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Web Crippling Behaviour of Thin-Walled Lipped Channel Beams Subjected to EOF and ETF Loading

Martin Macdonald[1], Manoj A. Heiyantuduwa[1] and Jim Rhodes[2]

Abstract

This paper presents the results of an investigation conducted to study web crippling behaviour of cold-formed thin-walled steel lipped channel beams subjected to End-One-Flange (EOF) and End-Two-Flange (ETF) loading conditions as defined by the American Iron and Steel Institute (AISI). An experimental program was designed to obtain the load-deformation characteristics of beam members with varying cross-sectional and loading parameters under the two web crippling loading conditions. The results of the experiments mainly comprised of the ultimate web crippling strength values of thirty-six specimens tested. Nonlinear finite element models were developed to simulate web crippling failure of the two loading conditions considered in the experimental program. The comparison of experimental and finite element results revealed that the nonlinear finite element models were capable of closely simulating the web crippling failure behaviour observed in the experiments. Web crippling strength predicted from the AISI Specification was also compared with the experimental results and the comparisons indicated considerable underestimations for the range of specimens under EOF and ETF loading conditions.

Introduction

Web crippling failure may occur at places where thin-walled flexural members are subjected to high concentrated loadings or support reaction forces. Figure 1 illustrates web crippling failure at a loading point. Four different loading conditions where web crippling may take place, have been defined by the AISI

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based on the number of loadings involved and the location of failure initiated, namely, Interior-One-Flange (IOF), Interior-Two-Flange (ITF), End-One-Flange (EOF) and End-Two-Flange (ETF) loading conditions (Rhodes, 1991).

Figure 1: Web crippling at loading point.

A considerable amount of research has been carried out on web crippling by numerous researchers particularly to validate various design rules for web crippling, and the majority were based on experimental investigations. The early research work conducted by Winter and Pian (1946), Ratliff (1975), Hetrakul and Yu (1979), etc. provided the basis for web crippling design rules that appeared in the early versions of the AISI Specification and consequently adopted by the other major design codes. In the recent past, a number of investigations were carried out by Young and Hancock, Prabakaran and Schuster and by Shaojie, Yu and LaBoube, and these resulted in a more unified form of design rule which was adopted by the AISI Specification - 2001 edition.

A research program was initiated to investigate web crippling behaviour of cold-formed thin-walled lipped channel beams under the four loading conditions. The results of the experimental investigations and the finite element analysis of lipped channels beams under IOF and ITF loading conditions were reported in previous publications (Heiyantuduwa, 2007 and Macdonald, 2006). The aim of this paper is to present the results of experimental investigations and finite element analysis carried out on web crippling behaviour of lipped channel sections under EOF and ETF loading conditions. The experimental results were also compared with the web crippling strength predictions from the AISI Specification.

Experimental Investigations

Experimental investigations were designed to examine the influence of various cross-sectional and loading parameters on web crippling strength. Two separate series of tests were performed considering EOF and ETF loading conditions. The test specimens were fixed on to load bearing plates during both series of tests to prevent flange rotations and possible lateral movements of specimens during loading. Each series comprised of eighteen test specimens manufactured from 0.78mm thickness carbon steel sheets. The test specimens were designed to have three different corner radii and two different web heights, and were loaded with three different sizes of load bearing plate. Figure 2 illustrates the cross-sectional and loading parameters used in the specimen design. A separate series of tensile tests were carried out prior to specimen manufacture in order to obtain the material properties of the individual steel sheets.

During the web crippling tests, applied load, displacement at the loading point and the displacement at a number of other critical points were measured. The results of the experimental investigations were used to validate the finite element models and also to check the validity of web crippling strength predictions obtained from design codes.

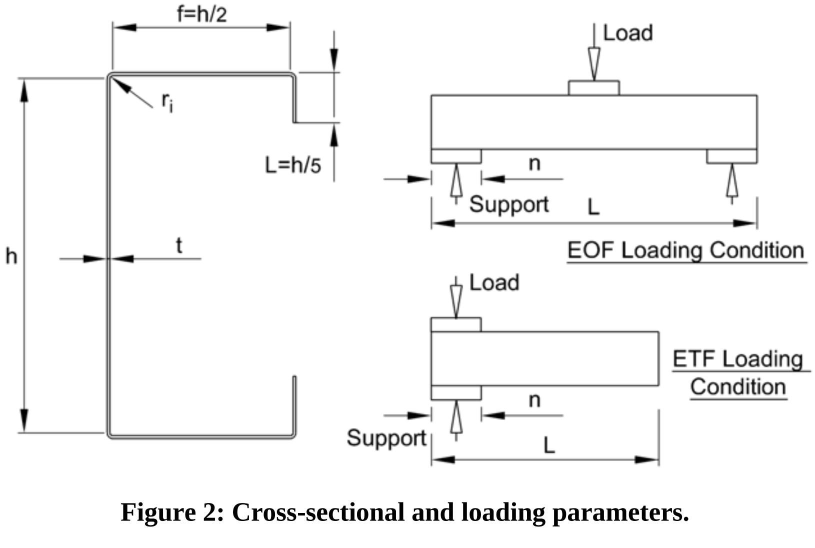

Figure 2: Cross-sectional and loading parameters.

EOF Loading Tests

EOF loading tests were performed as three point bending tests, however, the failure was intended to occur at the end of the beam (at supports) and the loading was applied to the mid-point of the beam. The load bearing plate was fully fixed at the mid-point in order to prevent failure around this area. The test rig used in the EOF loading tests is shown in Figure 3, and Figure 4 shows a photograph of the test rig with displacement transducers attached.

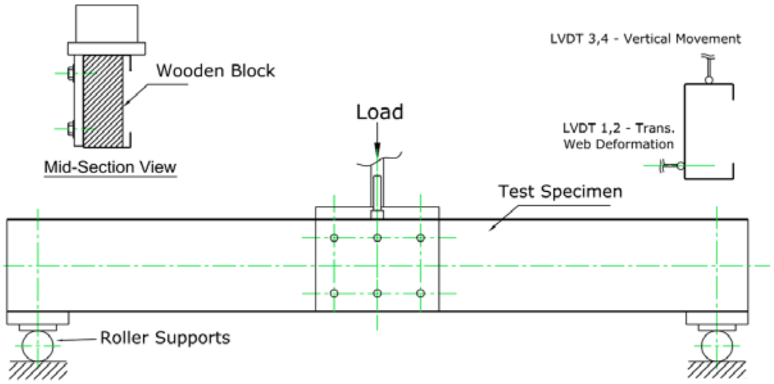

Figure 3: Test rig for EOF loading tests.

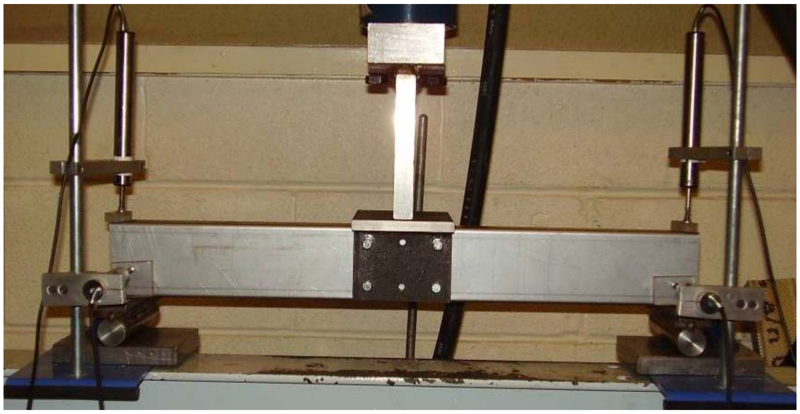

Figure 4: Photograph showing EOF loading test rig with displacement transducers.

ETF Loading Tests

ETF loading tests were performed by applying a load which was directly above the support. Hence, the failure initiated at the end of the beam due to the heavy loading and the support reaction force. The test rig used in the ETF loading tests is shown in Figure 5, and Figure 6 shows a photograph of the test rig with displacement transducers attached.

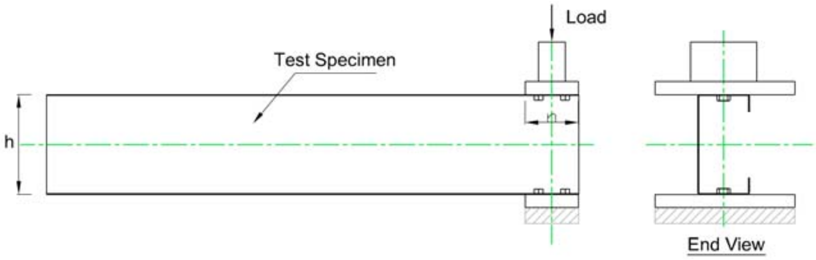

Figure 5: Test rig for ETF loading tests.

Figure 6: Photograph showing ETF loading test rig with displacement transducer.

Finite Element (FE) Models

Finite element models were developed to simulate the tests conducted in the experimental investigations. Finite element analysis package ANSYS® was employed for the modelling and analysis procedure (ANSYS, 2004). Nonlinear characteristics such as material nonlinearity, geometric nonlinearity and contact situations were considered to accurately represent web crippling failure. Two different finite element models were developed to represent EOF and ETF loading tests described in the experimental investigations.

FE Models for EOF Loading Condition (EOF-FE Models)

EOF-FE models were developed to simulate the EOF loading tests carried out in the experimental investigations. The geometric model for the EOF-FE models was similar to the test setup used in the EOF loading tests. However, the advantage of the vertical symmetry was used to create a half-model in this case. The geometry was initially created using the solid modelling techniques within ANSYS. Figure 7 shows the element mesh generated for EOF-FE models. In this case, web crippling failure was expected to occur at the support reaction point. Thus, the mesh was controlled to have relatively finer elements closer to the support area and coarser elements further away from the support area.

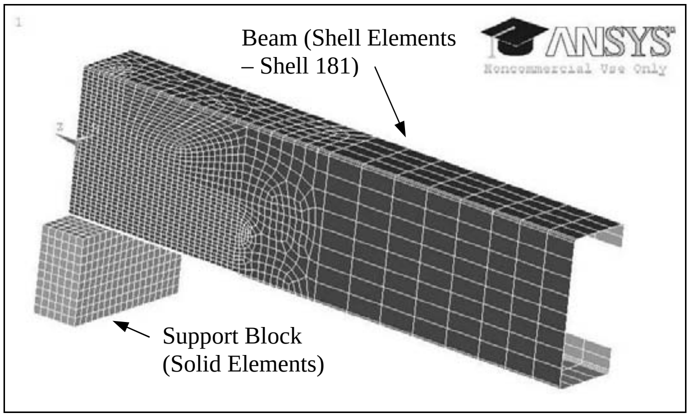

Figure 7: Element mesh for EOF-FE models.

The support reaction force was applied using a support block modelled with solid elements and appropriate boundary conditions were employed to simulate the actual supports used in the experiments. Contact elements were employed in between the support block and the lipped channel beam to represent the actual loading situation. Furthermore, the flange-fixed condition was represented using a set of nodes with coupled degrees-of-freedom. The loading was applied with displacement control onto a set of nodes selected along the bottom centre line of the support block. The rotation about the Z axis was restrained along the centre line to represent the actual support conditions in the test setup. Figure 8 shows the boundary conditions used for the EOF-FE models. A set of nodes around the mid-span of the beam were fully restrained against translations and rotations in all directions.

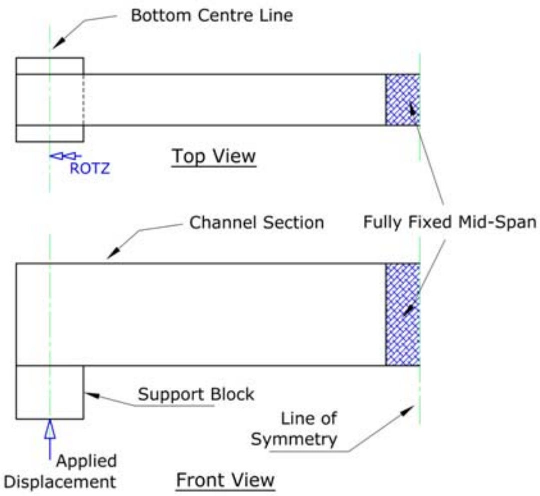

Figure 8: Boundary conditions for EOF-FE models.

FE Models for ETF Loading Condition (ETF-FE Models)

ETF-FE models were developed to simulate the ETF loading tests carried out. In this case, web crippling failure was expected to occur at the end of the beam under two opposite forces inline with each other. The geometric model for the ETF-FE models was similar to the test setup used in the ETF loading tests. The ETF loading setup was symmetrical about the horizontal plane passing through the centre line of the beam. Therefore, only one-half of the setup was modelled to use the advantage of symmetry. Figure 9 shows the element mesh generated for the ETF-FE models. Web crippling failure was identified to occur around the central area of the web under the load bearing plates. Thus, the mesh was created to have relatively small elements around the central part of the web and coarse elements further away from the failure region.

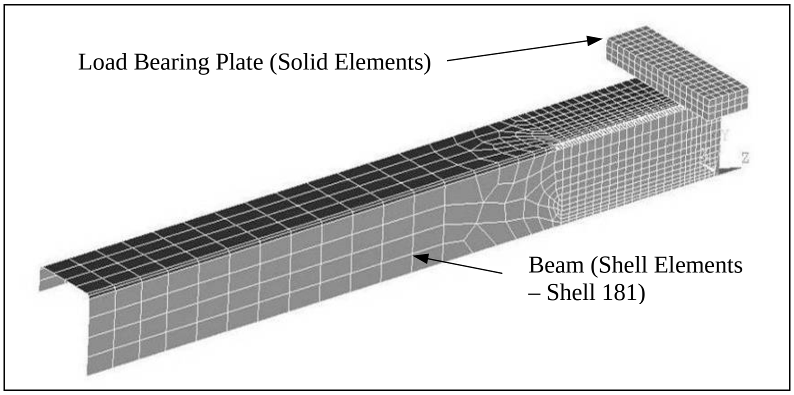

Figure 9: Element mesh for ETF-FE models.

The loading was applied through a load bearing plate using the displacement control method. Contact elements were used between the load bearing plate and the top flange of the beam. Figure 10 shows the boundary conditions used in the ETF-FE models.

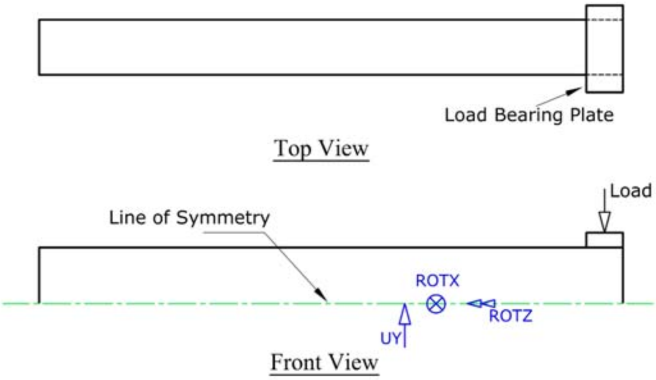

Figure 10: Boundary conditions for ETF-FE models.

AISI Web Crippling Strength Predictions

The nominal web crippling strength of thirty-six specimens under EOF and ETF loading conditions was determined using the AISI Specification (AISI, 2001). The AISI Specification, 2001 edition provides a single equation to determine the nominal web crippling strength with a number of coefficients to select from the tables provided based on the type of cross-section profiles, loading condition and the flange condition where applicable.

Results and Comparisons

The load-displacement graphs obtained from the tests and finite element analysis were used to determine the ultimate web crippling strength of the specimens. Tables 1 and 2 present the web crippling strength results obtained from the tests ($P_{exp:ult.}$), finite element analysis ($P_{FE:ult.}$) and from the AISI specification (P_{AISI}) for EOF and ETF loading conditions respectively. Figures 11 and 12 illustrate sample load-displacement graphs obtained from tests and finite element analysis along with the corresponding AISI web crippling strength predictions. The finite element strength and the nominal web crippling strength predicted from the AISI specification were compared with the experimental web crippling strength results. Table 3 shows the mean and standard deviation of ratios between finite element strength and experimental strength ($P_{FE:ult.}$ / $P_{exp:ult.}$) as well as the AISI predictions and experimental strength (P_{AISI} / $P_{exp:ult.}$).

Table 1: Web crippling strength results for EOF loading condition.

Test No.	h (mm)	r_i (mm)	n (mm)	t (mm)	Span Length-Ls (mm)	0.2% Proof Stress (MPa)	$P_{exp:ult.}$ (kN)	$P_{FE:ult.}$ (kN)	P_{AISI} (kN)
EOF-1	95.2	4.0	25	0.78	600	220	1.18	1.14	0.85
EOF-2	95.5	2.6	25	0.78	600	220	1.24	1.19	0.93
EOF-3	97.3	1.2	25	0.78	600	220	1.46	1.41	1.02
EOF-4	95.2	4.0	100	0.78	600	220	1.74	1.61	1.41
EOF-5	95.5	2.6	100	0.78	600	220	2.00	1.92	1.54
EOF-6	97.3	1.2	100	0.78	600	220	2.25	2.39	1.71
EOF-7	95.5	2.6	50	0.78	600	220	1.43	1.52	1.18
EOF-8	97.3	1.2	50	0.78	600	220	1.70	1.93	1.31
EOF-9	95.2	4.0	50	0.78	600	220	1.34	1.34	1.08
EOF-10	73.3	1.2	50	0.78	600	220	1.80	2.09	1.36
EOF-11	70.0	2.6	50	0.78	600	220	1.44	1.57	1.23
EOF-12	69.2	4.0	50	0.78	600	220	1.32	1.40	1.13
EOF-13	73.3	1.2	25	0.78	600	220	1.44	1.43	1.06
EOF-14	70.0	2.6	25	0.78	600	220	1.12	1.23	0.96
EOF-15	69.2	4.0	25	0.78	600	220	1.10	1.20	0.88
EOF-16	73.3	1.2	100	0.78	600	220	2.35	2.61	1.77
EOF-17	70.0	2.6	100	0.78	600	220	1.90	2.17	1.60
EOF-18	69.2	4.0	100	0.78	600	220	1.62	1.75	1.47

Table 2: Web crippling strength results for ETF loading condition.

Test No.	h (mm)	r_i (mm)	n (mm)	t (mm)	Span Length-Ls (mm)	0.2% Proof Stress (MPa)	$P_{exp:ult.}$ (kN)	$P_{FE:ult.}$ (kN)	P_{AISI} (kN)
ETF-1	73.0	1.6	25	0.78	400	220	0.87	0.91	0.80
ETF-2	73.4	2.4	25	0.78	400	220	0.81	0.95	0.77
ETF-3	65.2	5.0	25	0.78	400	220	0.76	0.82	0.75
ETF-4	98.2	1.6	25	0.78	400	220	1.25	0.98	0.69
ETF-5	96.2	2.4	25	0.78	400	220	0.98	0.92	0.68
ETF-6	89.8	5.0	25	0.78	400	220	0.80	0.81	0.65
ETF-7	73.0	1.6	50	0.78	400	220	1.38	1.29	0.93
ETF-8	73.4	2.4	50	0.78	400	220	0.92	1.18	0.91
ETF-9	65.2	5.0	50	0.78	400	220	1.14	0.95	0.88
ETF-10	98.2	1.6	50	0.78	400	220	1.24	1.20	0.80
ETF-11	96.2	2.4	50	0.78	400	220	1.22	1.12	0.79
ETF-12	89.8	5.0	50	0.78	400	220	0.98	0.96	0.76
ETF-13	73.0	1.6	100	0.78	400	220	1.84	1.90	1.12
ETF-14	73.4	2.4	100	0.78	400	220	1.76	1.72	1.09
ETF-15	65.2	5.0	100	0.78	400	220	1.58	1.34	1.06
ETF-16	98.2	1.6	100	0.78	400	220	1.72	1.64	0.97
ETF-17	96.2	2.4	100	0.78	400	220	1.56	1.52	0.95
ETF-18	89.8	5.0	100	0.78	400	220	1.28	1.32	0.92

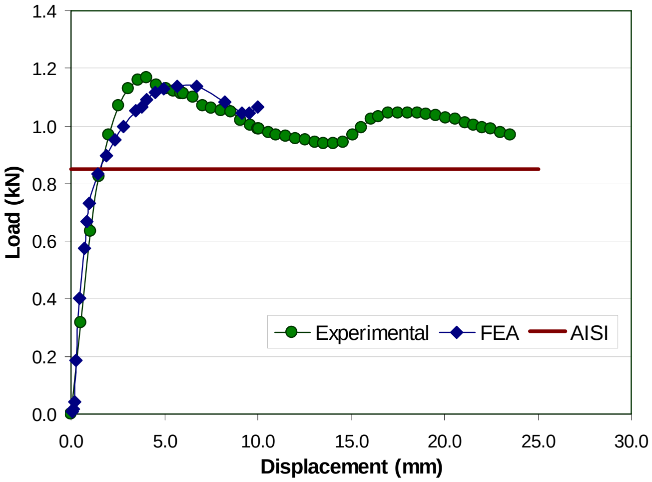

Figure 11: Experimental and FE load-displacement graphs compared with AISI web crippling strength prediction for a sample EOF test (EOF – 1).

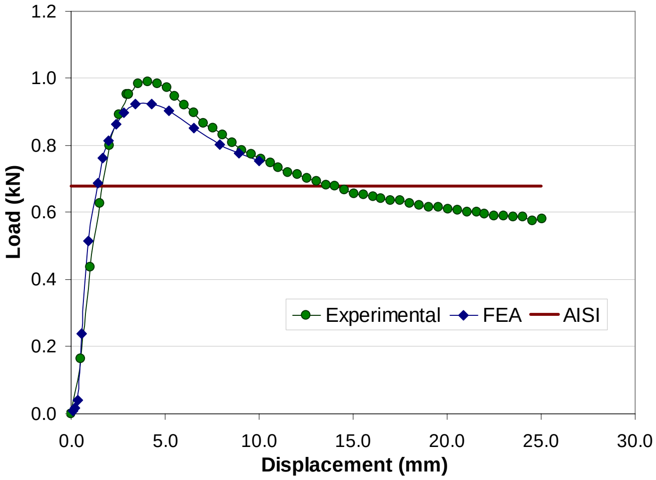

Figure 12: Experimental and FE load-displacement graphs compared with AISI web crippling strength prediction for a sample ETF test (ETF – 5).

Table 3: Summary of comparisons.

Loading Condition	Mean of Strength Ratios		Standard Deviation of Strength Ratios	
	$P_{FE:ult.} / P_{exp:ult.}$	$P_{AISI} / P_{exp:ult.}$	$P_{FE:ult.} / P_{exp:ult.}$	$P_{AISI} / P_{exp:ult.}$
EOF	1.01	0.77	0.13	0.05
ETF	0.98	0.73	0.11	0.12

Conclusions

Experimental investigations were conducted to study web crippling behaviour of cold-formed steel lipped channel beams under EOF and ETF loading conditions. The tests provided results which mainly comprised of ultimate web crippling strength values of thirty-six specimens with varying cross-sectional dimensions and loaded with three separate load bearing plates having different dimensions. Finite element models were developed to simulate the tests conducted in the experimental investigations. The nonlinear characteristics such as material nonlinearity, geometric nonlinearity and contact situations were employed to represent the actual web crippling failure observed during the tests.

The results showed that the nonlinear finite elements models developed were capable of closely representing the web crippling failure of the specimens considered in this research. An average deviation of ± 2% of finite element strength from experimental results was observed.

The nominal web crippling strength of the thirty-six specimens was predicted using the AISI Specification and the predictions were compared with the experimental results. The comparisons indicated averages of 23% and 27% underestimations of the AISI web crippling strength predictions for EOF and ETF loading conditions respectively.

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