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**BEHAVIOUR OF WEBS OF WELDED WIDE
FLANGE SHAPES SUBJECTED TO
CONCENTRATED LOADS**

by

Robert J. Kirkhope, P.Eng.

**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

OTTAWA, CANADA

March, 1995

*** The Masters Degree in Civil Engineering
is a joint program with the University of Ottawa, administered by
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**BEHAVIOUR OF WEBS OF WELDED WIDE FLANGE
SHAPES SUBJECTED TO CONCENTRATED LOADS**

**submitted by
Robert J. Kirkhope, P. Eng.**

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

J.L. Humar, Chair, Department of Civil and Environmental Engineering

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**Carleton University
Ottawa, Ontario, Canada**

March 23, 1995

Abstract

This investigation is an experimental study of the behaviour of the web's of welded wide flange (WWF) beams under concentrated interior and end reaction loading conditions. Sixteen tests were conducted on seven WWF shapes that represent the full range of behaviour from elastic web buckling to inelastic web buckling to web yielding, and which represent the range of geometry and class of sections produced by Canadian mills. The ultimate loads were compared with the predicted capacities based on the current design standard, CAN/CSA S16.1-M89, and those predicted by Benichou's equivalent column model. Limitations, variations in predicted capacities and behaviour and the applicability of both models are discussed. Further investigations, both experimental and analytical, are required to develop the necessary modifications to the column model (effective length factors, column length and the appropriate normal stress distribution) to include WWF shapes. The test data and behaviour obtained in this study can serve as a benchmark for this development.

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Nomenclature

A	Area of equivalent column.
a	Distance from flange tip to face of web.
b	Width of flange.
B_r	Bearing resistance of web.
c	Length of patch load.
c_1	$c + 5k$.
d, d_1, d_2	Depth of beam.
E	Modulus of elasticity.
E_{π}	Strain hardening modulus.
F_y	Yield stress of web plate material.
h	Height of web plate.
I	Moment of inertia.
K	Effective length factor of equivalent column.
k	Distance from outer face of flange to the toe of the web fillet.
l	Span of beam.

M_{Ult}	Ultimate moment capacity of beam.
N	Length of patch load.
P_{cr}	Elastic buckling load of equivalent column.
P_{Ult}	Ultimate capacity of web.
P_y	Yield load of equivalent column.
r	Radius of gyration of web.
t	Thickness of flange plate.
w	Thickness of web plate.
x	Dimension down webs depth.
α, β	Dimensions defining Roberts (1981) collapse mechanism.
ϵ_{Bend}	Local bending strain.
ϵ_{Bot}	Strain on bottom surface of flange.
ϵ_f	Strain at fracture.
ϵ_H	Strain at commencement of strain hardening.
ϵ_{Top}	Strain on top surface of flange.
ϵ_u	Strain at ultimate.
ϵ_y	Strain at yield.
λ	Slenderness parameter.
λ_e	Equivalent column slenderness parameter.
ϕ	Material resistance factor.
ν	Poissons ratio.
$\sigma(x)$	Uniform stress on equivalent column at web depth x .

σ_b	Normal stress on web plate due to bending.
σ_f	Stress at fracture.
σ_{Max}	Maximum uniform stress on equivalent column.
σ_p	Stress at proportional limit.
σ_{sy}	Static yield stress.
σ_u	Stress at ultimate.
σ_y	Stress at yield.
σ_{yl}	Lower yield stress.
σ_{yu}	Upper yield stress.

Chapter 1

Introduction

1.1 Literature Review

Web plates of beams and girders are commonly required to resist concentrated point or patch loads resulting from beams or purlins, wheel loads on gantry girders, or roller loads during the launching of plate or box girders. Generally web stiffeners can be added at these load locations to provide an increased capacity, however, as the number of stiffeners used increases, so does the cost of the beam or girder. Thus it is economically desirable to be able to accurately determine the capacity of an unstiffened web to minimize the number of stiffeners used.

An unstiffened web under a concentrated load can fail by elastic web buckling, inelastic web buckling, or by yielding, as shown schematically in Figure 1.1. These failure modes are analogous to that of a column or edge loaded plate, and so the load vs

slenderness behaviour of a web would be expected to be similar to that of a column or plate as illustrated in Figure 1.2, with the possibility of post buckling strength for plates.

Since the beginning of the 20th century over 650 tests have been conducted on a wide range of built up rolled sheet steel shapes, rolled shapes, and welded plate girders. These tests determined the effects of the web thickness, the flange thickness and width, the material properties, and numerous other parameters, ranging from the shear span to load eccentricity, on the capacity of a web under a concentrated load. Numerous analytical investigations of the problem have also been completed ranging from solutions for the elastic behaviour of a simple edge loaded plate to inelastic finite element analysis of the behaviour of stiffened plate girder panels.

1.1.1 Web Behaviour

Based on existing test data, observations, and analytical studies, the behaviour of a web under a concentrated load can be summarised for the following load stages.

Initially as load is applied, the loaded flange will behave as a beam on an elastic foundation, distributing the load into the web. Skaloud and Novak (1972) found that the flexural rigidity of the flange had a significant effect on the size of the zone of the web influenced by the load. As the load level is increased, the zone of the web influenced by the load will begin to undergo membrane yielding. Out-of-plane deformations remain insignificant at this stage. Bergfelt (1979) noted that if the t/w ratio was large, greater than 2, the web plate would tend to buckle elastically under the load prior to membrane yielding. This buckling would not constitute failure due to the post buckling strength provided to the restrained web plate by the surrounding web plate.

Once a significant region of the web plate has yielded, the rotational restraint provided to the web plate by the loaded flange is lost, and significant out-of-plane deformations (same order of magnitude as the web thickness) will occur. Elgaaly (1983), Roberts and Markovic (1983), and Shimizu et al (1989) among others, found that this out-of-plane bending of the plate led to the formation of two yield bands in the web, one located at or just below the loaded flange/web junction, and the other located at the locations of maximum out-of-plane displacements of the web plate. This maximum displaced shape is generally in the form of a circular arc directly below the load. If the web plate is stocky enough though, plate bending would be insignificant and failure would tend to be by membrane yielding. Bergfelt (1979), Roberts (1981), and Shimizu et al (1989) found that very slender webs, or webs subjected to very short load lengths would buckle inelastically with the formation of three yield bands, folding the web locally like an accordion. Elgaaly (1983) found that by increasing the flange plate to web plate thickness ratio, t/w , the ultimate load capacity of the web would be increased.

1.1.2 Web Capacity Prediction

Elgaaly (1983) and Benichou (1994) summarised a number of studies carried out on webs subjected to concentrated loads. The major conclusions from these studies are;

- (1) the ultimate capacity of the web is almost directly proportional to the square of the web plate thickness;
- (2) a limited increase in the ultimate capacity of the web can be achieved by either increasing the web material yield stress, the t/w ratio or the load length to flange thickness c/t ratio; and

(3) the ultimate capacity of the web is virtually independent of the web plate's depth, h .

Numerous formulae were presented for the prediction of a web's capacity as a result of these studies. In general the analytical and numerical solutions proposed were empirical or semi-empirical in nature, and assumed idealized boundary conditions, geometry, material behaviour, and load configurations. As noted, a detailed account of these formulae can be found in Elgaaly (1983) and Benichou (1994). The following is a brief summary of the current state of the art.

The elastic web buckling capacity is generally predicted by buckling formulas such as those proposed by Zetlin (1955), and Khan et al (1975, and 1977). These formulae include buckling coefficients which can account for such variables as the boundary conditions, the web plate's aspect ratio, the flange to web thickness ratio, the load length to web plate width ratio, and/or the presence of any inplane moment or shear forces. These buckling coefficients are generally determined from interaction curves or are given in charts.

The inelastic web buckling and web yielding capacity is generally predicted by empirical or semi-empirical formulae based on assumed collapse mechanisms. These mechanisms were based on observations made by Winter and Pian (1946), Graham et al (1959), Roberts and Rockey (1979), and Roberts (1981) among others, during testing of beam specimens. The ability of these formulae to predict the web capacity is dependent on the assumptions made by the authors, as to the formation of plastic hinges in the loaded flange and yield lines in the web, both in the numbers formed and their location.

The effects of residual stresses, localized loading, and imperfections were generally ignored.

The impact of a coexistent bending moment on the load carrying capacity of a web has been investigated by Skaloud and Novak (1972), Elgaaly and Rockey (1973), and Roberts and Rockey (1979). Empirical web capacity reduction factors, of the form given in equation 1.1, vary as a function of the square or cube of the ratio σ_b/σ_y of the web plate material. These formulae were based on a limited number of tests. Elgaaly and Rockey (1973) noted that the presence of the coexistent moment did not significantly reduce the capacity of the web until the ratio of σ_b/σ_y exceeded 50%,

$$\left[1 - \left(\frac{\sigma_b}{\sigma_y} \right)^{a_1} \right]^{\frac{1}{a_2}} \quad (1.1)$$

where, σ_b Normal stress on web plate due to bending, *MPa*.
 σ_y Yield stress of web plate, *MPa*.
 a_1, a_2 are curve fit constants for the given researcher.

The range of geometric parameters of the shapes used in the experimental and analytical studies completed to date, are not representative of the range of these same parameters for the W and WWF shapes currently available from Canadian mills, Benichou (1994). Hence the applicability of the semi-empirical design rules based on this research, which are used for the design of the currently produced range of Canadian W and WWF shapes, is questionable.

1.1.3 Applicability of Clause 15.9 of the Current CAN/CSA S16.1-M89 Provisions

Clause 15.9 of the current Canadian standard, CAN/CSA S16.1-M89, describes the resistance of a web subjected to a concentrated inplane load as being the lesser of its

predicted web yielding or web crippling capacity, given by the semi-empirical expressions for interior load conditions in equations 1.2 and 1.3, respectively,

$$B_r = 1.10\phi w(c+5k)F_y \quad (1.2)$$

$$B_r = 300\phi w^2 \left[1 + 3 \left(\frac{c}{d} \right) \left(\frac{w}{t} \right)^{1.5} \right] \sqrt{F_y \frac{t}{w}} \quad (1.3)$$

where,	B_r	Bearing resistance of web, <i>N</i> .
	c	Length of patch load, <i>mm</i> .
	d	Depth of beam, <i>mm</i> .
	F_y	Yield stress of web plate material, <i>MPa</i> .
	k	Distance from outer face of flange to the toe of the web fillet, <i>mm</i> .
	t	Thickness of flange plate, <i>mm</i> .
	w	Thickness of web plate, <i>mm</i> .
	ϕ	Material resistance factor.

For the end load condition (reactions), Clause 15.9(b), the $(c+5k)$ term in equation 1.2 is reduced to $(c+2.5k)$, and the constant 300 in equation 1.3 is reduced to 150.

Equation 1.2 giving the web yielding capacity, was adopted by S16.1 in 1989 from Graham et al (1959) who showed that a conservative estimate of the strength of the web is obtained by assuming a yielded length of $c + 5k$. The coefficient 1.10 results from calibration of this equation to the previous working stress standard.

Equation 1.3 giving the inelastic web crippling capacity, is based on a failure mechanism developed by Roberts (1981), it was also adopted by S16.1 in 1989. Roberts' mechanism considers the formation of four plastic hinges in the flange plate, and three yield lines in the web plate as illustrated in Figure 1.3. Approximations and empirical modifications were introduced by Roberts to simplify the complex geometry of the model.

The formulation of these design equations brings their applicability into question,

specific issues related to their applicability are listed below:

(1) The web yielding equation is based on Graham et al (1959) which investigated beam-column moment connection behaviour. The portion of the experimental work devoted to web yielding involved modelling the compressive loads resulting from the flanges of a beam framing into a column. The experimental program involved placing the web sections in direct compression, and was concerned with only the short load lengths to be expected due to a beam's flange thickness. Only a small number of shapes were investigated (eleven total), and all were wide flange columns. The short load lengths (not necessarily representative of bearing lengths anticipated in buildings), the application of direct compression through the full depth of the web, the limited number of test specimens (number and range of geometry), and the use of calibration coefficients (1.10) to give comparable loads from one version of the standard to another, make the use of this equation suspect.

(2) The web crippling equation is based on Roberts' collapse mechanism, Roberts (1981). The slenderness of the web plate and rigidity of the flange plate will significantly influence the formation of plastic hinges and yield lines, both in the number formed and their locations. Benichou (1994) showed that the range of the web slenderness and flange rigidities of the shapes physically tested by Roberts, and of published test results used by Roberts to verify his model, which are similar to those produced by Canadian mills is very limited.

(3) Roberts placed a restriction on the geometric parameters c and d limiting the applicability of his model. This restriction, limiting $c/d \leq 0.2$, limits the load length for

shallow sections to impractical lengths. This restriction does not appear in CAN/CSA S16.1-M89 or its commentary.

(4) Roberts noted that his model tended to underestimate the collapse load of beams with very thin webs and flanges, and imposed a second geometric limit, limiting $t/w \geq 3$. Roberts only used this limit to achieve a better fit when comparing his model with published test data, and recommended against its use in practical situations. Benichou (1994) showed that this limit excludes 97% of the currently produced Canadian W and WWF shapes from applicability.

(5) The coefficient 300 in equation 1.3 results from a simplification of two constants in Roberts' model, one is a coefficient of 0.5, the other is the square root of the modulus of elasticity, E . The product of these two values is 224, thus the use of 300 by S16.1 represents a 34% increase in the predicted capacity over Roberts' model.

(6) A portion of the capacity predicted by Roberts' model includes the load required to cause the formation of the plastic hinges in the loaded flange. Normal bending stresses due to bending will reduce the effectiveness of the flange to resist the formation of these hinges. Roberts recognized this and recommended the inclusion of a reduction factor to account for the impact of the global bending stresses, Roberts (1981). CAN/CSA S16.1-M89 makes no reference to this effect or the reduction factor in the standard or its commentary. As a beams flanges are generally used to carry the bending moments, they cannot be relied upon to have any capacity to resist transverse concentrated loads.

(7) For the end reaction case, CAN/CSA S16.1-M89 adopted Roberts' mechanism and adapted it by simply factoring it by 0.5. There is no experimental evidence to justify this

modification.

Furthermore there is no formulation in CAN/CSA S16.1-M89 to account for the elastic buckling failure of a web. These concerns do not explicitly imply that the current code formulations are unsafe, they only address the uncertainty of their applicability, lack of understanding, and the lack of a unified design approach for web yielding, inelastic and elastic web buckling.

1.2 Equivalent Column Model

Recognizing the analogy between the behaviour of columns and that of a web under a concentrated load and as a result of the perceived limitations in the applicability of the current standard CAN/CSA S16.1-M89, Benichou (1994) proposed an equivalent column model for predicting the strength of webs, which reflects the internal force distribution across the width and depth of the web; and that takes into account the influence of the flange, the load bearing area and the two dimensional restraint provided to the web plate.

The equivalent column dimensions and normal stress distribution were determined from elastic and inelastic finite element analyses of selected W and WWF shapes which fail by either elastic or inelastic web buckling or by web yielding, and represent the full range of geometry and classes of sections. The column is defined as having a width of $c + 5k$, with a uniform load that varies from a maximum at the root of the fillet on the web near the loaded flange to zero at the far end as shown in Figure 1.4. The normal

stress distribution down the length of the column (depth of the web) is given by equation 1.4, below,

$$\sigma(x) = \frac{\sigma_{Max}}{2} [1 - \cos(\frac{\pi x}{h})] \quad (1.4)$$

where, h Height of web plate, *mm*.
 x Dimension down webs depth, *mm*.
 $\sigma(x)$ Uniform stress on equivalent column model at web depth x , *MPa*.
 σ_{Max} Maximum uniform stress on equivalent column, *MPa*.

The elastic buckling load for such a column, with pinned end supports was determined from the conservation of energy method to be,

$$P_{cr} = 2.74\pi^2 \frac{EI}{h^2} \quad (1.5)$$

where, P_{cr} Elastic buckling load of equivalent column, *N*.
 E Modulus of elasticity, *MPa*.
 I Moment of inertia of column, *mm*⁴.

To account for boundary conditions other than pins at the supports, an effective length factor was included, yielding,

$$P_{cr} = 2.74\pi^2 \frac{EI}{(Kh)^2} \quad (1.6)$$

This effective length factor, K , is a function of the restraint provided to the web by the surrounding web and the loaded flange within the equivalent column width. Using the results of an elastic finite element analysis, Benichou carried out a parametric study on 22 different W and WWF shapes to find the relationship between the web and flange geometric properties and K . Two empirical functions for K were established from this study for the cases where the loaded flange is permitted and restrained from rotating,

these functions are given in equations 1.7 and 1.8 respectively,

$$K = 0.873 \sqrt{\frac{\left(\frac{c_1}{h}\right)}{\left(\frac{t}{w}\right)}} + 0.1246 \quad (\text{flange rotation permitted}) \quad (1.7)$$

$$K = 0.513 \sqrt{\frac{\left(\frac{c_1}{h}\right)}{\left(\frac{t}{w}\right)}} + 0.161 \quad (\text{flange rotation restrained}) \quad (1.8)$$

where, $c_1 = c + 5k$, mm.

Kennedy (1995) indicated that the values of the effective length factor, K , obtained from equations 1.7 and 1.8 should be limited to values greater than or equal to 0.5.

The slenderness of the equivalent column was obtained by evaluating the ratio of the buckling load given by equation 1.6 and the corresponding yield load, P_y , given by,

$$P_y = wF_y(c+5k) \quad (1.9)$$

The equivalent slenderness parameter, λ_e , expressed as a function of the radius of gyration of the equivalent column is given by,

$$\lambda_e = 0.604 \left(\frac{Kh}{r}\right) \sqrt{\frac{F_y}{\pi^2 E}} \quad (1.10)$$

where, r Radius of gyration of the web, mm.

Benichou presented two proposals for modifying Clause 15.9 of S16.1-M89 to incorporate this model. The first option was to use the equivalent slenderness parameter

with the column curves of Clause 13.3.1 of CAN/CSA S16.1-M89; the second option proposed a best fit approximation of the inelastic web crippling capacity. Benichou considered the expressions for the effective length factor K too complex for design purposes and recommended that constant values be used instead. The options are:

• **Option A Equivalent Web Buckling Slenderness Parameter and S16.1 Column Curves.**

The factored compressive resistance of the web shall be calculated using clause 13.3.1 with an equivalent slenderness parameter λ_e , given by,

$$\lambda_e = 0.6 \left(\frac{Kh}{r} \right) \sqrt{\frac{F_y}{\pi^2 E}} \quad (1.11)$$

The effective length factor for interior reactions shall be:

$$\begin{array}{ll} K = 0.6 & \text{when the flange is restrained against rotation.} \\ K = 0.8 & \text{when the flange is free to rotate.} \end{array}$$

The effective length factor for end reactions shall be:

$$\begin{array}{ll} K = 0.6 & \text{when the flange is restrained against rotation.} \\ K = --- & \text{when the flange is free to rotate.†} \end{array}$$

The area of the equivalent column, A , is equal to:

$$\begin{array}{ll} w(N + 5k) & \text{for interior reactions.} \\ w(N + 2.5k) & \text{for end reactions.} \end{array}$$

† Note: Benichou specified no value for K for this condition.

• **Option B Equivalent Web Buckling Slenderness Parameter and Best Fit Approximation for Inelastic Web Buckling.**

The factored compressive resistance of the web shall be calculated as follows:

(a) Loaded flange free to rotate.

$$\begin{array}{ll} \text{(i)} & 0.0 \leq \lambda_e \leq 0.35 & B_r = \phi A F_y \\ \text{(ii)} & 0.35 \leq \lambda_e \leq 1.6 & B_r = \phi A F_y (1.168 - 0.480\lambda_e) \\ \text{(iii)} & 1.6 < \lambda_e & B_r = \phi A F_y \lambda_e^{-2} \end{array}$$

(b) Loaded flange restrained against rotation.

(i)	$0.0 \leq \lambda_e \leq 0.13$	$B_r = \phi A F_y$
(ii)	$0.13 \leq \lambda_e \leq 1.5$	$B_r = \phi A F_y (1.052 - 0.401\lambda_e)$
(iii)	$1.5 < \lambda_e$	$B_r = \phi A F_y \lambda_e^{-2}$

Where, λ_e , K , A are defined as per option A.

To verify these proposed models, Benichou developed an experimental program to test a range of W and WWF shapes representative of those currently produced by Canadian mills, which would exhibit the three typical web failure modes. Benichou completed the investigation of the W shapes. The purpose of this thesis is the investigation of the behaviour of the WWF shapes.

1.3 Objectives and Scope

The objectives of this experimental study are;

- (1) To conduct an experimental program on welded wide flange shapes of different classes that exhibit the various failure modes of webs when subjected to concentrated inplane loads. This included both interior and end reaction tests on five different WWF beam sections varying in depth and span from 350 mm to 1800 mm and 1500 mm to 6000 mm respectively.
- (2) To conduct ancillary tests to determine the material properties, and to measure the geometry and initial imperfections of the beams for further, more precise, finite element analyses.

(3) To perform a preliminary analysis on the data obtained from each of the interior load tests.

(4) To compare the failure modes and loads obtained in the experimental program with those predicted by the equivalent column model, the current Canadian design standard CAN/CSA S16.1-M89, and Roberts' model, Roberts (1981).

(5) To design and develop a computer program and hydraulics system for data acquisition and load control during testing.

1.4 Outline of Thesis

This thesis first presents a general review of the state of the art concerning the failure modes and prediction of the capacity of webs subjected to concentrated loads, the current Canadian design standard rules are reviewed and perceived limitations to these rules are presented, finally an equivalent column model developed by Benichou (1994) to predict the capacity of webs is reviewed. Chapter two provides a detailed description of the experimental program. Chapter three presents the results of the experimental program, a description of the behaviour of the specimens, and any other pertinent observations. Chapter four provides a discussion of the beam behaviour, the preliminary analysis of the test results, and the comparisons of the test loads with the capacities predicted by the equivalent column model, the current design equations in S16.1 and Roberts model. Conclusions and recommendations from the study are presented in chapter five.

Figure 1.1 Typical Failure Modes of a Beam Web Under a Concentrated Load.

Figure 1.2 Load vs Slenderness Behaviour of a Beam Web, Analogous to Column Behaviour.

Figure 1.3 Roberts' Mechanism, Roberts (1981).

(a) Assumed Stress Distribution Along the Web.

(b) Assumed Normal Stress Distribution Through Web Depth.

Figure 1.4 Normal Stress Distribution Used in Equivalent Column Model.

Chapter 2

Experimental Program

2.1 General

The experimental program was designed to obtain the data necessary to describe the strength and behaviour of the webs of typical welded wide flange (WWF) shapes produced in Canadian mills, that are subjected to concentrated inplane loads for both interior loads and end reactions. The data obtained was then used to validate the equivalent column model described in section 1.2.

Simply supported WWF beams, subjected to a concentrated load at midspan, were each tested three times with strategically placed stiffeners to generate local web failure under the applied load, at one reaction, and then the other. The span lengths varied

between 1500 *mm* and 6000 *mm* to give a minimum shear span to depth ratio of 1.5 to avoid deep beam behaviour and to ensure that the beam web failed locally prior to the load to cause flexural failure (inplane lateral torsional buckling capacity or section strength). The geometric properties (web thickness, flange thickness, depth, and flange width) of the specimens ranged from 11 *mm* to 20 *mm*, 20 *mm* to 30 *mm*, 350 *mm* to 1800 *mm*, and 350 *mm* to 500 *mm* respectively. The web slenderness ratio and length over which the concentrated loads act vary from 14.5 to 87, and 100 *mm* to 300 *mm*, respectively. The shapes, the class of section and the relevant geometric identities are summarised in Table 2.1, and the probable failure load and type are given in Table 2.2.

In addition, three lengths of WWF 500x197 were tested to determine the contribution of the loaded flange to the capacity of an interior load location after the web has failed and as the flange capacity is utilized in carrying the bending moment.

2.2 Test Set-Up

The test set-up consisted of a reaction frame, a 500 Ton hydraulic actuator, load plates, knife-edge-roller assemblies, lateral support frames, electronic and mechanical instrumentation, a data acquisition/hydraulic control system, and the test specimens. Figures 2.1 through 2.4 show elevations, sections, and details of the set-up. The instrumentation is not shown in these figures for clarity.

2.2.1 Loading System and Support Details

The vertical load from the hydraulic actuator was applied through load plates of

differing load lengths to the top flange of the beams. The beam ends were supported on knife-edge-roller assemblies. If necessary, the beam ends were set in beds of hydrostone on top of the knife-edge-rollers to achieve a vertical web at either the midspan or beam end, depending on the test series being carried out.

Lateral support and out of plane rotational restraint of the top flange of the beams was provided at the loading point by friction between the top flange, load plate, and actuator head. Lateral support and out of plane rotational restraint of the top flange at the beam ends, was provided by lateral support frames with roller assemblies attached to their ends, as shown in figure 2.4. These roller assemblies were oriented to allow free vertical movement and the keeper plates on the rollers were loosened to permit movement parallel to the span. The lateral supports were fixed to support the top flange of the WWF 500x197, WWF 900x262, and the WWF 1400x405 as shown in Figure 2.5(a) and to the WWF 1800x510 as shown in Figure 2.5(b). Lateral support was not provided to the top flange at the ends of the WWF 350x212 beam, this beam was extremely stocky and so it was felt that it would not be subjected to significant lateral torsional distortions.

2.2.2 Instrumentation and Measurements

Measurements of the test specimens were recorded in three phases; prior to testing, during testing, and after testing.

Prior to testing, the geometry of each specimen; the beam depth, flange width, overall geometry, weld sizes, plate thicknesses, and plate imperfections (out-of-straightness) was measured and recorded. Figure 2.6(a) details the measurements taken to determine the beams' geometry and dimensions. Twenty five measurements were taken

of the top and bottom flange widths and thicknesses, and of the flange tip to flange tip depths of each beam. The depth of the beam at the web was measured at each end. Web thicknesses were measured at five locations along the web height at each end. Data for the web thickness was also culled from tension coupon measurements. The weld size was measured at the four locations available at each end of each beam. The location of the web with respect to the flange tip was measured for both the top and bottom flanges at both ends.

Mechanical dial gauges fixed to different lengths of angles with hardened steel points, were used to determine the plate out-of-straightness for both the flange and web plates as shown in Figure 2.6(b). The device was calibrated on a milling bed to determine the initial zero readings. Three evenly spaced gauges were used for each of the flange plates and for the web plates of the WWF 350x212, WWF 500x197, and the WWF 900x262 shapes. Five evenly spaced gauges were used for the web plates of the WWF 1400x405 and WWF 1800x510 shapes. These measurements were recorded and will be used in future finite element analyses of the test specimens.

Throughout the duration of the testing, applied loads, strains, and displacements were measured. The locations of the measurements made for strains on the beam web and flanges are shown in Figures 2.7 and 2.8, respectively; for displacements on the web (out-of-plane) for interior loads and end reactions in Figures 2.9 and 2.10, respectively; and for displacements of the flanges in Figures 2.11 to 2.13.

The electric resistance strain gauge and displacement transducer locations on the webs of the shapes were selected to correspond, within the limits of these devices

physical geometry and practicality, with nodes on the finite element mesh used in the preliminary analytical modelling of the shapes carried out by Benichou (1994). Strains and displacements are reported at these nodes during finite element analysis enabling direct comparisons between future possible analytical predictions and the test data. Strain gauges located on the flanges permit an evaluation of the inplane loads carried by the flanges. Strain gauge measurements were not made during the end reaction series of tests.

Displacement transducers located on the flanges give the vertical displacement of the beam, and the relative displacements of the top and bottom flanges (reduction in beam depth and any rotation of the flanges). Displacement transducers located at the ends of the top and bottom flanges enable the determination of the rotation occurring at the reaction, and permit an estimation of rotational restraint, if any, imparted by the lateral support devices.

The type of measurements, instrumentation used, purpose, and frequency of measurements are described in Table 2.3.

After testing, measurements of the residual deformations of the web and/or flanges were taken. Plaster casts of the buckled interior web locations were taken for the WWF 500x197 series of tests.

2.3 Testing Procedure

A description of the test sequence for each beam follows. For the first test on each beam, doubler plates were clamped to the web at both beam ends to prevent web

instability and the possibility of a local failure at these locations, and to ensure failure underneath the applied load. Subsequently the midspan web location was drilled and the doubler plates from one end were bolted through to provide stability. If torquing of the bolts was not sufficient to remove the residual deformations resulting from the interior load test, the plates would be bolted to the web with hydrostone plaster set between the web and plates. The other set of doubler plates would remain clamped at the non tested beam end and the beam was retested for the first end reaction test. The reaction plates at the supports and doubler plates at the beam ends were switched, and the remaining end was tested.

The following is a description of the test procedure used for both the interior and end reaction tests:

1. Beam specimen, knife edge roller assemblies, and load plate were aligned vertically and horizontally with respect to the hydraulic actuator within the reaction frame.
2. Doubler plates were clamped into place and the lateral supports installed.
3. Electric resistance strain gauge circuits were completed with the data acquisition system, the displacement transducers were located and their wiring circuits completed. Circuits were tested to verify that they were functioning properly.
4. Power supplies were adjusted if necessary. A small load (less than 5 kN) was applied to the beam and the keeper plates on knife edge roller assemblies were removed. The keeper plates on the lateral support rollers were loosened.
5. A preload of approximately $1/20^{\text{th}}$ of the estimated load capacity was applied to

seat the specimen. The preload was removed and all instruments were zeroed.

6. Load was applied to the beam in approximately 25 *kN* increments. After each load increment, all electronic measurements were recorded.
7. After every 100 *kN* of load, a visual inspection was conducted, observations were recorded, and any manual readings were taken.
8. As web yielding/crippling began, the magnitude of the load increment was reduced accordingly.
9. Electronic measurements were recorded after each load/displacement increment. If long delays occurred between load steps and/or deformations continued to progress without additional load, additional sets of measurements were recorded as necessary.
10. After failure, the beam was unloaded in 200 *kN* increments, with electronic measurements being recorded after each load decrement.
11. After the load was released, residual measurements were recorded electronically and manually.

2.4 Ancillary Tests

Tension coupon tests were conducted on a series of coupons taken from the flange and web plates of each beam shape to determine the stress-strain characteristics of the plate materials used to fabricate these shapes. The coupons were cold cut from the shapes in the locations shown in Figure 2.14 and milled in accordance with ASTM E8M-91

(1991) recommendations, using a gauge length of 200 *mm* and a width of 40 *mm*. A typical tension coupon is shown in Figure 2.15. The cross sectional dimensions of the coupons were determined from 11 measurements of both the width and thickness of the coupon taken along the length of the reduced section.

Longitudinal strains were measured during testing using electrical resistance strain gauges mounted longitudinally on each face of the coupon. These gauges were used for measuring small strains up to 2 percent, and dividers and a scale over a 200 *mm* gauge length were used to determine large strains.

Additional electrical resistance strain gauges were mounted transversely on two of each of the web plate coupons to measure transverse strains, which enabled Poisson's ratio to be determined. Figure 2.14 identifies these coupons.

The load and strains from the electrical resistance strain gauges were recorded automatically by the data acquisition system, and strains from the divider measurements were recorded manually. Testing of the coupons was carried out in a 1780 *kN* Tinius Olsen testing machine in accordance with the recommendations of ASTM E8M-91 (1991).

2.5 Data Acquisition/Hydraulics Control Program and Hydraulics System Development

2.5.1 General

In order to enable the experimental program to be carried out it was necessary

to develop a data acquisition/hydraulics control program and a hydraulics system. The assembled components necessary for this system include; a 386 personal computer, a pair of Hewlett Packard data acquisition control units, a hydraulics subsystem control unit (developed at the Carleton University Civil Engineering Laboratories), electronic solenoid operated control valves, and a number of Enerpac hydraulic actuators. It was necessary to interconnect these components and to create a computer program that could control the resulting system.

2.5.2 Data Acquisition/Hydraulics Control Program - LABCON

The completed program, called LABCON, provides a user friendly interface which allows the user to create an interactive data acquisition/hydraulics control system for data acquisition, instrument control, and data presentation, that can be tailored to suit the users particular test. The program allows for simple automated control of the hydraulics system (either in load or stroke control; up to three systems acting simultaneously), while giving the capacity to monitor and record data from the assembled electronic measurement devices. The types of measuring devices LABCON is able to read include; electric resistance strain gauges, displacement transducers, load cells, and pressure transducers.

The LabWindows® programming package, developed by National Instruments Corporation, was selected to produce the user interface graphics and digital interface necessary to make LABCON "user friendly" and capable of communicating with and controlling the assembled components. The program was written using the QuickBASIC language to accommodate LabWindows. LABCON was completed in December 1993 and has the following specifications:

- **Data acquisition:**

- (1) **Records data from any combination of the following measurement devices;**

- 100 electric resistance strain gauges (1/4 bridge circuits only)
- 50 displacement transducers
- 10 load cells
- 5 pressure transducers

- (2) **Permits the monitoring of all measurement devices throughout the duration of testing.**

- (3) **Allows displacement transducers to be reset if their stroke is exceeded (providing continuous displacement data).**

- **Hydraulics control:**

- (1) **Simultaneous automated control (displacement or load) of up to three separate and independent hydraulics systems.**

Appendix A includes a copy of the user manual produced for LABCON and gives a more detailed account of this program's capabilities and describes its operation. To date LABCON has been successfully used on a wide variety of tests, including the beam web crippling tests of this and Benichou's experimental programs, numerous tension coupon tests, and two large scale icebreaking ship hull tests. Table 2.4 gives details of the data acquisition and hydraulics requirements of these tests demonstrating the flexibility of LABCON. The following is a brief description of some of the problems encountered while developing LABCON, and their solutions.

In general, a data acquisition system must collect, analyze, monitor, and save data from the connected measurement devices. Data from the measurement devices is collected in the form of voltage signals via the Hewlett Packard data acquisition control units which read the signals from the strain gauges, load cells, and displacement transducers, and via

the hydraulics subsystem control unit which reads the signals from the pressure transducers.

LabWindows has an existing digital interface feature which allows direct communication with the hydraulics subsystem unit, hence, the voltage signals from the pressure transducers can be recorded directly. The Hewlett Packard (HP) units, however, were originally designed as stand alone units which were operated by simple programs. The user inputs simple instructions (commands) through a keypad built into the units or from a computer connected with the units. Hewlett Packard developed computer code for the latter called HP-IB code. This HP-IB arrangement is used for LABCON, therefore to communicate with the HP units, LABCON had to be able to generate programs internally that would instruct the HP units of the data acquisition process desired (define the desired process in HP-IB code, receive the output files, and then read the various voltage signals). LABCON was programmed to generate new HP-IB programs to suit any number and combination of measurement devices, and each of the possible types of data acquisition processes desired.

Voltage signals were converted into engineering units through simple multiplication by calibration factors which are particular to the type of measurement device and must be determined by the user. A second program, called CALIB, was developed specifically for this purpose and enables the determination of calibration factors for load cells, pressure transducers, and displacement transducers using the method of least squares.

Due to the limited size of the computer screen, it was not feasible to show or

monitor all of the data from the measurement devices at the same time. To permit as much access as possible to the test data during the test, LABCON was designed to provide:

- a) On screen space for up to eleven different devices, which are selected by the user for continuous monitoring during testing,
- b) On screen space for the devices used to control the hydraulics system so that the applied load or displacement would be known continuously during the test,
- c) Two graphs to view the characteristic behaviour of two separate pairs of measurement devices as readings are taken. One is shown on the screen at all times, the user can simply toggle a switch to view the other. and,
- d) Access to listings of the last recorded sets of readings for all measuring devices.

Saving the data presented another problem, as LabWindows will only permit one input/output file to be open at any given time. A data file could not be maintained open at all times as it would not permit communication with the HP units. To overcome this, the data file would be opened and closed only when storing readings. This results in a secondary benefit, in that in the case of a system failure, the data collected up until failure will be saved and cannot be lost.

2.5.3 Hydraulic Control and the Hydraulics System

In general, a hydraulics control system must give the operator control over the system at all times and must also be flexible enough to accommodate the wide variety of test situations possible. Control of the hydraulics system is achieved through commands to the hydraulics subsystem unit, which sends electronic signals to the solenoid operated

valves. LABCON was developed to permit the use of displacement transducers, load cells, and pressure transducers to control the actuators. Control using these devices was easily established for load cells and displacement transducers through the data acquisition processes already developed in LABCON. Control via the pressure transducers, however, required modification of the Enerpac actuators. This modification involved pairing each actuator with a dedicated pressure transducer, essentially turning the actuators into load producing load cells. The actuator/pressure transducer assemblies were calibrated using CALIB in a 1780 *kN* Tinius Olsen testing machine controlled by an MTS system. The capacity of the testing machine permitted full range calibration of the 200 Ton (1780 *kN*) actuators, and calibration of only 40% of the full range of the 500 Ton (4450 *kN*) actuators. This lower range was considered sufficient for full range operation of the 500 Ton actuators as the pressure transducer signal is stable and linear over its full range.

Various hydraulic components; an air powered pump, hydraulic lines, additional solenoid control valves, manifolds, and pressure transducers were assembled to complete the hydraulics system. The final system enables the user to control a maximum of three separate hydraulics systems either in load or stroke control. Currently each system can serve a pair of actuators.

Figure 2.1 Elevation of Reaction Frame Showing Hydraulic Actuator, WWF Beam Specimen, and Knife-edge Roller Assembly.
Note: Lateral support frames not shown, see Figure 2.4.

Figure 2.2 Cross Section Through Reaction Frame Showing Typical Test Setup for an Interior Reaction Test.
Note: Lateral support frames not shown, see Figure 2.4.

Figure 2.3 Cross Section Through Reaction Frame Showing Typical Test Setup for an End Reaction Test.
Note: Lateral support frames not shown, see Figure 2.4.

Figure 2.4 Elevation of Lateral Support Frames at WWF Beam Ends.

(a) Typical Lateral Support Arrangement for WWF 500x197, WWF 900x262, and WWF 1400x405 Beam Tests.

(b) Typical Lateral Support Arrangement for WWF 1800x510 Beam Tests.

Figure 2.5 Typical Lateral Support Details at WWF Beam Ends.

(a) Recorded Dimensions and Geometry.

Dial Gauges evenly spaced
between hardened steel points.

Number of web
measurements
is dependent on
the depth of the
web.

(b) Recorded Plate Imperfections (exaggerated).

Figure 2.6 Location and Type of Measurements Recorded to Establish Beam Dimensions, Geometry, and Plate Imperfections.

(a) Rosette Layout Used for WWF500x197, WWF 900x262, WWF 1400x405, and WWF 1800x510 Tests.

(b) Rosette Layout Used for WWF 350x212 Test.

Figure 2.7 Location and Identification of Web Strain Gauge Rosettes, Typical for Both Sides of the Beam Webs.

(a) Location of Gauges on Top Flange.

(b) Location of Gauges on Bottom Flange.

Figure 2.8 Location of Flange Strain Gauges for all WWF Beam Shapes.
Note: Gauges are Located on Both Sides of the Flange.

(a) Displacement Transducer Layout Used for WWF 500x197, WWF 900x262, WWF 1400x405, and WWF 1800x510 Tests.

(b) Displacement Transducer Layout Used for WWF 350x212 Test.

Figure 2.9 Location of Web Displacement Transducers for Interior Reaction Tests.

(a) Displacement Transducer Layout Used for WWF 500x197, WWF 900x262, WWF 1400x405, and WWF 1800 Tests.

(b) Displacement Transducer Layout Used for WWF 350x212 Test.

Figure 2.10 Location of Web Displacement Transducers for End Reaction Tests.

(a) Typical Locations of Displacement Transducers at Midspan.

(b) Typical Location of Displacement Transducers at the reaction point.

Figure 2.11 Locations of Flange Displacement Transducers for Both Interior and End Reaction Tests.

Figure 2.12 Location of Flange Displacement Transducer at the Reaction Point for WWF 350x212 Interior Test.

Note : No lateral support was provided at ends of this beam.

Figure 2.13 Location of Flange Displacement Transducers at the Reaction Point For WWF 350x212 End Reaction Test.

Note : No lateral support was provided at ends of this beam.

(a) WWF 1800x510 Coupon Identification.

(b) WWF 1400x405 Coupon Identification.

Note: * Indicates Coupons Gauged for the Determination of Poisson's Ratio.

Figure 2.14 Tension Coupon Identification.

(c) WWF 900x262 Coupon Identification.

(d) WWF 500x197 Coupon Identification.

Note : * Indicates Coupons
Gauged for determination
of Poisson's Ratio.

(e) WWF 350x212 Coupon Identification.

Figure 2.14 (continued) Tension Coupon Identification.

Figure 2.15 Typical Tension Coupon Dimensions.

Table 2.1 Test Parameters and Nominal Dimensions of WWF Shapes Selected for Experimental Program.

Designation	c (mm)		l (mm)	t (mm)	w (mm)	b (mm)	d (mm)	h (mm)	$\frac{b}{2t}$	$\frac{h}{w}$	Class
	interior	end									
WWF 350x212	100	50	1500	30	20	350	350	290	5.83	14.5	1
WWF 500x197	200	100*	1700	20	11	500	500	460	12.5	41.8	4
WWF 500x197	200	100	2000	20	11	500	500	460	12.5	41.8	4
WWF 500x197	200	100	3000	20	11	500	500	460	12.5	41.8	4
WWF 900x262	300	150	4000	30	11	400	900	840	6.67	76.3	2
WWF 1400x405	300	150	5800	30	16	500	1400	1340	8.33	83.7	2
WWF 1800x510	300	150	6000	30	20	500	1800	1740	8.33	87.0	2

Notes: a. One end reaction test of this beam used a reaction bearing length of 50 mm.

Table 2.2 Predicted Failure Loads and Type of Failure by Different Models, from Benichou (1994).

Designation	P_{σ} (kN)	Lusas (kN)	S16.1 (kN)	Roberts (kN)	P_y (kN)	Probable Mode of Failure
WWF 350x212	18026	2509	3733	2993	2013	Yielding
WWF 500x197	2277	1049	1263	905	1252	Inelastic Buckling
WWF 900x262	1335	1226	1269	905	1797	Inelastic Buckling
WWF 1400x405	1995	2099	2278	1916	2614	Elastic Buckling
WWF 1800x510	2504	2866	3238	2941	3333	Elastic Buckling

Note: Lusas is nonlinear finite element analysis prediction based on nominal properties and geometry. Refer to Benichou (1994), Chapter 2, for a detailed description of how these results were determined.

Table 2.3 Types of Measurement and Instrumentation.

Instrumentation	Location/Description	Purpose	Frequency of Measurement
Pressure Transducer.	Located at advance port of the hydraulic actuator.	Applied Loads	
		Gives the applied Load.	Discrete readings taken after each load or deformation increment.
Electric resistance strain gauges.	Strain gauge rosettes distributed on web as shown in Figure 2.7.	Steel Strains	
		Give the measurement of strains at discrete locations on the web.	Discrete readings taken after each load or deformation increment.
		Strain gauges distributed on flanges as shown in Figure 2.8.	Discrete readings taken after each load or deformation increment.
Displacement transducers.	Displacement transducers located on the web as shown in Figures 2.9 and 2.10.	Displacements	
		Give the measurement of the lateral deformations of the web plate.	Discrete readings taken after each load or deformation increment.
		Displacement transducers located on the flanges as shown in Figures 2.11, 2.12, and 2.13.	Discrete readings taken after each load or deformation increment.

Table 2.4 Specifications of Tests Completed Using LABCON.

Test type.	No. completed.	Data Acquisition/Hydraulics requirements.
W and WWF; interior loading web crippling	13	<ul style="list-style-type: none"> • Between 41 and 60 strain gauges. • Between 14 a. : 19 displacement transducers. • 1 pressure transducer. • One hydraulic system with 1 hydraulic actuator.
W and WWF; end reaction web crippling	19	<ul style="list-style-type: none"> • Between 10 and 15 displacement transducers. • 1 pressure transducer. • One hydraulic system with 1 hydraulic actuator.
Tension coupons	over 150	<ul style="list-style-type: none"> • Between 2 and 4 strain gauges. • 1 load cell.
Icebreaking ship hull test	2	<ul style="list-style-type: none"> • 100 strain gauges. • 35 displacement transducers. • 5 pressure transducers. • Three separate hydraulics systems, two containing paired actuators, one containing a single actuator.

Chapter 3

Test Results

3.1 Beam Dimensions and Geometry

Prior to testing, each beam was measured to determine the initial cross-sectional dimensions, overall geometry, and to establish the degree of any plate imperfections. Figure 2.6 of Chapter 2 shows the type and location of the measurements taken, and Tables 3.1 and 3.2 give the recorded values for these measurements.

Table 3.1 gives the average measured values for the cross-sectional geometry for each WWF shape. Generally, the depth and flange widths of the beams are within the specified manufacturing tolerances given in CAN/CSA G40.20-M87. The depth of the WWF 350x212 is on average 1.53 *mm* greater than that permissible per the aforementioned tolerances. Comparing the measured depths d_1 and d_2 with the depth at

the web, d , gives an estimate of the warpage and tilt of the beam flanges. The difference between either d_1 or d_2 and d gives the total average warpage and tilt for both the top and bottom flanges of one side of the beam. The largest average difference recorded is 10.60 mm for d_1 of the WWF 500x197. This can be interpreted as giving an average tilt of 5.30 mm for each flange, which is slightly less than the maximum permissible tolerance of 6 mm. It is not possible, from the dimensions as they were recorded, to confirm any of the beams conformance with the warpage and tilt tolerances, but the magnitudes of the individual measurements and of the average tilts suggests that the WWF 500x197, WWF 1400x405, and WWF 1800x510 flanges are outside the acceptable tolerances.

Larger and smaller than nominal plate thicknesses were provided for all beams. The WWF 350x212, WWF 900x262, WWF 1400x405, and WWF 1800x510 flanges, and the WWF 900x262 and WWF 500x197 webs are thicker than nominal. Thinner than nominal plate was provided for the WWF 350x212 web. The average ratio of plate thickness supplied to nominal was 1.047 with a coefficient of variation of 0.063. These variations in plate thicknesses did not alter the class of the beams. The measured web slenderness for the WWF 500x197 and WWF 900x262 beams changed significantly and are 37.3 and 66.3 as compared to 41.8 and 76.4, respectively, based on nominal dimensions. The eccentricity of the web with respect to the face of the web is given by the dimension a , which was measured from one side of the beam. All beams fall within manufacturing tolerances for web eccentricity, as given in CAN/CSA G40.20-M87.

Table 3.2 gives the recorded maximum deviation from flatness for both the web and flange plates of each beam. CAN/CSA G40.20-M87 gives tolerance limits for only

the web plate flatness of WWF shapes, expressed as a function of the beam depth, the limit is $d/150$. All beam web plates fall within this tolerance. If the same tolerance was applied to the flanges, expressed as a function of the flange width, then all beams, with the exception of the WWF 500x197 beams, would fall within this tolerance.

3.2 Stress-Strain Characteristics

Tension coupons from the web and flange plates of the WWF beams were tested to establish the uniaxial stress strain characteristics of the material used in the fabrication of the shapes. Characteristic parameters from these stress strain curves were then used in a strain gauge interpretation program developed by Benichou, Benichou (1994), to evaluate the principal strains (and stresses) measured in the webs for the interior load tests.

Tables 3.3(a) and (b) to 3.7(a) and (b) give the uniaxial stress strain characteristic parameters determined for each of the tension coupon tests of the WWF 350x212, WWF 500x197, WWF 900x262, WWF1400x405, and WWF 1800x510, web and flange plates, respectively.

As a result of the fabrication process, coupons taken from different regions of the web and flange plates exhibit varying levels of residual stresses and display three distinct stress strain behaviour curve shapes. Figure 3.1 shows typical examples of the three curve shapes obtained, and identifies the locations where specific characteristic parameters are measured. The type of stress strain curve shape for each coupon is identified in Tables

3.3 through 3.7. The strain gauge readings for coupon C46 (Table 3.3(b)) were suspect, and all related values calculated for this test have been excluded from calculations of the average characteristic parameters.

In general the average yield strength of the flange plate material of all beams was the same at approximately 380 *MPa*. The average yield strength of the web plate material varied greatly from a high of approximately 450 *MPa* for the WWF 500x197 beam to a low of approximately 280 *MPa* for the WWF 1400x405 beam. Only the WWF 1800x510 beam had web and flange plates with equivalent yield strengths. 350 *MPa* steel was specified, the mean static yield strength and the corresponding coefficient of variation for the web and flange plates was 338.7 *MPa* and 0.181, and 354.2 *MPa* and 0.027, respectively. The differences in yield strength from nominal, combined with the different plate thicknesses recorded did not alter the class of any of the sections.

3.3 Web Behaviour

A description of the test histories giving the section tested, type of test, date performed, failure load and mode, and observations related to the web behaviour are summarized in Table 3.8.

Based on observations and measurements recorded during the tests, the omission of the lateral support devices on the WWF 350x212 tests was justified, and these devices imparted negligible rotational restraint at the reactions in all other tests.

3.3.1 Load vs Out-of-Plane Web Behaviour

The best description of the web behaviour is given by the applied load vs out-of-plane web deformation curves shown in Figures 3.2 through 3.8 for each section tested. Figures (a) are for the interior load tests, and Figures (b) and (c) are for the end reaction tests. Each graph illustrates the load displacement curve for the LVDT indicated, which is associated with the maximum out-of-plane displacement. Also illustrated is the overall buckled shape of the web at ultimate. The deformed shapes shown are based on the five discrete LVDT measurements of the out-of-plane web displacements taken at the midspan or web edge depending on the test. For most interior load tests the bottom flange twisted about its longitudinal axis. Because of this twisting, some lateral displacement of the flange may also be likely, and since this was not measured, the deformed web shape was not drawn from the last recorded displacement to the bottom flange/web junction. The magnitude and direction of the flange twist at midspan at ultimate is noted on the appropriate figures.

In a number of the tests, initial seating of the flange under the load plate resulted in a rotation of that flange and an apparent lateral displacement of the web. This is clearly illustrated in Figure 3.7(a) by the initial jump in displacement. The LVDT support frames, which were clamped to the loaded flange, also rotated during seating, causing a fictitious series of rigid body displacements to be measured by these LVDT's. Corrections of these displacements were attempted by subtracting the calculated fictitious displacements, based on the measured rotations of the flange and the location of the web LVDT, from the recorded displacements. The flange, however, tended to deform locally in combination

with some rotation. As there was an insufficient number of measurements to determine the actual rotations of the flanges, corrections of these fictitious displacements was impossible. In a number of the end reaction tests, initial seating of the bottom flange over the end reaction plate also resulted in fictitious displacements being recorded. Refer to Figures 3.3(b) and 3.7(b). For these specific cases the deformed shapes plotted in Figures 3.2 through 3.14 were corrected by these initial displacements, to show the correct magnitude of deformations.

The corresponding deformed shapes of the web centred under the applied load or over the end reaction for the ultimate load (P_{Uk}) and last load level (P_{Max}) prior to unloading are shown in Figures 3.9 through 3.14 for the WWF 500x197 all spans, WWF 900x262, WWF 1400x405, and WWF 1800x510, respectively. One additional deformed shape is plotted for the WWF 1400x405 interior test at 2400 kN, (P_{2400}), Figure 3.13(a), and for the WWF 1800x510 interior test at 3600 kN, (P_{3600}), Figure 3.14(a). The reasons for these additional shapes are discussed in the following section. No deformed web shapes are plotted for the WWF 350x212 specimen. In all cases, loading was continued past ultimate to accentuate the formation of plastic hinges and yield lines in the webs. Yield lines were not physically visible on any of the specimens as the steel was relatively clean (with little or no mill scale), but are easily identified in the exaggerated views of the deformed shape.

3.3.1.1 Interior Load Tests

Figure 3.2(a) illustrates the load vs out-of-plane web displacement for the WWF 350x212 test, which failed by web yielding. The maximum out-of-plane displacement

occurs at $3/4h$ down the web and probably results from the top and bottom flanges being rotated in opposite directions about their longitudinal axis as the beam was loaded. As indicated in Table 3.1, the flanges were not parallel. As expected the out-of-plane displacements were relatively small.

Figures 3.3(a) through 3.7(a) illustrates the load vs out-of-plane web displacement for the WWF 500x197, WWF 900x262, and WWF 1400x405 tests, which all failed by inelastic web buckling. For interior loads on the WWF 500x197 beams, Figures 3.3(a), 3.4(a), and 3.5(a), the curves show little or no out-of-plane displacements up to roughly 80% of ultimate, followed by a sudden loss of lateral stability. This load level generally coincides with the yielding of the web at the flange/web junction under the length of the load plate. For interior loads on the WWF 900x262 and WWF 1400x405 specimens, Figures 3.6(a) and 3.7(a) respectively, the curves do not exhibit obvious inelastic buckling failure behaviour. These curves exhibit a gradual increase in out-of-plane displacements with increased load that reflects the large initial out-of-straightness of these beams web's, an average of 3.3 mm (0.24w). Similar to the WWF 500x197 beams, the rate of the web deformations for the WWF 1400x405 increased significantly after yielding of the web at the top flange/web junction under the load plate was complete. This aspect of the load deformation behaviour is not obvious on the WWF 900x262 curve. A final aspect of the behaviour of the WWF 1400x405 test that should be noted is the fact that the slope of the load vs out-of-plane deformation curve remains constant between the load of 2400 kN and ultimate. This suggests that the 2400 kN load represents the inelastic buckling capacity of the web, and that the subsequent constant stiffness of the curve results from

the post buckling capacity of the web and the top flange contribution. This phenomenon was anticipated as shown in Figure 1.2, and should be present in all inelastic failure tests. The impact of such a phenomenon may be insignificant for the relatively stocky WWF 500x197 beams, and may be obscured by the imperfection altered behaviour of the WWF 900x262. All curves exhibit relatively long plateaus at ultimate as the plastic hinges which form a mechanism, were able to sustain load with the stabilizing effect of the flange. Subsequent decreases in the load are a result of the load acting on the web with large out-of-plane displacements (a minimum of $0.5w$).

Figure 3.8(a) illustrates the load vs out-of-plane web displacement for the WWF 1800x510 test, which failed by elastic web buckling. This curve displays typical elastic buckling behaviour, with a gradual increase in the out-of-plane displacement with increased load. The lateral displacements were essentially linear and insignificant up to approximately 2400 kN. Similar to the other beams behaviour, the rate of lateral deformations increased significantly after yielding of the web at the top flange/web junction under the load plate was complete, approximately 2700 kN. After approximately 3600 kN of load, the stiffness of the load vs out-of-plane web displacement curve remained constant, and inelastic deformations of the web started to occur at the top flange/web junction. The test was stopped at 4010 kN as the out-of-plane web displacements were becoming large, approximately equal to the web thickness. Because of this constant stiffness behaviour, it is suspected that the elastic buckling capacity of the web was achieved at approximately 3600 kN, and that constant stiffness and continued load carrying capacity can be attributed to the post buckling capacity of the web, and the

top flange contribution.

3.3.1.2 End Reaction Tests

Figure 3.2(b) illustrates the load vs out-of-plane web displacement for the WWF 350x212 end test. The magnitude of the recorded displacements is again insignificant, especially when combined with the lack of lateral support of the top flange at the beam end. These out-of-plane web displacements did not increase as the yield load was reached.

The load vs out-of-plane web displacement curves for the end reaction tests on the inelastic web buckling specimens, the WWF 500x197 all spans, WWF 900x262, and WWF1400x405 are illustrated in Figures 3.3(b), 3.4(b) and (c), 3.5(b), 3.6(b) and (c), and 3.7(b), respectively. These specimens failed by local inelastic web buckling. These failures, with the exception of the WWF 500x197 3000 mm span and WWF 1400x405 specimens, Figures 3.5(b) and 3.7(b), are distinctly "softer", or less sudden, than was the case for the corresponding interior reaction test, with significant deformations occurring at much lower loads. This behaviour is not obvious for the WWF 900x262 specimen, Figures 3.6(b) and (c), possibly because of the previously noted large imperfections. The WWF 500x197 3000 mm span and WWF 1400x405 specimens end reaction curves, Figures 3.5(b) and 3.7(b), respectively, show that these beams failed by sudden local inelastic web crippling, with none of the noted "softness" in the other tests. Interestingly, the WWF 1400x405 specimen displayed a very "soft" failure for its interior reaction test, which is opposite to the trend noted above. In general, all curves exhibited relatively long plateaus at ultimate as the plastic hinges were able to sustain load.

Figure 3.8(b) illustrates the load vs out-of-plane web displacement curve for the

WWF 1800x510 end test. The failure mode and behaviour of this specimen was very similar to the initial portion of the interior load test. The lateral displacements did not become significant until after approximately 60% to 70% of the ultimate load. This end reaction was an elastic buckling failure, as no flange mechanism was observed, and the web essentially rebounded to its original position upon unloading.

3.3.2 Web Strain Distribution

The principal strains and their orientation at ultimate are shown schematically for the discrete rosette locations on both sides of the web, for each interior load test, in Figures 3.15 through 3.21. These strains were calculated using the strain gauge interpretation program developed by Benichou, Benichou (1994), and the inplane strains measured on the web. In these figures the first value is associated with the principal strain aligned with the vertical leg of the 'T' and the second to the horizontal leg. The value in the brackets gives the orientation of the principal strains from the vertical to the vertical leg of the 'T', positive is counterclockwise. Negative strains indicate compression. At the bottom of the figure, the sides of the web are identified as near side or far side. Near side indicates the side of the web which would have buckled out of the page. The locations of the yield lines and plastic hinges in the web can be determined from these figures.

Figure 3.15, for the WWF 350x212, shows large compressive strains ($\approx 18600 \mu\epsilon$) from the flange web junction to yield values at $1/3h$ down the web. Large bending strains, indicated by differences in the principal strains on either side of the web are not a result of web buckling, but are simply the result of the previously noted rotations of the top and bottom flanges.

Figures 3.16, 3.17, and 3.18 for the three WWF 500x197 beams show that in general, plastic hinges formed at the flange/web junction and at $1/8h$ down the web for all specimens.

Figure 3.19 for the WWF 900x262 beam shows that a plastic hinge formed at the flange/web junction and that a yield line or hinge formed at or near $1/4h$ to $3/8h$ down the web.

Figure 3.20(a), for the WWF 1400x405 beam, shows that at the 2400 kN load level no yield lines have formed, although significant bending strains are evident at the flange/web junction and around the $1/4h$ to $1/2h$ web depth region. Figure 3.20(b), for the WWF 1400x405 beam at ultimate, shows definitely that a plastic hinge has formed at the flange/web junction. The location of a second hinge or yield line is elusive, the magnitudes of the strains at $1/8h$ down the web, and the deformed shape of the web in Figure 3.13(a) suggest that one could have formed somewhere between $1/8h$ and $1/4h$ down the webs depth.

The web strains shown in Figure 3.21(a), for the WWF 1800x510 beam at a load of 3600 kN, are similar to those in the WWF 1400x405 at 2400 kN. Yield has occurred along the flange/web junction under the load. Figure 3.21(b) shows the web strains at 4010 kN. The strains along the flange/web junction have increased slightly in compression while the average vertical axial strains of the other locations have remained essentially the same and elastic. The transverse strains (along the length of the beam) measured at midspan increased in tension with increasing load after the load of approximately 3600 kN. These last two points are indicative of the redistribution of axial stresses which occurs

in plates with post buckling capacity. The axial stresses will redistribute from the buckled inner zone of the plate, which has a low stiffness, to the stiffer regions of the surrounding web. Membrane tension, in the transverse direction of the plate, will also contribute to its post buckled capacity, but to a lesser extent than the redistribution of axial stresses, Galambos (1988). The buckled zone of the web extended far beyond the zone of $c + 5k$, where the strain gauges were located. Hence, the change in axial stress levels outside the $c + 5k$ zone of the web are unknown. As a result, the proportion of the additional load capacity which is due to post buckling strength versus that which is due to the flange contribution is unknown. It should be noted that the out-of-plane bending of the web is occurring in one direction only, this was due to rotation of the flange under the actuator head, similar to the WWF 350x212 case.

3.4 Flange Contribution

Table 3.9 and Figures 3.22 through 3.24 give the results of the flange contribution tests carried out on the WWF 500x197 series of beams for the interior loads, all of which failed by inelastic web buckling. Table 3.9 lists the failure load, the average of the measured flange strains for both sides of the top and bottom flanges, and the ratio of these measured strains to the yield strain obtained from the tension coupon tests.

Figure 3.22 shows the load vs out-of-plane web deformation curves for the web LVDT located at $1/4h$ for the three beam spans. From these curves it is obvious that the inelastic buckling of the web, initiated by yielding of the flange/web junction, began at

approximately the same load, 1650 *kN*, for all beam spans, and that the ultimate load capacity obtained is greater as the span decreases. The difference in this additional capacity is minimal for the 1700 *mm* and 2000 *mm* spans.

Figure 3.23 shows the load vs average local bending strains recorded in the top flanges of the three beams. The local bending strain was determined by subtracting the strain recorded on the bottom surface of the top flange from the strain recorded on the top surface. After yield of the flange/web junction in the load range of 1400 *kN* to 1600 *kN*, the flange starts to contribute to the web capacity in flexure as indicated by the significant increase in the local bending strains. In all cases, the flange had not yielded due to global and/or local bending.

Figure 3.24 shows the load vs average vertical deflection of the top flange for the three beam spans. This figure should demonstrate when the top flange begins to behave as a beam on an inelastic foundation in a significant fashion, and begins to supplement the webs capacity. The vertical deflections will become nonlinear once the flange begins this behaviour. Again there is little difference in the load at which nonlinear behaviour begins for the 1700 *mm* and 2000 *mm* spans, approximately 1500 *kN*, while the 3000 *mm* span first displays nonlinear behaviour at approximately 1200 *kN*.

Table 3.10 gives the average measured strains for both the top and bottom flanges of all specimens at ultimate, the ratio of the measured strain to the yield strain obtained from the tension coupon tests, along with the average magnitude of the local bending strains recorded in the top flange at ultimate. Strains are reported at two separate load levels for the WWF 1400x405 and WWF 1800x510 beams, reflecting the suspected

buckling load and the ultimate loads of these beams as discussed earlier in section 3.3.1.1.

Figure 3.1 Typical Uniaxial Stress Strain Curve Shapes up to Strain Hardening Obtained From Tension Coupon Tests, and Definitions of Characteristic Parameters.

(a) Interior Reaction Web Deformation.

(b) End Reaction Web Deformation.

Figure 3.2 Load vs Out of Plane Web Deformation for WWF 350x212.

(a) Interior Reaction Web Deformation.

(b) End Reaction Web Deformation.

Figure 3.3 Load vs Out of Plane Web Deformation for WWF 500x197, 1700 mm span.

(a) Interior Reaction Web Deformation.

(b) End Reaction One Web Deformation.

Figure 3.4 Load vs Out of Plane Web Deformation for WWF 500x197, 2000 mm span.

(c) End Reaction Two Web Deformation.

Figure 3.4 (Cont.) Load vs Out of Plane Web Deformation for WWF 500x197, 2000 mm span.

(a) Interior Reaction Web Deformation.

(b) End Reaction Web Deformation.

Figure 3.5 Load vs Out of Plane Web Deformation for WWF 500x197, 3000 mm span.

(a) Interior Reaction Web Deformation.

(b) End Reaction One Web Deformation.

Figure 3.6 Load vs Out of Plane Web Deformation for WWF 900x262.

(c) End Reaction Two Web Deformation.

Figure 3.6 (Cont.) Load vs Out of Plane Web Deformation for WWF 900x262.

(a) Interior Reaction Web Deformation.

(b) End Reaction Web Deformation.

Figure 3.7 Load vs Out of Plane Web Deformation for WWF 1400x405.

(a) Interior Reaction Web Deformation.

(b) End Reaction Web Deformation.

Figure 3.8 Load vs Out of Plane Web Deformation for WWF 1800x510.

(a) Interior Reaction.

(b) End Reaction.

Figure 3.9 Out of Plane Web Deformation of WWF 500x197, 1700 mm span.

(a) Interior Reaction.

(b) End Reaction One.

Figure 3.10 Out of Plane Web Deformation of WWF 500x197, 2000 mm span.

(c) End Reaction Two.

Figure 3.10 (Cont.) Out of Plane Web Deformation of WWF 500x197, 2000 mm span.

Figure 3.11 Out of Plane Web Deformation of WWF 500x197, 3000 mm span.

1

PM-1 3½"x4" PHOTOGRAPHIC MICROCOPY TARGET
NBS 1010a ANSI/ISO #2 EQUIVALENT

PRECISIONSM RESOLUTION TARGETS

2

PM-1 3½"x4" PHOTOGRAPHIC MICROCOPY TARGET
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PRECISIONSM RESOLUTION TARGETS

(a) Interior Reaction.

(b) End Reaction One.

Figure 3.12 Out of Plane Web Deformation of WWF 900x262.

Figure 3.12 (Cont.) Out of Plane Web Deformation of WWF 900x262.

(a) Interior Reaction.

(b) End Reaction.

Figure 3.13 Out of Plane Web Deformation of WWF 1400x405.

(a) Interior Reaction.

(b) End Reaction.

Figure 3.14 Out of Plane Web Deformation of WWF 1800x510.

Figure 3.15 Strain Distribution at Ultimate for WWF 350x212, 2242 kN.

Figure 3.16 Strain Distribution at Ultimate for WWF 500x197, 1700 mm span, 2157 kN.

Figure 3.17 Strain Distribution at Ultimate for WWF 500x197, 2000 mm span, 2115 kN.

Figure 3.18 Strain Distribution at Ultimate for WWF 500x197, 3000 mm span, 1909 kN.

Figure 3.19 Strain Distribution at Ultimate for WWF 900x262, 2164 kN.

(a) Strain Distribution at 2400 kN.

(b) Strain Distribution at Ultimate, 2582 kN.

Figure 3.20 Strain Distribution for WWF 1400x405.

(a) Strain Distribution at 3600 kN.

(b) Strain Distribution at 4010 kN.

Figure 3.21 Strain Distribution for WWF 1800x510.

Figure 3.22 Load vs Out of Plane Deformation at 1/4h Web Depth LVDT Location on WWF 500x197 Beams.

Figure 3.23 Load vs Local Bending strains in WWF 500x197 Top Flanges at $c/2 + 2.5k$ From Midspan.

Figure 3.24 Load vs Average Vertical Deflection of Top Flanges of WWF 500x197 Beams.

Table 3.1 Measured Geometry for the Cross-Section Dimensions of WWF Shapes.

Designation	d		d ₁ ^a		d ₂ ^a		b ^b		t ^c		w		k		a	
	Avg.	Std. Dv.	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)
WWF 350x212	355.53		350.91	1.93	356.58	2.12	347.52	0.78	31.99	0.09	18.91	0.07	43.08	1.69	164.92	0.92
WWF 500x197 ^d	499.98		489.38	0.45	501.40	0.94	499.67	0.19	19.45	0.08	12.36	0.12	30.34	1.50	242.76	1.05
WWF 900x262	903.0		897.5	0.8	904.7	0.5	398.22	0.32	31.92	0.09	12.66	0.16	41.94	1.80	191.82	0.77
WWF 1400x405	1401.0		1390.5	1.5	1404.8	1.2	500.80	0.32	32.04	0.12	16.24	0.15	42.75	1.71	240.15	0.58
WWF 1800x510	1800.0		1792.8	1.1	1803.4	1.2	500.30	0.45	32.29	0.16	19.69	0.37	42.63	0.95	241.26	1.57

Notes:

- See figure 2.6(a) for definition.
- Average of top and bottom flange width measurements.
- Average of top and bottom flange thickness measurements.
- Average of 1700, 2000, and 3000 mm span beam measurements.

Table 3.2 Measured Plate Out-of-Straightness for the Web and Flange Plates.

Designation	Maximum web plate out of straightness (mm)	Maximum web plate out of straightness (fcn. of d)	Maximum flange plate out of straightness (mm)	Maximum flange plate out of straightness (fcn. of b)
WWF 350x212	0.19	d/1842	1.00	b/350
WWF 500x197 (1700 mm span)	1.11	d/450	4.35	b/115
WWF 500x197 (2000 mm span)	0.98	d/510	3.82	b/131
WWF 500x197 (3000 mm span)	1.02	d/490	4.12	b/121
WWF 900x262	3.54	d/254	2.10	b/190
WWF 1400x405	3.15	d/444	2.20	b/227
WWF 1800x510	1.81	d/994	2.50	b/200

Table 3.3(a). Characteristic parameters determined from uniaxial stress strain curves for the WWF 350 x 212 web plate*.

Coupon No.	E (MPa)	σ_p (MPa)	$\epsilon_p \times 10^{-4}$	σ_n (MPa)	σ_{11} (MPa)	σ_{17} (MPa)	$\epsilon_n \times 10^{-4}$	E_n (MPa)	$\epsilon_n \times 10^{-4}$	σ_n (MPa)	$\epsilon_n \times 10^{-4}$	σ_t (MPa)	curve type
51	187810	181.5*	2050	339.7	337.0	312.2	14790	5030	182050	518.5	246880	420.2	A
52	206600	-*	1600	347.0	343.8	-*	15660	4555	197010	522.8	216960	422.3	A
53	209760	-*	1605	343.4	342.5	-*	9790 ⁴⁶	1825 ⁴⁴	150000	528.2	235000	401.6	A
54	183530	183.6*	1826 ⁴	340.0	338.2	304.8	13175	5475	170000	520.1	235000	469.3	A
Avg.	196930	-	1770	342.5	340.0	308.5	14540	5020	174760	522.4	233460	428.4	-
Std. dv.	11400	-	185	3.0	2.8	3.7	1030	375	17200	3.7	10700	25.0	-

* Poissons Ratio for web plate material was calculated to be $\nu = 0.283$.

Notes:

- See fig. 3.1(a) for definition.
- See fig. 3.1(b) for definition.
- See fig. 3.1(c) for definition.
- Value interpolated from data collected due to low recording precision.
- Value not reportable due to coupon behaviour.
- Value determined using 0.2% offset method.
- Value not included when calculating average.
- Value not recorded.

Table 3.3(b). Characteristic parameters determined from uniaxial stress strain curves for the WWF 350 x 212 flange plate.

Coupon No.	E (MPa)	σ_p (MPa)	$\epsilon_y \times 10^{-4}$	σ_m (MPa)	σ_H (MPa)	σ_{HT} (MPa)	$\epsilon_u \times 10^{-4}$	E_u (MPa)	$\epsilon_o \times 10^{-4}$	σ_o (MPa)	$\epsilon_o \times 10^{-4}$	σ_r (MPa)	curve type
45	195340	202.9 ^a	2090	373.3	368.7	341.2	14570	4560	177060	560.5	211970	552.7	A
46	175550 ^a	185.6 ^a	2514 ^{a,c}	379.4	- ^b	361.7	15010 ^a	4137	172070	576.2	231920	505.5	B
47	196610	204.9 ^a	2290	373.1	371.3	361.2	16300	5424	- ^b	562.6	- ^b	- ^b	A
48	196840	236.4 ^a	2155	373.7	371.9	338.7	14800	5780	180000	560.7	220000	547.4	A
49	191670	247.2 ^a	2580 ^a	373.2	370.8	354.9	14400	4506	169150	577.8	213930	563.1	B
50	193250	235.5 ^a	2601 ^b	373.1	371.7	346.5	15750	4620	172070	562.1	216960	547.0	B
Avg.	194740		2343	374.3	370.9	350.7	15160	4840	174070	566.7	218960	543.1	-
Std. dev.	1995	-	212	2.3	1.2	9.1	735	570	3900	7.4	7030	19.7	-

Notes:

- See fig. 3.1(a) for definition.
- See fig. 3.1(b) for definition.
- See fig. 3.1(c) for definition.
- Value interpolated from data collected due to low recording precision.
- Value not reportable due to coupon behaviour.
- Value determined using 0.2% offset method.
- Value not included when calculating average.
- value not recorded.

Table 3.4(a). Characteristic parameters determined from uniaxial stress strain curves for the WWF 500 x 197 web plate *

Coupon No.	E (MPa)	σ_p (MPa)	$\epsilon_p \times 10^{-4}$	σ_m (MPa)	σ_A (MPa)	$\sigma_{1/2}$ (MPa)	$\epsilon_m \times 10^{-4}$	E_m (MPa)	$\epsilon_s \times 10^{-4}$	σ_s (MPa)	$\epsilon_s \times 10^{-4}$	σ_t (MPa)	curve type
40	202450	306.9 ^a	2626	463.9	453.8	426.9	24060	2046	137160	532.3	157110	519.3	A
41	206530	404.0 ^b	2480 ^b	448.7	440.3	401.9	20995	1913	159200	523.5	194030	508.5	B
42	201350	384.9 ^b	2348 ^b	445.9	442.6	412.2	21550	2625	155000	525.5	185000	513.2	B
43	203220	377.3 ^b	2213 ^b	450.1	446.0	- ^b	21100	2193	150000	528.6	185000	501.5	B
44	203410	271.6 ^c	2662	446.7	443.2	411.9	21100	2140	155000	528.0	197500	502.8	A
Avg.	203390	-	2466	451.1	445.2	413.2	21760	2183	151270	527.6	183750	509.1	-
Std. dv.	1730	-	169	6.6	4.7	8.9	1165	240	7630	3.0	14200	6.6	-

* Poissons Ratio for web plate material was calculated to be $\nu = 0.260$.

Notes:

- a. See fig. 3.1(a) for definition.
- b. See fig. 3.1(b) for definition.
- c. See fig. 3.1(c) for definition.
- d. Value interpolated from data collected due to low recording precision.
- e. Value not reportable due to coupon behaviour.
- f. Value determined using 0.2% offset method.
- g. Value not included when calculating average.
- h. Value not recorded.

Table 3.4(b). Characteristic parameters determined from uniaxial stress strain curves for the WWF 500 x 197 flange plate.

Coupon No.	E (MPa)	σ_p (MPa)	$\epsilon_p \times 10^{-4}$	σ_{yp} (MPa)	σ_{y1} (MPa)	σ_{y2} (MPa)	$\epsilon_{u1} \times 10^{-4}$	E_u (MPa)	$\epsilon_u \times 10^{-4}$	σ_u (MPa)	$\epsilon_f \times 10^{-4}$	σ_f (MPa)	curve type
34	199250	245.9 ^a	2073	396.1	390.9	352.9	11274	5592	147130	569.6	187030	559.0	A
35	201340	298.8 ^a	3920 ^{4a}	393.9 ^f	- ^a	367.9 ^f	- ^a	- ^a	- ^a	597.3	162090	586.7	C
36	202540	258.2 ^a	2347	396.1	- ^a	368.9	10090	3700	150000	576.0	182500	559.1	A
37	202220	216.5 ^a	1840 ^b	354.8	- ^a	331.1	10610	5690	146400	555.9	171220	545.8	B
38	201380	270.1 ^a	3770 ^{4a}	364.3 ^f	- ^a	337.5 ^f	- ^a	- ^a	144280	579.5	164180	575.6	C
39	203270	231.0 ^a	3509 ^{4a}	367.3	368.7	345.4	10780	6704	155000	556.4	185000	549.2	C
Avg.	201670	-	2090	379.1	379.8	350.6	10690	5422	148560	572.5	175340	562.6	-
Std. dv.	1270	-	210	17.0	11.1	14.2	425	1085	3700	14.3	9990	14.4	-

Notes:

- See fig. 3.1(a) for definition.
- See fig. 3.1(b) for definition.
- See fig. 3.1(c) for definition.
- Value interpolated from data collected due to low recording precision.
- Value not reportable due to coupon behaviour.
- Value determined using 0.2% offset method.
- Value not included when calculating average.
- Value not recorded.

Table 3.5(a). Characteristic parameters determined from uniaxial stress strain curves for the WWF 900 x 262 web plate *

Coupon No.	E (MPa)	σ_p (MPa)	$\epsilon_f \times 10^{-4}$	σ_m (MPa)	σ_H (MPa)	σ_y (MPa)	$\epsilon_u \times 10^{-4}$	E_u (MPa)	$\epsilon_u \times 10^{-4}$	σ_u (MPa)	$\epsilon_f \times 10^{-4}$	σ_f (MPa)	curve type
29	190870	221.6 ^a	1772 ^b	399.6	397.6	361.4	14225	2000	150000	497.3	190000	470.8	B
30	195070	333.9 ^b	2074 ^b	402.7	399.8	357.6	- ^c	- ^c	167540	491.4	214660	472.4	B
31	200120	350.4 ^b	2273 ^b	413.3	412.8	386.2	14490	1300	172070	497.2	211970	481.3	B
32	194080	350.1 ^b	2366 ^b	413.7	- ^d	387.1	10660 ^d	1100 ^d	160000	496.4	207500	487.2	B
33	200020	198.4 ^e	2856 ^b	408.2	407.4	372.9	14480	1720	162370	500.8	217330	455.3	B
Avg.	196030	-	2268	407.5	404.4	373.0	14400	1670	162400	496.6	208290	473.4	-
Std. dev.	3580	-	357	5.6	6.1	18.5	120	290	7480	3.0	9700	10.8	-

* Poissons Ratio for web plate material was calculated to be $\nu = 0.262$

Notes:

- See fig. 3.1(a) for definition.
- See fig. 3.1(b) for definition.
- See fig. 3.1(c) for definition.
- Value interpolated from data collected due to low recording precision.
- Value not reportable due to coupon behaviour.
- Value determined using 0.2% offset method.
- Value not included when calculating average.
- Value not recorded.

Table 3.5(b). Characteristic parameters determined from uniaxial stress strain curves for the WWF 900 x 262 flange plate.

Coupon No.	E (MPa)	σ_p (MPa)	$\epsilon_y \times 10^{-4}$	σ_m (MPa)	σ_u (MPa)	σ_y (MPa)	$\epsilon_u \times 10^{-4}$	E_u (MPa)	$\epsilon_u \times 10^{-4}$	σ_u (MPa)	$\epsilon_f \times 10^{-4}$	σ_f (MPa)	curve type
23	205960	220.4 ^a	2005	379.0	359.7	347.1	10130	1780	180000	566.3	225000	549.8	A
24	198090	332.4 ^c	3960 ^{d,e}	381.5 ^f	- ^g	359.3 ^f	- ^g	- ^g	155000	591.7	200000	523.1	C
25	203470	250.3 ^a	2150	379.0	378.2	- ^h	14970	2340	177950	564.6	218050	550.1	A
26	202570	252.0 ^a	2150 ^b	379.9	380.7	356.4	14995	4264	175000	571.8	220000	550.2	B
27	200700	316.7 ^a	3870 ^{d,e}	375.9 ^f	- ^g	359.3 ^f	- ^g	- ^g	159200	601.1	203960	579.9	C
28	205090	233.1 ^a	2164 ^b	372.4	370.0	351.0	10420	2756	170000	569.7	210000	545.2	B
Avg.	202650	-	2120	378.0	372.2	354.6	12510	2785	169530	577.5	212840	549.7	-
Std. dv.	2650	-	65	3.0	8.2	4.8	2360	920	9390	13.8	8920	16.5	-

Notes:

- a. See fig. 3.1(a) for definition.
- b. See fig. 3.1(b) for definition.
- c. See fig. 3.1(c) for definition.
- d. Value interpolated from data collected due to low recording precision.
- e. Value not reportable due to coupon behaviour.
- f. Value determined using 0.2% offset method.
- g. Value not included when calculating average.
- h. Value not recorded.

Table 3.6(a). Characteristic parameters determined from uniaxial stress strain curves for the WWF 1400 x 405 web plate *

Coupon No.	E (MPa)	σ_p (MPa)	$\epsilon_y \times 10^{-4}$	σ_H (MPa)	σ_H (MPa)	σ_H (MPa)	$\epsilon_H \times 10^{-4}$	E_H (MPa)	$\epsilon_H \times 10^{-4}$	σ_e (MPa)	$\epsilon_e \times 10^{-4}$	σ_t (MPa)	curve type
18	203230	156.0 ^a	1840	282.4	280.6	255.0	13430	6040	172070	477.1	246880	431.5	A
19	185350	266.6 ^b	1560 ^c	281.4	280.3	243.9	11780 ^d	6185	187030	467.5	236910	426.5	B
20	191240	- ^e	1520	278.3	- ^b	- ^b	12050 ^d	6270	195000	477.1	235000	471.4	A
21	210350	280.6 ^b	1440 ^c	282.2	280.4	249.2	12710	3790 ^d	197000	472.1	226930	456.7	B
22	204630	144.1 ^f	1720	302.0	293.4	259.2	12590	4910	190000	479.8	232500	466.5	A
Avg.	198960	-	1616	285.3	283.7	251.8	12520	5850	188220	474.7	235650	450.5	-
Std. dv.	9220	-	144	8.5	5.6	5.8	570	550	8810	4.4	6540	18.3	-

* Poissons Ratio for web plate material was calculated to be $\nu = 0.291$.

Notes:

- See fig. 3.1(a) for definition.
- See fig. 3.1(b) for definition.
- See fig. 3.1(c) for definition.
- Value interpolated from data collected due to low recording precision.
- Value not reportable due to coupon behaviour.
- Value determined using 0.2% offset method.
- Value not included when calculating average.
- Value not recorded.

Table 3.6(b). Characteristic parameters determined from uniaxial stress strain curves for the WWF 1400 x 405 flange plate.

Coupon No.	E (MPa)	σ_p (MPa)	$\epsilon_p \times 10^{-4}$	σ_m (MPa)	σ_H (MPa)	$\epsilon_H \times 10^{-4}$	E_H (MPa)	$\epsilon_H \times 10^{-4}$	σ_o (MPa)	$\epsilon_o \times 10^{-4}$	σ_r (MPa)	curve type
12	200660	187.8 ^a	2350	373.1	371.5	14880	4330	177060	561.7	206980	548.9	A
13	202740	306.8 ^a	3680 ^a	378.6 ^f	- ^a	- ^a	- ^a	157110	592.4	187030	575.2	C
14	206550	235.1 ^a	1940 ^a	370.2	- ^a	15445	4515	172070	562.0	206980	552.7	B
15	207400	219.0 ^a	2260	373.1	372.9	12640	3185 ^d	- ^a	562.4	206980	546.3	A
16	203380	266.9 ^a	3765 ^a	373.2 ^f	- ^a	- ^a	- ^a	147130	598.3	177060	587.2	C
17	206140	204.5 ^a	2250	375.9	370.5	15425 ^d	3850	172070	564.7	206980	558.3	A
Avg.	204480	-	2200	373.8	371.6	14600	3970	165090	573.6	198670	561.4	-
Std. dv.	2390	-	155	2.6	1.0	1150	515	11200	15.5	12100	14.9	-

Notes:

- See fig. 3.1(a) for definition.
- See fig. 3.1(a) for definition.
- See fig. 3.1(a) for definition.
- Value interpolated from data collected due to low recording precision.
- Value not reportable due to coupon behaviour.
- Value determined using 0.2% offset method.
- Value not included when calculating average.
- Value not recorded.

Table 3.7(a). Characteristic parameters determined from uniaxial stress strain curves for the WWF 1800 x 510 web plate *

Coupon No.	E (MPa)	σ_p (MPa)	$\epsilon_p \times 10^{-4}$	σ_m (MPa)	σ_A (MPa)	σ_y (MPa)	$\epsilon_y \times 10^{-4}$	E_u (MPa)	$\epsilon_u \times 10^{-4}$	σ_u (MPa)	$\epsilon_u \times 10^{-4}$	σ_t (MPa)	curve type
7	192810	327.2 ^b	2360 ^b	356.4	- ^a	337.3	11530	7230	160000	552.5	220000	446.3	B
8	212310	- ^c	1850	382.8	381.7	346.8	14160	7725	170000	555.6	- ^a	- ^a	A
9	207250	- ^c	2090	385.1	- ^a	371.5	13500	7960	160000	563.8	220000	516.2	A
10	202160	- ^c	1850	385.9	- ^a	351.0	11100	9750	155000	563.7	210000	529.6	A
11	197460	322.6 ^b	2240 ^b	361.8	- ^a	337.2	11880	9205	160000	557.7	225000	515.9	B
Avg.	202400	-	2080	374.4	381.7	348.8	12435	8375	161000	558.7	218750	502.0	-
Std. dev.	6900	-	200	12.6	-	12.6	1185	950	4900	4.5	5450	32.6	-

* Poissons Ratio for web plate material was calculated to be $\nu = 0.299$.

Notes:

- See fig. 3.1(a) for definition.
- See fig. 3.1(b) for definition.
- See fig. 3.1(c) for definition.
- Value interpolated from data collected due to low recording precision.
- Value not reportable due to coupon behaviour.
- Value determined using 0.2% offset method.
- Value not included when calculating average.
- Value not recorded.

Table 3.7(b).

Characteristic parameters determined from uniaxial stress strain curves
for the WWF 1800 x 510 flange plate.

Coupon No.	E (MPa)	σ_p (MPa)	$\epsilon_p \times 10^{-4}$	σ_m (MPa)	σ_d (MPa)	σ_w (MPa)	$\epsilon_w \times 10^{-4}$	E_w (MPa)	$\epsilon_w \times 10^{-4}$	σ_o (MPa)	$\epsilon_o \times 10^{-4}$	σ_t (MPa)	curve type
1	204960	200.0 ^a	2435	377.2	- ^b	349.0	15670	3015	175000	575.8	245000	549.3	A
2	200580	300.0 ^a	3830 ^{a4}	387.5 ^f	- ^c	383.3 ^f	- ^d	- ^e	- ^b	605.3	- ^b	- ^b	C
3	203000	200.0 ^a	2470	383.7	381.6	363.0	12660	3925	175000	576.4	230000	544.3	A
4	207640	225.0 ^a	2315	375.8	371.0	364.1	- ^b	- ^b	170000	573.8	240000	478.8	A
5	216710	287.1 ^a	3815 ^{a4}	393.5 ^f	- ^c	393.5 ^f	- ^d	- ^e	150000	610.2	- ^b	- ^b	C
6	212580	195.0 ^a	2270	391.1	387.7	- ^b	- ^b	3400	165000	574.4	230000	531.8	A
Avg.	207580	-	2375	384.8	380.1	370.6	14165	3450	167000	586.0	236250	526.0	-
Std. dv.	5555	-	85	6.6	6.9	15.8	1505	375	9275	15.5	6495	28.0	-

Notes:

a. See fig. 3.1(a) for definition.

b. See fig. 3.1(a) for definition.

c. See fig. 3.1(a) for definition.

d. Value interpolated from data collected
due to low recording precision.

e. Value not reportable due to coupon behaviour.

f. Value determined using 0.2% offset method.

g. Value not included when calculating average.

h. Value not recorded.

Table 3.8 Test Histories.

Section, Load location, Load length, Date tested.	Failure load and max. out of plane web deformation, and location. [†]	Mode of failure and observations.
WWF 350x212 Interior c = 100 mm April 29, 1994	2242 kN 0.94 mm @ 3/4 h	<p>Web yielding.</p> <ul style="list-style-type: none"> •1200 kN, local bending in top flange at c/2 + 2.5k from midspan begins. •1600 kN, Compression yielding of one side of the web at the flange/web junction under load plate is complete resulting in a coincident increase in the rate of the top flange vertical deflections. •2000 kN, Compression yielding of both sides of web at the flange/web junction under the load plate is complete resulting in a significant increase in the rate of both the top and bottom flange vertical deflections. •2242 kN, Ultimate capacity of web. Compression yielding of both sides of the web at the flange/web junction has extended to c/2 + 2.5k from midspan; compression yielding of the web on side two at midspan extends to 1/4h of the webs depth; significant horizontal tensile strains in the web below the edges of the load plate at the flange/web junction indicate the possible formation of plastic hinges in the flange.
WWF 350x212 End one c = 50 mm May 3, 1994	N/A	Knife edge roller assembly failed at 1000 kN load, no attempt to retest.

[†] Location of deformation is given as a function of the web depth, h, measured from the loaded flange.

Failure loads for end reaction tests are determined from statics, based on the recorded actuator force and the measured span geometry.

Table 3.8 cont. Test Histories Continued.

Section, Load location, Load length, Date tested.	Failure load and max. out of plane web deformation, and location. [†]	Mode of failure and observations.
WWF 350x212 End two c = 50 mm May 4, 1994	967 kN 0.15 mm @ 3/4 h	Web yielding. •Rate of vertical deflection of the top flange over the reaction at the tested end continually increases during the duration of the testing, local bending of the bottom flange occurred at approximately 130 mm from end.
WWF 500x197 1700 mm span Interior c = 200 mm April 11, 1994	2157 kN 2.75 mm @ 1/8 h	Inelastic web buckling. •Bottom flange of beam twisted about its longitudinal axis throughout the duration of the test. •1600 kN, Local bending in the top flange at c/2 + 2.5k from midspan begins. •1700 kN, Compression yielding of the web at the flange/web junction under the load plate is complete; lateral deformations at the 1/4h web LVDT location at midspan begin. •1800 kN, Bending of the web at the flange/web junction at midspan begins, lateral deformations of the web at all web LVDT locations began; marked increase in the rate of top flange vertical deflections. •1950 kN, Plastic hinges form in the top flange at the edges of the load plate. •2.57 kN, Ultimate capacity of web. A two yield line mechanism forms in the web, yielding at the flange/web junction and at 1/8h down the web. Twisting of the bottom flange has reached a magnitude of 0.004 radians from the flanges original position.

[†] Location of deformation is given as a function of the web depth, h, measured from the loaded flange.

Failure loads for end reaction tests are determined from statics, based on the recorded actuator force and the measured span geometry.

Table 3.8 cont. Test Histories Continued.

Section, Load location, Load length, Date tested.	Failure load and max. out of plane web deformation, and location. [†]	Mode of failure and observations.
WWF 500x197 1700 mm span End one c = 100 mm April 23, 1994	788 kN 3.32 mm @ 1/4 h	Inelastic web buckling. •No twisting of the bottom flange of the beam occurred during the test. •1200 kN, Lateral deformations of the web at the 1/4h, 3/8h, and 1/2h web LVDT locations begin. •1450 kN, Lateral deformations of the web at all web lvdT locations markedly increase. •1623 kN, Ultimate capacity of web.
WWF 500x197 1700 mm span End two c = 50 mm April 25, 1994	N/A	Knife edge roller assembly failed at 1250 kN load, no attempt to retest.

[†] Location of deformation is given as a function of the web depth, h, measured from the loaded flange.

Failure loads for end reaction tests are determined from statics, based on the recorded actuator force and the measured span geometry.

Table 3.8 cont. Test Histories Continued.

Section, Load location, Load length, Date tested.	Failure load and max. out of plane web deformation, and location. [†]	Mode of failure and observations.
WWF 500x197 2000 mm span Interior c = 200 mm April 4, 1994	2115 kN 1.81 mm @ 1/4 h	<p>Inelastic web buckling.</p> <ul style="list-style-type: none"> •1600 kN, Local bending in top flange at c/2 + 2.5k from midspan begins. •1650 kN, Compression yielding of the web at the flange/web junction under the load plate is complete; lateral deformations of the web began at all web LVDT locations; increase in the rate of top flange vertical deflections. •1800 kN, Local bending in the top flange at the load plate edges becomes significant, bottom flange begins to twist about its longitudinal axis. •2050 kN, Bending of the web at the flange/web junction at midspan began; compression yielding of the web at midspan has extended to 1/8h of the web depth; significant increase in the rate of lateral deformations of the web at all web LVDT locations and of the vertical deflections of the top flange; plastic hinges form in the top flange at the edges of the load plate. •2115 kN, Ultimate capacity of web. A two yield line mechanism forms in the web, yielding at the flange/web junction and at 1/8h down the web; twisting of the bottom flange has reached a magnitude of 0.001 radians from the flanges original position. •Unload, Yield lines noted under load plate on top surface of top flange, radiating from edges of load plate towards midspan; yielded areas approximately 100 mm wide.

[†] Location of deformation is given as a function of the web depth, h, measured from the loaded flange.

Failure loads for end reaction tests are determined from statics, based on the recorded actuator force and the measured span geometry.

Table 3.8 cont. Test Histories Continued.

Section, Load location, Load length, Date tested.	Failure load and max. out of plane web deformation, and location. [†]	Mode of failure and observations.
WWF 500x197 2000 mm span End one c = 100 mm April 13, 1994	754 kN 3.84 mm @ 1/4 h	Inelastic web buckling. •1000 kN, Lateral deformations of the web at the 1/4h, 3/8h, 1/2h, and 3/4h web LVDT locations at midspan began; rate of vertical deflection of top flange increases. •1300 kN, Yield lines form on bottom flange at approximately 140 mm from end at tested end, and at approximately 120 mm from end at non tested end; rate of lateral deformations of web at all web LVDT locations increase significantly. •1545 kN, Ultimate capacity of web.
WWF 500x197 2000 mm span End two c = 100 mm April 14, 1994	836 kN 1.80 mm @ 1/4 h	Inelastic web buckling. •700 kN, Beam is having seating problems, possibly a result of flange failure during first end test; bottom flange of beam twisted about its longitudinal axis throughout the duration of the test. •1475 kN, Bottom flange at end one began to yield. •1650 kN, Lateral deformations of web at all web LVDT locations began. •1713 kN, Ultimate capacity of web.

[†] Location of deformation is given as a function of the web depth, h, measured from the loaded flange.

Failure loads for end reaction tests are determined from statics, based on the recorded actuator force and the measured span geometry.

Table 3.8 cont. Test Histories Continued.

Section, Load location, Load length, Date tested.	Failure load and max. out of plane web deformation, and location. [†]	Mode of failure and observations.
WWF 500x197 3000 mm span Interior c = 200 mm April 7, 1994	1909 kN 2.45 mm @ 1/8 h	Inelastic web buckling. <ul style="list-style-type: none"> • Bottom flange of beam twisted about its longitudinal axis throughout the duration of the test. • 1300 kN, Local bending in the top flange at $c/2 + 2.5k$ from midspan begins. • 1500 kN, Compression yielding of the web occurs first at 1/8h down the web on far side; significant increase in the rate of vertical deflection of the top flange. • 1700 kN, Compression yielding of the web at the flange/web junction under the load plate is complete; lateral deformations of the web at the 1/8h, and 1/4h web lvdt locations began; bending of the web at the flange/web junction at midspan becomes significant; rate of vertical deflection of the top flange tips differ greatly from side one to side two. • 1909 kN, Ultimate capacity of web. A two yield line mechanism forms in the web, yielding at the flange/web junction and at 1/8h down the web; lateral deformations of the web at the 3/8h, 1/2h, and 3/4h web LVDT locations began just prior to ultimate; rotation of the bottom flange has reached a magnitude of 0.014 radians from the flanges original position. • Unload, Yield lines noted under load plate on top surface of top flange, radiating from edges of load plate towards midspan, yielded areas approximately 100 mm wide.

[†] Location of deformation is given as a function of the web depth, h, measured from the loaded flange.

Failure loads for end reaction tests are determined from statics, based on the recorded actuator force and the measured span geometry.

Table 3.8 cont. Test Histories Continued.

Section, Load location, Load length, Date tested.	Failure load and max. out of plane web deformation, and location. [†]	Mode of failure and observations.
WWF 500x197 3000 mm span End one c = 100 mm April 20, 1994	822 kN 1.61 mm @ 1/4 h	Inelastic web buckling. •Excessive rotation of knife-edge roller assembly at end two due to local bending of the bottom flange noted at 1400 kN, test halted and unloaded; knife-edge assembly reset, flange reinforced, and test restarted. •1500 kN, Rate of bottom flange deflections increases. •1650 kN, Lateral deformation of web at all web LVDT locations begins, bottom flange begins to yield at approximately 145 mm from end. •1672 kN, Ultimate capacity of web.
WWF 500x197 3000 mm span End two	N/A	End not tested due to failure of flange during test of end one.

† Location of deformation is given as a function of the web depth, h, measured from the loaded flange. Failure loads for end reaction tests are determined from statics, based on the recorded actuator force and the measured span geometry.

Table 3.8 cont. Test Histories Continued.

Section, Load location, Load length, Date tested.	Failure load and max. out of plane web deformation, and location. [†]	Mode of failure and observations.
WWF 900x262 Interior c = 300 mm May 30, 1994	2164 kN 11.84 mm @ 3/8 h	<p>Inelastic web buckling.</p> <ul style="list-style-type: none"> • Lateral deformations of the web occur throughout the duration of the test, bottom flange of beam twists about its longitudinal axis throughout duration of test. • 1400 kN, Rate of twisting of the bottom flange increases. • 1500 kN, Bending of the web becomes significant at midspan at 1/2h web depth. • 1610 kN, Compression yielding of the web at the flange/web junction on the near side under the load plate is complete; far side of web does not yield in compression. • 1700 kN, Local bending in the top flange at c/2 + 2.5k from midspan began. • 2000 kN, A two yield line mechanism forms in the web, yielding at the flange/web junction and at 1/4h to 3/8h down the web; local bending of the top flange at the edges of the load become significant. • 2164 kN, Ultimate capacity of web. Plastic hinge has formed in the web at the flange/web junction along the c + 5k length; rotation of the bottom flange has reached a magnitude of 0.009 radians from its original position.

† Location of deformation is given as a function of the web depth, h, measured from the loaded flange. Failure loads for end reaction tests are determined from statics, based on the recorded actuator force and the measured span geometry.

Table 3.8 cont. Test Histories Continued.

Section, Load location, Load length, Date tested.	Failure load and max. out of plane web deformation, and location. [†]	Mode of failure and observations.
WWF 900x262 End one c = 150 mm June 2, 1994	876 kN 6.72 mm @ 1/4 h	Inelastic web buckling. •750 kN, Lateral deformations of the web at all web LVDT locations began; rate of deformation remains constant to 1600 kN. •1600 kN, Rate of lateral deformations of web at all web LVDT locations markedly increase. •1758 kN, Ultimate capacity of web. Maximum out of plane web deformation at ultimate is virtually the same at the 1/4h and 3/8h web LVDT locations; bending of bottom flange occurred at approximately 300 mm from end.

† Location of deformation is given as a function of the web depth, h, measured from the loaded flange.

Failure loads for end reaction tests are determined from statics, based on the recorded actuator force and the measured span geometry.

Table 3.8 cont. Test Histories Continued.

Section, Load location, Load length, Date tested.	Failure load and max. out of plane web deformation, and location. [†]	Mode of failure and observations.
WWF 900x262 End two c = 150 mm June 3, 1994	887 kN 7.03 mm @ 1/2 h	<p>Inelastic web buckling.</p> <ul style="list-style-type: none"> • "Rolling" of the bottom flange over the reaction plate resulted in the web buckling in double curvature, web LVDT's at 1/8h and 1/4h locations displace opposite to other LVDT's. • 400 kN, Lateral deformations of the web began at all web LVDT locations except the 3/8h location, rate of deformation remains constant until 1400 kN. • 1400 kN, Rate of lateral deformations of web at 1/2h and 3/4h web LVDT locations markedly increase. • 1500 kN, Lateral deformations stop at 1/4h web LVDT location until 1700 kN, deformations of web at 3/8h web LVDT location markedly increase. • 1700 kN, Lateral deformations of web at 1/4h web LVDT location markedly increase, displacing in the direction opposite to the original direction of deformation. • 1785 kN, Ultimate capacity of web; double curvature of web disappears upon unloading.

[†] Location of deformation is given as a function of the web depth, h, measured from the loaded flange.

Failure loads for end reaction tests are determined from statics, based on the recorded actuator force and the measured span geometry.

Table 3.8 cont. Test Histories Continued.

Section, Load location, Load length, Date tested.	Failure load and max. out of plane web deformation, and location. [†]	Mode of failure and observations.
WWF 1400x405 Interior c = 300 mm June 22, 1994	2582 kN 5.10 mm @ 1/4 h	<p>Inelastic web buckling.</p> <ul style="list-style-type: none"> •1600 kN, Lateral deformations of the web at all web LVDT locations began. •1900 kN, Local bending in the top flange at c/2 + 2.5k from midspan began. •2000 kN, Compression yielding of both sides of web at the flange/web junction under the load plate is complete; increase in the rate of top flange vertical deflections; twisting of the bottom flange about its longitudinal axis begins. •2400 kN, Lateral deformations of web at all web LVDT locations began to increase at a constant rate; significant bending strains noted in web at midspan at the 1/4h and 3/8h web locations. •2582 kN, Ultimate capacity of web. A two yield line mechanism forms in web, yielding at the flange/web junction and at 1/8h down the web; horizontal tension yielding of the web at the flange/web junction at the edges of the load plate indicate formation of plastic hinges in the top flange; rotation of the bottom flange has reached a magnitude of 0.009 radians from the flanges original position.

[†] Location of deformation is given as a function of the web depth, h, measured from the loaded flange.

Failure loads for end reaction tests are determined from statics, based on the recorded actuator force and the measured span geometry.

Table 3.8 cont. Test Histories Continued.

Section, Load location, Load length, Date tested.	Failure load and max. out of plane web deformation, and location. [†]	Mode of failure and observations.
WWF 1400x405 End one c = 150 mm July 4, 1994	1196 kN 0.94 mm @ 1/2 h	Inelastic web buckling. •2402 kN. Ultimate capacity of web. Sudden web crippling occurred; lateral web deformations up to this load were insignificant, web had sustained this load for over one minute prior to failure; lateral deformation of 48 mm at the 1/4h web LVDT location occurred within 30 seconds of commencement of buckling; local bending of the bottom flange occurred at approximately 500 mm from end.
WWF 1400x405 End two	N/A	End not tested due to time constraints.
[†] Location of deformation is given as a function of the web depth, h, measured from the loaded flange. Failure loads for end reaction tests are determined from statics, based on the recorded actuator force and the measured span geometry.		

Table 3.8 cont. Test Histories Continued.

Section, Load location, Load length, Date tested.	Failure load and max. out of plane web deformation, and location. [†]	Mode of failure and observations.
WWF 1800x510 Interior c = 300 mm June 13, 1994	4010 kN 17.43 mm @ 3/8 h	<p>Elastic web buckling.</p> <ul style="list-style-type: none"> •2400 kN, Lateral deformations of the web at all web LVDT locations began. •2700 kN, Compression yielding of both sides of the web at the flange/web junction centred under the load plate is complete; local bending in the top flange at c/2 + 2.5k from midspan began; twisting of the bottom flange about its longitudinal axis begins. •3050 kN, Compression yielding of both sides of the web at the flange/web junction under the load plate is complete. •3600 kN, Rate of lateral deformations of all web LVDT's stop increasing, continue at a constant rate to ultimate load achieved (4010 kN); rate of twisting of the bottom flange becomes constant. •3670 kN, Hinge forms in web at flange/web junction at c/2 + 2.5k and midspan gauge locations. •3770 kN, A single yield line has formed in the web at the flange/web junction; significant bending strains are occurring in the web at the 1/4h to 1/2h web depth region. •4010 kN, Test halted due to large out-of-plane displacements of web (approximately equal to the web thickness; rotation of the bottom flange i.e. reached a magnitude of 0.0186 radians from the flanges original position.

† Location of deformation is given as a function of the web depth, h, measured from the loaded flange.

Failure loads for end reaction tests are determined from statics, based on the recorded actuator force and the measured span geometry.

Table 3.8 cont. Test Histories Continued.

Section, Load location, Load length, Date tested.	Failure load and max. out of plane web deformation, and location. [†]	Mode of failure and observations.
WWF 1800x510 End one c = 150 mm June 16, 1994	1648 kN 12.17 mm @ 3/8 h	Elastic web buckling. •1700 kN, lateral deformations of the web at 3/8h, 1/2h, and 3/4h web LVDT locations began. •1900 kN, Buckling of web at midspan halts at a maximum deformation of 5.00 mm at 1/2h. •2400 kN, Lateral deformations of web at 1/4h web LVDT location began. •3000 kN, Lateral deformations of web at 1/8h web LVDT location began. •3200 kN, Lateral deformations of web at all web LVDT locations began increasing at a constant rate. •3309 kN, Ultimate capacity of web.
WWF 1800x510 End two	N/A	End not tested.
[†] Location of deformation is given as a function of the web depth, h, measured from the loaded flange. Failure loads for end reaction tests are determined from statics, based on the recorded actuator force and the measured span geometry.		

Table 3.9 Test Results from WWF 500x197 Beam Series Investigating Flange Contribution Effects.

Beam Span (mm)	Failure Load (kN)	Average Flange Strain at Ultimate				Ratio of Measured Strain to Yield Strain ^{††}			
		Top Flange [†] (microstrain)		Bottom Flange (microstrain)		Top Flange		Bottom Flange	
		Near side [‡]	Far side [‡]	Near side [‡]	Far side [‡]	Near side [‡]	Far side [‡]	Near side [‡]	Far side [‡]
1700	2157	-555	-525	820	775	0.266	0.251	0.392	0.371
2000	2115	-810	-810	1005	1075	0.388	0.388	0.481	0.514
3000	1909	-1100	-1220	1400	1360	0.526	0.584	0.670	0.651

[†] Measured at c/2 + 2.5k from midspan.

^{††} $\epsilon_y = 2090$ microstrain from Table 3.4(b).

[‡] Same designation as used in Figures 3.15 through 3.21.

Table 3.10 Average Flange Strains Recorded at Ultimate, and Average Magnitude of Local Bending Strains Recorded in Top Flange at Ultimate, for Interior Loads.

Beam	Failure Load (kN)	Average Flange Strain at Ultimate		Ratio of Average Flange Strain to Yield Strain.†		Magnitude of Local Bending Strains in Top Flange. (microstrain)
		Top Flange †† (microstrain)	Bottom Flange (microstrain)	Top Flange ††	Bottom Flange	
WWF 350x212	2242	-810	+990	0.350	0.423	640
WWF 500x197 1700 mm span	2157	-540	+780	0.259	0.382	395
WWF 500x197 2000 mm span	2115	-810	+1040	0.388	0.498	235
WWF 500x197 3000 mm span	1909	-1160	+1380	0.555	0.660	390
WWF 900x262	2164	-700	+745	0.330	0.351	240
WWF 1400x405	2400	-555	+600	0.252	0.273	515
	2582	-610	+640	0.272	0.291	660
WWF 1800x510	3600	-620	+665	0.261	0.280	550
	4010	-740	+670	0.312	0.282	830

† Yield Strain from tension coupon tests, Tables 3.3(b) through 3.7(b).

†† Measured at $c/2 + 2.5k$ from midspan.

Chapter 4

Discussion and Comparisons

4.1 Behaviour Under Loading

Specific comments related to the behaviour of the seven WWF shapes tested under interior loads as described in chapter three with respect to observations made by other researchers, follow:

- (1) The behaviour and failure modes of the web plates (number and location of web yield lines) is generally consistent with tests reported by Graham et al (1959), Skaloud and Novak (1972), Roberts and Rockey (1979), Roberts and Markovic (1983), and Elgaaly and Nunan (1989) among others.
- (2) The behaviour and failure mode of the loaded flange plates did not conform with the typical behaviour noted by Bergfelt (1971), Skaloud and Novak (1972), Elgaaly and

Rockey (1973), Roberts (1981), and Roberts and Chong (1981) among others, where the failure of the loaded flange at ultimate formed a mechanism involving three or four plastic hinges. These mechanisms, generally form with one or two hinges under or at the edges of the load plate (the number depending on the load length and stiffness of the flange), while the remaining two hinges form at the ends of the flange and are always coincident with vertical web stiffeners. In the tests completed, plastic hinges were physically observed on the loaded flange of only the WWF 500x197, 2000 *mm* and 3000 *mm* span beams, at or just inside the edges of the load plate. Based on the strains observed in the web plates at the flange/web junction directly below the edges of the load plate, it is likely that hinges formed or were forming, in the flanges of the other beams at these same locations (with the exception of the WWF 1800x510).

The beams tested in this study had no vertical web stiffeners and no definite stiff vertical reaction point from a stiffener about which the loaded flange could bend, hence the remaining pair of hinges did not form. The flange sections on either side of the load, behaved like two cantilever beams, connected by a rigid link under the load plate. These cantilever portions behaved as if they were supported on a variable stiffness (elastic/inelastic) foundation, where the stiffness of the foundation increases as you move away from the load location.

(3) The unloaded flange was observed to rotate about its longitudinal axis in all tests, and although it was not measured, it appeared to have drifted laterally. Of the papers reviewed, only Bergfelt (1979) made this observation. This rotation is the result of the flange resisting reactions due to bending imposed on the web plates by imperfections and

eccentricities. Rotations were evident from the start of the tests, even before significant out-of-plane web displacements occurred. Benichou's preliminary finite element analysis, Benichou (1994), did not include all relevant geometric imperfections. Rotations of the bottom flanges were not observed and not reported. The functions for the effective length K given in equations 1.7 and 1.8 were based on these results and hence do not include these effects.

(4) Global bending stresses in the flanges of the test specimens did not exceed 50% of the flange yield stress (with the exception of the WWF 500x197, 3000 mm span). It is unlikely that any significant reduction in the web capacity occurred as a result of these coexistent bending stresses.

4.2 Normal Stress Distributions for Interior Loads

As described in section 1.2 and illustrated in Figure 1.4, the equivalent column model developed by Benichou, Benichou (1994), was based on a normal stress distribution that varies sinusoidally from a maximum at the loaded flange/web junction to zero at the unloaded flange. The normal stress is assumed to be constant across the width of the equivalent column, and is statically equivalent to the variable stress distribution that exists in the web (measured along the length of the beam).

Figures 4.1(a) and (b) through to 4.7(a) and (b)¹ give the calculated average normal stresses at the discrete rosette locations as determined from the measured strains;

¹ The vertical scale on these figures was selected to accurately reflect the locations of the strain gauge rosettes on the web.

their distribution through the web depth at midspan and $c/2$ from midspan; and the corresponding distribution for the equivalent column model (equation 1.4), for each WWF shape tested. Figures 4.1(a) through 4.7(a) show the distributions for load levels ranging between 74% and 89% of ultimate and correspond with the load at which yielding of the web at the flange/web junction under the length of the load occurred. Figures 4.1(b) through 4.7(b) show the distributions at ultimate. The maximum normal stress, σ_{Max} , used in equation 1.4 is equal to the applied load divided by the area of the equivalent column.

The measured stress distributions, at midspan and $c/2$, through the depth of the WWF 350x212 web, which failed by yielding, closely match the shape and magnitude of the stress distribution modeled by equation 1.4 for both loads given in Figures 4.1(a) and 4.1(b). The measured stress distributions at midspan and $c/2$ through the depth of the webs of the WWF 500x197's, WWF 900x262, and WWF 1400x405, which all failed by inelastic web buckling, differ significantly from one shape to another as well as with that modelled by equation 1.4. Generally for the WWF 500x197's and WWF 900x262 at the load at which yielding occurred at the flange/web junction, Figures 4.2(a), 4.3(a), 4.4(a), and 4.5(a), the midspan distribution is sinusoidal and the $c/2$ distribution is parabolic with a maximum at the loaded flange/web junction and varying to zero at or near the unloaded flange. For the WWF 1400x405, Figure 4.6(a), both distributions are parabolic. At ultimate, the WWF 500x197's distributions, Figures 4.2(b), 4.3(b), and 4.4(b), take on the shape illustrated by the dashed line in Figure 4.2(b). The WWF 900x262 distributions, Figure 4.5(b), appear to become random. The WWF 1400x405 distributions, Figure 4.6(b), become sinusoidal, closely matching the shape modeled by equation 1.4, but with

magnitudes of stress far below those modeled (approximately $0.6\sigma_{Max}$). The measured stress distributions through the depth of the web of the WWF 1800x510, which failed by elastic buckling, are distinctly parabolic at both locations and at both load levels, Figures 4.7(a) and (b).

The distribution of the normal stresses at the flange/web junction along the length of all beams generally changes from a narrow normal shaped distribution at the load at which yielding of the flange/web junction occurred (with a maximum stress at midspan) to a broader more uniform normal shaped distribution at ultimate, with similar magnitudes of stress occurring at midspan and $c/2$ from midspan. In general, the stresses at midspan and $c/2$ from midspan are lower at ultimate than the previous load level. In the case of the WWF 500x197's, which had the most flexible flanges and where flange mechanisms were definitely developed, the distribution generally changed to a bimodal shaped distribution at ultimate, with maximum stresses at $c/2$ and $c/2 + 2.5k$ and smaller stresses at midspan.

In general, the magnitude of the stresses at the flange/web junction at midspan and $c/2$, for all shapes, decreased as the ultimate load was reached. This decrease is consistent with the failure stages of a web as described in section 1.1.1. The smaller values at ultimate indicate that the web has yielded (or is yielding) in bending, and that this portion of the web now carries less of the applied load than it did at the previous load level. This fact, coupled with the above noted changes in the normal stress distribution along the length of the beams, suggest that wider portions of the web, close to the flange/web junction, carry the applied load as the ultimate load is reached. The equivalent column

model, with a fixed width of $c + 5k$, would underestimate the load for these cases.

Extrapolating the distributions for the WWF 1400x405 and WWF 1800x510 shapes, Figures 4.6(a) and (b) and 4.7 (a) and (b), to a point of zero normal stress (for the average of the measured stresses) suggests that the applied load is fully transferred into the web in shear in a distance less than the full depth of the web. For these cases, the equivalent column model, which uses a column length equal to h , would underestimate the web's capacity.

These variations in the normal stress distribution along the length and depth of the web are significantly different from those used in the equivalent column model and need to be investigated thoroughly with further analyses of the test data and analytical finite element studies which can be calibrated against the test data. The effective length of the column for the model could possibly incorporate the effects of both variations in the stress distribution on the capacity, and could possibly be expressed as a simple function of the load length and section depth.

4.3 Comparison of Predicted Failure and Test Loads

Ultimate test loads and loads predicted by Clause 15.9 of CAN/CSA S16.1-M89, Roberts' model, Roberts (1981), and the equivalent column model, Benichou (1994), options A, B and the original derivation, where K is expressed as per equations 1.7 and 1.8, are listed in Table 4.1 and 4.2 for interior loads and end reactions, respectively. The predicted failure loads were calculated using the average measured dimensions of the

beam specimens given in Table 3.1, and the static yield stress of the web plate determined from the tension coupon tests as listed in Tables 3.3(a) through 3.7(a) (for example σ_y for the WWF 900x262 was taken as 373 MPa from Table 3.5(a)).

For interior loads, Table 4.1, both S16.1 and Roberts' model underestimate the load capacity of the web with mean test to predicted ratios and coefficients of variation of 1.13 and 0.06, and 1.72 and 0.13, respectively. The web crippling expression given in S16.1 was derived from Roberts' semi-empirical expression, Roberts (1981), which is based on the collapse mechanism illustrated in Figure 1.3. For the WWF shapes which failed by elastic and inelastic web buckling, failure manifested itself with the formation of one or two yield lines in the web and the formation of two plastic hinges at the edges of the load plate. These failures bear no resemblance to the mechanism upon which Roberts developed his model. Despite the apparent accuracy for S16.1 and conservativeness of these equations, their applicability for predicting the resistance of the web is suspect. The proposed options A and B, along with the original derivation of the equivalent column model consistently underestimate the web capacity, with the accuracy of the predictions becoming worse as the failure mode changes from web yielding to inelastic web buckling to elastic web buckling. The mean test to predicted ratios and coefficients of variation for option A, option B, and the original derivation are 1.83 and 0.69, 1.68 and 0.42, and 1.59 and 0.43, respectively. As noted in section 4.2, there are suspected variations in the effective column width at ultimate and in the column length for deep sections, which would both lead to an underestimation of the web capacity. In addition, the flange contribution resulting from the loaded flange acting as a beam on an

elastic/inelastic foundation (with or without the formation of plastic hinges) was not incorporated into the model. For the class of problems where the flanges of the beam are being utilized (even partially) to carry bending moments, the flange contribution should be ignored for design purposes. The series of tests carried out on the WWF 500x197 beams, which were designed to obtain an understanding and estimation of this flange contribution component were unsuccessful. Strain measurements were made at an insufficient number of locations along the length of the loaded flange in the vicinity of the load plate to enable a proper investigation and analysis. The flange contribution, and hence the web capacity alone can only be obtained through a vigorous finite element study of these and other beams. The test data obtained, however, will provide a good benchmark for verification.

For end reactions given in Table 4.2, S16.1 generally overestimates the load capacity of the web with a mean test to predicted ratio of 0.93 and coefficient of variation of 0.09. Though only a limited number of tests were completed, the results appear to justify the concern noted in section 1.1.3 regarding the halving of Roberts' model for application to end reactions. The proposed options A and B along with the original derivation of the equivalent column model, again underestimate the web capacity with the accuracy of the predictions again becoming worse as the failure mode changes from web yielding to elastic web buckling. The mean test to predicted ratios and coefficients of variation for option A, option B, and the original derivation are 1.52 and 0.62, 1.39 and 0.40, and 1.32 and 0.40, respectively. Table 4.3 gives the estimated magnitude of force required to produce the observed flange mechanism in the end reaction tests. This

mechanism represents between 10% and 30% of the web's capacity for slender to stockier webs. The equivalent column model does not incorporate this component of the end reaction capacity, indicating that the load predictions of the model should be considered less conservative than the test to predicted ratios suggest (in fact the predictions for the web capacity for the WWF 350x212 and WWF 500x197 can be considered unconservative for all models, and unconservative for the WWF 900x262 for the original derivation). The flange capacity, based on the development of a single hinge, could be incorporated as long as the web is stable enough to allow its development.

Figure 4.1(a) Average Vertical Compressive Stress Distribution for VWF 350x212 at 2000 kN, and Comparison With Stress Distribution Per Benichou (1994).

Figure 4.1(b) Average Vertical Compressive Stress Distribution for WWF 350x212 at Ultimate, 2242 kN, and Comparison With Stress Distribution Per Benichou (1994).

Figure 4.2(b) Average Vertical Compressive Stress Distribution for WWF 500x197, 1700 mm span, at Ultimate, 2157 kN, and Comparison With Stress Distribution Per Benichou (1994).

Figure 4.3(a) Average Vertical Compressive Stress Distribution for WWF 500x197, 2000 mm span, at 1650 kN, and Comparison With Stress Distribution Per Benichou (1994).

Figure 4.3(b) Average Vertical Compressive Stress Distribution for WWF 500x197, 2000 mm span, at Ultimate, 2115 kN, and Comparison With Stress Distribution Per Benichou (1994).

Figure 4.4(a) Average Vertical Compressive Stress Distribution for WWF 500x197, 3000 mm span, at 1700 kN, and Comparison With Stress Distribution Per Benichou (1994).

Figure 4.4(b) Average Vertical Compressive Stress Distribution for WWF 500x197, 3000 mm span, at Ultimate, 1909 kN, and Comparison With Stress Distribution Per Benichou (1994).

Figure 4.5(a) Average Vertical Compressive Stress Distribution for WWF 900x262 at 1610 kN, and Comparison With Stress Distribution Per Benichou (1994).

Figure 4.5(b) Average Vertical Compressive Stress Distribution for WWF 900x262 at Ultimate, 2164 kN, and Comparison With Stress Distribution Per Benichou (1994).

Figure 4.6(a) Average Vertical Compressive Stress Distribution for WWF 1400x405 at 2000 kN, and Comparison With Stress Distribution Per Benichou (1994).

Figure 4.6(b) Average Vertical Compressive Stress Distribution for WWF 1400x405 at Ultimate, 2582 kN, and Comparison With Stress Distribution Per Benichou (1994).

Figure 4.7(a) Average Vertical Compressive Stress Distribution for WWF 1800x510 at 3050 kN, and Comparison With Stress Distribution Per Benichou (1994).

Figure 4.7(b) Average Vertical Compressive Stress Distribution for WWF 1800x510 at Ultimate, 4010 kN, and Comparison With Stress Distribution Per Benichou (1994).

Table 4.1 Comparison of Interior Test Failure Loads With Predicted Loads from Clause 15.9 of CAN/CSA S16.1-M89, Roberts (1981) Model, and Benichou (1994).

Beam	Failure Load ^a (kN)	S16.1 ^b (kN)		Roberts ^c (kN)		Benichou (1994) ^d					
		(kN)		(kN)		Option A (kN)		Option B (kN)		Model ^e (kN)	
						Load	T/P ^f	Load	T/P ^f	Load	T/P ^f
WWF 350x212	2242	2024	1.11	N/A	N/A	1791	1.25	1769	1.27	1796	1.25
WWF 500x197 1700 mm	2157	1879	1.15	1145	1.99	1449	1.50	1394	1.55	1505	1.42
WWF 500x197 2000 mm	2115	1879	1.13	1145	1.85	1449	1.46	1394	1.52	1505	1.41
WWF 500x197 3000 mm	1909	1879	1.02	1145	1.67	1449	1.32	1394	1.37	1505	1.27
WWF 900x262	2164	1843	1.17	1251	1.73	1224	1.77	1424	1.52	1527	1.42
WWF 1400x405	2582	2173	1.19	1595	1.62	1053	2.45	1231	2.10	1317	1.96
WWF 1800x510	4010 ^f	3444	1.16	2583	1.55	1293	3.10	1656	2.42	1655	2.42

Notes:

a. Failure loads include flange contribution and post buckling strength.

b. ϕ taken as 1.0.

c. Formulation of Roberts' model, Roberts (1981), is identical to Equation 1.3, except maximum limit of 0.2 is set for ratio c/d , and the constant 300 is replaced by $0.5\sqrt{E}$.

d. K values based on equation 1.8.

e. Not failure load.

f. Test to predicted ratio.

Table 4.2 Comparison of End Reaction Failure Loads with Predicted Loads from CAN/CSA S16.1-M89 Clause 15.9 (b), and Benichou (1994).

Beam	Failure Load ^a (kN)	S16.1 ^b (kN)		Benichou (1994) ^c					
		(kN)		Option A (kN)		Option B (kN)		Model ^e (kN)	
				Load	T/P ^d	Load	T/P ^d	Load	T/P ^d
WWF 350x212	976	1012	0.96	896	1.09	885	1.10	898	1.09
WWF 500x197 1700 mm	788	940	0.84	725	1.09	697	1.13	753	1.05
WWF 500x197 2000 mm	795 ^d	940	0.85	725	1.10	697	1.14	753	1.06
WWF 500x197 3000 mm	822	940	0.87	725	1.13	697	1.18	753	1.09
WWF 900x262	882 ^d	922	0.96	612	1.44	712	1.24	764	1.15
WWF 1400x405	1196	1087	1.10	527	2.27	616	1.94	659	1.81
WWF 1800x510	1648	1722	0.96	647	2.55	828	1.99	828	1.99

Notes: a. Failure loads include flange contribution.

b. ϕ taken as 1.0.

c. K values based on equation 1.8.

d. Based on average of two tests.

e. Test to predicted ratio.

Table 4.3 End Reaction Loads and Flange Mechanism Loads Based on Observed Mechanism Geometry.

Beam	Failure Load (kN)	Location of hinge measured from end of beam (mm)	Force Required to Produce Observed Flange Mechanism (kN)
WWF 350x212	976	130 ^a	265
WWF 500x197 1700 mm	788	-	None Observed
WWF 500x197 2000 mm End One	754	135	210
WWF 500x197 2000 mm End Two	863	115	275
WWF 500x197 3000 mm	822	150	180
WWF 900x262 End One	876	300 ^b	160
WWF 900x262 End Two	887	300 ^c	165
WWF 1400x405	1196	500	110
WWF 1800x510	1648	-	None Observed

- Notes: a. At ultimate, local deformations of flange and rotations of the knife-edge roller assembly at the reaction, had reduced bearing length to approximately 10 mm.
b. At ultimate, local deformations of flange and rotations of the knife-edge roller assembly at the reaction, had reduced bearing length to approximately 130 mm.
c. At ultimate, local deformations of flange and rotations of the knife-edge roller assembly at the reaction, had reduced bearing length to approximately 145 mm.

Chapter 5

Summary, Conclusions and Recommendations

The objectives of this study were to conduct an experimental program on welded wide flange shapes of different classes that exhibit the various failure modes of a web subjected to concentrated inplane loads for both interior loads and end reactions, to conduct a preliminary analysis of the test data, and to compare the failure modes and loads obtained with those predicted by the current Canadian steel design standard CAN/CSA S16.1-M89 and the equivalent column model proposed by Benichou, Benichou (1994).

A summary of the work completed in this thesis includes the following:

- (1) A computer program, called LABCON, was developed to automatically control up to three multiple actuator hydraulics systems while performing electronic data acquisition. To date this program has been successfully used on over 180 separate tests. These tests

ranged from tension coupon tests involving only 3 electronic measurement devices, to large scale ship hull load tests involving 140 electronic measurement devices and 3 separate hydraulics systems.

(2) For the experimental program of this thesis 16 separate beam tests (7 interior load and 9 end reaction tests) were successfully completed on the seven WWF beams; ancillary tests were completed to determine the stress-strain characteristics of the plate material used to fabricate the beams; and the geometry, dimensions, and initial imperfections of the seven beams were measured.

(3) Data from the experimental program was reduced and has been presented in chapter three. Preliminary analyses of the test data and comparisons of the test loads with the predicted loads of the models have been completed and were presented in chapter four.

Conclusions from this study are summarised below:

(1) Based on the preliminary analyses of the data, the equivalent column model, as developed, cannot be applied directly to WWF shapes. Modifications to the effective column width and column length (for deep sections) are required to better reflect the measured normal stress distributions at ultimate. Data suggests that the effective column length, for deep sections, is less than the web depth and is possibly a function of the ratio of the load length to web depth.

(2) Clause 15.9 (a) (ii) of CAN/CSA S16.1-M89, uses a semi-empirical formula based on Roberts' mechanism, Roberts (1981), to predict the web crippling capacity of W and WWF shapes under interior load conditions. Despite the apparent accuracy of the formula

in predicting the failure loads of the test beams, the fact that the formula is based on a failure mechanism which bears no resemblance to the interior load failures of the WWF shapes tested, suggests that its applicability is questionable.

(3) Clause 15.9 (b) (ii) of CAN/CSA S16.1-M89, uses a modification of the semi-empirical formula based on Roberts' mechanism, Roberts (1981), to predict the web crippling capacity of W and WWF shapes under end reaction conditions. This formula is based on a failure mechanism which bears no resemblance to the end reaction failures of the WWF shapes tested, and gives unconservative predictions of the web capacity for four of the five WWF shapes tested, indicating that its applicability is extremely questionable.

(4) Due to insufficient instrumentation of the WWF 500x197 series of beams, the flange contribution to the web capacity for interior loads could not be determined from the limited test data.

(5) The flange contribution should be ignored for determining the capacity of a web under an interior load condition, and should be ignored for determining the capacity of a web at an end reaction condition where the web will become unstable prior to the flange developing a single hinge.

The recommendations resulting from this experimental study, preliminary data analyses, and discussions of the test results include:

(1) Further detailed analysis of the test data obtained from the interior load tests. Specifically:

- A study of the distributions in the measured normal stresses at load levels other than those studied in this thesis, to establish if and how these distributions change as

loading and failure progresses.

- Finite element analyses of the tested WWF shapes that includes the measured dimensions, geometry, imperfections, and material properties so that refined models, which accurately predict the observed behaviour can be developed. Based on the results of this analyses, the flange contribution should be evaluated and the web capacity determined to permit more accurate comparisons between the test loads and the capacities predicted by the equivalent column model.

(2) Additional finite element analyses to investigate and determine: the possibility of an effective column length function; the effective column width; the effect of normal stresses due to bending on the web capacity; the flange contribution phenomenon; and, the effect of the rotation and suspected drift of the unloaded flange on the effective length factor, K , and the overall stability of the beams under interior load conditions.

(3) Further verification of the equivalent column model, with recommended revisions incorporated if possible, using published test results and/or further experimental investigation.

Chapter 6

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Appendix A

Operating Manual for LABCON

LABCON

Structures Laboratory Test Control System

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A1 Introduction to LABCON.

A1.1 General features of LABCON.

LABCON is a computer program written in QuickBasic using the LabWindows programming package. It was created to be used for loading control and data acquisition during quasi-static structural testing in the laboratory. At present LABCON has the following capabilities :

- * Simultaneous Data acquisition of up to 100 strain gauges, 50 LVDT's, 10 load cells, and 5 pressure transducers.
- * Simultaneous control of up to three different and independent hydraulic systems, using either the jacking force, the jack head displacement, the hydraulic oil pressure levels, or load cells as the controls.
- * Continuous on-screen monitoring of up to eleven different data acquisition devices, on screen plotting of two sets of data acquisition devices, and a display of the status of all data acquisition devices updated after each set of readings.

LABCON is basically made up of a number of different screens and panels which contain switches, buttons, lists, and/or information windows. The user works with these switches, buttons, etc. to create the loading control and data acquisition systems they desire for the structural test to be performed.

To push the buttons, switch the switches, select list items, menu items, and/or information windows, the user simply manipulates the mouse to "click" on the desired button, switch, menu item, or information window, and then, if required, types any information through the keyboard. "clicking" the mouse is achieved by moving the on screen cursor over the switch, button, or window with the mouse tracking ball, and then pressing the left-most button on the mouse.

To start a LABCON session, change to the LABCON directory (in drive C:) and type LW<ret> to begin LabWindows. Once LabWindows is loaded click on *File* from the menu displayed, followed by *Load*, a listing will appear offering the available programs, select LABCON.BAS by clicking on its name in the listing. This will highlight the LABCON.BAS listing, now click on the *Load* button. In a few seconds LABCON will be loaded and the program code will be displayed. Click on *Program* from the menu followed by *Run*. It takes a couple of minutes for LABCON to compile and initialise. The user can begin working in LABCON once the LABCON title panel has disappeared.

A1.2 Introduction to LABCON manual

This manual describes the general features of LABCON and provides the user with information that is essential to properly use the program. Each available option is described, and where possible, actual screen images are illustrated to familiarize the user with the program. The manual describes each option beginning with the main menu, followed by each available option in its order on the menu. The appendices contained at the end of the manual include additional information regarding the data acquisition systems electronic components and the hydraulic's system components. To simplify reading this manual, when the names of buttons, switches, or windows are written, they are typed in bold italic, such as *Run!*.

A2 The Main Menu.

When LABCON is first started, a menu bar and title panel will appear on the screen. The title panel will disappear after a few seconds, after which the user can begin work. The menu bar, as shown below, lists the major options available to the user.

figure 1. The Main menu bar.

When an item is selected from this menu, a pull down menu will appear listing the further options available. *File...* allows for file operations such as loading setup files, saving setup files, and creating data files. *Test Setup...* allows for setting up the data acquisition, the loading control, the operating screen, and verifying the setup prior to testing. Selecting *Run!* or *Quit!* will not produce a pull down menu, either the test operation screen will appear to begin a test (*Run!*) or the session will be ended (*Quit!*).

A3 File Operations.

There are two types of files the user will deal with in LABCON, setup files and data files.

Setup files contain all information regarding data acquisition devices and loading control settings for individual tests. The user can create a test setup in LABCON and save it for later use, or reuse it any number of times for similar tests (NOTE! setup files DO NOT save the information regarding the test operating screen setup). Setup files can be printed out for a hardcopy of the test setup.

Data files contain the data recorded from the data acquisition devices during a test. A data file will contain the following information in the following order:

- 1) The file name and directory path.
- 2) User supplied information identifying the test.
- 3) The number of pressure transducers, Strain gauges, LVDT's, and load cells. (all less one, for programming purposes ie: 1 means 2 devices, 4 means 5 devices etc.)
- 4) The zero readings. (In a single column list, pressure transducers first, followed by LVDT's, and load cells. NOTE! There are no zero readings for the strain gauges.)
- 5) The readings. (In a single column list, pressure transducers first, followed by strain gauges, LVDT's, and load cells)

See appendix 1 for examples of printouts of both types of files. Selecting *File...* from the main menu will produce a pull down menu offering the following options: *Load Setup File...*, *Save Setup File...*, and *Create Data File...*

A3.1 Load Setup File.

Load Setup File... allows the user to load a previously saved test setup file for editing and/or running. A file selection panel will appear which contains a *File Name* window, *File/Directory* and *Drive* lists, and *Select* and *Cancel* buttons.

Existing setup files can be selected from the *File/Directory* listing which displays the directories available under the current drive (indicated in the *Drive* list) and the files available in the current directory (which initially will be the default directory C:\LABCON\). To select a file or new directory, click on the file name or directory in the listing with the cursor, or use the scrolling arrows at the side of the listing. The filename or directory gets highlighted when it is selected. To retrieve the file or directory, click on the *Select* button. If a setup file is in another directory, or drive, it can be retrieved as noted above by setting the highlight in the *Drive* list to the desired drive, selecting the proper directory (as discussed above) and then selecting the file. Files can also be loaded by typing the full directory path and file name into the *File Name* window at the top of the panel, and then clicking on the *Select* button. Clicking on the *Cancel* button will return to the main menu bar, no file will have been loaded.

A3.2 Save Setup File.

Save Setup File... allows the user to save the test setup information created so far to a file for later use or editing. A panel similar to the load setup file panel will appear.

To save a newly created file, click on the information window at the top of the save setup file panel, and type in the new file's name, then click on the *Select* button. This will create this file in the default directory (C:\LABCON). Clicking on the *Cancel* button will return to the main menu, and no file will have been created. Saving to an existing file is similar to the steps described above for *Load Setup File....* Selecting an existing file will overwrite the previous file.

After the file name has been selected, a file information panel appears as shown in figure 2, below. This panel asks for supplementary information, and is purely optional. To add information the user simply clicks on the information window where they want to add the information, and types from the keyboard. Hitting return on the keyboard will move the cursor to the next information window (If the current file has been previously saved, the original information entered in this panel will be re-displayed and can be edited). Select the *Ok* button when the information is complete (or if nothing is to be added or changed).

figure 2. File information Panel.

LABCON specifies a .STP extension to the setup files it creates, this extension does not have to be used, however, failing to use the extension will result in this file not being displayed in the default directory listing (if it is in the default directory) when *Load Setup File...* is later selected to retrieve the file. It is recommended that the .STP extension be used for setup files to avoid confusion.

A3.3 Create Data File.

Create Data... is selected when the user wishes to specify the file to which they would like the test data to be written. A file selection panel similar to that discussed in section A3.1 will appear. Operation of this panel is as described above for the setup files. The file information panel (fig. 2.) will also appear, again the information is optional. If an existing data file is selected, the new data will be appended to the end of the existing file. (NOTE! A warning panel will appear when *Run!* is selected from the main menu, if no data file has been created. This warning can be ignored if LABCON is only being used to control loading.)

LABCON specifies a .DAT extension to the data files, again this extension is not mandatory but is recommended. Do not use a .PLT extension, as LABCON generates files with this extension.

A4 Test Setup.

Selecting *Test Setup...* from the main menu will produce a pull down menu offering the following options: *Data Acquisition...*, *Loading Control...*, *Operating Screen...*, and *Verify Setup...*.

A4.1 Data Acquisition Setup.

Selecting *Data Acquisition...* from the Test Setup pulldown menu allows the user to enter all of the necessary information regarding the LVDT's, strain gauges, load cell's, and pressure transducers to allow LABCON to record readings from these devices during a test. The panel shown in figure 3. will appear.

figure 3. Data Acquisition setup panel.

Clicking on any of the buttons on this panel will cause the setup panel for that device type to appear. Selecting the *Ok* button will return the user to the main menu. The setup panel for all devices is similar, so the LVDT setup panel will be used as an example, figure 4., below, is the LVDT setup panel.

figure 4. LVDT Setup panel.

As noted, the user uses this panel to enter the required information on the data acquisition devices to enable LABCON to read these devices. The first item in the listing is the identification number of the LVDT, this is an identifying number used by LABCON. This numbering is entered by the user, and must begin with the number one, and must be consecutive. The second item is the channel, this is the channel to which the LVDT leads are physically wired to on the multiplexer cards in the HP3497a (see appendix 2 for a full description of wiring for all types of devices). The third item is the calibration factor for the device (in Volts/mm for LVDT's, Volts/kN for Load Cells and Pressure Transducers (as given by the program CALIB), and the ratio of recorded strain to actual strain for strain gauges). The final item is an optional description of the location of the LVDT on the test specimen. (There is an additional item in the strain gauge setup listing, the gage factor for the gauge.)

Selecting the *Generate* button allows the user to quickly create a number of listings. A panel will appear requesting the number of LVDT's the user wishes to enter, the number at which to begin the identification numbering of these LVDT's, and the channel at which the wiring of these LVDT's begins. These listings will be generated beginning at the location of the cursor in the listing (if the location is a currently listed LVDT they will begin immediately after this location). After the information has been completed in the generate panel, and the *Ok* button has been selected, a second panel

appears which requests the calibration factor and description for each LVDT being generated. Select the *Next* button on this panel to increment to the next LVDT to be generated. If there are no more LVDT's to be generated, clicking on the *Next* button will return the user to the LVDT Setup panel and the information will be inserted into the listing.

Selecting the *Add* button allows the user to enter a single LVDT listing, a panel will appear requesting the necessary information. By selecting the *Add/Replace* button, this listing will be inserted into the LVDT list below whichever listing was currently highlighted. The user can highlight a particular listing by clicking on that listing or using the scrolling arrows at the side of the list.

Selecting the *Cut* button will erase the currently highlighted listing from the list.

Selecting the *Edit* button allows the user to edit the currently highlighted listing. A panel will appear which contains the listing information, any or all items in this panel can be edited. Selecting the *Add/Replace* button revises the listing to reflect the changes made.

Selecting the *Ok* button returns the user to the Data acquisition setup panel, where the user may select the other devices to work on, or return to the main menu.

A4.2 Loading Control Setup.

Selecting *Loading Control...* from the Test setup pull down menu allows the user to set up the loading control for the test. As noted earlier, the user can control up to three separate hydraulic systems at once using LABCON, using the jacking force, the jack head displacement, the hydraulic line pressure, or load cells as the control. Each of the three hydraulic systems are limited to a maximum of two "paired" jacks (meaning the user will only have control over the pair, and not the individual jacks). Control over the pair is achieved in LABCON by averaging the readings of the individual jack's control devices (see below), and using this average as the controlling reading. The panel shown in figure 5. below, will appear when Loading control is selected.

The *Jacking Direction* switches control the direction of each jacking system, and/or whether each jack line is on or off. Extend pushes the piston out of the jack body, retract pulls the piston into the jack body. As an example, if you need one jack to extend, then switch the line 1 jacking direction switch to extend, and the line one number of jacks per line switch to one, leaving the other jack switches as is.

figure 5. Loading Control setup panel.

The **Jacking Control** switch is used to select the type of measuring device to be used to control the jacks. Jack load control uses the calibrated pressure transducers attached to each jack as the control devices. Line pressure control also uses the calibrated pressure transducers, however the load is divided by the jack head area provided by the user to produce a pressure. Head displacement control uses LVDT's located on the heads of the jacks (or at loading points). Load cell control uses load cells.

The **Number of Jacks per Line** switches are used to specify how many jacks are controlled in each system. Depending on how many Jacks per line are specified, a number of information windows will appear below the jacking control devices title. Each of these windows is where the identification number of the jack control devices should be entered (this is the identification number from the data acquisition setup). Thus, for example, if the jack in the previous example is to be controlled by head displacement, switch the jacking control switch to head displacement, and type in the identification number of the LVDT you are using to control the jack in the window which appeared below the line No. 1 jacking control devices label.

The **Jack Area** windows are where the jack head areas for each jack are entered. This is optional unless line pressure control is desired, then the jack head area must be entered. If more than one jack is on each line, only the area of one jack head is entered (both jacks must be the same size). See appendix 3 for Data on the jacks and hydraulics system.

Selecting the **Ok** button returns the user to the main menu.

A4.3 Operating Screen Setup.

Selecting **Operating Screen...** from the test setup pulldown menu allows the user to select the measuring devices they would like to be able to monitor on-screen during the test. As noted earlier, the user may select up to eleven different devices, along with two pairs of devices which can be plotted on two separate graphs. Selecting **Operating Screen...** will cause the test operation screen to appear along with the panel shown in figure 6., below.

figure 6. Device Monitor selection Panel.

This panel contains a **Window Number** display, a **Device Type** selection switch, a **Device Identification Number** information window, and a **Next Device** button. The **Window Number** display indicates the position at which the device the user selects will be entered into the operating screen list. This number changes automatically with each

new device entered (each time the *Next Device* button is clicked). To select a device, the user first selects the type of device they wish to view from the *Device Type* switch, they then type in the identification number of that device into the *Device Identification Number* window, and click on the *Next Device* button. This increments the *Window Number* display to the next value. These steps are to be repeated until all eleven spaces are filled, all eleven spaces must be filled, therefore if fewer than eleven devices are to be monitored, select the *No Device* setting on the *Device Type* switch to complete the list (the identification number is ignored if *No Device* is selected). Once all eleven devices have been selected, the device monitor selection panel will disappear, and the Graph Setup panel, shown in figure 7., will appear.

figure 7. Graph Setup Panel.

This panel features a *Device Type* switch, a *Device Identification Number* information window, and an *Ok* button. The graph number and axis identification will automatically change with each device selected. The order of the selection is: X axis of graph one, Y axis of graph one, X axis of graph two, Y axis of graph two. To set the graphs up, select the type of device on the *Device Type* switch, and enter the identification number of the device in the *Device Identification Number* information window and click the *Ok* button. Repeat these steps until all four axis have been used. Use the *No Graph* setting on the *Device Type* switch if no graph is to be plotted.

A4.4 Verification of Setup.

Selecting *Verify Setup...* from the test setup pulldown menu allows the user to verify that their wiring connections for the LVDT's, load cells, and pressure transducers to the HP3497a and DAS subsystem match with the data acquisition setup specified in their LABCON program.

Using *Verify Setup...* is similar to creating the data acquisition setup. First a panel similar to the Data Acquisition Setup panel (figure 3.) will appear offering the different types of devices available for verification. Selecting any of the device buttons will produce the verification panel for that device, all verification panels are similar, so the LVDT verification panel (figure 8.) will be used as an example.

Figure 8. LVDT Verification Panel.

In this panel, the listings created for the device type during the data acquisition setup are displayed. The user can select any of the listed devices by clicking on that device in the listing or using the scrolling arrows at the side of the listing. The device listing gets highlighted when it is selected.

Once selected, the excitation being experienced by that device is displayed in the window at the bottom of the panel (displacement for LVDT's, load for load cells and pressure transducers). By putting a known voltage across the device, or by exciting it (ie.

moving an LVDT's shaft) the user can verify that the wiring connections are correct. Clicking on the *Ok* button returns the user to the device type selection panel. The user can select a different device type or click on the *Ok* button to return to the main menu.

Strain gage circuits can not be verified in this manner, so wiring up the data acquisition system for the gages must be done very carefully. It is, however, possible to verify that all of the strain gauge circuits are working correctly (ie. there are no short or open circuits). To do this, select *Run!* from the main menu (it is not necessary to set up the loading control, the operating screen, or to create a data file for this process). Once the operating screen has appeared (ignore the create data file warning) zero the system and take a reading (see section A5.3). Select strain gauges from the *View Status* buttons (see section A5.1). By reviewing the absolute voltage readings of the gauges, the user can verify the wiring. A short circuit will appear as a very large voltage relative to the other voltages, and an open circuit will appear as zero voltage (NOTE! this method will only verify that the electrical circuit is good, it does not verify that the wiring connections to the strain gauge card channels is correct, ie the strain recorded for gauge ten may not be from gauge ten if the channels are wired incorrectly).

A5 Running Tests.

Selecting *Run!* from the main menu will allow the user to begin a test. The test operation screen will appear as shown in figure 9, below. This panel contains all of the controls and displays required to operate a test.

As stated earlier, a warning panel will appear if no data file was created using *Create Data File....* The user can click on the *Ok* button of the warning panel to cause it to disappear. Now the user may either continue operation of a test (with no data being saved) or they can click on the *Quit* button of the test operation screen and create a data file (see section A3).

A5.1 Operating Screen Displays.

There are four different data displays available during a test.

The Graph displays will plot the data for the devices selected for the graphs during the operating screen setup (section A4.3). The display window at the top of the graph indicates which devices are currently being plotted. They are listed in a "X axis" vs "Y axis" fashion. The scales of these graphs will automatically change to suit the extent of the readings taken from the devices. Each graph is updated with every reading taken. The *Switch Graph* button on the right hand side of the screen can be clicked to switch to the other available graph (and back). The *Graph On/Off* button behaves like a toggle switch to turn the plotting of the graphs on and off. This is useful if readings are to be taken at

short time intervals, as replotting of data points can sometimes take a few seconds, especially if the scale of the graph needs to change. All data recorded while the graphs are turned off can be replotted by turning the graphs on again (use the *Switch Graph* button to update the graphs, or take another set of readings). Both the *Switch Graph* and *Graph On/Off* buttons operate only when loading/unloading is stopped.

Figure 9. Test Operation Screen.

The *Current Device Status* list at the top right hand corner of the screen lists the eleven devices selected for on screen monitoring during the operating screen setup (section A4.3). Beside this listing are two information display windows, the *Voltage Reading* window, and the *Engineering Units* window. These windows display the current voltage and associated calibrated engineering unit readings (mm for LVDT's, kN for pressure transducers and load cells, and micro-strain for strain gauges) of the highlighted device in the *Current Device Status* list. These values are absolute and DO NOT reflect any zeroing out of the initial readings (except for strain gauges). The different devices in

the *Current Device Status* list can be selected at any time during a test by either clicking on the item in the list, or by using the scrolling arrows at the side of the list.

The *View Status* buttons in the bottom left hand corner of the screen can be selected to show the last set of readings taken for all devices. When a device type is clicked, a status panel will appear, all panels are similar, so the LVDT status panel will be used, it is shown in figure 10, below.

The information displayed in these panels includes the identification number of the device, the last recorded reading for the device in its engineering units (which are zeroed) and in volts (which are absolute), and the description of the device. Clicking on the *Ok* button of these panels returns the user to the operating screen.

The final display is the *Jack Status* display at the bottom middle of the screen. These displays show the current magnitude of the jack control device readings in the suitable units (shown to the right of the display), these readings are zeroed.

Figure 10. LVDT Status Panel.

A5.2 Loading Control.

The initial load control setup for the test will be based on the setup selected during the loading control setup (section A4.2). This control setup can be changed during a test by clicking on the ***Change Ctrl*** button on the right hand side of the screen. This will cause the loading control setup panel (figure 5) to appear. Operation of this panel is as discussed earlier in section A4.2. This option can not be activated while loading/unloading is occurring.

Control of the loading during a test uses the three ***Jack Control Target*** information windows and the ***Go*** and ***Stop*** buttons. The ***Jack Control Target*** windows are located directly below the ***Jack Control Status*** windows. The user clicks on these windows and types in the desired target load, pressure, or displacement (depending on the control device type). Different target values may be entered for each line (zero is an acceptable target, resulting in no change in the jack status). It is important to note that in the case of paired jacks, the displayed value for the loading control and the jack control target value, are for ONE JACK ONLY and not the pair.

Clicking the ***Go*** button will start the loading/unloading process. Each jack line will stop independently when its particular target value is reached. The user can stop the loading/unloading process at any time by clicking the ***Stop*** button, this will stop all jack lines currently in operation.

A5.3 Options Available During Tests.

As mentioned in the preceding sections, the user has the options of changing the load control setup, switching the graphs, turning the graphs on and off, and viewing the status of the measuring devices. There are five remaining options available to the user during a test.

Clicking on the ***Take Reading*** button will initiate the recording of readings from all measuring devices. These recordings are written directly to the data file specified in the create data file panel (see section A3.3), the ***View Status*** panels and graphs will also be updated. ***Take Reading*** will operate only when loading/unloading is stopped.

Clicking on the ***Zero System*** button will initiate the recording of readings from all measuring devices, these readings will then be subtracted from all subsequent readings to give the zero based readings. The zero readings are recorded in the data file specified in the create data file panel (see section A3.3). ***Zero System*** should be selected only after the test apparatus has been preloaded and unloaded. ***Zero System*** MUST be selected to generate strain readings. A confirmation panel will appear to confirm the users desire to

zero the system (to prevent accidental zeroing. However, if the initial zeroing is unacceptable for any reason the system can be rezeroed).

LVDT's can be reset if the displacements recorded approach the limit of the LVDT's range (generally if the absolute voltage reading is near zero or the maximum excitation voltage). To reset an LVDT, select the *LVDT* button from the *View Status* buttons. Highlight the listing of the LVDT to be reset and click on the *Reset LVDT* button at the bottom of the panel (see Figure 10). An LVDT Reset panel will appear as shown in figure 11 below. This panel features a listing of the LVDT description entered in the data acquisition setup, to confirm selection of the proper LVDT, and two information windows showing the old and new readings (both readings will currently be the same). The user can now physically reset the LVDT to its new setting. Once the LVDT has been shifted, click the *Reset* button. The information window at the bottom of the panel will now display the adjusted LVDT reading, it should be the same as the old reading. Clicking on the *Ok* button will return the user to the LVDT status panel, and resetting is complete.

figure 11. LVDT Reset Panel.

The user may select a different LVDT to reset, or can select the *Ok* button to return to the operating screen. LVDT's may be reset at any time during a test (while loading/unloading is stopped) and may be reset any number of times.

The final option available is Printing the Screen. By clicking the *Print Screen* button, a postscript file will be created in the default directory (C:\LABCON\) containing the image of the current operating screen. The postscript filename will be in the format SCREEN1.PLT. The screen may be printed any number of times, and the resulting files will be numbered in increasing order (ie SCREEN1, SCREEN2, SCREEN3, etc.). Plotting the screen takes a few seconds, the cursor will appear as a white box with a diagonal cross during plotting. Wait until the cursor returns to normal before proceeding. *Print Screen* will operate only when loading/unloading is stopped.

Selecting the *Quit* button ends the test session, closes the data file, and returns the user to the main menu. A confirmation panel prevents accidental quitting.

Appendix 1 Sample files from LABCON

1a Sample test setup file.

The following is a printout of a LABCON test setup file used for a web crippling test. The data acquisition includes 13 LVDT's, 41 Strain Gauges, no load cells, and one pressure transducer.

```
12  40  -1   0
 1   2   2   0
 1   0   0
 1   0   0
 0   0   0
      1.0      0.0      0.0
```

<----- Information for LABCON

----- DATA ACQUISITION SET UP SUMMARY -----

C:\LABCON\WEBCRIP.STP
Setup for web crippling test
R. J. Kirkhope, N. Benichou
Jan. 5 1994

----- JACKING CONTROL SETUP -----

Jacking Controlled by : Jack Load

Jacking Direction :
line one line two line three
extend off off

Number of Jacks per Hydraulic line :
line one line two line three
1 0 0

Jacking Control Devices are : Pressure Transducer's
line one line two line three
1 0 0
0 0 0

Jack Cylinder Area's :
line one line two line three
1.0 0.0 0.0

----- LVDT SET UP: -----

LVDT ID.	DAS Channel	Calibration Factor	Location
1	121	0.06644	top of web at load point
2	122	0.06658	second from top, web, load
3	123	0.06653	third from top, web, load p
4	124	0.06638	fourth from top, web, load
5	125	0.06673	fifth from top, web, load p
6	126	0.06638	top of web edge of load p
7	127	0.06637	second from top, web, edg
8	128	0.06623	third from top, web, edge
9	129	0.0665	1/4 span, top web.
10	130	0.06653	1/4 span, second from top
11	131	0.06681	1/4 span, third from top

12	132	0.06622	bottom flange, centre spa
13	133	0.06663	load plate, centre span

STRAIN GAGE SET UP:

GAGE ID.	DAS Chan.	Calibration Factor	Gage Factor	Location
1	0	1.0	2.11	flange gage 1.0, normal
2	1	1.0	2.11	flange gage 2.1, normal
3	2	1.0	2.11	flange gage 3.2, normal
4	3	1.0	2.11	flange gage 4.3, normal
5	4	1.0	2.11	flange gage 5.4, normal
6	5	1.0	2.11	flange gage 6.5, normal
7	6	1.0	2.11	flange gage 7.6, normal
8	7	1.0	2.11	flange gage 8.7, normal
9	20	1.0	2.11	web, gage 1.20, normal
10	21	1.0	2.11	web, gage 2.21, normal
11	22	1.0	2.11	web, gage 3.22, normal
12	23	1.0	2.11	web, gage 4.23, normal
13	24	1.0	2.11	web, gage 5.24, normal
14	25	1.0	2.11	web, gage 6.25, normal
15	26	1.0	2.11	web, gage 7.26, normal
16	27	1.0	2.11	web, gage 8.27, normal
17	28	1.0	2.11	web, gage 9.28, normal
18	40	1.0	2.055	web, gage 10.40, high el
19	41	1.0	2.055	web, gage 11.41, high el
20	42	1.0	2.055	web, gage 12.42, high el
21	43	1.0	2.055	web, gage 13.43, high el
22	44	1.0	2.055	web, gage 14.44, high el
23	45	1.0	2.055	web, gage 15.45, high el
24	46	1.0	2.055	web, gage 16.46, high el
25	47	1.0	2.055	web, gage 17.47, high el
26	48	1.0	2.055	web, gage 18.48, high el
27	49	1.0	2.055	web, gage 19.49, high el
28	60	1.0	2.11	web, gage 20.60, normal.
29	61	1.0	2.11	web, gage 21.61, normal.
30	62	1.0	2.11	web, gage 22.62, normal.
31	63	1.0	2.11	web, gage 23.63, normal.
32	64	1.0	2.11	web, gage 24.64, normal.
33	65	1.0	2.11	web, gage 25.65, normal.
34	66	1.0	2.11	web, gage 26.66, normal.
35	67	1.0	2.11	web, gage 27.67, normal.
36	68	1.0	2.11	web, gage 28.68, normal.
37	69	1.0	2.11	web, gage 29.69, normal.
38	100	1.0	2.11	web, gage 30.100, normal
39	101	1.0	2.11	web, gage 31.101, normal
40	102	1.0	2.11	web, gage 32.102, normal
41	103	1.0	2.11	web, gage 33.103, normal

LOAD CELL SET UP:

CELL ID.	DAS Channel	Calibration Factor	Location
----------	-------------	--------------------	----------

PRESSURE TRANSDUCER SET UP:

TRAN. ID.	DAS Channel	Calibration Factor	Location
1	0	0.0004	pressure transducer one

1b Sample Data File.

The following is the first few data readings from the web crippling test using the previous setup program.

C:\LABCON\W310X31.DAT
W310x31 Web crippling
N. Benichou, R. Kirkhope
Jan 6 1994

```
0 40 12 -1 <-- Number of transducers, gauges, LVDT's, and load cells
Zero Reading (all less one)
1.220703 <-- Pressure transducer zero reading (kN)
136.14991 <-- Next 13 readings are LVDT zero readings (mm)
138.658756 Note! there are no zero readings for strain gauges
137.268901
142.66044
132.592537
123.705936
125.180051
121.061453
123.320301
122.359838
116.8373
78.477801
75.661114
Reading No. 1
2.075195 <--- Pressure transducer (kN)
4.148688 <--- Next 41 readings are strain gauges (microstrain)
-41.484881
6.223045
-49.781421
20.743802
26.96712
16.594969
20.743802
4.148688
6.18528
-12.370317
-2.061742
6.18528
-16.493684
-2.061742
8.247057
-12.370317
-10.58452
-4.233836
-12.682362
-4.227491
-16.909743
-10.568658
-2.11375
-8.454945
-10.568658
-14.796057
-10.293172
2.058661
```

-6.344734
-10.574509
-8.459626
-10.574509
4.22987
0.0
-14.804247
-4.229832
-12.689383
2.11493
-6.421604
14.984081
0.0
0.0
0.001503
0.0
0.0
0.0
0.0
0.00151
0.0
0.0
-0.00449
0.072486
0.249137

<--- Next 13 readings are LVDT's (mm)

3 of/de 3

PM-1 3½"x4" PHOTOGRAPHIC MICROCOPY TARGET
NBS 1010a ANSI/ISO #2 EQUIVALENT

Appendix 2 Hewlett Packard HP3497a and DAS subsystem.

2a Hewlett Packard HP3497a.

The HP3497a is the component of the data acquisition system used to read the voltage signals from LVDT's, strain gauges, and load cells. It consists of two housing units, the 3497a unit and the 3498a extender unit. Basically, LVDT's, load cells, and strain gauges are wired to circuit board assemblies (called cards) which are plugged into slots in the back of the 3497a and 3498a units.

Looking at the back of the units, there are a total of 15 slots. Five in the 3497a unit (the top unit) numbered 0 to 4, and ten in the 3498a unit (the bottom unit) numbered 0 to 9. Each of these slots contains up to twenty channels. LVDT's and load cells can be wired twenty to a slot, strain gauges can only be wired ten to a slot. The table below summarizes the units and the channels associated with each slot in the unit.

UNIT	SLOT	Corresponding Channel for Data Acquisition.
3497a	0	0 to 19
	1	20 to 39
	2	40 to 59
	3	60 to 79
	4	80 to 99
3498a	0	100 to 119
	1	120 to 139
	2	140 to 159
	3	160 to 179
	4	180 to 199
	5	200 to 219
	6	220 to 239
	7	240 to 259
	8	260 to 279
	9	280 to 299

The cards consist of two pieces, a circuit board (which is generally interchangeable with all types of device wiring boxes, and should be left in the housing units), and the wiring box (which can be removed). The wiring boxes are particular to the type of device being connected. Strain gauges use strain gauge bridge boxes, LVDT's and load cells use thermocouple (T-Couple) or multiplexer boxes.

As noted, only ten strain gauges can be wired to each card, so care must be taken to properly identify the channels used. In addition, LABCON was written with the

intention that if strain gauges are being used, the strain gauge cards **MUST** fill the first slots (ie. assume you have 65 gauges, you will need seven strain gauge cards, and they must occupy slots 0,1,2,3, and 4 in the 3497a, and slots 0, and 1 in the 3498a. In addition the gauges must also occupy the first 65 available channels in the cards, you can not skip channels). The table below summarizes the strain gauge channels associated with each unit and slot.

It is important to note that LABCON uses only unbalanced quarter bridge strain gauge circuits.

UNIT	SLOT	Channel Available for Strain Gauges.
3497a	0	0 to 9
	1	20 to 29
	2	40 to 49
	3	60 to 69
	4	80 to 89
3498a	0	100 to 109
	1	120 to 129
	2	140 to 149
	3	160 to 169
	4	180 to 189

Wiring connections for LVDT's and load cells, are far simpler, these devices may occupy any channel in any slot in any order in the housing units (but only after the slots occupied by strain gauge cards if there are any).

For further detailed information on the units and cards refer to the Hewlett Packard manuals.

2b DAS Subsystem.

The DAS subsystem controller was constructed by ETC electronics here at Carleton (to specifications outlined by Stanley Conley. Jacques Lemieux of ETC electronics constructed the unit). This unit is used to control the hydraulic system and to read the voltage signals from the pressure transducers.

Looking at the back of the subsystem unit, there are a number of plug locations. Along the bottom of the unit are five plugs numbered t1, t2, t3, t4, and t5. These are where the cables from the pressure transducers are connected. Any number of pressure transducers can be connected to any of these plugs in any order. On the right hand side of the unit are another series of plugs numbered s1-s2, s3-s4, and s5-s6. These are the

plugs where the cables from the solenoid valves are connected. Lights on the front of the unit indicate the status of the valves. There is room in the subsystem unit to have one more transducer channel, and one more pair of solenoid control channels installed.

PLUG	Corresponding Pressure Transducer Channel for Data Acquisition with LABCON. *
t1	0
t2	1
t3	2
t4	3
t5	4

* These channels are independent of the Hewlett Packard unit's channels, so it is possible to have a pressure transducer and some other measuring device identified as being connected to the same channel in LABCON's data acquisition setup.

PLUG	Corresponding Hydraulic Line in LABCON controlled by solenoid.
s1-s2	1
s3-s4	2
s5-s6	3

Appendix 3 Hydraulics System.

There are essentially three main components to the hydraulics system used with LABCON; The hydraulic jacks, the solenoid valves, and the pump and hydraulic lines.

3a Hydraulic Jacks.

The structures lab has a large selection of hydraulic jacks, however, the 200 Ton (1780 kN) and 500 Ton (4450 kN) Enerpac jacks will be the units most commonly used. These jacks operate at a maximum hydraulic oil pressure of 10000 psi, and are double acting (they can produce force both when they extend and retract). These jacks have been calibrated with dedicated pressure transducers (the jacks and pressure transducers have been numbered one through five. These numbers are painted on the jack base plates and the pressure transducers). The pressure transducers are removable, but the calibration factor determined for each transducer is applicable only when they are coupled with their corresponding jack.

Jack/Transducer Number		Calibration Factor Volts/kN *
1	(500 T)	0.0004
2	(500 T)	0.000392
3	(500 T)	0.000398
4	(200 T)	0.001027
5	(200 T)	0.001044

* Determined in 400 Kip Tinius Olsen controlled by MTS system. Calibration from CALIB in November 1993.

The pressure transducers have only been calibrated for extending the jacks, and should be connected at the advance port of the jacks, this is the port at the base of the jacks (nearest the base plate). General information regarding the jacks is noted below, for detailed information refer to the Enerpac product manual.

Jack	Travel	Status	Load Capacity	Effective Area
500T	18 in.	extend	500 Ton	113 sq.in.
	18 in.	retract	314 Ton	63 sq.in.
200T	18 in.	extend	200 Ton	44 sq.in.
	18 in.	retract	112 Ton	22 sq.in.

Accuracy in controlling the jacks via the pressure transducers is highly dependent on the number of jacks in operation, and the operating pressure. Generally, better accuracy is achieved at lower operating pressures, so the pressure should be set at about 500 psi to 1000 psi to begin a test, and then increased as the test progresses and more load is required (each 1000 psi increment in oil pressure corresponds with force increments of approximately 450 kN in a 500 Ton jack and 180 kN in a 200 Ton Jack).

Once a test has been finished and the hydraulics are to be taken apart, the operator should start the jacks extending (freely), then turn the air supply off at the pump, and then close the solenoid valves. This will eliminate any possible residual pressure in the system which could make uncoupling of the hydraulic lines very difficult.

3b Solenoid Valves.

The solenoid valves are used to open and close the hydraulic lines, thus extending or retracting the jacks. The valves should have their connecting cables already attached, and these cables should generally not be removed (the plugs are fragile and incorrectly reconnecting is very easy). Connecting the hydraulic lines to the valves is as follows.

Looking down on a valve you will see that the four ports are identified by stamped letters, one pair are stamped P and T, the others are stamped A and B. The pressure line from the pump is connected to port P (pressure), the return line to the pump is connected to port T (tank). The advance line from the jack (The advance port on the jack is the port closest to the base) is connected to port A (advance), and the retract line from the jack is connected to port B.

3c Hydraulic Pump and Accessories.

The hydraulic pump is powered by pressurised air available in the lab, it operates at a maximum air pressure of 100 psi (the air in the lab is 100 psi but is sometimes lower depending on demand from other users).

Prior to each loading step, and at the beginning of the pump operation, the pump usually requires priming, the following steps outline this procedure.

- 1) Close the air shutoff valve (pointed sideways is closed) and open the bypass valve (turn counterclockwise).
- 2) Regulate the air pressure with the air pressure valve (10 psi air pressure equals about 1000 psi oil pressure).
- 3) Turn the air on at the air shutoff valve (pointed up is open).
- 4) Let the pump run for a few seconds (about 5 is ok), then close the bypass valve.
- 5) The oil pressure will slowly build up to its operating level (indicated on the oil

pressure indicator). To increase the pressure increase the air, to decrease the pressure decrease the air. The bypass valve will need to be opened and closed to adjust the pressure to its new setting.

There are various lengths of 10000 psi hydraulic line and accessories available, they include :

- 6 - 30 ft. lengths of line.
- 8 - 10 ft. lengths of line.
- 8 - 6 ft. lengths of line.
- 29 pairs of couplers for lines.
- 6 - six port manifolds.
- 4 - one way valves.

Threading for all of the components is 3/8" NPTF, and couplers have been provided to enable quick assembly and disassembly. The pump was purchased from Wainbee Ltd in Ottawa, the jacks, valves and hydraulic lines were purchased from Enerpac. Refer to the product manuals from these companies for further detailed information.

Appendix 4 Calibration Program CALIB.

CALIB is another Quickbasic program written with LabWindows. Calib can be used to calibrate LVDT's and load cells (the jacks coupled with their pressure transducers are basically load cells). The calibration routine uses a least squares curve fit to obtain the calibration factor for LVDT's and load cells. To calibrate these devices, complete the connections of the LVDT's and/or load cells to the Hewlett Packard units as discussed earlier for LABCON.

Begin CALIB as you would LABCON (see section A1.1) by selecting CALIB.BAS and running it (CALIB>BAS is in the LABCON directory). Once running, CALIB will offer the choice of calibrating LVDT's, Load cells, or quitting. Select the option or device type desired by clicking on its button. Calibration of LVDT's and load cells is similar and involves similar panel displays, so calibration of LVDT's will be used as the example.

When the user first selects the device type they wish to calibrate, a small panel will pop up requesting the channel to scan during the calibration, type in the channel occupied by the LVDT or load cell to be calibrated, followed by a carriage return. The calibration panel features two display windows, the first, *New Displacement (New Load)*, is where the user types in the displacement (load) that the device has experienced. The other window, *Voltage Reading*, shows the current voltage reading from that device.

The general steps to follow to calibrate a device are as follows:

- 1) Take an initial zero reading (fully extend the LVDT, or have no load on the load cell) by clicking on the *Enter Point* button.
- 2) Take a series of readings by moving the LVDT through known displacements using machinists blocks etc.(or put known loads on load cell). After each displacement (load) increment, type the known displacement (or load) into the *New Displacement (New Load)* window and click on the *Enter Point* button. Repeat until a sufficient number of readings have been recorded.

Select the *Calculate* button to calculate the calibration factor. A new panel will appear featuring a graph showing all of the data points entered. This panel is useful if non-linear behaviour is suspected or evident in the points plotted. At the bottom of the panel are windows requesting the high and low cut off points, by providing these cut off points, data points which fall in a non-linear area can be excluded from the calculation of the calibration factor. To enter the cut off points, click on the window and then type in the value. Cut off points must always be provided. Data points below the low cut off point (but not including the cut off point) will be excluded, similarly data points above the high cut off point (but not including the cut off point) will be excluded. The cut off points are in terms of the displacement (load for load cells).

Clicking on the **Ok** button after entering these values will display a further panel which displays a graph similar to the previous panel, except that the calculated calibration curve is displayed over the data points (all data points entered are displayed). The calibration factor and offset values are also displayed at the bottom of the panel. Selecting the **Print Graph** button will send the image on screen into a postscript file which can be printed later. A file selection panel will appear, this panel simply requests the file name to save the image to. A .SCR extension is recommended. Click on the **Ok** button when the file name is complete. Plotting the graph takes a few seconds, the cursor will appear as a white box with a diagonal cross during plotting, wait until the cursor returns to normal before proceeding. Selecting the **Ok** button will return the user to the original calibration panel.

Selecting the **Save** button will write all of the calibration information generated to a file. A File selection panel will appear where existing calibration files can be selected or new files created. Operation of this panel is similar to the Save setup file panel in LABCON (see section 3.2 of LABCON manual). The default directory is C:\LABCON\ . A .CAL extension is initially specified by CALIB, it is recommended that this extension be used.

Selecting the **Reset** button will clear all of the local memory in CALIB for a new calibration, any information from a previous calibration will be lost unless previously saved, the channel for the new device will be requested.

Selecting the **Quit** button will end the calibration session and return the user to the original device menu.

END

2 4 - 1 1 - 9 5

FIN