = critical tripping stress (MPa)

The lowest value of σ gives the critical tripping stress. For a tee-section hinged at its toe, with simply supported end conditions, with $E\tau \approx E$ and $G\tau \approx G$, the critical tripping stress determined by Bleich is,

$$\sigma = \frac{\pi^2 E}{l^2} \left(\frac{a^2 I_y + C_w}{I_p} \right) + \frac{GJ}{I_p} \quad (2.15)$$

The first term in this equation represents the warping and lateral displacement strength while the second term represents the torsional strength. The critical buckling stress for lateral torsional buckling as defined by DNV Rules (DNV 1984) is equal to the yield stress if

$$\sqrt{\frac{\sigma_y}{\sigma}} \leq 0.6 \quad (2.16)$$

Three design rules were developed for ASPPR (1993) from simplifications of Equation 2.15 as related to the stiffeners slenderness, loading and its corresponding behaviour. Simplifications and assumptions used in the derivation of the equations for tripping of flat bar plate stiffeners include:

1. the ends of the stiffener are simply supported, hence the solution for the rotation β varies sinusoidally in n half waves over the unbraced length.

$$\beta = D \sin \frac{n\pi z}{l} \quad (2.17)$$

2. the stiffener is hinged at its toe, hence the hull plate provides no rotational restraint to the stiffener.
3. the effects of residual stresses and geometric imperfections, inelastic buckling and post buckling strength were neglected.

4. the use of a safety factor to relate the behaviour of axially loaded members under uniform compressive stresses and transversely loaded members under linearly varying stresses.

1. Stocky Stiffeners - Overall Buckling due to Axial Load.

The torsional term predominates and the first term in Equation 2.15 can be neglected. Equating equations 2.15 and 2.16 and substituting for the geometric properties, the equation for tripping of a stocky flat bar stiffener can be expressed as,

$$\frac{b}{t} \leq \frac{168}{\sqrt{F_y}} \quad (2.18)$$

where, b = stiffener web depth (mm)
 t = stiffener web thickness (mm)

2. Slender Stiffeners - Flexural Torsional Buckling due to Transverse Load.

The warping and lateral displacement term will predominate and the second term in equation 2.15 can be neglected. Equating equations 2.15 and 2.16 and substituting for the geometric properties, the equation for tripping of a slender flat bar stiffener can be expressed as,

$$\frac{l}{t} \leq \frac{326}{\sqrt{F_y}} \quad (2.19)$$

where, l = unsupported span of the stiffener (mm)

This equation is based on axial loads and uniform compressive stresses in the cross-section. When transverse loads are applied to the hull plate, such as ice loads, the stress distribution varies linearly (normal stresses due to flexure) and generally exhibits tensile

flexural stresses at midspan. As a result of this more favourable stress distribution, the load to cause tripping to occur is significantly larger. Ings and Trahair (1984) studied the lateral buckling of restrained roof purlins subjected to uniform lateral loads and determined that the maximum dimensionless buckling moment, $M_m L^2 / \{\pi^2 \sqrt{(EI_y EI_w)}\}$ at the critical section was 4.7 times higher than that were the load applied axially. Based on this work, the unsupported length in Equation 2.19 can be increased by $\sqrt{4.7}$, or 2.17 times to give the same load capacity. Applying this, Equation 2.19 becomes,

$$\frac{l}{t} \leq \frac{710}{\sqrt{F_y}} \quad (2.20)$$

The applicability of this empirical modification is questionable.

3. Intermediate Slenderness Stiffeners.

An interaction equation taking into account overall buckling and flexural torsional buckling as described in parts 1 and 2 is given by Equation 2.21.

$$\frac{l}{t} \leq \frac{710}{\sqrt{F_y} \sqrt{1 - \left(\frac{168}{\sqrt{F_y}} \frac{t}{b} \right)^2}} \quad (2.21)$$

This expression incorrectly combines behaviour defined by slenderness parameters b/t and l/t with different load actions (transverse and inplane loads).

Applying the factors which take into account the frame tilt or cant, and the flexural stress factor, which is based on the fact that flexural stresses drive stiffener tripping, gives the three design formulae for tripping of flat bar stiffeners (section 24.3, ASPPR (1993)),

$$\frac{b}{t} \leq 168 \frac{N}{V} \quad (2.22)$$

$$\frac{l}{t} \leq 710 \frac{N}{V} \quad (2.23)$$

$$\frac{l}{t} \leq \frac{710 N}{V \sqrt{1 - \left(168 \frac{N}{V} \frac{t}{b} \right)^2}} \quad (2.24)$$

where, N = frame tilt factor
 $= 1.0$ when $\delta \geq 85^\circ$
 $= (1 - \cos\delta)$ when $\delta < 85^\circ$
 δ = angle between the web and the shell, degrees
 V = flexural stress factor
 $= (F_y Z_r/Z_p)^{1/2}$
 Z_r = required frame plastic section modulus, mm^3
 Z_p = provided frame plastic section modulus, mm^3

The framing members consisting of flat bar sections need to satisfy only one of these to be considered satisfactory.

Hu (1993) attempts to clarify the behaviour of stiffened plates subject to axial and transverse loads. The Canadian and British Ship Standards, DMEM10 (Structural Design of Surface Warship, Canadian Forces), NES110 (Naval Engineering Standard, UK MOD), and SSCP23 (Design of Surface Ship Structures, UK MOD) are reviewed. Hu (1993) incorporates an extra term to account for the effect of rotational restraint provided by the hull plate for an axially loaded singly symmetric section (stiffener alone). Buckling of the hull plate is neglected.

$$\sigma_{cl} = \frac{\pi^2 E n}{l^2} \left(\frac{a^2 I_y + C_w}{I_p} \right) + \frac{GJ}{I_p} + \frac{k_\phi l^2}{n \pi^2 I_p} \quad (2.25)$$

where, k_ϕ = rotational rigidity of the plate
 $= E/(3b_e/t_{hull}^3 + 3.64b/t^3)$
 b_e = hull plate effective width (mm)
 t_{hull} = hull plate thickness (mm)
 b = stiffener web depth (mm)
 t = stiffener web thickness (mm)
 n = number of half waves in longitudinal direction

Although this equation was derived for an axially loaded member, Hu considers it applicable for laterally loaded stiffened plates as the stiffener acts like the compressive flange of a beam.

As a laterally loaded member, Hu (1993) developed a modified equation for the lateral-torsional buckling moment of a doubly symmetric stiffener, M_{cr} , which is rotationally restrained by the hull plate and loaded with uniform moments about its major axis. This expression would only be applicable to flat bar stiffeners in which the contribution of the hull plate is ignored in carrying transverse loads. The equivalent moment factor for varying moment fields has not been incorporated making the applicability of this expression to real stiffened plates questionable.

$$M_{cr} = \frac{\pi}{l} \sqrt{EI_y GJ + (I_y^2 a^2 + I_y C_w) \frac{E^2 \pi^2}{l^2} + EI_y k_\phi \frac{l^2}{\pi^2}} \quad (2.26)$$

where, $k_\phi = Et_{hull}^3/3b_e$

Hu (1993) also considered the case of in-plane loaded stiffened plates that buckle with the stiffener twisting about its toe while the plate buckles in an alternate fashion.

Because of the simultaneous buckling of the plate, rotational restraint is not provided to the stiffener by the plate. Therefore, the buckling stress is determined as the average of the buckling stresses of the plate and the stiffener calculated separately. The elastic buckling stress for a long plate ($l > b$) is,

$$\sigma_{ce} = \frac{\pi^2 E}{12(1-\nu^2)} \frac{t^2}{b^2} \left(\frac{l}{nb} + \frac{nb}{l} \right)^2 \quad (2.27)$$

Combining the flexural-torsional buckling stress of the stiffener with the elastic buckling stress of the plate and assuming that both buckle in one half-wave ($n=1$), the average buckling stress of the stiffened plate becomes,

$$\sigma_{cr} = \frac{\left(\frac{GJ}{I_p} + (I_y a^2 + C_w) \frac{E\pi^2}{I_p l^2} \right) A_s + \left(\frac{\pi^2 E}{12(1-\nu^2)} \frac{t^2}{b^2} \left(\frac{l}{b} + \frac{b}{l} \right)^2 \right) bt}{A_s + bt} \quad (2.28)$$

where, A_s = area of the stiffener, mm^2

2.2.2.4 Design for Local Buckling

The elastic critical buckling stress of a long plate segment is a function of the width-to-thickness ratio, b/t , the restraint conditions at the edge of the plate and the elastic material properties, and is given as,

$$\sigma_{cr} = \frac{k \pi^2 E}{12 (1-\nu^2) \left(\frac{b}{t} \right)^2} \quad (2.29)$$

where, k = buckling coefficient

For flat bar stiffeners, simply supported on three edges with the fourth edge being free, under uniform compressive stress, the buckling coefficient is 0.425. Equating the critical stress to the yield stress and making the appropriate substitutions gives the equation for local buckling in section 23.3 in the ASPPR (1993).

$$\frac{b}{t} \leq \frac{282}{\sqrt{F_y}} \quad (2.30)$$

The effect of compressive residual stresses has been ignored.

(a)

(b)

Figure 2.1 - Schematic of Stiffener Buckling about Enforced Axis of Rotation

Chapter 3

Experimental Program

3.1 General

Two structural steel stiffened plate panels with dimensions of 5000 mm by 2600 mm were tested using a five point load system transverse to the hull plate. The specimens were fully fixed at their boundaries to the supporting horizontal reaction frame through the use of full penetration groove and fillet welds.

The first test panel was a minimum cost design compliant with the proposed Arctic Shipping Pollution Prevention Regulations (ASPPR). The loaded main frames were loaded eccentrically with a 50 mm offset (in the same direction) to induce lateral instability in those stiffening members. The depth to thickness ratio (b/t) of the main frames was 11.34 and the unsupported length to thickness ratio (l/t) of the main frames was 77.13.

The second test panel was designed to promote instability of the flat bar main frames by increasing the slenderness of the element such that the width to thickness ratios of the main frames varied from 9.76 to 29.92 and the unsupported length to thickness

ratios of the main frames from 89.68 to 179.35. The load points in the second test were centrally located with respect to the loaded main frames. There were a total of nine main frames in the middle quadrant. Once again these were bounded by web frames and stringers.

The steel plate for both test specimens was provided by Algoma Steel Inc. and the specimens were fabricated by the CANAM MANAC Group.

Ancillary tests performed included tension coupons on each steel plate thickness and one residual stress specimen of a typical main frame-hull plate section that was fabricated along with the first test panel.

3.2 Test Panel Design

3.2.1 Test Panel #1

The first test panel was designed to achieve a minimum weight, minimum cost panel that would be constructible, testable and to be compliant with the proposed Arctic Shipping Pollution Prevention Regulations.

The design process was driven by the following constraints. First, the test specimen size had to be large enough to provide sufficient access for instrumentation purposes, to avoid scaling effects which could alter stability and behaviour characteristics, and to eliminate any difficulties associated with scaling welds below practical sizes. In addition, the load available that can be applied to the specimen is limited to 16900 kN. These constraints led to the selection of the midbody portion of the ship to be

investigated.

A spreadsheet was developed, incorporating all of the requirements of the proposed ASPPR Schedule 1, which details all structural requirements, and weight and cost data to select the most cost efficient structural configuration from a number of different structural framing schemes. The cost data incorporated material and labour components (welding, cutting, handling, setup, and overhead). A sample of the design spreadsheet format is shown in Appendix B.

The CCG HENRY LARSEN, an existing icebreaker vessel, was selected as a starting point in the design process. The LARSEN is a medium size Canadian Arctic Class 4 icebreaker. It has a displacement of 8290 tonnes and shaft power of 12.0 MegaWatts. The midbody structural layout of the LARSEN is given in Table 3.1.

The portion of the LARSEN that was modelled spans longitudinally between bulkheads and transversely between the main deck and bottom structure with an intermediate deck. The intermediate deck is a relatively light structure and was modelled as a stringer with similar stiffness.

Before analyzing the LARSEN as a possible test panel, the steel with which the specimen was to be constructed had to be determined. The grade of steel that is most readily available from Canadian steel suppliers is CAN/CSA G40.21-M 300W. This steel is weldable and has a yield strength of 300 MPa, which is slightly lower than the yield strength than that of the LARSEN and does not have notch toughness requirements. This was considered acceptable since room temperature testing would be performed and the lower yield strength would allow for a larger scale test to be performed. Furthermore,

it was decided to design a vessel of slightly smaller power and displacement than the LARSEN due to the limitations of the test load available. It was decided that the design vessel would have a displacement of 7500 tonnes and shaft power of 8.0 Megawatts. With the 'experimental' steel, displacement, and power, the LARSEN was analyzed using the spreadsheet and modified slightly to be ASPPR compliant. Parametric studies were undertaken to determine the optimum structural configuration and it was decided to use a configuration of two longitudinal angle stringers, two transverse tee web frames, and five flat bar main frames between the web frames. The spreadsheet calculations showing the unscaled scantlings are given in Appendix C.

Once the basic structural layout was determined, the scale of the specimens had to be finalized. The maximum load available and the laboratory layout affected this parameter. The ultimate strength of the stiffened plate could not exceed the maximum total load available. An analysis of the plate was performed using the computer program IMASP (Inelastic Membrane Analysis Steel Plates), developed by Mr. James Bond at Carleton University for various smeared plate thicknesses representing different scales. The program calculates the full membrane load that the plate could withstand prior to rupture of the weld, the HAZ, or the parent plate and the corresponding reaction loads at the boundaries. For a 40% scale model, this load was determined to be 16300 kN. Given the load limit of 16900 kN in the laboratory, a 40% scale model was considered reasonable. In scaling the specimen, all depth to thickness ratios (b/t) and all length to thickness ratios (l/t) of the stiffeners were kept the same as those of the full scale specimen to give the same characteristic behaviour.

The final design constraint which had to be considered, was that of the holes in the strong floor of the laboratory, to which the reaction frame was anchored by the use of high strength steel rods. In plan, these holes are spaced 600 mm on centre in both directions. Ideally, the rods should pass through the reaction frame at no more than 200 mm from the inside edge of the frame of the long side to minimize the torsional moments in the frame. The width of the test specimen becomes a multiple of 600 mm less 400 mm. A width of 2600 mm was selected for the test panel (3000 mm from centre to centre of the rods), which was 250 mm larger than the 40% scaled version of the LARSEN. Typically, icebreaker panels for the midship region have aspect ratios of 2:1 or greater, setting the length of the panel as 5000 mm (aspect ratio = 1.92). This length was selected to give a shorter reaction frame with lower bending moments during loading. James Bond of MIL Systems designed the first panel, shown in Fig 3.1, to the plan dimensions of 2600 mm by 5000 mm and according to the criterion listed above.

3.2.2 Test Panel #2

Test panel #2 was designed to provide experimental data to establish the slenderness ratios (b/t , l/t) in which unstable behaviour of the flat bar main frames would occur. This data along with the corresponding finite element analysis will be used subsequently to evaluate and to refine the proposed design rules. A total of nine main frames with five different slenderness ratios, equally spaced, were placed symmetrically in the central quadrant which was bounded by the web frames and stringers. Only one was ASPPR compliant with respect to tripping and local buckling. The (b/t) and (l/t)

ratios range from 9.8 to 29.9 and from 89.7 to 179.4, respectively. One of the type 3 main frames was canted at a 15° angle to the vertical. All main frames were proportioned to give similar strength parameters (shear area and plastic section modulus) that were ASPPR compliant to eliminate the potential failure modes associated with those characteristics from the problem.

The stringers and web frames were designed to be ASPPR compliant and the collar plate connections between the stringer and web frame were eliminated to avoid the problem of scaling the cutouts and the failure of the eccentrically loaded weld groups exhibited in the first test. The stringer was composed of three pieces which were fully welded to the web frame making it continuous.

Because of the increased span of the central portion in both directions, all members were tapered in the exterior quadrants in order to give a flexural stiffness equivalent to the central portion. The second test panel fabrication drawings are shown in Figure 3.2 (a) and (b). A summary of the dimensions and design ratios of the different main frame types is given in Table 3.2. For the second test panel, the hydraulic actuators were placed directly under and in line with the main frames to reduce the possibility of local tearing of the hull plate that resulted from large local strains associated with increased local rotations due to eccentric loading in the first test.

3.3 Test Set-Up

The test set-up consisted of a horizontal reaction frame, support columns, high strength steel tie-down rods, a stiffened plate girder, electronic and mechanical

instrumentation, a data acquisition system, and the test specimen. Figure 3.3 shows a plan view of test specimen #1 in the horizontal reaction frame along with its internal diaphragms and stiffeners. Figure 3.4 shows a cross sectional view of test specimen #1 in the test apparatus. The instrumentation has not been included in these figures for clarity.

3.3.1 Loading Apparatus

Transverse loads were applied along the longitudinal centreline axis of the test specimens through a series of five load points. Each load point consisted of a hydraulic jack and a knife-edge-roller assembly as shown in Figure 3.4. The hydraulic jacks, in compression, react off of a stiffened plate girder which in turn sits on the strong floor of the laboratory. The load is transferred from the hydraulic actuator through the knife-edge-roller assembly, through copper plates, to the test specimen. The knife-edge-roller assemblies allow the test specimen to freely displace laterally (up to 70 mm) and to freely rotate (up to 30°) with respect to the hydraulic actuator. The copper plates soften the sharp shearing edges of the load plates. The location of the load application points are shown for test panel #1 and test panel #2 in Figures 3.5 (a) and (b) respectively.

3.3.2 Horizontal Reaction Frame

The horizontal reaction frame lay in the same plane as that of the test specimen. It represents the stiffness of the surrounding ship structure, transverse bulkheads and deck levels, and provides the in-plane restraint necessary to develop membrane action. The

reaction frame was designed as four rigidly connected box beams. The frame had to be sufficiently deep to contain the full depth of the test panel which was fully welded to its inside face. The frame was designed to behave elastically under ultimate test conditions since it was to be reused for more than one test.

The horizontal reaction frame, high strength rods and supporting columns were modelled and analyzed using the structural analysis program SFRAME. The reactions resulting from an incremental plastic analysis of typical test panels, modelled as grillages, and from an inelastic membrane analysis (using IMASP) of the test panel with an equivalent smeared plate thickness were applied to the SFRAME model as loads. Internal force distributions (axial loads, shear, bending moments, twisting moments) and displacements were determined. The box girders were designed according to CAN/CSA-S16.1-M89 as beam-columns and stiffened internally at locations where high local load intensities were anticipated. Fabrication drawings of the horizontal reaction frame are shown in Figures 3.6 (a) - (h). The total dead weight of the frame was approximately forty tons. To facilitate in the erection process, the frame was built in two pieces with a bolted connection at midspan of the shorter box beams.

The horizontal reaction frame was restrained from vertical displacements through the use of eight W310X118 columns, two supporting each box, and twelve 2-1/2" diameter high strength tie-down rods, four tying down each long box and two tying down each short box. The columns were used to support the dead weight of the frame and in conjunction with the tie-rods as a force couple system to take out the torque applied to the frame by the loaded specimen, as shown in Figure 3.7. The columns are bolted to the

underside of the reaction frame while the tie-rods pass through the frame and are secured to the top of the frame with a nut threaded on the end.

3.3.3 Instrumentation and Measurement

Applied loads, steel strains, and displacements were measured throughout the test using pressure transducers, electrical resistance gauges, Demec gauges (mechanical extensometer), and linear variable differential transformers (LVDT's) respectively. The locations of the strain gauges on the hull plate; main frames M8, M9, M10 and web frame D2; stringer S2; and for Demec gauge reading locations for test panel #1 are shown in Figures 3.8, 3.9, 3.10, and 3.11, respectively. The location and LVDT numbers for vertical and horizontal displacements are shown in Figures 3.12 and 3.13. Figure 3.14 (a) and (b) indicate the vertical position of the LVDT's measuring the lateral displacement of the main and web frames, and of the stringer, respectively.

The locations of strain gauges on the hull plate; main frames M4 to M12 and web frame D1; stringer S1; and for Demec gauge reading locations for test panel #2 are shown in Figures 3.15, 3.16, 3.17 and 3.18, respectively. The location and LVDT numbers for vertical and horizontal displacements are shown in Figures 3.19 and 3.20. The vertical position of the LVDT's measuring the lateral displacement of the main frames was maintained at approximately 400 mm above the inside of the hull plate, and those for the web frame and stringer were similar to test panel #1. The type of measurement, the instrumentation, its accuracy, location, purpose, and frequency of measurement are shown in Tables 3.3 and 3.4.

3.4 Assembly of Test Frame

The test frame was assembled in the following order:

1. the columns were aligned horizontally on the laboratory strong floor and bolted down using the column tie-down rods;
2. the horizontal reaction frame was lifted into place, one half at a time, and bolted to the tops of the columns and then to each half at the connection plate;
3. the tie-down rods were lowered through the horizontal reaction frame and through the strong floor and secured at the top of the frame and underside of the strong floor by nuts and washers;
4. the plate girder was aligned and seated in plaster to provide a level working surface off which the loading takes place;

3.5 Assembly of Test Apparatus

The assembly of the test apparatus, instrumentation and installation of each icebreaker hull test panel consisted of the following steps:

1. the hydraulic actuators were bolted to the plate girder and the hydraulic system was assembled;
2. the knife-edge-roller assemblies were lifted into place and positioned;
3. initial geometry and out-of-straightness of the main frames was measured;
4. the test panel was instrumented with Demec gauge points and all the strain gauges that would not be affected by the welding. Initial Demec gauge

readings were taken;

5. the test panel was lifted into position (resting on steel pegs mounted in the horizontal reaction frame) and welded into place;
6. Demec gauge readings were taken to determine the strains induced due to the welding process;
7. the remaining strain gauges were installed on the plate and stiffeners;
8. the frame to support the LVDT's was attached to the horizontal reaction frame (all deflections are relative to the reaction frame);
9. LVDT's were connected. Strain gauge wires and LVDT cables were routed and attached to the data acquisition system;
10. the data acquisition control files were created. The knife-edge-rollers were brought into contact with the hull plate;
11. the power supply voltages were adjusted;
12. the specimen was subjected to a small preload, the instrumentation checked, and malfunctioning (shorted wires, etc.) instrumentation fixed;
13. the specimen was unloaded and the data acquisition system zeroed;
14. initial observations and measurements were made;
15. photos of the undeformed structure were taken.

3.6 Test Procedure

The specimens were loaded using five hydraulic actuators. The hydraulic system consisted of an air driven pump, a hydraulic oil reservoir, solenoid valves and manifolds.

The valves and manifolds allowed for different increments in pressure and thus load for three sets of actuators, those being the 2-200 ton exterior actuators, the 2-500 ton interior actuators and the central 500 ton actuator. For test panel #1, the load was applied with the loading ratio in proportion to their full range (5:2 for the 500 ton to 200 ton actuators). This gives the same pressure in all hydraulic lines and allows all the actuators to achieve their full capacity simultaneously. For test panel #2, the load was applied equally up to 7000 kN total load. Additional load beyond this was applied through the 500 ton actuators. Load in the 200 ton actuators was kept constant at 1400 kN. In both tests, the load was applied monotonically up to failure.

The load sequence consisted of the following steps:

1. initial readings were taken at zero load with the actuator pistons in contact with the hull plate;
2. the total load increment was approximately 50 kN;
3. all electronic measurements were taken;
4. LVDT channels were scanned and LVDT's whose voltages were close to the limits of the linear range were reset;
5. observations were made and recorded with respect to yielding, yield patterns, and progression of failure;
6. photographs were taken of deflected shapes, yielded areas, and of any phenomenon related to instability behaviour;
7. a video was taken of the centre portion of the test panel #1;
8. plots of deflected shapes and load deflection curves were recorded at 250

kN total load increments to monitor the behaviour as the test progressed;

9. Demec gauge readings were taken at 500 kN total load increments;

After failure the test panel was unloaded, a complete photographic record made, and residual deformations recorded.

3.7 Ancillary Tests

Ten tension coupons from both the longitudinal and transverse directions were tested in uniaxial tension to determine the stress-strain characteristics of the 11.11 mm steel plate thickness used in the construction of the test panels. Five coupons from both the longitudinal and transverse directions were tested for the remaining steel plate thicknesses. The coupons were taken from a piece of plate which was flame cut from the parent plate as shown in Figure 3.21. The coupons were cut and milled following ASTM E8M-88 recommendations using a gauge length of 200 mm and a width of 40 mm. A typical tension coupon is shown in Figure 3.21.

The cross-sectional dimensions were determined from twelve measurements of the reduced width and thickness made along the length of the coupon prior to testing using a digital micrometer. Pairs of strain gauges were mounted on each side of six coupons, three from each direction, for the 11.11 mm steel plate thickness. For the remaining steel plate thicknesses, pairs of strain gauges were mounted on each side of two coupons, one from each direction. From measurements, the average longitudinal and transverse strains and Poisson's ratio could be determined. The remaining coupons had single longitudinal gauges mounted on each side. Large strains were measured with dividers and a scale

over a 200 mm gauge length. All tension coupons were tested in a 1780 kN Tinius Olsen testing machine in accordance with ASTM Designation E8M-88 (ASTM, 1988).

The residual stress specimen consisted of a typical main frame in test panel #1 welded to a section of hull plate. In accordance with Technical Memorandum No. 6 from Galambos (1988), the middle 500 mm portion of the specimen was marked into 18 sections of the same area (except for the intersecting area) and holes were drilled to the appropriate size for subsequent measurements with a Demec gauge. The gauge length was 200 mm. The definition of the sections for the residual stress specimen is shown in Figure 3.22. Initial readings were taken and the specimen was cold cut into its individual sections. Final readings were taken and the residual strain values were calculated from which the residual stress values were determined.

Table 3.1 Summary of LARSEN Structural Layout

Steel Grade	EH36 ($\sigma_y = 355$ MPa)
Plate Thickness	35 mm
Main Frame Spacing	460 mm
Web Frame Spacing	1840 mm
Longitudinal Stringer Spacing	980 mm
Distance Between Bottom Structure and Main Deck	5875 mm
Distance Between Main Deck and Intermediate Deck	2895 mm
Distance Between Bottom Structure and Intermediate Deck	2980 mm
Distance Between Bulkheads (Frames 61 and 89)	12880 mm

Table 3.2 - Geometry and Ratios Indicating Structural Compliance for Main Frames of Test Panel #2

Component	Type 1	Type 2	Type 3	Type 4	Type 5
b, mm	190	159	144	133	124
t, mm	6.35	7.94	9.52	11.11	12.70
Local Buckling	0.509	0.768	1.017	1.284	1.572
Tripping	0.327	0.459	0.606	0.766	1.242

- Notes: 1. The unsupported length of all main frames located in the central quadrant was 1139 mm.
2. The capacity for local buckling and tripping as related to the ASPPR is expressed as a ratio (provided/required).

Table 3.3 - Type of Measurement and Instrumentation

Instrumentation	Location/Description	Purpose	Frequency of Measurement
1. Applied Loads			
Pressure transducers	On the input pressure line of each actuator.	Multiplied by cylinder area gives applied load per actuator.	Discrete readings taken at the end of each load increment.
2. Steel Strains			
Electrical Resistance Gauges	At various locations along the length of the stiffeners, on the top and bottom of the hull plate, strain gauges were mounted in order to measure longitudinal and transverse strains. Refer to Figures 3.8-3.10 and Figures 3.15-3.17.	Provides a strain distribution throughout the depth of the stiffener and across the hull plate section.	Discrete readings taken at the end of each load increment.
Mechanical Extensometer	Locations and gauge lengths are shown in Figures 3.11 and 3.18.	Provides a measure of the strains at locations where electrical resistance gauges would have been damaged by the welding process.	Readings were taken at the end of total load increments of 500 kN.

Table 3.3 (continued)

Instrumentation	Location/Description	Purpose	Frequency of Measurement
3. Deflected Shape			
LVDT's	A series of calibrated LVDT's were mounted on the stiffeners in order to measure both vertical and lateral deflections as shown in Figures 3.12-3.14 and Figures 3.19-3.20.	Used to monitor the load deflection response of the structural element.	Discrete readings taken at the end of each load increment.

Table 3.4 - Measurement, Range and Accuracy

Measurement	Instrument	Specified Range	Accuracy
Applied Load	5 Calibrated Pressure Transducers	0-10000 psi	± 10 psi
Steel Strains	100-1/4 Bridge Micro-Measurement High Elongation Strain Gauges. Resistance $120.0 \pm 0.15\%$ ohms. Gauge length 8 mm. Gauge Factor $2.055 \pm 0.5\%$ at 24°C .	0-200000 μs	$\pm 0.5 \mu\text{s}$
	Mechanical Extensometer Gauge Length 50 mm 200 mm	0-66000 μs 0-22000 μs	$\pm 25.1 \mu\text{s}$ $\pm 8.1 \mu\text{s}$
Deflected Shape	LVDT's	$\pm 3.0''$	$\pm 0.006''$

Note: LVDT's were reset to keep the instruments within their operating range.

Figure 3.1 - Fabrication Drawing of Test Panel #1

Figure 3.2 (a) - Fabrication Drawing of Test Panel #2

Figure 3.2 (b) - Fabrication Drawing of Test Panel #2

Figure 3.3 - Cross-Section Plan View of Test Panel #1 in Reaction Frame

Figure 3.4 - Cross-Section of Test Panel #1 in Test Apparatus

(a) Test Panel #1

Note: All loading areas 200 mm by 300 mm

(b) Test Panel #2

Figure 3.5 - Load Application Points for Test Panels #1 and #2

Figure 3.6 (a) - General Fabrication Drawing of Horizontal Reaction Frame

Figure 3.6 (b) - Fabrication Drawing of Horizontal Reaction Frame, Connection Detail

Figure 3.6 (c) - Fabrication Drawing of Horizontal Reaction Frame, Short Box End Detail

Figure 3.6 (d) - Fabrication Drawing of Horizontal Reaction Frame, Stiffener Weld Details

Figure 3.6 (e) - Fabrication Drawing of Horizontal Reaction Frame, Stiffener Weld Details

Figure 3.6 (g) - Fabrication Drawing of Long Box Support Column

Figure 3.6 (h) - Fabrication Drawing of Short Box Support Column

Figure 3.7 - Schematic Diagram of Vertical Load Resisting System

Figure 3.8 - Location of Strain Gauges on Hull Plate for Test Panel #1

- NOTES: 1) strain gauges are also located on the opposite side of the web in the same locations as shown.
2) all dimensions in millimetres.

Figure 3.9 (a) - Location of Strain Gauges on Main Frame M8, Test Panel #1

Figure 3.9 (b) - Location of Strain Gauges on Main Frames M9 and M10, Test Panel #1

Figure 3.9 (c) - Location of Strain Gauges on Web Frame D2, Test Panel #1

NOTES: 1) strain gauges are also located on the opposite side of the web
in the same locations as shown.
2) all dimensions in millimetres.

Figure 3.10 - Location of Strain Gauges on Stringer S2 for Test Panel #1

Figure 3.12 - Vertical LVDT Locations and Numbering for Test Panel #1

Figure 3.13 - Lateral LVDT Locations and Numbering for Test Panel #1

Figure 3.14 (a) - Location of Lateral LVDT's on Main and Web Frames

Figure 3.14 (b) - Location of Lateral LVDT on Stringer

Figure 3.1.5 - Location of Strain Gauges on Hull Plate Top for Test Panel #2

- NOTES: 1) strain gauges are also located on the opposite side of the web in the same locations as shown.
2) all dimensions in millimetres.

Figure 3.16 (a) - Location of Strain Gauges on Main Frames M4, M5, M6, M7, M8, M10, M12
Test Panel #2

Figure 3.16 (b) - Location of Strain Gauges on Main Frames M9 and M11, Test Panel #2

Figure 3.16 (c) - Location of Strain Gauges on Web Frame D1, Test Panel #2

NOTES: 1) strain gauges are also located on the opposite side of the web
in the same locations as shown.
2) all dimensions in millimetres.

Figure 3.17 - Location of Strain Gauges on Stringer S1 for Test Panel #2

Figure 3.18 - Demec Gauge Reading Locations on Hull Plate Bottom for Test Panel #2

Figure 3.19 - Vertical LVDT Locations and Numbering for Test Panel #2

Figure 3.20 - Lateral LVDT Locations and Numbering for Test Panel #2

Figure 3.21 - Tension Coupon Definition

(a) Cross-Section and Segment Definition

(b) Plan View

Figure 3.22 - Residual Stress Specimen

2

PM-1 3 1/2" x 4" PHOTOGRAPHIC MICROCOPY TARGET
NBS 1010a ANSI/ISO #2 EQUIVALENT

PRECISIONSM RESOLUTION TARGETS

Chapter 4

Test Results And Discussion

To aid in the presentation and the discussion of the test results, schematic diagrams labelling the framing members of test panels #1 and #2 are shown in Figures 4.1 and 4.2 respectively.

4.1 Initial Conditions and Material Properties

Test panel #1 was constructed from one main steel plate, 11.11 mm (7/16 inch) thick and a small quantity of 6.35 mm (1/4 inch) thick plate which was used for the flange of the web frames. Test panel #2 was constructed from the 11.11 mm (7/16 inch) plate for the hull section and from five different plate thicknesses, ranging from 12.7 mm (1/2 inch) to 6.35 mm (1/4 inch), for the framing members. In the construction of both test panels, flame cutting was used to obtain the desired member sizes which were then welded to the hull plate. The chemical and mechanical properties reported on the mill certificates are given in Tables 4.1 and 4.2 respectively.

The average measured thicknesses of the framing elements for test panels #1 and #2 are given in Tables 4.3 and 4.4, respectively. The average thickness of the hull plate for test panel #1 was 10.99 ± 0.21 mm while for test panel #2, it was 10.98 ± 0.10 mm. All other dimensions were as specified in the fabrication drawings.

The initial out-of-straightness measurements of the framing elements for test panels #1 and #2 as specified in Figures 4.1 and 4.2, are given in Tables 4.5 and 4.6, respectively. The out-of-straightness are expressed by the maximum imperfection in millimetres and as a ratio of span to the maximum imperfection.

The initial in-plane strains developed in the hull plate due to welding of test panel #1 to the test frame are given in Table 4.7. The largest tensile strain due to this process was approximately 36% of the yield value in the transverse direction.

The material properties for the 12.7 mm plate, 11.11 mm plate, 9.53 mm plate, 7.94 mm plate, and 5.97 mm plate in both the longitudinal and transverse directions as determined from the tension coupons tests are shown in Tables 4.8 and 4.9, 4.10 and 4.11, 4.12 and 4.13, 4.14 and 4.15, and 4.16 and 4.17 respectively. Stress-strain curves for typical coupons with cold cut edges (interior sample) and with one flame cut edge, for the 11.11 mm plate, for the longitudinal and transverse directions are shown in Figures 4.3 and 4.4, respectively. The coupons exposed to a flame cut edge begin to exhibit inelastic characteristics at a lower stress level than that of the cold cut coupons. Once the strain hardening value has been reached, there is essentially no difference between the two curves.

The residual stresses obtained from one residual stress specimen of a typical main

frame hull segment are shown in Figure 4.5. The stresses were obtained by multiplying the residual strain value by the modulus of elasticity for the steel used. The residual stress distribution indicates compression at the tip of the flat bar which gradually changes to tension at approximately half way down the stiffener, and then to yield in tension at the welded intersection. The hull plate generally shows large compressive residual stresses throughout (approximately $0.5\sigma_y$).

4.2 Finite Element Modelling

A finite element analysis, which included initial imperfections (out-of-straightness), and material and geometric nonlinearities, was used to investigate the behaviour of the icebreaker grillages under transverse loading. This analysis allowed for a direct comparison with the experimental data.

ANSYS finite element software developed and supported by Swanson Analysis Systems Inc. of Houston, PA, was used for the analysis of both test panels. The grillages were modelled with an assemblage of plastic shell elements (SHELL43). These elements are well suited for modelling nonlinear behaviour of flat or warped, thin to moderately thick shell structures. These elements have six degrees of freedom at each node, those being translations in the x, y, and z directions and rotations about the x, y, and z axes. The deformation shape is linear in the two in-plane directions. The out-of-plane motion is predicted using a mixed interpolation of tensorial components (ANSYS, 1992).

The SHELL43 element is defined by four corner nodes, four thicknesses, and the orthotropic material properties. A triangular element is formed by giving the third and

fourth nodes the same node number.

To describe the plastic behaviour, the Multilinear Isotropic Hardening (MISO) option in ANSYS was used. The MISO option uses the von Mises criteria coupled with an isotropic work hardening assumption. This option was used since it gives the best results for large strain analyses. The Newton-Raphson equilibrium iterations were used to drive the solution to equilibrium convergence within some tolerance limit.

A static nonlinear analysis, which corresponds to the static loading conditions of the experimental program, was used. To trace the post yield behaviour, incremental loading was used. The edges of the model were fully fixed against all translations and rotations. The loading was applied as patch loads with dimensions of 200 mm by 300 mm which corresponds to the contact surface of the load plates. A refined mesh was used directly under the load. To simplify the modelling procedure, ratholes and all openings used to facilitate the fabrication of the test panels were omitted. The collar plate connections between the stringers and web frames, and all fillet welds were omitted. The finite element meshes used for each test panel are illustrated in Figures 4.6 and 4.7 respectively. The finite element models and analysis were performed by Mr. James Bond and Mr. Jay Srinivasan of MIL Systems Engineering Inc.

4.3 Test Panel #1

4.3.1 General Behaviour

The general behaviour of the hull structure as a whole is characterized by the total load versus centreline deflection curve shown in Figure 4.8. The points shown on the curve indicate the major events that occurred during the test as the progression of failure took place. These events, which included yielding of all framing elements, web distortions and instability of the web frames and stringers, and the development of membrane action in the hull plate, along with the load levels at which they occurred are described in Table 4.18.

The behaviour of the structure can be divided into two general regions: elastic flexural and elastic plastic flexural membrane. The elastic flexural response was only a short lived one and culminated with yielding of the main frames due to the exceedence of their flexural capacity. The rest of the response was elastic plastic flexural membrane behaviour with a varying degree of both flexural and membrane response depending on the load level.

The flexural resistance of the structure was provided through the use of framing members. As the load resisted by these structural elements increased, they yielded resulting in a decrease in member stiffness and stability and thus slope of the load-deflection curves for both vertical and lateral deflections. The total load versus vertical deflection of the instrumented web frame, stringer, and centre main frame are shown in Figures 4.9, 4.10, and 4.11 respectively. The numbers in the circles indicate the LVDT

numbers and are followed by their location along the members length. Also, indicated on the figures are the events which caused a change in the member stiffness. The total load versus lateral deflection of the instrumented web frame, stringer, and centre panel main frames are shown in Figures 4.12, 4.13, and 4.14 respectively.

The test panel is a redundant structure. As members reached their load carrying capacity, additional load is sustained by other parts. The principal load carrying path is in the stiffer transverse direction. Load is also carried out to the reaction frame along the stringers in the long direction and out from the main frames in flexure. This contribution is relatively small and plays a minor role in the overall behaviour.

4.3.1.1 Elastic Flexural Behaviour

During the elastic flexural behaviour of the structure, the load was carried primarily by the main frames directly above the load points to the stringers, from the stringers to the web frames and out to the reaction frame as shown in Figure 4.15 (a). This corresponds to the FEA plot in Figure 4.16 (a). This behaviour continued up until approximately 900 kN and is seen in the main frame load-deflection curves as the initial straight line portion up until that load level. At this load level, the loaded main frames (3 span continuous members loaded centrally) yielded at midspan in tension ending the elastic flexural portion of the behaviour. Yielding caused a decrease in stiffness as indicated by the change in slope of the load-deflection curves. The main frames still have additional flexural capacity as they are continuous and have only started to develop one plastic hinge. The lateral deformations of the main frames were dominated at this point

by the deformations caused by the 50 mm eccentric load, as shown in Figure 4.14.

4.3.1.2 Elastic Plastic Flexural Membrane Behaviour

With the onset of yielding of the loaded main frames, the increased deformations of those frames coupled with the decreased stiffness resulted in membrane forces being developed in the hull plate spanning between the main frames. With further load, the primary load path was altered with the load increment being carried by the hull plate to the main frames not positioned over a load point. As before, the load is then transferred from the main frames to the stringers, from the stringers to the web frames and then out to the reaction frame, as shown in Figures 4.15 (b).

Those main frames now involved in the new primary load path soon yielded in tension at midspan, resulting in a spread in the hull plate membrane action. Subsequently, the top fibres of the main frames in the central panel, bounded by the web frames and stringers, yielded in compression at the intersections with the stringers. Yield lines propagated upwards on the main frames from the hull plate towards the stringers at an angle of about 20 degrees. The hull plate spanning between the stringers had deformed by approximately its own thickness and membrane action was fully engaged in the central panel. The membrane action occurs primarily in the short direction spanning between stringers. The compression yield of the main frames resulted in a decrease in lateral stability of the stringer as indicated by the change in the load-deflection curve, point a, in Figure 4.13. Additional load is being carried by the hull plate to the stringers, the stringers to the web frames and out to the reaction frame as shown in Figure 4.15 (c).

Load was incremented until the stringers, like the main frames, yielded in tension at midspan as dictated by their support and loading conditions. This had no effect on the lateral stability of the stringer as shown by point b in Figure 4.13. As the stringer yielded at midspan, the hull plate deformations had spread outwards in both principal directions in an elliptical fashion past the stringers and to the web frames. The lateral deformations of the main frames is being dominated more by the increasing global deformations of the stiffened hull section. This phenomenon was noted as the direction of the lateral deformations of the main frames began to reverse themselves as shown by point b in Figure 4.14. The primary load path now became the hull plate, which had developed full membrane action throughout the interior portion of the structure, carrying the increment in load directly to the web frames and out to the reaction frame. With further load (total load of 2250 kN), the web frames yielded in compression in the flanges at the reaction frame. This corresponds to the FEA plot in Figure 4.16 (b). Parallel yield lines formed transversely on the top flange of the web frames at their ends. Yield lines at the flange-web junction propagated downwards in a radial fashion as shown in Figure 4.17.

With further load (total load of 3400 kN), the web frames yielded in tension at midspan. This corresponds to the FEA plot in Figure 4.16 (c). The lateral deformations of the web frames started to increase significantly with further loading, as shown by point b in Figure 4.12, due to the instability which results from compressive forces that develop through the depth and to the eccentric loads on the web from the collar plates. Eventually, the portion of the web frames extending above the stringers rotated in the same direction (due to collar plate load transfer) until they were almost resting on top of

the stringer as shown in Figure 4.18. The web frames have tripped over. The vertical deformations of the web frames, as seen in Figure 4.9 seem not to increase and even decrease once a certain load level is reached. This is misleading, as the depth of the web frame is decreasing faster, as a result of large flange and web distortions, than the vertical deflection of the stable portion of the web frame.

With further load (total load of 3900 kN), the top flange of the stringers yielded in compression at their ends causing a significant decrease in lateral stiffness as shown by point c in Figure 4.13.

As yielding propagated downwards at the ends of the web frames, more load was carried by the hull plate in the area of their intersection as indicated by the distribution of the membrane strains at the hull plate edge between the web frames shown in Figure 4.19.

The large loads transferred from the stringer to the web frame by shear caused the eccentrically loaded weld groups at the collar plate connections between the stringer S2 and web frames to tear at its top. These cracks propagated downwards with increased load and eventually failed at a total load of 6000 kN.

When the end spans of the web frames failed in shear with significant plasticity due to flexure (plastic hinge), the hull plate began carrying more of the load in the transverse (short) direction in membrane action as indicated by dramatic increases in strains (values approaching 20 000 to 25 000 μs) in Figures 4.19 and 4.20. The plastic hinge formation at the ends of the web frames was characterized by the development of a fold in the web extending from the web-hull plate junction upwards at about a 45° angle

to about 400 mm from the end and also the same pattern extending upwards to the top of the stringer as shown in Figure 4.21. With the loss of flexural capacity of the web frames, some additional load was carried in flexure by the portions of the main frames outside of the stringers between the web frames to the reaction frame. The capacity of these members was quickly exceeded, and they buckled at their ends as shown in Figure 4.22. This corresponds to the FEA plot in Figure 4.16 (d).

As more load was applied, the membrane action spread outside of the central panel. Refer to Figure 4.20. The main frames outside of the web frames began to buckle at their ends. The kink in the strain distribution at a load level of 6222 kN shown in Figure 4.20 at the end of web frame D2 is due to fracture of the weld connection between stringer S2 and the web frame. This resulted in less load being transferred to that side of the structure through the web frame and a decrease in the membrane strains. The weld fracture is shown in Figure 4.23. This manifests itself in Figure 4.9 as no increase in displacement occurs with an increase in total load for vertical LVDT's 9 and 10. The connection was unable to transfer the shear force to the end portion of the web frame. The weld tear caused a visible kink at that location in the hull plate.

The formation of plastic hinges at the ends of the stringers occurred at a total load of 6450 kN. The flange of the stringers buckled downwards at the reaction frame and the stringer laterally between the web frame and reaction frame as shown in Figure 4.24. The primary grillage system (web frames, stringers and main frames) had collapsed. The dominant support mechanism is hull plate membrane action. This action spread out in an elliptical fashion to encompass the whole plate. The main framing members exhibited

membrane characteristics in their midspan regions. The lateral deformations of these members became less at midspan as they were pulled straight (upright) like cables. The structure gained stiffness as load was carried in-plane across the entire structure until local tearing of the hull plate occurred in the vicinity of the load plate where the combination of large bending strains and membrane strains exceeded the capacity of the material as shown in Figure 4.25. This corresponds to the FEA plot in Figure 4.16 (e). The ultimate load level reached was approximately three times the design load specified in ASPPR.

The final deflected shapes along the centreline of the panel in the longitudinal and transverse directions are shown in Figures 4.26 (a) and (b), respectively. The flanges of both web frames deflected and rotated in the same direction as a result of the web frame-stringer connection which transferred the shear force eccentrically to the web. This will be discussed further in the comparisons with the finite element analysis results.

4.3.2 Comparisons with Finite Element Analysis Results

4.3.2.1 General Modelling Procedure Used in the FEA

In order to accurately monitor and record the behaviour of the experimental test panel in response to loading, the finite element analysis was conducted prior to the experimental program and the results were used to gauge the progress of the experiment. Stress-strain curves estimated from the material properties given in the Mill Certificate were used in the analysis since the coupon tests had yet to be conducted. Imperfections and fabrication details (ratholes, collar plate connections) were not modelled. Heat

affected zones (from flame cutting and welding) and welds were not modelled. Nominal plate thicknesses were used. The load was modelled as a pressure and stays normal to the plate as it deflects, as compared to the rigid load plates. As a result, large bending strains occurred locally around the load plate edges in the test. Significant friction occurred between the load plate and the test panel during the test. This was not modelled.

4.3.2.2 Load-Deflection Curves

4.3.2.2.1 Web Frame Curves

The vertical displacements of the web frame as given by LVDT's 6 through 10, 11 and 16 with respect to the total transverse load and for the corresponding finite element predictions are shown in Figures 4.27 (a) to (g), respectively. The lateral displacements at the top of the web frame as given by LVDT's 12, 13 and 14 with respect to the total transverse load and for the corresponding finite element predictions are shown in Figures 4.28 (a) to (c), respectively.

A comparison of the experimental load-deflection curves and those predicted by the finite element model show that they are similar in shape and behaviour up to a load level of approximately 6200 kN, with the experimental curves being consistently less stiff. At load levels above 6200 kN, the lateral deflections and rotations of the flange become very large making the LVDT measurements difficult and less accurate. In addition, the weld in the connection between stringer S2 and web frame D2 began to tear at about

5200 kN which is clearly illustrated by the radical change in deflection of LVDT 9 which was positioned over the connection. The weld tear propagated through at approximately 6200 kN. The change in lateral displacement for this web frame segment, given by LVDT 14, goes to zero at this load indicating no further load transfer through the connection. The other eccentrically loaded welded connection on stringer S2 fractured through soon after. These occurrences drastically changed the load paths in the structure and the stability of the web frame. Comparisons above this load level are not meaningful.

The less stiff behaviour of the experimental web frame with respect to the finite element model is the result of two simplifications. Firstly, to make the stringer continuous a significant portion of the web frame cross-sectional area was removed in two locations along the member in order to fabricate the test panel. This reduction in member shear area of about 27% at these locations was not modelled. Secondly, the eccentric shear load transfer from the collar plate connections caused additional out-of-plane moments to be induced in the member which lowers its load carrying capacity.

4.3.2.2.2 Stringer Curves

The vertical displacements of the stringer as given by LVDT's 15, 17, 18 and 19 with respect to the total transverse load and for the corresponding finite element predictions are shown in Figures 4.29 (a) to (d), respectively. The lateral displacement of the stringer as given by LVDT 20 with respect to the total transverse load and for the corresponding finite element predictions is shown in Figure 4.30.

The experimental vertical load-deflection curves are similar in shape to the finite

the loaded region since the integration of the strains over the length, which gives the displacements, must be the same since the displacements were quite similar. The differences between the modelled load and the physical load caused the main frame to experience large changes in curvature (bending) over the load plate edge while the analytical main frame experienced a gradual change in curvature with maximum curvature occurring at midspan. As a result of large bending strains over the load plate edges coupled with the membrane strain, fracture occurred at that location. A probable strain distribution for the test frame is illustrated by the dotted line on Figure 4.51. The magnitude of the strains, consisting of bending and membrane strains, over the load plate edge were large enough to have caused the fracture.

The final strain comparison relates the strains developed along the longitudinal edges of the hull plate itself, shown in Figure 4.52, with the physical strains being recorded through the use of Demec gauges. What can be observed from this figure is the smoothing effect that the finite element analysis produces on the strain results. The distribution is a gradually increasing one with no plateaus or sudden increases. The correlation at moderate load levels is very good while at high load levels there is some deviation. This may be attributed to physical variances in the test panel which weren't modelled.

Also of note is the development of compressive strains at the furthestmost ends of the test panel. The reaction frame was subjected to large transverse tensile forces along the long box which produces positive bending moments at midspan and, because of the fixity with the short box, negative bending moments at its ends. This would cause small

are given in Figures 4.32 (a) to (d), respectively.

The analytical model predicted the vertical load-deflection behaviour of the main frames very well as can be seen from the close correlation of the curves. This should be expected as the main frames had no cutouts or ratholes for fabrication purposes. The only noticeable difference is the load at which membrane action occurs in some curves. This occurrence is a global and not a local phenomenon. It can be attributed to the more flexible analytical structure, due to cutouts, ratholes, and weld tears, which lead to membrane behaviour to be initiated at an earlier load stage than the finite element model.

The trends of the analytical lateral load-displacement curves were similar up to a load level of approximately 2500 kN after which the analytical model predicted increasing lateral deformations up to failure which was distinctly different than the test. The main frames in the test panel remained very stable throughout the full range of loading as they developed plastic zones in bending, and subsequently, as they went into tension and membrane action, as indicated by the much smaller lateral deformations. To achieve a level of confidence in the accuracy of the lateral deformation readings, residual deformations were measured by alternate methods at the conclusion of the test. These compared well with the LVDT measurements. The only main frame that exhibited the same type of behaviour as the finite element analysis was M10 (LVDT 34). Reasons for variations of the other measurements with respect to the finite element predictions have not been established.

4.3.2.3 Strain Distributions

4.3.2.3.1 General

Electrical resistance strain gauges located at discrete points along the length of framing members as discussed in Section 3.3.3 were used to measure strains. At various load levels, strain distributions through the depth of the web frame D2, stringer S2, and main frames M8, M9, and M10 are shown in Figures 4.33-4.37 respectively. Indicated on those figures are the FEA results represented by the solid line and the experimental results represented by the points. The strain values are given on these figures, with the values being given in the form of $x \pm y$, where x is the in-plane (axial + bending) strain obtained by taking the average value of the pair of gauges mounted on either side of the plate, and y is the out-of-plane strain obtained as the difference between the individual readings and the average value. Applicable Demec gauge readings are also indicated.

4.3.2.3.2 Web Frame Strain Distribution

The first load level corresponds to yield of one end of the web frame member of the test panel in compression. The distributions at midspan and at the ends are close to the finite element analysis values. The distributions at the stringer-web frame intersections vary due to the effect of the cut-outs. The finite element analysis predicts lower strains as would be expected with a greater cross-sectional area.

The second load level corresponds to the web-frame yielding in tension at midspan. Again, the distributions at midspan and at the ends compare well to those

predicted by the FEA.

The third load level corresponds to the web-frame reaching strain hardening values in tension at midspan. The strain correlations seem to deviate at this load level. This can be attributed to strain values occurring on the yield plateau of the stress-strain curve, where any small differences in stress can result in large differences in strain. At this load level, the weld at the left-most stringer in the diagram began to tear which resulted in less load being transferred to that side of the member and strains half of those at the opposite end.

The final load level is that at which the grillage system has collapsed and plastic hinges have formed at the ends of the web frame. Direct comparisons are not possible as an insufficient number of gauges were installed to give the correct principle strains for this complex strain state. Strain gradients in all directions in this region are large. Any variances in location will lead to large strain variations.

4.3.2.3.3 Stringer Strain Distribution

The first load level corresponds to yield of the stringer in tension at midspan and the second to compression yield at the ends. The third load level corresponds to the decrease in lateral stability of the stringer and the final load level is that at which plastic hinges have formed at the ends of the stringer.

Overall, the strain distributions at midspan and at the ends show that the finite element model results were reasonable. At the stringer-web frame intersections, the results were not as good. This can be attributed to the sudden change in geometry at that

location and differences in the finite element model at this location (ie. no cutouts). Some small differences exist between the measured and predicted strains for the lower set of strains measured at midspan. This may be attributed to local strain raising effects near the centre main frame and the averaging of the results of the gauges on either side of the centre main frame.

4.3.2.3.4 Main Frame Strain Distributions

The first load level corresponds to yield of the main frames at midspan in the test panel. The next two load levels correspond to changes in stiffness in the lateral load-deflection curves of the individual main frames and the final load level corresponds to membrane behaviour at midspan.

Upon reviewing the main frame strain distributions, the degree to which the finite element analysis accurately predicted the strain distributions in the main frames depends on whether or not the member was loaded directly. The distributions showed large discrepancies between the measured strains and the finite element predictions at midspan for the loaded main frames. This is attributed to the differences in the finite element modelling and the behaviour of the loaded mainframe directly above the load plate. A large friction force occurs between the hull plate and the 50 mm thick load plate. This restrains the stiffener and hull plate from straining (stretching), which results in significantly smaller strains. At the middle of the load plate only membrane strains (with maximum friction effects) were experienced. Little or no bending strains existed as the stiffener was essentially flat over the load plate. The rigid load plate forces the stiffener

to deform sharply over the edges producing large local changes in curvature. Although it was not measured, the geometry indicates that the stiffener experienced large membrane strains (with little friction effects) and large bending strains at the edges of the load plate. In the analytical model, the pressure caused a more gradual curvature in the stiffener over the entire load length. As a result, the predicted strains at midspan indicated large membrane strains (no frictional effects) with significant bending strains.

In addition, the large differences in measured strains can be attributed to variations in the stress-strain curve and whether or not the stress level was in a strain sensitive region (yield plateau) where variances can be 15 000 μs without any significant differences in stress. For this case, the analytical stress-strain curve used had a lower yield stress and gave a much softer response in the strain hardening portion of the curve. As a result, the FEA predicted larger strain values for each stress level after yield stress was reached. The differences in the predicted and measured strains increased as the load (stress) increased as indicated in Figures 4.35 and 4.36. Notwithstanding the midspan location of loaded main frames, the predicted strains reflected the measured strains at all other locations.

4.4 Test Panel #2

4.4.1 General Behaviour

The general behaviour of the second hull structure is illustrated by the total load versus centreline vertical deflection curve shown in Figure 4.38. Indicated on the curve

is a brief description of the major events that occurred during the test as the progression of failure occurred. Also shown as a dashed line on the figure is the load deflection curve for test panel #1. The instrumentation was concentrated on the main frames in the central quadrant in order to monitor their stability. Events for other elements were recorded as they were observed.

The first change in stiffness in the load deflection curve occurred at 675 kN total load when lateral deformations became noticeable in main frame M12, $b/t = 29.92$, outside of the centre panel. There wasn't any indication of yielding from visual observations. Whether or not this frame buckled elastically cannot be stated with any certainty as strain gauges and LVDT's were not located on this part of the main frame as it was outside the panel of interest. The initial sinusoidal shape had maximum amplitudes occurring at distances of 185 mm and 235 mm measured from the stringer.

At a total load of 700 kN, main frames M4 and M12, $b/t = 29.92$, yielded in tension at midspan. The lateral deformations of these main frames are driven by the initial out-of-straightness of that element. At a total load of 850 kN, the remaining loaded main frames yielded in tension at midspan. Main frame M11, outside the centre panel (adjacent to the buckled frame M12) appears to have buckled at approximately a load of 1050 kN. This is attributed to the large imperfection in that frame.

At a total load of 1500 kN the unloaded main frames top fibre yielded in tension at midspan and the loaded main frames yielded in compression at the intersections with the stringers. As this occurred, main frame M12 buckled locally inside the centre panel near the stringer. With further load (1900 kN), main frames M4 and M12 (opposite side

of plate panel to previous buckle) buckled at their ends outside of the stringers (rapid increase in lateral deformation). At a total load of 2000 kN, the loaded main frames developed yield lines which radiated outwards and upwards in both directions from the edge of the load plate, indicating that a substantial amount of bending was occurring in that region. At 2200 kN, the stringer yielded in tension at midspan. With further load (2800 kN), main frames M5 and M11, $b/t = 20.03$, started to buckle at their ends.

The web frames yielded at their ends at a load of 3300 kN. The yield line pattern was indicative of a shear failure with vertical yield lines developing on the web of the member. The larger flange and the elimination of the cutout connection detail allowed the web frames to remain very stable throughout the test and quite likely contributed to the increased stiffness of the second test panel over the first test panel throughout the last half of the test. The global deformations of the stiffened hull section are significant and seem to be governing the measured lateral deformations of the main frames in the centre panel.

With the yielding of the web frames and stringers, more load is being transferred to the reaction frame by the main frames in the centre panel in flexure resulting in yielding in the fixed ends at the reaction frame in compression (denoted as vertical yield lines on the members). At 3900 kN, the buckles at the ends of main frames M5 and M11 were quite pronounced and main frames M6 and M10 buckled in the same region. The hull plate began yielding along its longitudinal edges at a load of 4200 kN. The largest strains, as indicated from the Demec gauges, occurred at mid-length and decreased towards the ends. Refer to Figure 4.52. The stringers began to severely distort (fold)

over above the main frames at 4750 kN. A horizontal yield line pattern developed above the last three main frames at either end of the stringers between the web frames. The only visible occurrence of hull plate yielding was seen as tension yield lines which developed in a radial fashion radiating outwards from the stringer-web frame regions towards the reaction frame. This observation was recorded at 6100 kN.

At 7625 kN, the centre main frame M8, $b/t = 9.76$, fractured in the centre panel at one edge of the load plate to a depth of $1/3$ of the frame height. This fracture is attributed to the exceedence of the materials maximum strain capacity by membrane strains coupled with the large bending strains over the edge of the load plate. The vertical deflections were largest at the centre of the plate structure, hence the curvature and the corresponding bending strains. The crack propagated downwards towards the hull plate with increased load. At 8100 kN, the fractured main frame developed another crack over the other edge of the load plate. Loading continued until the initial crack propagated into the fillet weld connecting the frame and the hull plate at 8825 kN. At 9275 kN, the crack developed in the main frame had propagated into the hull plate a distance of 3 mm. The test was terminated at 9325 kN due to crack development in the hull plate above a corner of the centre load plate.

4.4.2 Comparisons with Finite Element Analysis Results

The finite element analysis modelling procedure was similar to that of the first test with the exception that the initial out-of-straightness was incorporated in the model for the main frames in the centre panel.

4.4.2.1 Load-Deflection Curves

4.4.2.1.1 Web Frame and Stringer Curves

The vertical displacement of the web frames with respect to the total transverse load as given by LVDT's 7, 9 and 11 are shown in Figures 4.39 (a) to (c), respectively. The lateral displacement at the top of the web frame with respect to the total transverse load as given by LVDT's 6, 8 and 10 are shown in Figures 4.40 (a) to (c), respectively. The vertical displacement of the stringer with respect to the total transverse load as given by LVDT 13 is shown in Figure 4.41. The lateral displacement of the top of the stringer with respect to the total transverse load as given by LVDT 12 is shown in Figure 4.42. The predicted load deflection curves from the finite element analysis for the corresponding locations are also shown.

In general, the test and predicted behaviour of the web frame are very similar throughout the entire load history, as shown by the relatively close correlation of the curves. The increased flange size and the elimination of the cutouts made the web frames stiffer and more stable than in the first test. For example, at 6000 kN the maximum vertical deflection of the web frame in the first test was about 20 mm while in the second test, it was approximately 13 mm. The lateral displacement of the web frame was caused by global deformations of the stiffened hull plate structure. There weren't any noticeable web distortions nor any signs of instability. The measured deflections compared well with the finite element results.

The test and predicted stringer load-vertical displacement curves are virtually

identical up to approximately 3000 kN when compression yielding occurred in the web frames. After this load level, the curves diverge with the test curve being less stiff. This is attributed in part to differences in the actual and modelled stress-strain curves where small changes in stress cause large changes in strain in the inelastic region, hence variations in displacements. The upwards rotation of the flange of the stringer will also cause increased vertical deflections as indicated by the schematic figure in Figure 4.42. There was insufficient instrumentation to quantify this although observations support this hypothesis. The load - lateral displacement curves show the same behavioral trends. Although the test curve was slightly stiffer than the predicted curve, the differences are quite small when considering the amplitudes of the lateral deformations. The curves indicate two different changes in direction of lateral motion during the test. Initially, the stringer deflects outward towards the reaction frame as a result of global deformations. Then the web distortion dominates the lateral deflection (lateral instability) until the stiffened hull plate deflections become large and once again dominate the apparent lateral displacement as shown in the inset of Figure 4.42. The lateral instability of the stringer (web distortions) diminish as large deformations occur and significant tension occurs along the stringers length between web frames.

4.4.2.1.2 Main Frame Curves

Shown in Figures 4.43 (a) to (m) are the total load versus vertical displacement curves of the main frames, with main frames of equal (b/t) ratios grouped on the same pages. Figures 4.44 (a) to (i) give the load versus lateral displacement of the

instrumented main frames. All figures show the corresponding finite element predictions.

The finite element prediction of vertical displacements exhibit the same behaviour as the measured displacements. Of note in the vertical displacement curves was the behaviour of main frames M4 and M12 shown in Figures 4.43 (c) and (d) respectively. The finite element analysis predicted a sudden increase in the stiffness of main frame M4 at 6500 kN while the physical test did not. The opposite is true of main frame M12. This phenomenon will be called *membrane straightening*. The thinnest main frames, which have buckled and deformed the greatest, are being pulled straight as the membrane effects dominate the behaviour. Regions of the member which were previously being compressed are pulled straight. This effect is more dramatic for frames with large lateral deformations. In the analytical model, main frame M4 buckled visibly while in the test, main frame M12 buckled, thus the difference in the curves. This can be expected as the specimens and model were symmetric and buckling may occur in either direction. The same sort of behaviour seems to be occurring with the canted main frame M10 in Figure 4.43 (h) although the member is not being pulled straight. Its lateral deformations continued to increase throughout the duration of the test. The lateral deformations reached a rate of increase that offsets the increase in the vertical deformations, giving the appearance of an increase in stiffness where there isn't.

The analytical model predicted the behaviour (lateral displacements) of the main frames well given the large strains and plastic deformations that occurred.

Figure 4.44 (a), shows the lateral displacement of the centre main frame. The variance between the test and predicted curve is the largest of any of the comparisons.

The behaviour is relatively the same up to approximately 6000 kN, although the test curve is slightly less stiff (keeping in mind the small magnitudes of the deformations). Around that load level, large straining and possibly necking occurred in the region of the fracture. At approximately 7500 kN, the main frame fractured. The analytical model was not capable of modelling a fracture. This will be discussed further in section 4.4.2.2.

In general, with the exception of main frames M4 and M12, the behaviour of the remaining main frames can be summarized as follows: 1) initial yielding caused the lateral deformations to increase, and 2) global deformations of the stiffened hull plate governed the lateral deformations causing deformation reversals in some cases where the initial deformations were in the opposite direction of the final deformed configuration. This is seen in the curves as the displacements went from positive to negative, or vice versa, as the test progressed.

For main frames M4 and M12, shown in Figures 4.44 (b) and (c) respectively, the global deformations of the stiffened hull section did not govern the final displaced shape. The compressive stresses at the ends of the main frames caused them to buckle and forced the main frames into triple curvature, with the ends bending opposite to the centre. Since the frames were so slender, they deformed plastically in this fashion (at the ends and at the middle). When membrane straightening occurred, the deformed ends were pulled straight and the middle portion deflected back. Since the central portion was bent opposite to the ends, it ended up past its original position and opposite to the global deformations of the stiffened plate.

4.4.2.2 Strain Distributions

As the focus of this test was the main frame behaviour, only strain distributions of main frames will be discussed.

Strain distributions through the depth of main frame M4, M5, M6, M7, M8 and M10 at various load levels are shown in Figures 4.45 to 4.50, respectively.

In general, the strains in the unloaded main frames, with the exception of main frame M4, were predicted more closely by the finite element analysis than in the loaded main frames for the reasons discussed previously in section 4.3.2.3.4. Tensile strains were present throughout the unloaded frame at low load levels, as shown in Figures 4.46 and 4.48. At moderate load levels, the strain distributions at the ends were mostly compressive throughout most of the depth and at large load levels, the compressive strains acted over half of the depth or less.

Shown in Figure 4.51 is the strain distribution along the centre main frame M8 between the stringers at a load level of approximately 7700 kN, the load level at which fracture took place. Indicated on the figure by the solid line is the finite element strain distribution both at the frame tip and at the frame-plate intersection. Also shown in the figure is the experimental strain gauge readings at their corresponding locations. The correlation between the finite element analysis results and the strain gauge readings are excellent at the frame ends and even at the midspan frame-plate intersection. There is, however, a large discrepancy at the midspan frame tip. The finite element analysis predicts very large strains while the physical frame did not experience this occurrence. It can be theorized that the distribution of strain along the frame must be different over

the loaded region since the integration of the strains over the length, which gives the displacements, must be the same since the displacements were quite similar. The differences between the modelled load and the physical load caused the main frame to experience large changes in curvature (bending) over the load plate edge while the analytical main frame experienced a gradual change in curvature with maximum curvature occurring at midspan. As a result of large bending strains over the load plate edges coupled with the membrane strain, fracture occurred at that location. A probable strain distribution for the test frame is illustrated by the dotted line on Figure 4.51. The magnitude of the strains, consisting of bending and membrane strains, over the load plate edge were large enough to have caused the fracture.

The final strain comparison relates the strains developed along the longitudinal edges of the hull plate itself, shown in Figure 4.52, with the physical strains being recorded through the use of Demec gauges. What can be observed from this figure is the smoothing effect that the finite element analysis produces on the strain results. The distribution is a gradually increasing one with no plateaus or sudden increases. The correlation at moderate load levels is very good while at high load levels there is some deviation. This may be attributed to physical variances in the test panel which weren't modelled.

Also of note is the development of compressive strains at the furthestmost ends of the test panel. The reaction frame was subjected to large transverse tensile forces along the long box which produces positive bending moments at midspan and, because of the fixity with the short box, negative bending moments at its ends. This would cause small

compressive strains in the test panel in this region.

4.4.3 Main Frame Buckled Shapes Outside of the Centre Panel

The buckled shapes of one end of main frames M11 and M12, and M4 are shown in Figures 4.53 and 4.54, respectively. These figures illustrate the changes in the buckled shapes of the stiffeners with increased load. The measurements were taken by hand and recorded at each load level indicated. Figure 4.53 illustrates the most slender main frame M12, $b/t = 29.92$, and the next main frame M11, $b/t = 20.03$. Main frame M12 initially buckled in a sine wave fashion with two waves, which progressed to three waves with an increase in load. The amplitudes of these waves simply increased with load. The stockier main frame M11 appeared to buckle with only one sine wave. The amplitude of this buckle did not significantly increase until a load of 4520 kN. At 4520 kN, the frame buckled in a sine wave with two waves.

Figure 4.54 shows the buckled shape of main frame M4, $b/t = 29.92$. This main frame buckled in a slightly different fashion with its maximum amplitude occurring closer to the stringer. Initially it buckled in a sine wave fashion with one wave, which increased in magnitude with further load. At the next recorded load level, the buckled shape had developed into three waves.

4.5 Applicability of the proposed ASPPR to Main Frame Design

The applicability of the proposed ASPPR to the design of transverse flat bar main frames, subject to transverse loads, for tripping and local buckling seems questionable.

Firstly, the tripping design equation(s) are based on various simplifications, noted in Section 2.2.2.3, with the most important being the use of the safety factor of 2.17 to relate the behaviour of an axially loaded member under uniform compressive stresses to a transversely loaded member. As seen throughout these tests, the areas of the flat bar members that were subjected to compressive stresses (ie. the ends) were very small and actually decreased with an increase in load. This caused the frames to be very stable, with respect to overall buckling, or tripping, as seen in both tests. Even the frames that were outside of the proposed tripping rules did not fail in this fashion although the tripping rules were more critical than the local buckling rules as indicated in Table 3.2. From the test results, the only instability that occurred in the main frames was due to local buckling. The proposed local buckling design equation is also questionable because it is based on a uniform compressive stress distribution and no compressive residual stresses. Figure 4.55 summarizes all the design rules for the tests conducted in relation to the main frames used. The design rules are shown as narrow bands rather than lines to account for the different steel strengths. Also shown are three different local buckling criteria based on linearly varying stress distributions and residual stresses.

From the results of the second test, the only main frame that buckled locally was main frame type 1 shown in Figure 4.55. Based on this result, and taking into consideration the different local buckling criteria presented, one can conclude that a better local buckling criteria is $b/t \leq 430/\sqrt{F_y}$ ($k=1.61$ corresponds to a plate with a free edge at the tip, a fixed edge at the hull plate-main frame junction, and simply supported edges along the length) with a linearly varying stress distribution that includes the effects of

residual stresses. Both these criteria are more realistic as seen from the experiments and the fabrication process. The use of the lateral torsional buckling equation similar to that presented by Hu (1993) in Equation 2.26 would be useful in determining a maximum unsupported length. This equation would have to be modified for singly symmetric sections (flat bar stiffener + hull plate combination) and would have to be modified to incorporate the equivalent moment factor for varying moment fields to be applicable.

Table 4.1 - Chemical Composition of the Structural Steel Plates from the Mill Certificates

Plate	Grade	Manufacturer	Heat No.	Chemical Composition, %												
				C	Mn	S	P	Si	Cr	Ni	Cu	Alt	Als	Cb	V	
12.7 mm x 2440 mm x 6096 mm	G40.21 300W	AHMSA, Mexico	140246	.20	0.99	.010	.019	.13	.014			.006				.003
11.11 mm x 2743 mm x 10262 mm	G40.21 300W	Algoma Steel Inc., Canada	0814P-55	.16	1.09	.011	.016	.21	.03	.01	.02	.035	.035	<.01		.032
11.11 mm x 2743 mm x 10262 mm	G40.21 300W	Algoma Steel Inc., Canada	0852P-07	.15	1.08	.011	.018	.21	.03	.01	.02	.040	.040	<.01		.030
9.53 mm x 2440 mm x 6096 mm	G40.21 300W	AHMSA, Mexico	140061	.18	.91	.012	.027	.10	.015			.007				
7.94 mm plate data not available																
5.97 mm x 1830 mm x not reported	G40.21 300W	Algoma Steel Inc., Canada	4280P-53	.15	1.03	.010	.008	.20	.02	.01	.01	.02	.035	<.008		.029

Table 4.2 - Mechanical Properties of the Structural Steel Plates from the Mill Certificates

Plate ¹	Yield Point, MPa	Ultimate Tensile Strength, MPa	Elongation, %
12.7 mm x 2440 mm x 6096 mm	330.8	482.4	27
11.11 mm x 2743 mm x 10262 mm	332.0	472.0	24
11.11 mm x 2743 mm x 10262 mm	354.0	494.0	25
9.53 mm x 2440 mm x 6096 mm	358.3	493.8	24
7.94 mm plate data not available			
5.97 mm plate data not available			

Notes: 1. Elongation was measured over a 200 mm gauge length.

Table 4.3 - Average Plate Thickness Measurements of the Framing Elements, Test Panel #1

Frame Number	Average Web Thickness ¹ , mm	Average Flange Thickness ¹ , mm	Frame Number	Average Web Thickness ¹ , mm	Average Flange Thickness ¹ , mm
M1 ₁	10.71	n/a - flat bar ²	M6 ₁	10.87	n/a - flat bar ²
M1 ₂	10.73	n/a	M6 ₂	10.94	n/a
M1 ₃	10.64	n/a	M6 ₃	10.92	n/a
M2 ₁	10.86	n/a	M7 ₁	10.98	n/a
M2 ₂	10.95	n/a	M7 ₂	11.01	n/a
M2 ₃	10.92	n/a	M7 ₃	10.99	n/a
M3 ₁	10.85	n/a	M8 ₁	11.03	n/a
M3 ₂	10.87	n/a	M8 ₂	10.99	n/a
M3 ₃	10.95	n/a	M8 ₃	10.90	n/a
M4 ₁	10.96	n/a	M9 ₁	10.66	n/a
M4 ₂	10.97	n/a	M9 ₂	10.67	n/a
M4 ₃	10.98	n/a	M9 ₃	10.70	n/a
M5 ₁	10.65	n/a	M10 ₁	10.88	n/a
M5 ₂	10.61	n/a	M10 ₂	10.87	n/a
M5 ₃	10.61	n/a	M10 ₃	10.95	n/a

Table 4.3 (cont'd)

Frame Number	Average Web Thickness ¹ , mm	Average Flange Thickness ¹ , mm	Frame Number	Average Web Thickness ¹ , mm	Average Flange Thickness ¹ , mm
M11 ₁	10.91	n/a - flat bar ²	M15 ₃	11.00	n/a
M11 ₂	10.87	n/a	D1 ₁	10.94 ³	5.95
M11 ₃	10.98	n/a	D1 ₂	11.06 ³	6.10
M12 ₁	10.92	n/a	D1 ₃		5.99
M12 ₂	10.91	n/a	D2 ₁	10.88 ³	6.10
M12 ₃	11.02	n/a	D2 ₂	10.93 ³	6.15
M13 ₁	11.06	n/a	D2 ₃		6.08
M13 ₂	11.02	n/a	S1 ₁	11.45	11.15
M13 ₃	11.07	n/a	S1 ₂	11.27	11.10
M14 ₁	10.99	n/a	S1 ₃	11.24	11.15
M14 ₂	11.01	n/a	S2 ₁	11.49	11.11
M14 ₃	11.01	n/a	S2 ₂	11.32	11.16
M15 ₁	11.05	n/a	S2 ₃	11.24	11.28
M15 ₂	11.05	n/a			

Notes: 1) Average measurement based on 3 readings along the specified member segment.

2) All main frames were flat bars.

3) Web frame web thickness based on readings taken at connection with stringer

Table 4.4 - Average Plate Thickness Measurements of the Framing Elements, Test Panel #2

Frame Number	Average Web Thickness ¹ , mm	Average Flange Thickness ¹ , mm	Frame Number	Average Web Thickness ¹ , mm	Average Flange Thickness ¹ , mm
M1 ₁	10.79	n/a - flat bar ²	M6 ₁	9.84	n/a - flat bar ²
M1 ₂	10.80	n/a	M6 ₂	9.73	n/a
M1 ₃	10.91	n/a	M6 ₃	9.65	n/a
M2 ₁	10.78	n/a	M7 ₁	10.74	n/a
M2 ₂	10.87	n/a	M7 ₂	10.98	n/a
M2 ₃	11.00	n/a	M7 ₃	10.94	n/a
M3 ₁	10.73	n/a	M8 ₁	12.50	n/a
M3 ₂	10.97	n/a	M8 ₂	12.67	n/a
M3 ₃	10.96	n/a	M8 ₃	12.80	n/a
M4 ₁	5.91	n/a	M9 ₁	10.76	n/a
M4 ₂	5.90	n/a	M9 ₂	10.81	n/a
M4 ₃	6.00	n/a	M9 ₃	10.96	n/a
M5 ₁	8.23	n/a	M10 ₁	10.10	n/a
M5 ₂	8.16	n/a	M10 ₂	9.73	n/a
M5 ₃	8.09	n/a	M10 ₃	9.78	n/a

Table 4.4 (cont'd)

Frame Number	Average Web Thickness ¹ , mm	Average Flange Thickness ¹ , mm	Frame Number	Average Web Thickness ¹ , mm	Average Flange Thickness ¹ , mm
M11 ₁	8.04	n/a - flat bar ²	M15 ₃	10.92	n/a
M11 ₂	8.28	n/a	D1 ₁	10.97 ³	8.42
M11 ₃	8.43	n/a	D1 ₂		8.27
M12 ₁	5.91	n/a	D1 ₃	11.00 ³	8.34
M12 ₂	6.02	n/a	D2 ₁	10.85 ³	8.38
M12 ₃	6.05	n/a	D2 ₂		8.31
M13 ₁	10.79	n/a	D2 ₃	10.94 ³	8.24
M13 ₂	10.96	n/a	S1 ₁	11.04	11.01
M13 ₃	10.97	n/a	S1 ₂		11.11
M14 ₁	10.85	n/a	S1 ₃	10.98	11.02
M14 ₂	10.95	n/a	S2 ₁	10.95	11.02
M14 ₃	10.91	n/a	S2 ₂		11.02
M15 ₁	10.91	n/a	S2 ₃	11.01	10.98
M15 ₂	10.93	n/a			

Notes: 1) Average measurement based on 3 readings along the specified member segment.

2) All main frames were flat bars.

3) Web frame web thickness based on readings taken at each end.

Table 4.5 - Out-of-Straightness Measurements at Top of Framing Members,
Test Panel #1

Frame Number	$\delta_{\max}$, mm	l/n	Frame Number	$\delta_{\max}$, mm	l/n
M1 ₁	0.54	1605	M6 ₁	2.15	405
M1 ₂	1.94	445	M6 ₂	0.85	1020
M1 ₃	1.25	695	M6 ₃	0.64	1355
M2 ₁	1.83	475	M7 ₁	1.83	475
M2 ₂	1.19	730	M7 ₂	0.38	2280
M2 ₃	1.64	530	M7 ₃	0.35	2475
M3 ₁	1.17	740	M8 ₁	0.30	2890
M3 ₂	1.65	525	M8 ₂	2.31	375
M3 ₃	0.87	995	M8 ₃	2.49	350
M4 ₁	0.48	1805	M9 ₁	2.18	400
M4 ₂	0.58	1495	M9 ₂	2.16	400
M4 ₃	1.60	540	M9 ₃	0.91	950
M5 ₁	0.48	1805	M10 ₁	2.18	400
M5 ₂	0.42	2060	M10 ₂	1.42	610
M5 ₃	3.22	270	M10 ₃	1.71	505

Table 4.5 (cont'd)

Frame Number	$\delta_{\max}$, mm	l/n	Frame Number	$\delta_{\max}$, mm	l/n
M11 ₁	2.25	385	D1 ₁	0.45	1925
M11 ₂	1.46	595	D1 ₂	1.70	510
M11 ₃	2.32	375	D1 ₃	2.12	410
M12 ₁	1.30	665	D2 ₁	1.60	540
M12 ₂	0.94	920	D2 ₂	1.93	450
M12 ₃	0.76	1140	D2 ₃	1.58	550
M13 ₁	1.38	630	S1 ₁	4.57	365
M13 ₂	1.01	855	S1 ₂	1.63	1020
M13 ₃	2.15	405	S1 ₃	2.33	715
M14 ₁	0.94	920	S2 ₁	4.85	345
M14 ₂	1.90	455	S2 ₂	3.10	540
M14 ₃	0.74	1170	S2 ₃	1.96	850
M15 ₁	0.77	1125			
M15 ₂	3.02	285			
M15 ₃	0.59	1470			

**Table 4.6 - Out-of-Straightness Measurements at Top of Framing Members,
Interior Panel, Test Panel #2**

Frame Number	$\delta_{\max}$, mm	l/n
M4 ₂	3.68	309
M5 ₂	4.23	269
M6 ₂	3.20	356
M7 ₂	1.16	982
M8 ₂	1.84	619
M9 ₂	0.62	1837
M10 ₂	3.08	370
M11 ₂	3.15	362
M12 ₂	0.39	2920

Table 4.7 - Initial Strains due to Welding in Test Panel #1

(a) - Transverse Direction

Location	L/6	L/3	4L/9	5L/9	2L/3	5L/6
Strain, $\times 10^{-6}$	478	178	178	146	65	284

(b) - Longitudinal Direction

Location	L/3	Centreline, north panel	Centreline, south panel	2L/3
Strain, $\times 10^{-6}$	389	292	251	292

Table 4.8 - Characteristic parameters determined from uniaxial stress strain curves for the 12.7 mm (1/2 in.) plates in the longitudinal direction.

Coupon No.	E (MPa)	$\epsilon_y \times 10^{-6}$	σ_p (MPa)	σ_y (MPa)	σ_{sy} (MPa)	$\epsilon_{st} \times 10^{-6}$	E_{st} (MPa)	$\epsilon_u \times 10^{-6}$	σ_u (MPa)	$\epsilon_f \times 10^{-6}$	σ_f (MPa)
L2	215749	1744	-	390.9	-	-	-	145000	518.3	195000	506.0
L4	212282	1759	-	376.8	338.4	9000	2745	160000	504.9	190000	503.2
L5	211198	1808	-	385.2	-	-	-	175000	508.7	-	-
L6	213674	1762	-	378.3	375.0	8489	1700	175000	509.1	200000	501.2
L9	212040	1775	-	379.1	375.7	8844	1510	185000	508.5	235000	453.9
Avg.	212989	1770	-	382.1	363.0	8778	1985	168000	509.9	205000	491.1
Std. dv.	1781	24	-	5.9	21.3	262	665	15652	5.0	20412	24.9

Notes: 1. The mean elastic value for Poisson's ratio is $\nu = 0.280$.

Table 4.9 - Characteristic parameters determined from uniaxial stress strain curves for the 12.7 mm (1/2 in.) plates in the transverse direction.

Coupon No.	E (MPa)	$\epsilon_y \times 10^{-6}$	σ_{yu} (MPa)	σ_y (MPa)	σ_{sy} (MPa)	$\epsilon_{st} \times 10^{-6}$	E_{st} (MPa)	$\epsilon_u \times 10^{-6}$	σ_u (MPa)	$\epsilon_f \times 10^{-6}$	σ_f (MPa)
T2	211863	1781	-	379.4	374.4	13944	2055	180000	512.5	255000	442.6
T4	211705	1753	-	373.6	372.0	9129	2355	180000	505.4	200000	496.3
T5	212395	1708	-	370.2	365.1	10709	1760	170000	504.5	215000	490.6
T6	211847	1747	-	373.4	370.0	9101	2345	170000	506.0	210000	494.0
T9	211833	1751	-	371.8	370.1	12106	2565	170000	508.0	220000	488.8
Avg.	211929	1748	-	373.7	370.3	10998	2216	174000	507.3	220000	482.5
Std. dv.	268	26	-	3.5	3.4	2067	313	5477	3.2	20917	22.5

Notes: 1. The mean elastic value for Poisson's ratio is $\nu = 0.280$.

Table 4.10 - Characteristic parameters determined from uniaxial stress strain curves for the 11.11 mm (7/16 in.) plates in the longitudinal direction.

Coupon No.	E (MPa)	$\epsilon_y \times 10^{-6}$	σ_p (MPa)	σ_y (MPa)	σ_{sy} (MPa)	$\epsilon_{st} \times 10^{-6}$	E_{st} (MPa)	$\epsilon_u \times 10^{-6}$	σ_u (MPa)	$\epsilon_f \times 10^{-6}$	σ_f (MPa)
1	205980	3775	295.0	339.1	298.5	9752	3314	155000	489.5	210000	460.1
2	205395	1609	-	336.4	290.1	19318	4906	175000	487.1	-	-
3	208560	1660	-	341.5	294.4	18139	4394	177500	495.5	225000	422.0
4	206336	1635	-	335.0	298.1	16735	4289	170000	487.9	215000	441.1
5	205644	1632	-	340.8	292.0	-	-	170000	493.8	217500	425.2
6	209441	1636	-	339.1	300.4	17827	5823	172500	490.9	207500	462.3
7	204843	1604	-	336.5	298.3	18461	5321	160000	488.7	215000	452.1
8	198676	1609	-	338.9	299.0	16088	1874	170000	490.2	212500	446.7
9	200650	1622	-	321.3	308.6	19674	6265	162500	489.9	-	-
10	210761	3775	230.0	324.7	294.1	16101	3540	185000	491.6	232500	451.5
Avg.	204943	1626	262.5	335.3	297.6	18035	4696	169688	490.5	215417	441.6
Std. dv.	3658	19	32.5	6.8	5.7	1294	1437	5892	2.9	5792	15.6

Notes: 1. The mean elastic value for Poisson's ratio is $\nu = 0.288$.

2. Coupon's 1 and 10 had a flame cut edge and were omitted from the average strain value.

Table 4.11 - Characteristic parameters determined from uniaxial stress strain curves for the 11.11 mm (7/16 in.) plates in the transverse direction.

Coupon No.	E (MPa)	$\epsilon_y \times 10^{-6}$	σ_p (MPa)	σ_y (MPa)	σ_{sy} (MPa)	$\epsilon_{st} \times 10^{-6}$	E_{st} (MPa)	$\epsilon_u \times 10^{-6}$	σ_u (MPa)	$\epsilon_t \times 10^{-6}$	σ_t (MPa)
11	202848	1622	-	337.2	302.2	18652	4714	177500	489.1	220000	470.1
12	208986	1634	-	338.8	288.5	17297	4039	185000	495.2	-	-
13	207686	1607	-	338.6	290.7	17124	5845	185000	490.5	235000	443.8
14	208129	1628	-	337.8	301.4	18070	5083	195000	491.2	237500	469.0
15	206680	1632	-	336.8	287.2	17409	2516	192500	492.0	245000	438.1
16	206273	1669	-	339.2	245.0	-	-	187500	493.5	235000	473.1
17	209014	1651	-	343.4	303.0	-	-	187500	496.3	222500	478.7
18	208056	1577	-	341.3	268.9	19421	5585	195000	492.5	260000	455.4
19	202954	1615	-	343.5	298.6	16289	2342	182500	494.1	242500	478.5
20	207743	2200	237.5	337.6	309.0	15175	5130	145000	497.6	230000	472.4
Avg.	206736	1626	237.5	339.6	287.3	17752	4303	187500	492.7	237188	463.3
Std. dv.	2358	26	0	2.5	19.2	1045	1409	5863	2.3	12708	15.7

Notes: 1. The mean elastic value for Poisson's ratio is $\nu = 0.285$.

2. Coupon 20 had a flame cut edge and was omitted from the average strain value.

Table 4.12 - Characteristic parameters determined from uniaxial stress strain curves for the 9.53 mm (3/8 in.) plates in the longitudinal direction.

Coupon No.	E (MPa)	$\epsilon_y \times 10^{-6}$	σ_p (MPa)	σ_y (MPa)	σ_{sy} (MPa)	$\epsilon_{st} \times 10^{-6}$	E_{st} (MPa)	$\epsilon_u \times 10^{-6}$	σ_u (MPa)	$\epsilon_f \times 10^{-6}$	σ_f (MPa)
L2 ²	204556	3668	253.0	413.9	408.8	8660	3330	160000	506.2	195000	495.2
L4 ²	205563	3887	227.0	385.1	-	10000	1665	160000	500.7	200000	464.1
L5 ²	205966	3938	273.0	405.1	397.4	9931	2170	160000	497.2	185000	483.0
L6	207698	2473	263.0	403.7	-	12050	1430	160000	494.8	180000	482.5
L9 ²	204442	3906	267.0	404.3	-	9138	1565	160000	492.8	200000	469.3
Avg.	205645	3850	256.6	402.4	403.1	9956	2032	160000	498.3	192000	478.8
Std. dv.	1319	123	18.1	10.5	8.1	1298	778	0	5.3	9083	12.3

Notes: 1. The mean elastic value for Poisson's ratio is $\nu = 0.270$.

2. 0.2% offset method was used to obtain the yield stress and strain.

3. Coupon L6 was omitted from the average strain value as it did not exhibit the same behaviour as the other coupons.

Table 4.13 - Characteristic parameters determined from uniaxial stress strain curves for the 9.53 mm (3/8 in.) plates in the transverse direction.

Coupon No.	E (MPa)	$\epsilon_y \times 10^{-6}$	σ_p (MPa)	σ_y (MPa)	σ_{sy} (MPa)	$\epsilon_{st} \times 10^{-6}$	E_{st} (MPa)	$\epsilon_u \times 10^{-6}$	σ_u (MPa)	$\epsilon_f \times 10^{-6}$	σ_f (MPa)
T2	210817	2353	373	443.3	440.7	8000	1400	140000	526.8	180000	512.6
T4	207066	2298	320	446.3	438.7	15360	1445	140000	520.2	160000	510.8
T5	216681	2091	-	452.6	439.9	7000	2340	125000	516.3	155000	485.8
T6 ²	207305	4000	260	450.2	427.0	14589	2073	100000	525.0	125000	514.3
T9	205142	2184	327	442.1	434.5	7488	1156	140000	513.2	165000	503.9
Avg.	209402	2232	320	446.9	436.2	10487	1683	129000	520.3	157000	505.5
Std. dv.	4555	117	46	4.5	5.7	4120	500	17464	5.7	20187	11.7

- Notes: 1. The mean elastic value for Poisson's ratio is $\nu = 0.280$.
2. 0.2% offset method was used to obtain the yield stress and strain.
3. Coupon T6 was omitted from the average strain value.

Table 4.14 - Characteristic parameters determined from uniaxial stress strain curves for the 7.94 mm (5/16 in.) plates in the longitudinal direction.

Coupon No.	E (MPa)	$\epsilon_y \times 10^{-6}$	σ_p (MPa)	σ_y (MPa)	σ_{sy} (MPa)	$\epsilon_{st} \times 10^{-6}$	E_{st} (MPa)	$\epsilon_u \times 10^{-6}$	σ_u (MPa)	$\epsilon_f \times 10^{-6}$	σ_f (MPa)
L2	214348	1945	-	420.1	414.6	12208	2165	175000	557.2	215000	524.6
L4	210508	1986	-	418.8	402.4	12000	2300	160000	553.6	210000	533.5
L5	221407	1888	-	420.9	387.9	15186	2265	160000	565.0	190000	561.5
L6	215554	1928	-	423.4	381.9	14202	2152	160000	567.0	225000	531.9
L9	212558	1984	-	437.3	415.3	12901	3230	160000	572.1	200000	507.8
Avg.	214875	1946	-	424.1	400.4	13299	2422	163000	563.0	208000	531.7
Std. dev.	4118	41	-	7.6	15.2	1361	456	6708	7.5	13509	19.4

Notes: 1. The mean elastic value for Poisson's ratio is $\nu = 0.290$.

Table 4.15 - Characteristic parameters determined from uniaxial stress strain curves for the 7.94 mm (5/16 in.) plates in the transverse direction.

Coupon No.	E (MPa)	$\epsilon_y \times 10^{-6}$	σ_p (MPa)	σ_y (MPa)	σ_{sy} (MPa)	$\epsilon_{st} \times 10^{-6}$	E_{st} (MPa)	$\epsilon_u \times 10^{-6}$	σ_u (MPa)	$\epsilon_r \times 10^{-6}$	σ_r (MPa)
T2	214696	1850	-	421.2	407.6	9704	1727	160000	565.2	205000	540.9
T4	215835	1959	-	421.6	410.6	15548	2684	160000	563.4	210000	541.3
T5	218943	1861	-	420.8	415.4	13500	2440	160000	559.9	190000	541.0
T6	215114	1870	-	414.4	411.6	11057	2385	170000	558.5	205000	537.6
T9	211005	1897	-	409.1	368.2	14000	2745	160000	555.0	225000	534.9
Avg.	215119	1887	-	417.4	402.7	12762	2396	162000	560.4	207000	539.1
Std. dv.	2839	44	-	5.5	19.5	2350	404	4472	4.0	12550	2.8

Notes: 1. The mean elastic value for Poisson's ratio is $\nu = 0.300$.

Table 4.16 - Characteristic parameters determined from uniaxial stress strain curves for the 5.97 mm plates in the longitudinal direction.

Coupon No.	E (MPa)	$\epsilon_y \times 10^{-6}$	σ_p (MPa)	σ_y (MPa)	σ_{sy} (MPa)	$\epsilon_{st} \times 10^{-6}$	E_{st} (MPa)	$\epsilon_u \times 10^{-6}$	σ_u (MPa)	$\epsilon_f \times 10^{-6}$	σ_f (MPa)
L2 ²	199573	3688	310.0	343.9	340.4	12088	3132	170000	487.9	220000	470.5
L4 ²	197910	3703	187.0	350.5	347.0	14250	2288	170000	487.1	215000	482.5
L5 ²	197591	3640	183.0	338.5	335.0	9000	2050	170000	472.1	200000	468.9
L6 ²	196949	3644	183.0	350.6	340.1	13423	2400	170000	479.4	200000	469.0
L9 ²	198618	3688	180.0	344.5	340.9	9284	2264	175000	482.1	190000	475.5
Avg.	198128	3673	183.3	345.6	340.7	11609	2427	171000	481.7	205000	473.3
Std. dv.	1007	29	2.9	5.1	4.3	2383	370	2236	6.4	12247	5.8

Notes: 1. The mean elastic value for Poisson's ratio is $\nu = 0.270$.

2. 0.2% offset method was used to obtain the yield stress and strain.

3. Coupon L2 was omitted from the average proportional stress value.

Table 4.17 - Characteristic parameters determined from uniaxial stress strain curves for the 5.97 mm plates in the transverse direction.

Coupon No.	E (MPa)	$\epsilon_y \times 10^{-6}$	σ_p (MPa)	σ_y (MPa)	σ_{sy} (MPa)	$\epsilon_{st} \times 10^{-6}$	E_{st} (MPa)	$\epsilon_u \times 10^{-6}$	σ_u (MPa)	$\epsilon_t \times 10^{-6}$	σ_t (MPa)
T2	203103	1932	260.0	373.0	355.1	15637	2592	150000	491.3	180000	484.7
T4	201241	1912	273.0	368.3	357.6	11606	2552	170000	486.9	185000	484.0
T5	204557	1876	207.0	363.9	353.2	10000	2712	170000	485.0	195000	478.1
T6	203102	1859	258.0	369.6	312.2	15288	1472	150000	496.5	195000	442.0
T9	200828	1959	220.0	362.5	348.3	14912	3315	150000	490.5	220000	454.1
Avg.	202566	1908	243.6	367.5	345.3	13489	2529	158000	490.0	195000	468.6
Std. dv.	1526	41	28.4	4.3	18.8	2530	666	10954	4.4	15411	19.4

Notes: 1. The mean elastic value for Poisson's ratio is $\nu = 0.280$.

Table 4.18 - Progression of Failure, Test Panel #1

Event	Load, kN	Description
1.	900	<ul style="list-style-type: none"> • Yielding of top fibre of flatbar main frames in centre panel in tension at midspan.
2.	1800	<ul style="list-style-type: none"> • Yielding of top fibre of flatbar main frames in centre panel in compression at intersections with stringers. • Hull plate yielding in tension in centre panel.
3.	2150	<ul style="list-style-type: none"> • Yielding of top flange of stringers in tension at midspan.
4.	2250	<ul style="list-style-type: none"> • Yielding of top flange of web frames in compression at ends.
5.	3400	<ul style="list-style-type: none"> • Yielding of top flange of web frames in tension at midspan - lateral instability increased markedly (initiation of tripping).
6.	3900	<ul style="list-style-type: none"> • Yielding of top flange of stringers in compression at ends causing decrease in lateral stiffness.
7.	4300	<ul style="list-style-type: none"> • Buckling (web crippling failure) of flatbar main frames at ends in centre panel.
8.	5000	<ul style="list-style-type: none"> • Yielding of hull plate in tension along longitudinal edges, maximum at deep frame intersections and spreading into centre panel.
9.	5550	<ul style="list-style-type: none"> • Plastic hinge formation at ends of web frames (sections fully yielded in compression). • Tensile strains along longitudinal edges of hull plate begin to increase markedly.
10.	6000	<ul style="list-style-type: none"> • Hull plate yielding spreading outside of centre panel along longitudinal edges. • Hull plate strains now higher in middle of centre panel than at deep frame intersections. • Fracture of weld at both web frame connections along stringer S2 (intersection with D2 fractured first). • Buckling of main frames at ends outside of central portion.
11.	6450	<ul style="list-style-type: none"> • Plastic hinge formation at ends of stringers (sections fully yielded in compression). • Collapse of grillage system - dominant support mechanism becomes membrane action.
12.	8644	<ul style="list-style-type: none"> • Shear failure by punching - termination of test.

Figure 4.1 - Schematic Diagram Labelling the Framing Members, Test Panel #1

Figure 4.2 - Schematic Diagram Labelling the Framing Members, Test Panel #2

Figure 4.3 - Stress-Strain Curve for Longitudinal Coupons, 11.11 mm thick plate

Figure 4.4 - Stress-Strain Curve for Transverse Coupons, 11.1 mm thick plate

Figure 4.5 - Residual Stress Distribution

Figure 4.6 - Finite Element Mesh, Test Panel #1

Figure 4.7 - Finite Element Mesh, Test Panel #2

Figure 4.8 - Total Load vs Centreline Vertical Deflection Curve, Test Panel #1

Figure 4.9 - Total Load vs. Vertical Displacement of Web Frame LVDT's, Test Panel #1

Figure 4.10 - Total Load vs. Vertical Displacement of Stringer LVDT's, Test Panel #1

Figure 4.11 - Total Load vs. Vertical Displacement of Centre Main Frame LVDT's, Test Panel #1

Figure 4.12 - Total Load vs. Lateral Displacement of Web Frame LVDT's, Test Panel #1

Figure 4.13 - Total Load vs. Lateral Displacement of Stringer at Midspan, Test Panel #1

Figure 4.14 - Total Load vs. Lateral Displacement of Main Frame LVDT's, Test Panel #1

(a) Elastic Load Path

(b) Change in Load Path Due to Yielding of Loaded Main Frames

Figure 4.15 - Primary Load Paths, Test Panel #1

(c) Membrane Action Centre Portion

(d) Propagation of Membrane Action

Figure 4.15 (cont'd) - Primary Load Paths, Test Panel #1

ANSYS 5.0 31
 APR 26 1994
 11:50:45
 PLOT NO. 1
 ELEMENT SOLUTION
 STEP 1
 SUB 2
 TIME 565.8
 SEQV (NOAVG)
 TOP
 DMX 3.1
 SMN 0.09945
 SMX 334.226

Figure 4.16 (a) - Finite Element Analysis Plot, 565.8 kN, Test Panel #1

ANSYS 5.0 31
 APR 26 1994
 13:12:45
 PLOT NO. 1
 ELEMENT SOLUTION
 STEP 3
 SUB 5
 TIME 2681
 SEQV (NOAVG)
 TOP
 DMX 321.934
 SMN 1.015
 SMX 414.879

Figure 4.16 (b) - Finite Element Analysis Plot, 2681 kN, Test Panel #1

ANSYS 5.0 31
 APR 26 1994
 13:23:35
 PLOT NO. 1
 ELEMENT SOLUTION
 STEP 3
 SUB 1
 TIME 3433
 SEQV (NOAVG)
 TOP
 DMX 47.053
 SMN 1.425
 SMX 464.576

Figure 4.16 (c) - Finite Element Analysis Plot, 3432.6 kN, Test Panel #1

ANSYS 5.0 31
 APR 26 1994
 14:01:46
 PLOT NO. 1
 ELEMENT SOLUTION
 STEP 4
 SUB 4
 TIME 5248
 SEQV (NOAVG)
 TOP
 DMX 101.481
 SMN -13.976
 SMX 498.908

Figure 4.16 (d) - Finite Element Analysis Plot, 5248 kN, Test Panel #1

Figure 4.16 (e) - Finite Element Analysis Plot, 8700 kN, Test Panel #1

Figure 4.17 - Yield Line Pattern, Web Frame, Test Panel #1

Figure 4.18 - Tripping of Web Frames, Test Panel #1

Figure 4.19 - Membrane Strain Distribution At Plate Edge Between Web Frames, Test Panel #1

Figure 4.20 - Distribution of Strain Along Plate Edge, Test Panel #1

Figure 4.21 - Plastic Hinge Formation in Web Frames, Test Panel #1

Figure 4.22 - Main Frame Buckling, Test Panel #1

Figure 4 23 - Weld Fracture, Test Panel #1

Figure 4.24 - Plastic Hinge Formation in Stringer, Test Panel #1

Figure 4.25 - Local Tearing of Hull Plate, Test Panel #1

(a) Longitudinal Deflected Shape

(b) Transverse Deflected Shape

Figure 4.26 - Final Deflected Shapes Along the Centerline of Test Panel #1

(a)

(b)

Figure 4.27 - Experimental and Finite Element Total Load vs. Vertical Displacement Curves for Web Frames, Test Panel #1

(c)

(d)

Figure 4.27 - Experimental and Finite Element Total Load vs. Vertical Displacement Curves for Web Frames, Test Panel #1 Cont'd

(e)

(f)

Figure 4.27 - Experimental and Finite Element Total Load vs. Vertical Displacement Curves for Web Frames, Test Panel #1 Cont'd

Figure 4.27 - Experimental and Finite Element Total Load vs. Vertical Displacement Curves for Web Frames, Test Panel #1 Cont'd

Figure 4.28 - Experimental and Finite Element Total Load vs. Lateral Displacement Curves for Web Frames, Test Panel #1

(b)

(c)

Figure 4.28 - Experimental and Finite Element Total Load vs. Lateral Displacement Curves for Web Frames, Test Panel #1 Cont'd

(a)

(b)

Figure 4.29 - Experimental and Finite Element Total Load vs. Vertical Displacement Curves for Stringers, Test Panel #1

(c)

(d)

Figure 4.29 - Experimental and Finite Element Total Load vs. Vertical Displacement Curves for Stringers, Test Panel #1 Cont'd

Figure 4.30 - Experimental and Finite Element Total Load vs. Lateral Displacement Curve for Stringer, Test Panel #1

Figure 4.31 - Experimental and Finite Element Total Load vs. Vertical Displacement Curves for Main Frames, Test Panel #1

(b)

(c)

Figure 4.31 - Experimental and Finite Element Total Load vs. Vertical Displacement Curves for Main Frames, Test Panel #1 Cont'd

(d)

(e)

Figure 4.31 - Experimental and Finite Element Total Load vs. Vertical Displacement Curves for Main Frames, Test Panel #1 Cont'd

(f)

(g)

Figure 4.31 - Experimental and Finite Element Total Load vs. Vertical Displacement Curves for Main Frame, Test Panel #1 Cont'd

(b)

(i)

Figure 4.31 - Experimental and Finite Element Total Load vs. Vertical Displacement Curves for Main Frames, Test Panel #1 Cont'd

(j)

(k)

Figure 4.31 - Experimental and Finite Element Total Load vs. Vertical Displacement Curves for Main Frames, Test Panel #1 Cont'd

(a)

(b)

Figure 4.32 - Experimental and Finite Element Total Load vs. Lateral Displacement Curves for Main Frames, Test Panel #1

3 of/de 3

PM-1 3 1/2" x 4" PHOTOGRAPHIC MICROCOPY TARGET
NBS 1010a ANSI/ISO #2 EQUIVALENT

PRECISIONSM RESOLUTION TARGETS

(c)

(d)

Figure 4.32 - Experimental and Finite Element Total Load vs. Lateral Displacement Curves for Main Frames, Test Panel #1 Cont'd

Figure 4.33 - Strain Distributions Through the Depth of Web Frame D2, Test Panel #1

Figure 4.34 - Strain Distributions Through the Depth of Stringer S2, Test Panel #1

Figure 4.35 - Strain Distributions Through the Depth of Centre Main Frame M8, Test Panel #1

Figure 4.36 - Strain Distributions Through the Depth of Loaded Main Frame M10, Test Panel #1

Figure 4.37 - Strain Distributions Through the Depth of Unloaded Main Frame M9, Test Panel #1

Figure 4.38 - Total Load vs Centreline Vertical Deflection Curve, Test Panel #2

(a)

(b)

Figure 4.39 - Experimental and Finite Element Total Load vs. Vertical Displacement Curves for Web Frame D1, Test Panel #2

(c)

Figure 4.39 - Experimental and Finite Element Total Load vs. Vertical Displacement Curves for Web Frame D1, Test Panel #2 Cont'd

(a)

Figure 4.40 - Experimental and Finite Element Total Load vs. Lateral Displacement Curves for Web Frame D1, Test Panel #2

(b)

(c)

Figure 4.40 - Experimental and Finite Element Total Load vs. Lateral Displacement Curves for Web Frame D1, Test Panel #2 Cont'd

Figure 4.41 - Experimental and Finite Element Total Load vs. Vertical Displacement Curve for Stringer S1, Test Panel #2

Figure 4.42 - Experimental and Finite Element Total Load vs. Lateral Displacement Curve for Stringer S1, Test Panel #2

(a) Main Frame M2, $b/t = 11.97$ (b) Main Frame M14, $b/t = 11.97$

Figure 4.43 - Experimental and Finite Element Total Load vs. Vertical Displacement Curves for Main Frames, Test Panel #2

(c) Main Frame M4, $b/t = 29.92$ (d) Main Frame M12, $b/t = 29.92$

Figure 4.43 - Experimental and Finite Element Total Load vs. Vertical Displacement Curves for Main Frames, Test Panel #2 Cont'd

(e) Main Frame M5, $b/t = 20.03$ (f) Main Frame M11, $b/t = 20.03$

Figure 4.43 - Experimental and Finite Element Total Load vs. Vertical Displacement Curves for Main Frames, Test Panel #2 Cont'd

(g) Main Frame M6, $b/t = 15.13$ (h) Canted Main Frame M10, $b/t = 15.13$

Figure 4.43 - Experimental and Finite Element Total Load vs. Vertical Displacement Curves for Main Frames, Test Panel #2 Cont'd

(i) Main Frame M7, $b/t = 11.97$ (j) Main Frame M9, $b/t = 11.97$

Figure 4.43 - Experimental and Finite Element Total Load vs. Vertical Displacement Curves for Main Frames, Test Panel #2 Cont'd

(k) Main Frame M8, $b/t = 9.76$ (l) Main Frame M8, $b/t = 9.76$

Figure 4.43 - Experimental and Finite Element Total Load vs. Vertical Displacement Curves for Main Frames, Test Panel #2 Cont'd

(m) Main Frame M8, $b/t = 9.76$

Figure 4.43 - Experimental and Finite Element Total Load vs. Vertical Displacement Curves for Main Frames, Test Panel #2 Cont'd

(a) Main Frame M8, $b/t = 9.76$

Figure 4.44 - Experimental and Finite Element Total Load vs. Lateral Displacement Curves for Main Frames, Test Panel #2

(b) Main Frame M4, $b/t = 29.92$ (c) Main Frame M12, $b/t = 29.92$

Figure 4.44 - Experimental and Finite Element Total Load vs. Lateral Displacement Curves for Main Frames, Test Panel #2 Cont'd

(d) Main Frame M5, $b/t = 20.03$ (e) Main Frame M11, $b/t = 20.03$

Figure 4.44 - Experimental and Finite Element Total Load vs. Lateral Displacement Curves for Main Frames, Test Panel #2 Cont'd

(f) Main Frame M6, $b/y = 15.13$ (g) Canted Main Frame M10, $b/t = 15.13$

Figure 4.44 - Experimental and Finite Element Total Load vs. Lateral Displacement Curves for Main Frames, Test Panel #2 Cont'd

(h) Main Frame M7, $b/t = 11.97$ (i) Main Frame M9, $b/t = 11.97$

Figure 4.44 - Experimental and Finite Element Total Load vs. Lateral Displacement Curves for Main Frames, Test Panel #2 Cont'd

Figure 4.45 - Strain Distributions Through the Depth of Main Frame M4, Test Panel #2

All values in units of microstrain unless otherwise indicated.

Figure 4.46 - Strain Distributions Through the Depth of Main Frame M5, Test Panel #2

All values in units of microstrain
unless otherwise indicated.

Figure 4.47 - Strain Distributions Through the Depth of Main Frame M6,
Test Panel #2

All values in units of microstrain
unless otherwise indicated.

Figure 4.48 - Strain Distributions Through the Depth of Main Frame M7,
Test Panel #2

All values in units of microstrain unless otherwise indicated.

Figure 4.49 - Strain Distributions Through the Depth of Central Main Frame M8, Test Panel #2

All values in units of microstrain
unless otherwise indicated.

Figure 4.50 - Strain Distributions Through the Depth of Canted Main Frame M10,
Test Panel #2

Figure 4.51 - Strain Distributions along Main Frame M8 @ 7700 kN (Fracture), Test Panel #2

Notes:

- 1) Symbols represent Demec gauge readings on plate bottom at corresponding load levels.
- 2) Lines represent FEA values on plate bottom at corresponding load levels.
- 3) All values in units of microstrain unless otherwise indicated.

Figure 4.52 - Distribution of Strain Along Plate Edge, Test Panel #2

Figure 4.53 - Typical Buckled Shapes of Main Frames, Test Panel #2

Figure 4.54 - Buckled Shape of Main Frame M4 , Test Panel #2

Figure 4.55 - Design Curves for Tripping and Local Buckling of Flat Bar Stiffeners

Chapter 5

Summary, Conclusions, Recommendations, and Future Work

5.1 Summary and Conclusions

An experimental program was undertaken to:

1. describe the post-yield behaviour of a typical icebreaking ship hull structure subjected to transverse loads;
2. verify the results of a nonlinear finite element analysis;
3. study the strength and stability of transverse flat bar stiffening members.

Two large scale test panels, measuring 2600 mm by 5000 mm, were tested under five transverse loads which modelled the design ice load pattern. The primary variables for flat bar main frame behaviour were section depth to thickness (b/t) and unsupported length to thickness (l/t). The first test panel was Arctic Shipping Pollution Prevention Regulations compliant and had flat bar main frames with $b/t = 11.34$ and $l/t = 77.13$. The second test panel ventured outside of the limits of the design equations given in ASPPR with five different main frames with b/t values ranging from 9.76 to 29.92 and l/t values

ranging from 89.68 to 179.35.

Material properties were established from a series of ancillary tests which included tension coupons for each plate thickness and a residual stress specimen of a typical main frame and hull section from test panel #1. Geometry and initial imperfections were measured.

The literature review presents the relevant research behind ASPPR for the structural design of icebreaker hull structures.

Load-deflection curves and strain distributions are presented. Comparisons were made between the experimental results and those predicted by finite element analysis.

Major conclusions drawn from this are:

1. Nonlinear finite element analysis is a valuable analytical tool in modelling icebreaker hull panel behaviour when subjected to transverse loads. The analytical model predicted vertical displacements very well. Lateral displacements of two out of three instrumented main frames in the centre panel of test panel #1 were not in agreement with the test results. Changes were made in mesh coarseness for test panel #2 and the predicted lateral behaviour agreed well with the test results. In general, strains were predicted well. Strains directly over the load application points tended to be overestimated in the analytical model. This can be attributed to variances in modelling the load and conditions that existed in the experiment.
2. The ASPPR design equations for tripping and local buckling of transverse flat bar framing members are suspect. The tripping rule is based on a derivation of an axially loaded, uniformly compressed member and its behaviour is related to a

transversely loaded member with a linearly varying stress distribution by use of a safety factor of 2.17. Also assumed in the derivation are simply supported frame ends, a hinged condition at the stiffener toe that causes the hull plate to provide no rotational restraint to the stiffener, and the omission of the effects of residual stresses. The local buckling rule is based on a section that is subjected to uniform compressive stresses and no residual stress effects. As shown from the experimental results, the flat bar stiffener is subjected to tensile stresses throughout except at its ends where there are linearly varying stress distributions due to flexure.

3. Based on observations of main frame behaviour from the second test, a local buckling criteria was developed for linearly varying normal stress distribution due to flexure with residual stresses. Flat bar stiffeners with a (b/t) ratio of 23 or less will reach yield at their tip prior to local buckling. This is considered to be a Class 3 type behaviour.

5.2 Recommendations and Future Work

Based on the conclusions drawn from this experimental study, there is a need to modify the ASPPR design equations for tripping and local buckling of transverse flat bar stiffening members subjected to transverse loads to reflect the observed behaviour. For local buckling, the equation should incorporate the buckling coefficient for members subjected to a linearly varying stress distribution due to flexure and residual stresses as is done in the current Canadian design standard for steel buildings, CAN/CSA-S16.1-M89.

In terms of tripping or overall buckling, an equation to determine the lateral-torsional buckling moment of a singly symmetric stiffener which incorporates the effects of the enforced centre of rotation, the rotational restraint provided by the hull plate, and the equivalent moment factor for varying moment fields, would give a more realistic value for the unsupported length.

Since this study focused only on the strength and stability of flat bar stiffeners loaded transversely, a series of tests on single elements of different shapes (ie. hull plate-T and hull plate-angle sections) subjected to combined axial and transverse loads would be beneficial in terms of developing a series of design rules for those elements under those conditions.

The U.S. Coast Guard will be conducting a full scale test, in the facilities developed from this study, on a panel constructed from the scantlings of an existing vessel called the Juniper as a proof test to verify its capacity in order to upgrade its operating class.

With respect to analytical modelling, the ice load can now be modelled accurately and dynamic effects can be taken into account. Individual panels can now be grouped into larger structures and the effects of loading adjacent panels on damaged panels can be studied.

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Appendix A

Parameters for the Design of Ship Hull Structures

Design Plate Pressure, D_p

$$D_p = \frac{A_f C_f O_f (5.79 + (0.02456(\Delta^{0.9} + \Delta^{0.68} P^{0.33})))}{S} \quad (MPa)$$

but not less than,

$2.3O_f / S$ (MPa)	in the bow and midbody/stern area for vessels of category CAC1, CAC2, and CAC3
$1.8O_f / S$ (MPa)	in the bow and midbody/stern area for vessels of category CAC4
$1.7O_f / S$ (MPa)	in the bottom area for vessels of category CAC1, CAC2, and CAC3
$1.4O_f / S$ (MPa)	in the bottom area for vessels of category CAC4

where,

- A_f = hull area factor (see Table A.1, Appendix A)
- C_f = ship class factor (see Table A.2, Appendix B)
- O_f = framing orientation factor
 - = 1.0 where the angle $\Omega \geq 70^\circ$ (a transverse frame)
 - = $1 + U \cos \Omega$ where $20^\circ < \Omega < 70^\circ$ (an oblique frame)
 - = $1 + U$ where $\Omega \leq 20^\circ$ (a longitudinal frame)
- Ω = acute angle in degrees between the chord of the waterline and the line of the first level of framing support to the shell where the first level of support is the stiffening with the lower scantlings and the closer spacing.
- U = 0.8 in the Bow and Iceskeg areas and their transitions
 - = 0.4 in the Midbody/Stern area and its transitions
 - = 0 in the Bottom area
- Δ = ship displacement (tonnes $\times 10^3$)
- P = shaft power (MegaWatts)

Ship Area Factors, A_f

Main Hull Areas	Area Factor, A_f
Appendage iceskeg area	2.0
Continuous iceskeg area	1.5
Bow area	1.0
Midbody & Stern area	0.5
Bottom area	0.3
All other locations	0.04L fore and aft or 0.1B on girth whichever gives the wider strakes at any point

Ship Class Factors, C_f

Category	Class Factor, C_f
CAC1, unrestricted icebreaking in multi-year ice	1.0
CAC2, controlled icebreaking in multi-year ice	0.8
CAC3, controlled icebreaking in second year ice	0.6
CAC4, controlled icebreaking in thick first year ice	0.4

Design Pressure, P_{av}

The design parameter D_{pt} for determining the design pressure, P_{av} , for transverse framing is,

$$D_{pt} = \frac{S}{H_p}$$

where, H_p = horizontal length of the design ice load (mm)
 $= 2.15 \sqrt{(\Delta^{0.9} + \Delta^{0.68} P^{0.33})}$

The design parameter D_{ph} for determining the design pressure, P_{av} , for the shear area of longitudinal framing is,

$$D_{ph} = \frac{L_s}{H_p}$$

and for the plastic section modulus of longitudinal framing is,

$$D_{ph} = \frac{L_B}{H_p}$$

where, L_s = effective shear span taking into account effective brackets (mm)
 L_B = frame length for bending calculation (mm)

The design pressure, P_{av} , is obtained from,

$$P_{av} = \frac{1}{(X+0.054)^{0.7}} + 4.285 \quad (MPa)$$

where, X = D_{pt} or D_{ph} as appropriate
 $X < 0.2$

$$P_{av} = \frac{1}{(X+0.3)^{1.6}} + 3.84 \quad (MPa)$$

where, $X \geq 0.2$

In tabular format, P_{av} is,

D_{pt} or D_{pb}	P_{av} (MPa)
0.00	12.00
0.03	10.20
0.05	9.16
0.08	8.48
0.10	7.99
0.15	7.33
0.20	6.87
0.25	6.44
0.30	6.10
0.35	5.83
0.40	5.61
0.45	5.42
0.50	5.27
0.60	5.02
0.70	4.84
0.80	4.70
0.90	4.59
1.00	4.50

Maximum Shear Factor, A

V_p/L_s	A	V_p/L_s	A
0.02	0.99	2.2	0.37
0.1	0.95	2.4	0.35
0.2	0.90	2.6	0.33
0.3	0.86	2.8	0.31
0.4	0.82	3.0	0.29
0.5	0.78	3.2	0.27
0.6	0.74	3.6	0.25
0.7	0.71	4.0	0.23
0.8	0.68	4.2	0.22
0.9	0.65	4.6	0.20
1.0	0.62	5.0	0.18
1.2	0.56	6.0	0.16
1.4	0.52	7.0	0.13
1.6	0.47	8.0	0.12
1.8	0.44	9.0	0.11
2.0	0.40	10.0	0.10

Appendix B

Design Spreadsheet Format

VESSEL:

Cell Requires Input

DISPLACEMENT:

tonnes

POWER:

MegaWatts

STEEL YIELD STRENGTH:

MPa

F_{max} =

ERR MN [Page 68 - (3)]

V_p =

0.0000 m

H_p =

0.0000 m [Schedule 1 - 2(1)]

CLAS FACTORS: [Table 1]

ARCTIC CLASS	FACTOR
CAC1	1.0
CAC2	0.8
CAC3	0.6
CAC4	0.4

AREA FACTORS: [Table 4]

HULL AREA	AREA FACTOR
Appendage Iceskeg	2.0
Continuous Iceskeg	1.5
Bow	1.0
Midbody & Stern	0.5
Bottom Area	0.3

MIDBODY REGION:Philosophy:

Heirarchy of supports – Deep frames support stringers
 – Stringers support main frames
 – Main frames support plating

Omega = 90

OF = 1.0

Corrosion Allow. =

mm

Approx. Panel

Length (mm) =

Dimensions:

Width (mm) =

Parameter	Transverse Main Frame Spacing (mm)			
PANEL LAYOUT				
# of Frames				
Panel Length (mm)	0	0	0	0
# of Stringers				
Deep Frame Spacing (# of Main Frames between)				
# of Deep Frames	0	0	0	0
Stringer Span (mm)	0	0	0	0
Stringer Spacing (mm)	0.0	0.0	0.0	0.0
Deep Frame Span (mm)	0	0	0	0

SHELL PLATE DESIGN					
Plate Design Pressure – Dpp (MPa)		ERR	ERR	ERR	ERR
Minimum – Dpp (MPa)		ERR	ERR	ERR	ERR
Minimum Shell Plate Thickness (mm)		ERR	ERR	ERR	ERR
Shell Plate Thickness (mm)		ERR	ERR	ERR	ERR
Perm. Deflection – Web (mm)		ERR	ERR	ERR	ERR
TRANSVERSE FRAME (MAIN) DESIGN					
Type =					
Dimensions:					
Web Depth (mm) =					
Web Thickness (mm) =					
Flange Width (mm) =					
Flange Thickness (mm) =					
DPT (Sch 1 Pg 9) =		ERR	ERR	ERR	ERR
PAV (Sch 1 Table 2) (MPa) =		ERR	ERR	ERR	ERR
Span		0.000	0.000	0.000	0.000
Vp / Span		ERR	ERR	ERR	ERR
A (Sch 1 Table 3 & Vp/Span<0.8) =		ERR	ERR	ERR	ERR
A (Sch 1 Table 3 & (0.8>Vp/Span<=2.2)) =		ERR	ERR	ERR	ERR
H		17320	17320	17320	17320
Min. Transverse Frame Shear Area (cm2)		ERR	ERR	ERR	ERR
Min. Trans. Frame Plastic Section Modulus (cm3)		ERR	ERR	ERR	ERR
Shear Area (cm2)		0.00	0.00	0.00	0.00
Trans. Frame Plastic Section Modulus (cm3)		ERR	ERR	ERR	ERR
Flange Width > 5 times Web thickness		NA	NA	NA	NA
Local Web Buckling		ERR	ERR	ERR	ERR
Flange Outstand		NA	NA	NA	NA
V		ERR	ERR	ERR	ERR
Tripping	Tee	NA	NA	NA	NA
	Angle	NA	NA	NA	NA
	Flat Bar	NA	NA	NA	NA
Web Thickness – Shell Thickness (Sch 1 Para 9)		ERR	ERR	ERR	ERR
Status		ERR	ERR	ERR	ERR

LONGITUDINAL FRAME (STRINGER) DESIGN				
Type =				
Dimensions:				
Web Depth (mm) =				
Web Thickness (mm) =				
Flange Width (mm) =				
Flange Thickness (mm) =				
DPH for shear area (Sch 1 pg 11)	ERR	ERR	ERR	ERR
DPH for plastic section modulus (Sch 1 pg 11)	ERR	ERR	ERR	ERR
Shear PAV (Sch 1 Table 2, $DPH \leq .30$) (MPa) =	ERR	ERR	ERR	ERR
Shear PAV (Sch 1 Tble 2, $0.3 < DPH \leq 0.70$) (MPa) =	ERR	ERR	ERR	ERR
Plast. Mod. PAV (Sch 1 Table 2, $DPH \leq .30$) =	ERR	ERR	ERR	ERR
Plast. Mod. PAV (Sch 1 Tble 2, $0.3 < DPH \leq 0.70$) =	ERR	ERR	ERR	ERR
Vp / S	ERR	ERR	ERR	ERR
Q	ERR	ERR	ERR	ERR
F	ERR	ERR	ERR	ERR
Minimum Stringer Shear Area (cm2)	ERR	ERR	ERR	ERR
G	ERR	ERR	ERR	ERR
Minimum Stringer Plastic Section Modulus (cm3)	ERR	ERR	ERR	ERR
Stringer Shear Area (cm2)	0.00	0.00	0.00	0.00
Stringer Plastic Section Modulus (cm3)	ERR	ERR	ERR	ERR
Flange Width > 5 times Web thickness	NA	NA	NA	NA
Local Web Buckling	ERR	ERR	ERR	ERR
Flange Outstand	NA	NA	NA	NA
V	ERR	ERR	ERR	ERR
Tripping	NA	NA	NA	NA
Tee	NA	NA	NA	NA
Angle	NA	NA	NA	NA
Flat Bar	NA	NA	NA	NA
Web Thickness - Shell Thickness (Sch 1 Para 9)	ERR	ERR	ERR	ERR
Status	ERR	ERR	ERR	ERR

DEEP WEB FRAME DESIGN				
Type =				
Dimensions:				
Web Depth (mm) =				
Web Thickness (mm) =				
Flange Width (mm) =				
Flange Thickness (mm) =				
DPT (Sch 1 Pg 9) =	ERR	ERR	ERR	ERR
PAV (Sch 1 Table 2 for $DPT \leq .30$) (MPa) =	ERR	ERR	ERR	ERR
PAV (Sch 1 Table 2 for $0.3 < DPT \leq 0.70$) (MPa) =	ERR	ERR	ERR	ERR
Span	0.000	0.000	0.000	0.000
Vp / Span	ERR	ERR	ERR	ERR
A (Sch 1 Table 3 & $Vp/Span < 0.8$) =	ERR	ERR	ERR	ERR
A (Sch 1 Table 3 & $(0.8 > Vp/Span \leq 2.2)$) =	ERR	ERR	ERR	ERR
H	17320	17320	17320	17320
Min. Transverse Frame Shear Area (cm ²)	ERR	ERR	ERR	ERR
Min. Trans. Frame Plastic Section Modulus (cm ³)	ERR	ERR	ERR	ERR
Web Frame Shear Area (cm ²)	0.00	0.00	0.00	0.00
Web Frame Plastic Section Modulus (cm ³)	ERR	ERR	ERR	ERR
Flange Width > 5 times Web thickness	NA	NA	NA	NA
Local Web Buckling	ERR	ERR	ERR	ERR
Flange Outstand	NA	NA	NA	NA
V	ERR	ERR	ERR	ERR
Tripping	NA	NA	NA	NA
Tee	NA	NA	NA	NA
Angle	NA	NA	NA	NA
Flat Bar	NA	NA	NA	NA
Web Thickness - Shell Thickness (Sch 1 Para 9)	ERR	ERR	ERR	ERR
Status	ERR	ERR	ERR	ERR

SUMMARY	Transverse Frame Spacing (mm)			
<p>PANEL LAYOUT</p> <p># of Frames Panel Length (mm) # of Stringers Deep Frame Spacing (# of Main Frames between) # of Deep Frames Stringer Span (mm) Stringer Spacing (mm) Deep Frame Span (mm)</p> <p>SHELL PLATE DESIGN</p> <p>Shell Plate Thickness (mm)</p> <p>TRANSVERSE FRAME (MAIN) DESIGN</p> <p>Type = Dimensions: Web Depth (mm) = Web Thickness (mm) = Flange Width (mm) = Flange Thickness (mm) =</p> <p>LONGITUDINAL FRAME (STRINGER) DESIGN</p> <p>Type = Dimensions: Web Depth (mm) = Web Thickness (mm) = Flange Width (mm) = Flange Thickness (mm) =</p> <p>DEEP WEB FRAME DESIGN</p> <p>Type = Dimensions: Web Depth (mm) = Web Thickness (mm) = Flange Width (mm) = Flange Thickness (mm) =</p> <p>STRUCTURAL WEIGHT (kg)</p> <p>Plate Main Frames Stringers Web Frames Total Weight of Steel (kg)</p> <p>Smeared Plate Thickness – All Material (mm) Smeared Plate Thickness – Short Distance (mm) Weight per metre Length of Panel (kg/m)</p>				
	ERR	ERR	ERR	ERR
	ERR	ERR	ERR	ERR
	ERR	ERR	ERR	ERR
	ERR	ERR	ERR	ERR
	ERR	ERR	ERR	ERR
	ERR	ERR	ERR	ERR
	ERR	ERR	ERR	ERR
	ERR	ERR	ERR	ERR
	ERR	ERR	ERR	ERR

COSTS:						
Main Frame Spacing:						
Materials:						
	Weight (kg)		ERR	ERR	ERR	ERR
	\$ per tonne		\$1,100	\$1,100	\$1,100	\$1,100
	Total \$ for Material		ERR	ERR	ERR	ERR
Labour:						
Welding	Metres of Weld	Perimeter	0.000	0.000	0.000	0.000
		Main Frames	0.000	0.000	0.000	0.000
		Stringers	0.000	0.000	0.000	0.000
		Web Frames	0.000	0.000	0.000	0.000
		TOTAL	0.000	0.000	0.000	0.000
	\$ per Metre of Weld		\$39.36	\$39.36	\$39.36	\$39.36
	Total \$ for Welding		\$0.00	\$0.00	\$0.00	\$0.00
Fabrication (Cutting, Handling & Set-Up)			ERR	ERR	ERR	ERR
Complexity Factors on Labour:						
	# of Pieces (Fab)		1	1	1	1
	# of Pieces per m ² (Fab)		ERR	ERR	ERR	ERR
	# of Intersections per m ² (Fab)		ERR	ERR	ERR	ERR
	Crowdedness (# of Panels/m ²) (Fab & Weld)		ERR	ERR	ERR	ERR
	Plate Butt Weld Thickness		ERR	ERR	ERR	ERR
	Fillet Weld (Weighted Average Thickness)		ERR	ERR	ERR	ERR
	Fillet Weld Area		ERR	ERR	ERR	ERR
	Butt Weld Area		ERR	ERR	ERR	ERR
	# of Butt Weld Passes		ERR	ERR	ERR	ERR
	# of Fillet Weld Passes		ERR	ERR	ERR	ERR
	Fabrication		ERR	ERR	ERR	ERR
	Welding		ERR	ERR	ERR	ERR
Total Cost:			ERR	ERR	ERR	ERR
Per Metre:						
	Weight of Structure per Metre Length		ERR	ERR	ERR	ERR
	Cost per Metre of Length		ERR	ERR	ERR	ERR

Appendix C

Spreadsheet Calculations of Panel #1 Scantlings (Unscaled)

4:

VESSEL:

DISPLACEMENT: 7500 tonnes

POWER: 8.0 MegaWatts

STEEL YIELD STRENGTH: 300 MPa

F_{max} = 36.317 MN [Page 68 - (3)]

V_p = 1.0037 m

H_p = 8.0298 m [Schedule 1 - 2(1)]

CLASS FACTORS: [Table 1]

ARCTIC CLASS	FACTOR
CAC1	1.0
CAC2	0.8
CAC3	0.6
CAC4	0.4

AREA FACTORS: [Table 4]

HULL AREA	AREA FACTOR
Appendage Iceskeg	2.0
Continuous Iceskeg	1.5
Bow	1.0
Midbody & Stern	0.5
Bottom Area	0.3

MIDBODY REGION:

Philosophy: Heirarchy of supports – Deep frames support stringers
– Stringers support main frames
– Main frames support plating

Omega = 90

OF = 1.0

Corrosion Allow. = 0.0 mm

Approx. Panel Length (mm) = 12500 (5000/0.40)
Dimensions: Width (mm) = 6500 (2600/0.40)

Parameter	Transverse Main Frame Spacing (mm)			
	685	505	895	725
PANEL LAYOUT	3 x 3 Rationalized	3 x 3 Rationalized	3 x 3 Rationalized	3 x 3 Rationalized
# of Frames	17	17	17	17
Panel Length (mm)	12330	9090	16110	13050
# of Stringers	2	2	2	2
Deep Frame Spacing (# of Main Frames between)	5	5	5	5
# of Deep Frames	2	2	2	2
Stringer Span (mm)	4110	3030	5370	4350
Stringer Spacing (mm)	2166.7	2166.7	2166.7	2166.7
Deep Frame Span (mm)	6500	6500	6500	6500

SHELL PLATE DESIGN				
Plate Design Pressure - Dpp (MPa)	1.7905	2.4287	1.3704	1.6917
Minimum - Dpp (MPa)	2.6277	3.5644	2.0112	2.4828
Minimum Shell Plate Thickness (mm)	27.8	23.8	31.73	28.6
Shell Plate Thickness (mm)	27.8	23.6	31.8	31.8
Perm. Deflection - Weh (mm)	1.712	1.087	2.559	1.680
TRANSVERSE FRAME (MAIN) DESIGN				
Type =	Flat Bar	Angle	Flat Bar	Flat Bar
Dimensions:				
Web Depth (mm) =	315	300	340	330
Web Thickness (mm) =	27.8	19.88	31.75	27.8
Flange Width (mm) =		105		
Flange Thickness (mm) =		15.88		
DPT (Sch 1 Pg 9) =	0.085	0.063	0.111	0.090
PAV (Sch 1 Table 2) (MPa) =	0.350	8.868	7.839	8.228
Span	2.167	2.167	2.167	2.167
Vp / Span	0.463	0.463	0.463	0.463
A (Sch 1 Table 3 & Vp/Span<0.8) =	0.795	0.795	0.795	0.795
A (Sch 1 Table 3 & (0.8>Vp/Span<=2.2)) =	Range	Range	Range	Range
H	17320	15000	17320	17320
Min. Transverse Frame Shear Area (cm2)	87.45	59.30	107.26	91.20
Min. Trans. Frame Plastic Section Modulus (cm3)	1455.12	1139.28	1784.81	1517.58
Shear Area (cm2)	87.57	59.64	107.95	91.74
Trans. Frame Plastic Section Modulus (cm3)	1500.95	1502.21	2006.52	1659.35
Flange Width > 5 times Web thickness	NA	OK	NA	NA
Local Web Buckling	OK	OK	OK	OK
Flange Outstand	NA	OK	NA	NA
V	17.054	15.084	16.336	16.564
Tripping	NA	NA	NA	NA
Tee	NA	FAIL	NA	NA
Angle	OK	NA	OK	OK
Flat Bar				
Web Thickness - Shell Thickness (Sch 1 Para 9)	OK	OK	OK	OK
Status	PASS	PASS	PASS	PASS

LONGITUDINAL FRAME (STRINGER) DESIGN				
Type =	Angle	Angle	Angle	Angle
Dimensions:				
Web Depth (mm) =	970	780	845	1015
Web Thickness (mm) =	19.84	19.84	27.8	19.84
Flange Width (mm) =	160	120	245	170
Flange Thickness (mm) =	19.84	15.88	31.75	19.84
DPH for shear area (Sch 1 pg 11)	0.512	0.377	0.669	0.542
DPH for plastic section modulus (Sch 1 pg 11)	0.512	0.377	0.669	0.542
Shear PAV (Sch 1 Table 2, $DPH \leq .30$) (MPa) =	Range	Range	Range	Range
Shear PAV (Sch 1 Tble 2, $0.3 < DPH \leq 0.70$) (MPa) =	5.240	5.710	4.896	5.166
Plast. Mod. PAV (Sch 1 Table 2, $DPH \leq .30$) =	Range	Range	Range	Range
Plast. Mod. PAV (Sch 1 Tble 2, $0.3 < DPH \leq 0.70$) =	5.240	5.710	4.896	5.166
Vp / S	0.463	0.463	0.463	0.463
Q	0.700	0.700	0.700	0.700
F	0.550	0.550	0.550	0.550
Minimum Stringer Shear Area (cm ²)	192.21	154.39	234.64	200.53
G	1.100	1.100	1.100	1.100
Minimum Stringer Plastic Section Modulus (cm ³)	5701.28	3376.16	9093.60	6295.50
Stringer Shear Area (cm ²)	192.45	154.75	234.91	201.38
Stringer Plastic Section Modulus (cm ³)	12756.01	7743.66	17117.89	14049.91
Flange Width > 5 times Web thickness	OK	OK	OK	OK
Local Web Buckling	OK	OK	OK	OK
Flange Outstand	OK	OK	OK	OK
V	11.579	11.437	12.624	11.594
Tripping				
Tee	NA	NA	NA	NA
Angle	OK	OK	OK	OK
Flat Bar	NA	NA	NA	NA
Web Thickness – Shell Thickness (Sch 1 Para 9)	OK	OK	OK	OK
Status	PASS	PASS	PASS	PASS

DEEP WEB FRAME DESIGN				
Type =	Tee	Tee	Tee	Tee
Dimensions:				
Web Depth (mm) =	1380	1295	1475	1440
Web Thickness (mm) =	27.8	23.8	31.75	27.8
Flange Width (mm) =	140	120	160	140
Flange Thickness (mm) =	15.88	15.88	15.88	15.88
DPT (Sch 1 Pg 9) =	0.512	0.377	0.669	0.542
PAV (Sch 1 Table 2 for DFT ≤ .30) (MPa) =	Range	Range	Range	Range
PAV (Sch 1 Table 2 for 0.3 < DPT ≤ 0.70) (MPa) =	5.240	5.710	4.896	5.166
Span	6.500	6.500	6.500	6.500
Vp / Span	0.154	0.154	0.154	0.154
A (Sch 1 Table 3 & Vp/Span < 0.8) =	0.923	0.923	0.923	0.923
A (Sch 1 Table 3 & (0.8 > Vp/Span ≤ 2.2)) =	Range	Range	Range	Range
H	17320	17320	17320	17320
Min. Transverse Frame Shear Area (cm ²)	382.37	307.14	466.79	398.93
Min. Trans. Frame Plastic Section Modulus (cm ³)	18439.37	14811.37	22510.07	19237.84
Web Frame Shear Area (cm ²)	383.64	308.21	468.31	400.32
Web Frame Plastic Section Modulus (cm ³)	30120.99	22828.93	39089.68	32712.90
Flange Width > 5 times Web thickness	OK	OK	OK	OK
Local Web Buckling	OK	OK	OK	OK
Flange Outstand	OK	OK	OK	OK
V	13.552	13.951	13.144	13.282
Tripping	OK	OK	OK	OK
Tee	NA	NA	NA	NA
Angle	NA	NA	NA	NA
Flat Bar	NA	NA	NA	NA
Web Thickness – Shell Thickness (Sch 1 Para 9)	OK	OK	OK	OK
Status	PASS	PASS	PASS	PASS

SUMMARY		Transverse Frame Spacing (mm)			
		685	505	895	725
PANEL LAYOUT		Rationalized	Rationalized	Rationalized	Rationalized
# of Frames		17	17	17	17
Panel Length (mm)		12330	9090	16110	13050
# of Stringers		2	2	2	2
Deep Frame Spacing (# of Main Frames between)		5	5	5	5
# of Deep Frames		2	2	2	2
Stringer Span (mm)		4110	3030	5370	4350
Stringer Spacing (mm)		2166.7	2166.7	2166.7	2166.7
Deep Frame Span (mm)		6500	6500	6500	6500
SHELL PLATE DESIGN					
Shell Plate Thickness (mm)		28	24	32	29
TRANSVERSE FRAME (MAIN) DESIGN					
Type =		Flat Bar	Angle	Flat Bar	Flat Bar
Dimensions:					
Web Depth (mm) =		315	300	340	330
Web Thickness (mm) =		27.8	19.88	31.75	27.8
Flange Width (mm) =			105		
Flange Thickness (mm) =			15.88		
LONGITUDINAL FRAME (STRINGER) DESIGN					
Type =		Angle	Angle	Angle	Angle
Dimensions:					
Web Depth (mm) =		970	780	845	1015
Web Thickness (mm) =		19.84	19.84	27.8	19.84
Flange Width (mm) =		160	120	245	170
Flange Thickness (mm) =		19.84	15.88	31.75	19.84
DEEP WEB FRAME DESIGN					
Type =		Tee	Tee	Tee	Tee
Dimensions:					
Web Depth (mm) =		1380	1295	1475	1440
Web Thickness (mm) =		27.8	23.8	31.75	27.8
Flange Width (mm) =		140	120	160	140
Flange Thickness (mm) =		15.88	15.88	15.88	15.88
STRUCTURAL WEIGHT (kg)					
Plate		17490.0	11038.9	26098.9	21141.6
Main Frames		6702.4	5840.9	8262.2	7021.6
Stringers		4339.9	2480.5	7909.0	4816.9
Web Frames		4141.9	3339.7	5038.4	4312.1
Total Weight of Steel (kg)		32674.3	22699.9	47308.5	37292.2
Smeared Plate Thickness - All Material (mm)		51.93	48.94	57.55	56.00
Smeared Plate Thickness - Short Distance (mm)		45.04	43.59	47.93	48.77
Weight per metre Length of Panel (kg/m)		2650.0	2437.2	2936.6	2857.6

COSTS:			685	505	895	725
Main Frame Spacing:						
Materials:						
	Weight (kg)		32674.3	22699.9	47308.5	37292.2
	\$ per tonne		\$1,100	\$1,100	\$1,100	\$1,100
	Total \$ for Material		\$35,941.72	\$24,969.94	\$52,039.36	\$41,021.41
Labour:						
Welding	Metres of Weld	Perimeter	37.660	31.180	45.220	39.100
		Main Frames	195.000	390.000	195.000	195.000
		Stringers	98.640	72.720	128.880	104.400
		Web Frames	52.000	52.000	52.000	52.000
		TOTAL	383.300	545.900	421.100	390.500
	\$ per Metre of Weld		\$39.36	\$39.36	\$39.36	\$39.36
	Total \$ for Welding		\$15,086.69	\$21,486.62	\$16,574.50	\$15,370.08
Fabrication (Cutting, Handling & Set-Up)			\$163,371	\$113,500	\$236,543	\$186,461
Complexity Factors on Labour:						
	# of Pieces (Fab)		20	20	20	20
	# of Pieces per m ² (Fab)		0.2495	0.3385	0.1910	0.2358
	# of Intersections per m ² (Fab)		0.4242	0.5754	0.3247	0.4008
	Crowdedness (# of Panels/m ²) (Fab & Weld)		0.674	0.914	0.516	0.637
	Plate Butt Weld Thickness		28.00	24.00	32.00	29.00
	Fillet Weld (Weighted Average Thickness)		24.63	18.08	29.30	24.55
	Fillet Weld Area		303.4	163.4	429.2	301.4
	Butt Weld Area		205.0	153.0	265.0	219.3
	# of Butt Weld Passes		4.1	3.06	5.3	4.385
	# of Fillet Weld Passes		6.067	3.267	8.584	6.029
	Fabrication		1.2233	1.3635	1.1709	1.2110
	Welding		7.4689	4.0767	10.5204	7.4378
Total Cost:			\$348,482	\$267,327	\$503,387	\$381,149
Per Metre:						
	Weight of Structure per Metre Length		2650	2497	2937	2858
	Cost per Metre of Length		\$28,263	\$29,409	\$31,247	\$29,207

END

2 4 - 1 1 - 9 5

FIN