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WEB CRIPPLING BEHAVIOUR OF CHANNELS WITH FLANGES RESTRAINED

Ben Young[†] & **Gregory J. Hancock***

ABSTRACT

The paper presents a comparison of web crippling tests of cold-formed unlipped channels with flanges restrained or unrestrained. The tests were performed under end and interior two-flange loading conditions specified in the Australian/New Zealand Standard (AS/NZS 4600, 1996) and the American Iron and Steel Institute (AISI, 1996) Specification for cold-formed steel structures, namely End-Two-Flange (ETF) and Interior-Two-Flange (ITF) loading conditions. The concentrated load was applied by a bearing plate at the top flange of the channels, and the reaction force applied by an identical bearing plate at the bottom flange of the channels. The bearing plates acted across the full flange widths of the channels. The flanges of the channels were bolted to the bearing plates for the specimens with flanges restrained. The web crippling test strengths are compared with the current design strengths obtained using the AS/NZS 4600 and the AISI Specification. It is shown that the design strengths predicted by the specifications are unconservative for the tested channels with flanges restrained or unrestrained.

1 INTRODUCTION

The web crippling strength of cold-formed unlipped channels with stockier webs have been investigated by Young and Hancock (1999 and 2000). The flanges of the specimens were not restrained to bearing plates. The web slenderness values of the channel sections ranged from 15.3 to 45, and the values are much lower than the intended web slenderness values used in the Australian/New Zealand Standard (AS/NZS 4600, 1996) and the American Iron and Steel Institute (AISI, 1996) Specification for cold-formed steel structures. The tests were performed under the four loading conditions specified in the AS/NZS 4600 and the AISI Specification, namely End-One-Flange (EOF), Interior-One-Flange (IOF), End-Two-Flange (ETF) and Interior-Two-Flange (ITF) loading. It was shown that the current design strengths predicted by the specifications are unconservative for unlipped channels (single unreinforced webs), except that the specifications closely predicted the web crippling strengths for the EOF loading condition in most of the tested channels. For a certain specimen subjected to ITF loading condition, the test strength is only 37% of the current design strength predicted by the specifications. This may be due to the fact that the flanges of the specimen were not restrained. Hence, it is important to investigate the web crippling strength of cold-formed unlipped channels with flanges restrained.

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In this paper, a test program on cold-formed unlipped channels with flanges restrained subjected to web crippling is investigated. A series of tests was conducted under the ETF and ITF loading conditions. The test specimens belonged to the same batch of specimens reported by Young and Hancock (1999 and 2000). The web crippling test strengths are compared with the current design strengths obtained using the AS/NZS 4600 and the AISI Specification.

2 EXPERIMENTAL INVESTIGATION

2.1 Test Specimens and Bearing Plates

A series of tests was performed on cold-formed unlipped channels with flanges restrained or unrestrained subjected to web crippling. The channel sections had a nominal depth of the webs ranging from 100 mm to 300 mm, nominal flange widths ranging from 50 mm to 90 mm, and nominal thicknesses ranging from 4 mm to 6 mm. The web slenderness (h/t) values ranged from 21.7 to 45.0. Hence, the specimens are considered to have stocky webs. The test specimens were rolled from structural steel sheets to have a final nominal yield stress of 450 MPa.

Tables 1 and 2 show the measured test specimen dimensions, using the nomenclature defined in Fig. 1, where d is the overall depth of web, b_f is the overall width of flange, t is the thickness and r_i is the inside corner radius of the channel sections. The specimen length (L) is equal to the bearing length (N) plus 1.5 times the overall depth of the web from the edge of the bearing plates, as shown in Figs 2, 3a and 4a for End-Two-Flange (ETF) and Interior-Two-Flange (ITF) Loading Conditions. The load or reaction forces were applied by means of bearing plates. The bearing plates were fabricated using high strength quench and tempered steel having a nominal yield stress of 690 MPa. All bearing plates were machined to specified dimensions, and the height was 50 mm for all bearing plates. The bearing plates were designed to act across the full flange widths of the channels excluding the rounded corner. The length of bearing (N) was chosen to be the full and half flange width of the channel specimens. The flanges of the channels were bolted to the bearing plates for the specimens with flanges restrained.

2.2 Specimen Labeling

In Tables 1 and 2, the specimens were labeled such that the loading condition, the depth of the web, the length of bearing and the number of flanges restrained could be identified from the label. For example, the label "ETF250N90-2F(1)" define the following specimen:

- The first three letters indicate that the loading condition End-Two-Flange (ETF) was used in the test.
- The next three digits (250) are the overall depth of the web in mm (250 mm).
- The notation "N90" indicates the length of bearing in mm (90 mm).
- The last two letters "2F" indicate that two flanges (both top and bottom flanges) were restrained. For letters "0F" and "1F" indicate that flanges unrestrained and one flange restrained respectively.
- If a test was repeated, then "(1)" indicates the first test and "(2)" indicates the second test.

This specimen belong to channel 250×90×6 section, where the nominal overall depth of web is 250 mm, the nominal overall flange width is 90 mm and the nominal thickness of the channel section is 6 mm.

2.3 Material Properties

The material properties of the test specimens were determined by tensile coupon tests. The coupons were taken from the centre of the web plate in the longitudinal direction of the finished specimens. The tensile coupons were prepared and tested according to the Australian Standard AS1391 (1991) for the tensile testing of metals using 12.5 mm wide coupons of gauge length 50 mm. All the coupons were tested in a 300 kN capacity MTS displacement controlled testing machine using friction grips. A calibrated extensometer of 50 mm gauge length was used to measure the longitudinal strain. A data acquisition system was used to record the load and the gauge length extensions at regular intervals during the tests. The static load was obtained by pausing the applied straining for one minute near the 0.2% tensile proof stress and the ultimate tensile strength. This allowed the stress relaxation associated with plastic straining to take place. Table 3 summarises the material properties determined from the coupon tests, namely the nominal and the measured static 0.2% tensile proof stress ($\sigma_{0.2}$), the static tensile strength (σ_u) and the elongation after fracture (ε_u) based on a gauge length of 50 mm.

2.4 Test Rig and Operation

The tested channels were performed under end and interior two-flange loading conditions specified in the Australian/New Zealand Standard (AS/NZS 4600, 1996) and the American Iron and Steel Institute (AISI, 1996) Specification for cold-formed steel structures. These loading conditions are End-Two-Flange (ETF) and Interior-Two-Flange (ITF), as shown in Fig. 2.

The test arrangement of ETF loading is shown in Figs 3a and 3b for the front and end views respectively. Two identical bearing plates of the same width were positioned at the end of the specimen. Figure 3 shows one flange of the specimen was bolted to the bottom bearing plate to restrain the flange. The mid-length of the overall flange width was bolted using high strength steel bolt M12 Grade 8.8 conforming to the Australian Standard AS 1252 (1983) together with a washer (28 mm nominal outer diameter with thickness of 2.5 mm) in the tests of channel 100×50×4. For channels 250×90×6 and 300×90×6, bolt M16 Grade 8.8 and washer (34.5 mm nominal outer diameter with thickness of 3 mm) were used in the tests. Web deformations of the specimen were measured between the two bearing plates, and the deformations obtained by the average of three transducers. Only one channel specimen was used in the tests, since the loads were always in the line of action of the force. Hinge supports were simulated by two half rounds. Photographs of the ETF tests are shown in Figs 5, 6 and 7 for specimens with flanges unrestrained, one flange restrained and two flanges restrained tests respectively.

The test arrangement of ITF loading is shown in Figs 4a and 4b for the front and end views respectively. The setup of the test is identical to the ETF loading, except that the two identical bearing plates were positioned at the mid-length of the specimen rather than at the end of the specimen. Figure 4 shows the specimen with two flanges restrained by bolting to the top and bottom bearing plates. Photographs of the ITF test are shown in Figs 8a and 8b for specimen with two flanges restrained. A 2000 kN capacity DARTEC servo-controlled hydraulic testing machine was used to apply a compressive force to the test specimens. Displacement control was used to drive the hydraulic actuator at a constant speed of 0.8 mm/min. A SPECTRA data acquisition system was used to record the load and the transducer readings at regular intervals during the tests. The static load was recorded by pausing for one minute near the ultimate load. This allowed the stress relaxation associated with plastic straining to take place.

2.5 Test Results

The experimental ultimate web crippling loads per web (P_{Exp}) are given in Tables 1 and 2 for ETF and ITF loading conditions respectively. The test of ETF250N90-2F was repeated and the test result is very close to the first test value with a difference of 1.3%. The small difference between the repeated test demonstrated the reliability of the test results.

3 COMPARISON OF TEST STRENGTHS WITH CURRENT DESIGN STRENGTHS

The web crippling loads per web obtained from the tests of specimen with flanges unrestrained (0F), one flange restrained (1F) and two flanges restrained (2F) are compared with the unfactored design strengths predicted using the Australian/New Zealand Standard (AS/NZS 4600, 1996) and the American Iron and Steel Institute (AISI, 1996) Specification for cold-formed steel structures. The AS/NZS 4600 has adopted the web crippling design rules from the AISI Specification, and no changes are introduced into the web crippling strength rules. Therefore, the design strength predicted by the AS/NZS 4600 and the AISI Specification are identical. Tables 4 and 5 show the comparison of the test strengths (P_{Exp}) with the unfactored design strengths (P_n) for ETF and ITF loading conditions respectively. The design strengths were calculated using the average measured cross-section dimensions and the measured material properties.

The current design strengths (P_n) predicted by the specifications are unconservative for the ETF and ITF loading conditions, even when the flanges of the specimens had restraint. For the ETF loading condition, the average values of the web crippling strength of specimens with flanges unrestrained (0F), one flange restrained (1F) and two flanges restrained (2F) were reached in the tests at 65%, 78% and 86% of the values predicted by the specifications respectively, as shown in Table 4. For ITF loading condition, the corresponding values of the specimens with flanges unrestrained, one flange restrained and two flanges restrained are 57%, 62% and 63% respectively, as shown in Table 5. The tests of the ITF loading condition are predicted more unconservatively than the tests of the ETF loading condition.

4 CONCLUSIONS

A series of web crippling tests on channel sections with flanges restrained or unrestrained has been presented. The tests were performed on high strength cold-formed steel unlipped channels having nominal yield stress of 450 MPa and the maximum web slenderness value is 45. The specimens were tested using the End-Two-Flange (ETF) and Interior-Two-Flange (ITF) loading conditions specified in the Australian/New Zealand Standard (AS/NZS 4600, 1996) and the American Iron and Steel Institute (AISI, 1996) Specification for cold-formed steel structures. The test strengths are compared with the current design strengths obtained using the AS/NZS 4600 and the AISI Specification. It is shown that the current design strengths predicted by the specifications are unconservative for the tested unlipped channels subjected to ETF and ITF loading conditions, even when the flanges of the specimens had restraint. Therefore, it is recommended that the web crippling design equations for ETF and ITF loading conditions in the AS/NZS 4600 and the AISI Specification be limited to web slenderness values greater than 45 when applied to unlipped channels irrespective of whether the flanges restrained or unrestrained. Design equations for the unrestrained case are given in Young and Hancock (1999 and 2000).

ACKNOWLEDGEMENTS

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NOTATION

b_f	Overall width of flange
COV	Coefficient of variation
d	Overall depth of web
h	Depth of flat portion of web measured along the plane of web
L	Length of specimen
N	Length of bearing
P_{Exp}	Experimental ultimate web crippling load per web
P_n	Nominal web crippling strength obtained from specifications (Unfactored current design strength)
r_i	Inside corner radius of specimen
t	Thickness of channel section
ε_u	Elongation (tensile strain) after fracture based on a gauge length of 50mm
$\sigma_{0.2}$	Static 0.2% tensile proof stress
σ_u	Static ultimate tensile strength

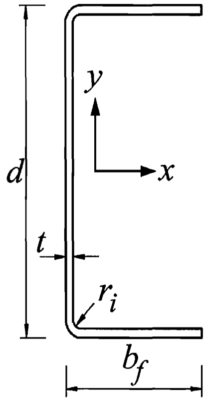
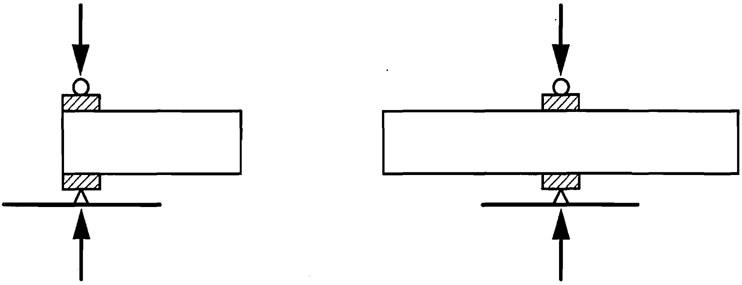


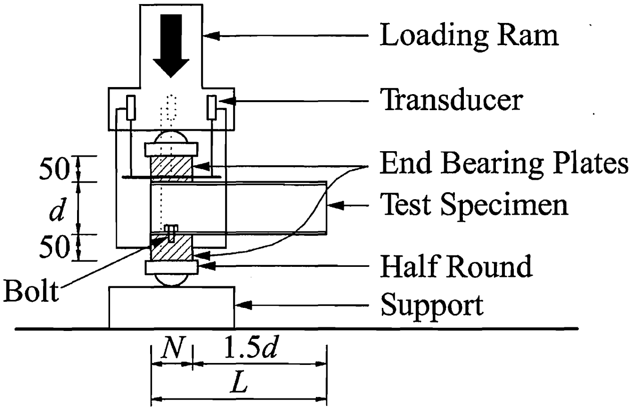
Fig. 1. Definition of Symbols



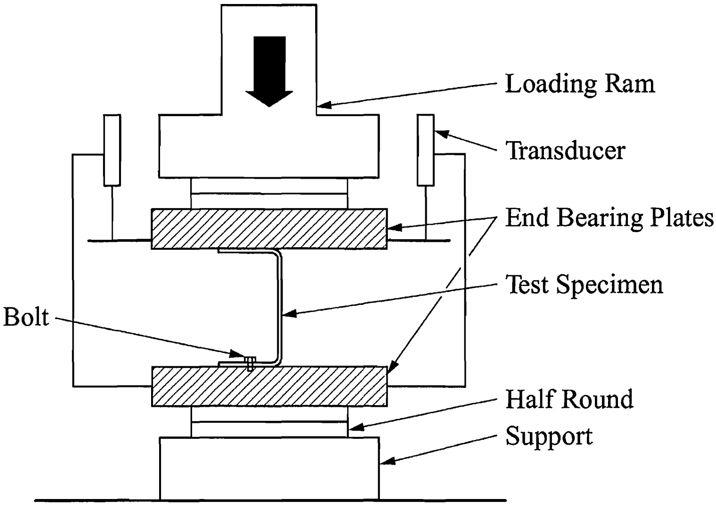
(a) ETF

(b) ITF

Fig. 2. End-Two-Flange (ETF) and Interior-Two-Flange (ITF) Loading Conditions

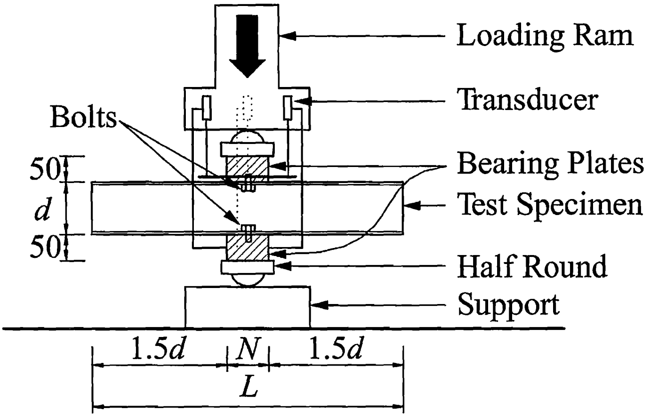


(a) Front view

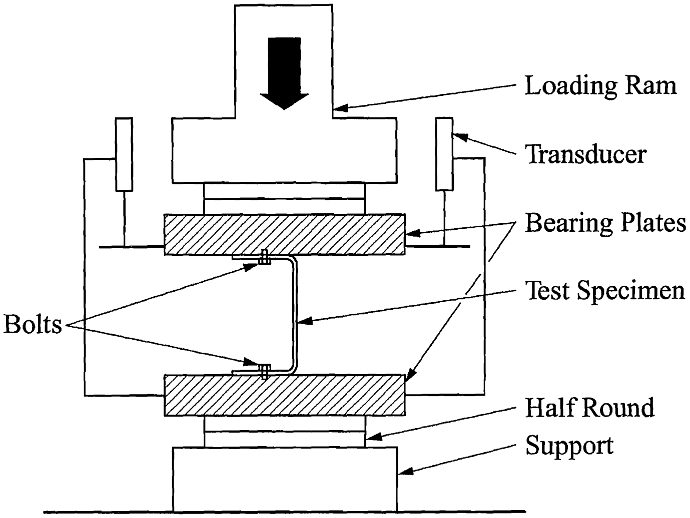


(b) End view

Fig. 3. Schematic View of Specimen with One Flange restrained for ETF Test Arrangement

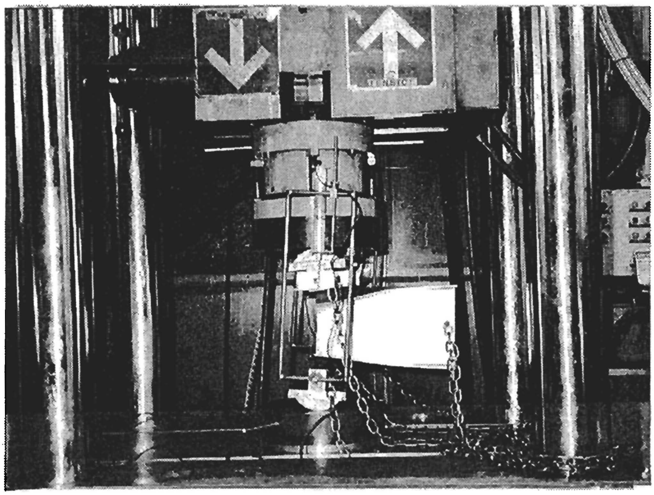


(a) Front view

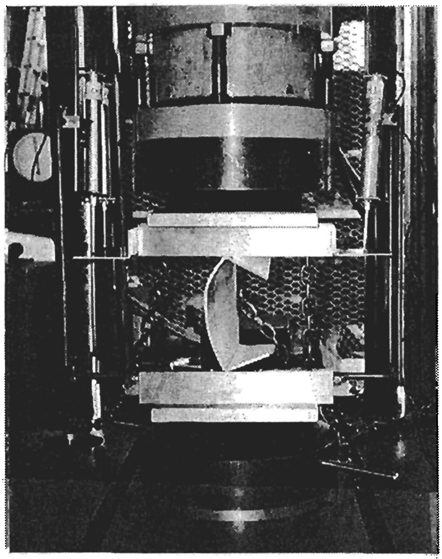


(b) End view

Fig. 4. Schematic View of Specimen with Two Flanges restrained for ITF Test Arrangement

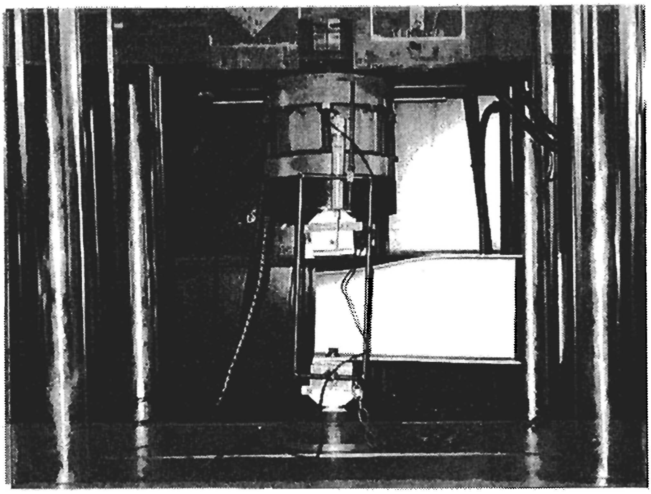


(a) Front view

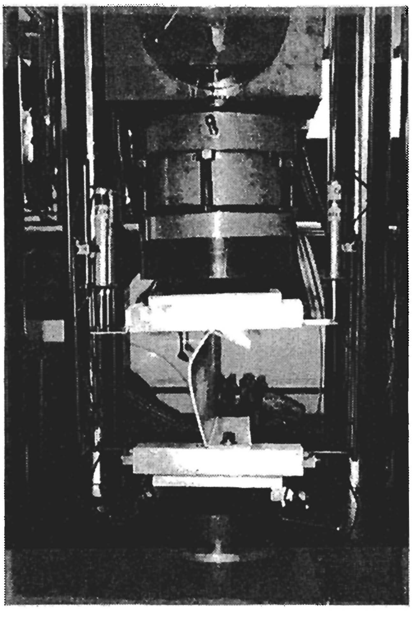


(b) End view

Fig. 5. Test of Specimen with Flanges Unrestrained for ETF Loading Condition

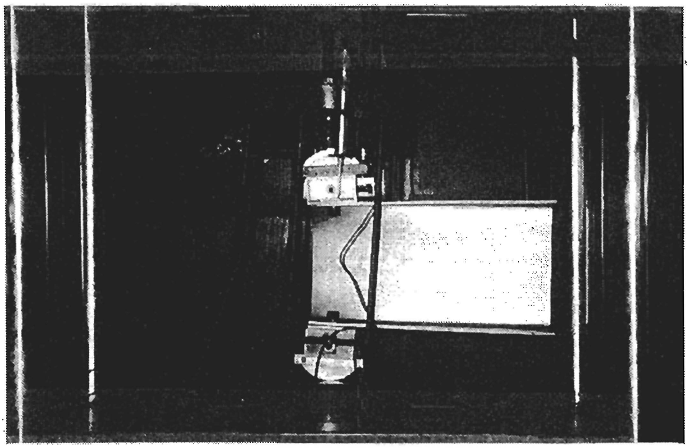


(a) Front view

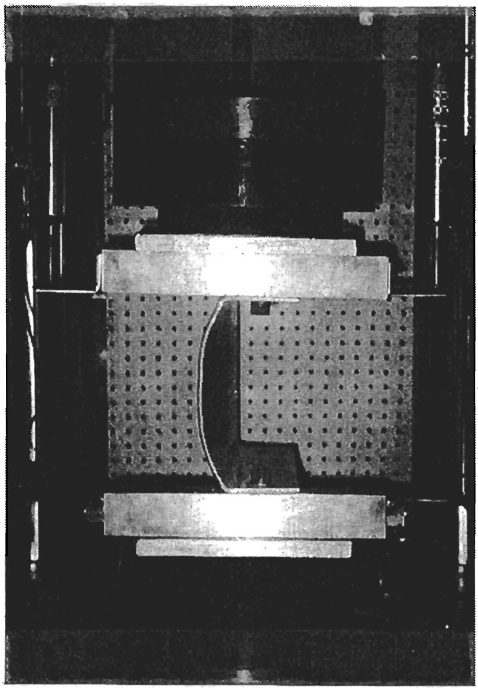


(b) End view

Fig. 6. Test of Specimen with One Flange Restrained for ETF Loading Condition

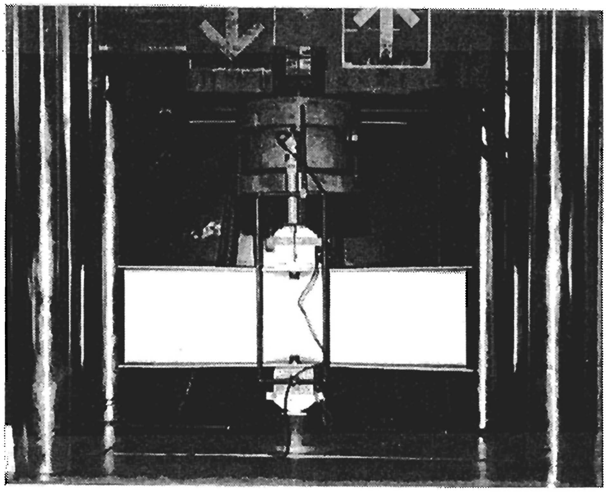


(a) Front view

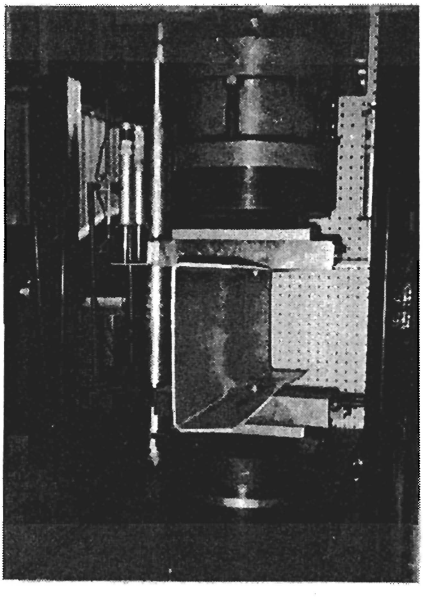


(b) End view

Fig. 7. Test of Specimen with Two Flanges Restrained for ETF Loading Condition



(a) Front view



(b) End view

Fig. 8. Test of Specimen with Two Flanges Restrained for ITF Loading Condition

Specimen	Web	Flanges	Thickness	Radius	Length	Exp. Load per Web
	d	b_f	t	r_i	L	P_{Exp}
	(mm)	(mm)	(mm)	(mm)	(mm)	(kN)
ETF100N50-0F	99.1	50.4	3.83	4.1	200.2	24.8
ETF100N50-1F	99.6	50.4	3.83	4.1	200.0	28.7
ETF100N50-2F	99.6	50.5	3.82	4.1	200.9	32.5
ETF100N25-0F	99.4	50.3	3.83	4.1	175.0	22.6
ETF100N25-2F	99.4	50.5	3.83	4.1	175.1	25.2
ETF250N90-0F	249.2	89.8	5.99	7.9	465.1	50.6
ETF250N90-1F	249.5	89.6	5.99	7.9	464.0	65.0
ETF250N90-2F(1)	249.2	89.9	6.00	7.9	464.7	74.6
ETF250N90-2F(2)	249.3	89.8	6.00	7.9	465.0	75.6
ETF250N45-0F	249.4	89.9	5.98	7.9	421.0	46.9
ETF250N45-2F	249.4	89.8	5.98	7.9	422.8	59.5
ETF300N90-0F	298.5	90.9	5.98	8.4	539.6	49.4
ETF300N90-1F	298.6	91.1	6.01	8.4	540.4	57.8
ETF300N90-2F	298.4	91.1	6.00	8.4	541.3	73.9
ETF300N45-0F	298.3	91.2	6.01	8.4	495.2	45.4
ETF300N45-2F	298.8	91.0	6.00	8.4	496.7	60.0

Note: 1 in. = 25.4mm; 1 kip = 4.45 kN

Table 1. Measured Specimen Dimensions and Experimental Ultimate Loads for ETF Loading Condition

Specimen	Web	Flanges	Thickness	Radius	Length	Exp. Load per Web
	d	b_f	t	r_i	L	P_{Exp}
	(mm)	(mm)	(mm)	(mm)	(mm)	(kN)
ITF100N50-0F	99.3	50.4	3.83	4.1	350.0	58.3
ITF100N50-1F	99.5	50.5	3.82	4.1	349.3	67.1
ITF100N50-2F	99.4	50.4	3.83	4.1	349.2	71.9
ITF100N25-0F	99.2	50.4	3.84	4.1	325.0	66.3
ITF100N25-2F	99.5	50.4	3.83	4.1	325.0	68.9
ITF250N90-0F	249.6	90.0	6.01	7.9	838.4	148.5
ITF250N90-1F	249.0	89.7	5.98	7.9	838.9	163.3
ITF250N90-2F	249.1	89.7	5.98	7.9	840.1	170.3
ITF250N45-0F	249.5	89.9	5.99	7.9	796.5	148.4
ITF250N45-2F	249.2	89.6	6.00	7.9	795.9	156.5
ITF300N90-0F	298.8	90.9	6.00	8.4	990.0	149.1
ITF300N90-1F	298.4	91.2	6.01	8.4	989.2	162.2
ITF300N90-2F	298.3	90.8	6.00	8.4	990.9	164.2
ITF300N45-0F	298.6	91.0	5.97	8.4	944.1	144.6
ITF300N45-2F	298.5	91.0	6.01	8.4	945.0	154.1

Note: 1 in. = 25.4mm; 1 kip = 4.45 kN

Table 2. Measured Specimen Dimensions and Experimental Ultimate Loads for ITF Loading Condition

Channel	Nominal	Measured		
$d \times b_f \times t$	$\sigma_{0.2}$	$\sigma_{0.2}$	σ_u	ε_u
(mm)	(MPa)	(MPa)	(MPa)	(%)
100×50×4	450	440	545	20
250×90×6	450	445	530	21
300×90×6	450	435	535	23

Note: 1 in. = 25.4 mm; 1 ksi = 6.89 MPa

Table 3. Nominal and Measured Material Properties

Channel (Nominal Dimensions)	Measured		Exp. Load per Web			AISI & AS/NZS 4600	Comparison		
	Bearing Length	Ratio	P_{Exp}			P_n	$\frac{P_{Exp}}{P_n}$		
$d \times b_f \times t$	N	h/t	0F	1F	2F	ETF	0F	1F	2F
(mm)	(mm)		(kN)			(kN)			
100×50×4	50.0	21.7	24.8	28.7	32.5	35.3	0.70	0.81	0.92
100×50×4	25.0	21.7	22.6	-------	25.2	33.2	0.68	-------	0.76
250×90×6	90.0	37.0	50.6	65.0	74.6 75.6$^{\#}$	80.9	0.63	0.80	0.92
250×90×6	45.0	37.0	46.9	-------	59.5	75.6	0.62	-------	0.79
300×90×6	90.0	45.0	49.4	57.8	73.9	78.4	0.63	0.74	0.94
300×90×6	45.0	45.0	45.4	-------	60.0	73.3	0.62	-------	0.82
						Mean	0.65	0.78	0.86
						COV	0.053	0.048	0.090

$^{\#}$ Second test

Where 0F = Flanges unrestrained
1F = One flange restrained
2F = Two flanges restrained

Note: 1 in. = 25.4 mm; 1 kip = 4.45 kN

Table 4. Comparison of Web Crippling Test Strengths with Current Design Strengths for ETF Loading Condition

Channel (Nominal Dimensions)	Measured		Exp. Load per Web			AISI & AS/NZS 4600	Comparison		
	Bearing Length	Ratio	P_{Exp}			P_n	$\frac{P_{Exp}}{P_n}$		
$d \times b_f \times t$	N	h/t	0F	1F	2F	ITF	0F	1F	2F
(mm)	(mm)		(kN)			(kN)			
100×50×4	50.0	21.7	58.3	67.1	71.9	114.4	0.51	0.59	0.63
100×50×4	25.0	21.7	66.3	-------	68.9	113.5	0.58	-------	0.61
250×90×6	90.0	37.0	148.5	163.3	170.3	263.1	0.56	0.62	0.65
250×90×6	45.0	37.0	148.4	-------	156.5	260.6	0.57	-------	0.60
300×90×6	90.0	45.0	149.1	162.2	164.2	253.1	0.59	0.64	0.65
300×90×6	45.0	45.0	144.6	-------	154.1	250.7	0.58	-------	0.61
						Mean	0.57	0.62	0.63
						COV	0.051	0.041	0.035

Where 0F = Flanges unrestrained
1F = One flange restrained
2F = Two flanges restrained

Note: 1 in. = 25.4 mm; 1 kip = 4.45 kN

Table 5. Comparison of Web Crippling Test Strengths with Current Design Strengths for ITF Loading Condition