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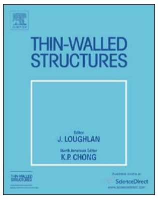

Full length article

New design rules for lipped channel beams subject to web crippling under two-flange load cases

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ABSTRACT

Lipped channel beams (LCBs) are commonly used as floor joists and bearers in the construction industry. These thin-walled LCBs are subjected to specific local and global failures, one of them being web crippling. Several experimental and numerical studies have been conducted in the past to study the web crippling behaviour and capacities of different cold-formed steel sections under different concentrated load cases. However, due to the nature of the web crippling phenomenon and many factors influencing the web crippling capacities, capacity predictions given by most of the cold-formed steel design standards are either unconservative or conservative. Therefore a detailed experimental study was conducted to study the web crippling under End Two-Flange (ETF) and Interior Two-Flange (ITF) load cases based on the new AISI S909 standard web crippling test method. Finite element models were developed and validated using the test results. These models were then used in a detailed parametric study to investigate the web crippling capacities of a wide range of LCB sections including different sectional geometric parameters such as section depth, inside bent radius, thickness and bearing length. This paper presents the details of the numerical study of LCBs subject to web crippling under ETF and ITF load cases. Using the extensive web crippling capacity data obtained from both numerical and experimental studies, improved unified web crippling design equations were developed. Suitable web crippling design rules were also developed under the direct strength method format.

1. Introduction

Due to the increasing availability of high performance computers and advanced numerical tools, numerical modelling and analyses are increasingly deployed in many research studies and are attributed as sustainable alternatives to experimental studies. The new discipline of scientific computing combines numerical analysis and computer graphics to make it easier to set up, solve and interpret complicated models of the real world. These tools have been deployed in recent years to study the web crippling behaviour of different cold-formed steel sections. A detailed experimental study including 36 tests was conducted by the authors to study the web crippling behaviour of cold-formed steel lipped channel sections under End Two-Flange (ETF) and Interior Two-Flange (ITF) load cases using the AISI S909 standard web crippling test method [1,2]. Tables 1 and 2 and, Fig. 1 present the details of this experimental study involving six lipped channel beams (LCB) and three bearing lengths (25, 50 and 100 mm) in each load case. The LCB sections varied in thickness (1.0–2.4 mm) and height (100–200 mm) and were made of high strength steels (G450, G500 and G550). This research was then continued using advanced numerical studies to enhance further the understanding of web crippling behaviour and to develop improved design equations. This paper describes the details of the web crippling finite element models developed for cold-formed steel lipped channel sections under ETF and ITF load cases including their calibration using the results obtained from the experimental study reported in [2] and, proposes design equations based on a detailed parametric study.

2. Numerical study

This section describes the development of finite element models of LCBs under ETF and ITF web crippling load cases. For this purpose, a general purpose finite element program, ABAQUS Version 6.14 [3], was used. Due to the convergence and contact difficulties faced in the non-linear static analysis, quasi-static analytical option was chosen to study the web crippling behaviour of cold-formed steel channel sections. Kaitila [4] and Natario et al. [5,6] also reported the use of quasi-static analysis method for web crippling as an alternative and economical analytical approach. Web crippling

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Table 1
Comparison of FEA and experimental web crippling capacities for ETF load case.

No	LCB	ℓ_b (mm)	f_y (MPa)	t_w (mm)	r_i (mm)	b_f (mm)	b_ℓ (mm)	d (mm)	L (mm)	$R_{b,Exp}$ (kN)	$R_{b,FEA}$ (kN)	$R_{b,Exp}/R_{b,FEA}$
1	ETF-C10010	25	581	1.03	3.5	50.5	13.4	100.4	306	1.76	1.80	0.98
2	ETF-C10015	25	540	1.52	4.0	50.0	15.4	100.0	307	4.24	4.40	0.96
3	ETF-C15012	25	556	1.21	4.0	62.0	19.6	150.0	456	2.06	2.21	0.93
4	ETF-C15015	25	531	1.52	4.5	62.5	18.1	150.2	456	3.63	3.68	0.99
5	ETF-C20019	25	506	1.91	5.0	77.0	22.1	203.7	609	5.51	5.15	1.07
6	ETF-C20024	25	526	2.41	5.0	76.5	20.4	203.6	609	9.10	9.04	1.01
7	ETF-C10010	50	581	1.03	3.5	50.5	13.6	100.3	306	1.74	1.95	0.89
8	ETF-C10015	50	540	1.52	4.0	51.3	15.7	100.9	307	4.47	4.61	0.97
9	ETF-C15012	50	556	1.21	4.0	61.8	19.5	150.7	456	2.23	2.13	1.05
10	ETF-C15015	50	531	1.52	4.5	62.5	18.4	150.0	456	3.74	3.67	1.02
11	ETF-C20019	50	506	1.91	5.0	76.5	21.9	203.4	609	5.63	5.50	1.02
12	ETF-C20024	50	526	2.41	5.0	76.4	20.4	203.5	606	7.20	9.63	0.75[a]
13	ETF-C10010	100	581	1.03	3.5	50.2	14.0	99.8	306	2.13	2.31	0.92
14	ETF-C10015	100	540	1.52	4.0	50.9	15.3	100.4	306	5.27	6.32	0.83
15	ETF-C15012	100	556	1.21	4.0	61.9	19.6	150.9	456	2.46	2.43	1.01
16	ETF-C15015	100	531	1.52	4.5	60.0	19.8	150.0	456	4.03	4.09	0.99
17	ETF-C20019	100	506	1.91	5.0	76.5	22.0	203.4	606	6.01	5.93	1.01
18	ETF-C20024	100	526	2.41	5.0	76.4	20.4	203.5	609	9.45	10.75	0.88
Mean												0.96
COV												0.08

Note: ℓ_b = Bearing plate length, f_y = yield stress, L = specimen length and others are defined in Fig. 1(c).

[a] Lower failure load ratio may be due to a premature failure caused by an error relating to ETF test set-up

tests conducted in a laboratory can be considered as a dynamic process with a very slow load rate. The experimental study conducted in this research was based on displacement controlled load application, where the cross-head of the testing machine was moved at a constant rate (0.7 mm/min) until the test specimen failed in web crippling. Therefore this loading process can be simulated using quasi-static analysis.

Quasi-static analysis is based on a dynamic equilibrium of inertia forces, frictional damping forces and liner stiffness matrix. When considering experimental web crippling scenario, contribution of inertia forces due to mass acceleration can be considered insignificant. The damping forces due to friction are also minimal. Therefore, in quasi-static analysis of web crippling, displacements due to the vertical movement of loading plate determines the equilibrium, which controls the non-linear stiffness matrix.

ABAQUS provides two solver options such as ABAQUS/Implicit (Standard) and ABAQUS/Explicit to solve static and quasi-static problems. The first option is recommended for solving smooth nonlinear problems and the later for dynamic equilibrium. According to ABAQUS user manual, both solvers can be used for quasi-static problems. But, it may have converging difficulties in ABAQUS/Standard due to contact and material complexities, resulting in a large number of iterations required for solving a bulk set of linear equations. Although a given analysis may require a large number of time increments using the explicit method, the analysis can be more efficient in ABAQUS/Explicit than in ABAQUS/Standard. For problems in which the computational cost of the two programs may be comparable, the substantial disk space and memory savings of ABAQUS/Explicit make it more attractive. Therefore, ABAQUS/Explicit solver was chosen in this research as it is more efficient for three-dimensional problems involving contact and large deformations.

Table 2
Comparison of FEA and experimental web crippling capacities for ITF load case.

No	LCB	ℓ_b (mm)	f_y (MPa)	t_w (mm)	r_i (mm)	b_f (mm)	b_ℓ (mm)	d (mm)	L (mm)	$R_{b,Exp}$ (kN)	$R_{b,FEA}$ (kN)	$R_{b,Exp}/R_{b,FEA}$
1	ITF-C10010	25	581	1.03	3.5	50.6	14.3	99.9	510	7.05	6.56	1.08
2	ITF-C10015	25	540	1.52	4.0	51.2	15.9	101.1	510	14.43	14.54	0.99
3	ITF-C15012	25	556	1.21	4.0	62.1	19.6	150.3	760	9.13	8.0	1.14
4	ITF-C15015	25	531	1.52	4.5	62.5	18.2	150.1	760	15.36	13.63	1.13
5	ITF-C20019	25	506	1.91	5.0	76.4	22.0	203.6	1015	22.99	19.92	1.15
6	ITF-C20024	25	526	2.41	5.0	76.6	20.0	203.7	1015	36.71	32.58	1.13
7	ITF-C10010	50	581	1.03	3.5	50.3	14.5	100.4	510	6.41	5.98	1.07
8	ITF-C10015	50	540	1.52	4.0	50.0	15.6	101.1	510	14.30	13.66	1.05
9	ITF-C15012	50	556	1.21	4.0	62.0	18.3	151.1	760	8.16	7.95	1.03
10	ITF-C15015	50	531	1.52	4.5	61.4	18.3	150.8	760	13.17	13.21	1.00
11	ITF-C20019	50	506	1.91	5.0	76.6	22.0	203.6	1015	20.70	20.54	1.01
12	ITF-C20024	50	526	2.41	5.0	76.7	20.6	203.6	1019	34.41	34.92	0.99
13	ITF-C10010	100	581	1.03	3.5	50.7	13.3	100.1	510	6.45	6.18	1.04
14	ITF-C10015	100	540	1.52	4.0	50.9	15.5	100.8	510	14.34	14.4	1.00
15	ITF-C15012	100	556	1.21	4.0	62.3	19.6	150.4	760	8.14	7.72	1.05
16	ITF-C15015	100	531	1.52	4.5	62.7	18.3	150.0	760	12.92	12.76	1.01
17	ITF-C20019	100	506	1.91	5.0	77.3	19.4	203.1	1015	20.19	18.62	1.08
18	ITF-C20024	100	526	2.41	5.0	76.7	20.2	203.6	1013	33.68	33.62	1.00
Mean												1.05
COV												0.05

Note: ℓ_b = Bearing plate length, f_y = yield stress, L = specimen length and others are defined in Fig. 1(c).