

FLEXURAL TEST ON COLD-FORMED STEEL I BEAMS

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Abstract

Currently, cold-formed steels are commonly used widely in the steel building industries. However, because of the weak torsional rigidity of singly-symmetric cold-formed steel sections such as lipped channel sections, an experimental investigation on cold-formed steel I sections under a 4-point bending test was conducted. The I sections, IC10019 and IC15019, were assembled with bolts on the webs of 2 identical lipped channel sections that resulted in 4 different connection spacings, $L/6$, $L/4$, $L/3$, and $L/2$ with a span length of $L_s = 3.8$ m. The web height and connection spacing (bolts spacing) were key parameters in this study. The results show that when the connection spacing is smaller, the web height is more influential on the increase of the maximum load, but it is less influential on the deflection reduction. The connection spacing is also influential on maximum loads. Local or/and distortional buckling occurred at the load-bearing plate, at mid-span, and between the load-bearing plate and mid-span.

Keywords: Lipped channel section, I section, connection spacing, 4-point bending test

Introduction

Because of the incredible advantages of cold-formed steels, such as their lightweight, highest strength-to-weight ratio, they have been popularly used for steel constructions as well as in research. However, cold-formed steel's singly-symmetric sections have insufficient torsional rigidity to carry heavy loads. This was the reason that a cold-formed steel built-up I

section was investigated. The provisions of the American Iron and Steel Institute's specification has only a little information about the cold-formed steel built-up I section in which only a connection spacing $L/6$ is provided for maximum value (American Iron and Steel Institute, 2016). Lateral-torsional buckling and distortional buckling were found in a study

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about the structural behavior of cold-formed steel C back-to-back beams without lateral bracing (Kang and Chaisomphob, 2016). The cold-formed steel built-up I section provided a very interesting result that the load capacity of built-up I sections was over 3.5 times larger than C-sections (Laim *et al.*, 2013). On the other hand, the ultimate moments obtained from the 3-point bending test were higher than those from the 4-point bending test for a built-up I section with lips while the ultimate moments of the 3-point bending test were lower than those from the 4-point bending test in the case of a built-up I beam without lips (Wang and Young, 2016). Moreover, a study on the behavior of a cold-formed steel built-up I section with circular web holes was also conducted (Wang and Young, 2015). The hole diameter-to-web depth ratio (d_h/h_w) is the parametric value in the study. The influence on moment capacity is small when the d_h/h_w is not more than 0.5 while it is large when the d_h/h_w increases to 0.7.

Therefore, this study focuses particularly on cold-formed steel built-up I beams of 3.8 m span length with lateral bracing under a 4-point bending test and the bolts that were used to make up these cold-formed steel built-up I beams.

Type of Connection

The bolt connection is a common fastener used in cold-formed steel built-up beams (Lee *et al.*, 2014). All specimens were made up by connecting 2 identical lipped channel sections bolted onto the flat portion of the webs and so doubling the thickness. There are 2 bolts in 1 connection in which 1 bolt is at the upper web and the other bolt is at the lower web by with a distance of 40 mm or 70 mm between each other in a vertical direction for sections IC10019 or IC15019, respectively (Figure 1). It is noted that there was 1 bolt connection placed 35 mm from each beam's end and another bolt connection placed 200 mm from each beam's end for strong protection against chance failure at each support. It was also the starting point for a clear span length, L , which was divided into 4 types of connection spacing, $L/6$, $L/4$, $L/3$, and $L/2$.

Lateral Bracing Steel Frame

Because of the low torsional rigidity and flexural rigidity about the y-axis, a lateral bracing steel frame (Figure 2) was proposed to reduce the unbraced length of the specimen in this study. It was installed at each load-bearing plate to prevent twisting, rotation, or bending about the y-axis of the specimens during testing. This lateral bracing steel frame was made with a hollow rectangular steel section with dimensions of 32 mm × 16 mm, which can provide strong protection for the lateral displacement of the specimens during testing without deformation. All hollow rectangular section steels were connected to each other with bolts and the holes can be adjusted to the built-up I section's dimensions in order to set up the specimens easily.

Test Set-up

The 4-point bending test was used for this study. The specimen (no.1 in Figure 2) was placed on a simple support (nos. 2 and 3 in Figure 2) with dimensions of 200 mm × 400 mm. Two vertical LVDTs (no. 4 in Figure 2) were put at mid-span of the specimen to measure the vertical deflections. Two strain gauges (no.5 in Figure 2) were placed on the center of each top flange and the other 2 strain gauges were at the center of each bottom flange of all specimens at mid-span to measure the deformation of the specimens. The support constraint steels (angle steels: no. 6 in Figure 2) were put at both the pinned support and roller support. The lateral bracing steel frame (no. 7 in Figure 2) was erected at each load-bearing plate (no. 8 in Figure 2)

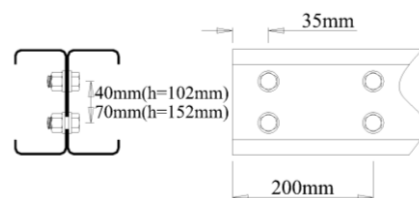


Figure 1. Detail of bolt connection

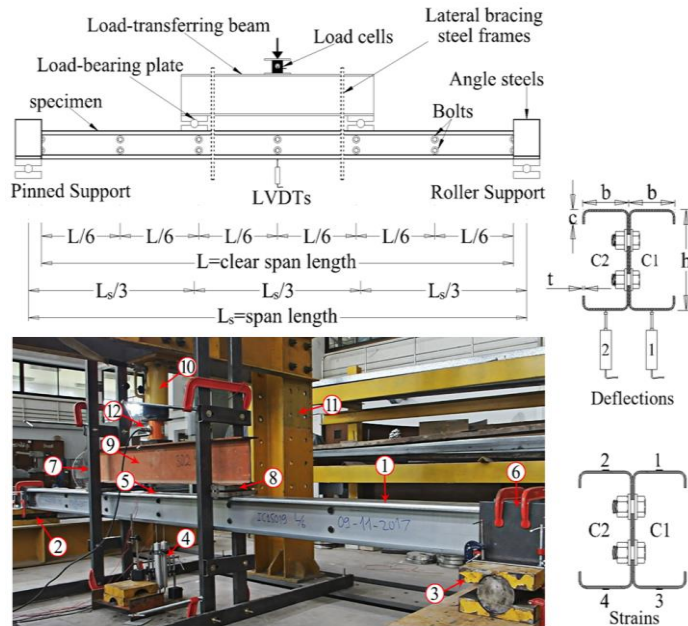


Figure 2. Overall on experiment set-up

which was placed at $L_s/3$ from the center of each support. The load-transferring beam (no. 9 in Figure 2) was necessary to put on load-bearing plates for converting the 1-point load from the hydraulic jack (no. 10 in Figure 2) connected with a 2D steel frame (no. 11 in Figure 2) to a 2-point load on the specimen by the load-bearing plates. A load cell (no. 12 in Figure 2) was put between the hydraulic jack and the load-transferring beam to record data from the load continuously. Finally, the strain gauges, LVDTs, and load cell were connected to a data logger for converting into numerical data and the specimen was also labelled.

Test Procedure

After the specimens and all transducers were completely prepared, they were loaded gradually with a hydraulic pump. A camera was also set up in order to examine the structural behavior of the specimens such as the failure modes. The specimens were loaded continuously until they reached their ultimate loads. A specimen

was considered to have failed when the load dropped noticeably and, then, unloading was conducted.

Specimen Geometry

The properties of the tested specimens' sections are shown in Table 1. The cold-formed steel built-up I sections used in the experiment were IC10019 and IC15019 with $F_y = 510$ MPa and $F_u = 546$ MPa. The experimental tests were conducted with a 3.8 m span length and 4 connection spacings (bolt spacings), $L/2$, $L/3$, $L/4$, $L/6$ where L is the clear span length. The inner radius of all sections of a specimen was equal to 5 mm. The name of the specimens related to the configuration of the cross section, thickness, and height.

Parametric Study

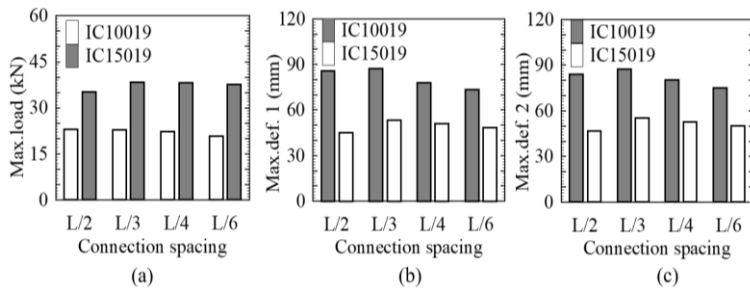
The influence of the web height and connection spacing is studied in this research. The load-

Table 1. Properties of sections

Name	Height h (mm)	Flange b (mm)	Thickness t (mm)	Lip c (mm)	Connection spacing (mm) L/6, L/4, L/3, L/2
IC10019	102	51	1.9	14.5	600, 900, 1200, 1800
IC15019	152	64	1.9	16.5	

Table 2. Experimental results of maximum loads and deflections

Specimen	Connection spacing	Maximum load (kN)	Deflection, Δ_{v1} (mm)	Deflection, Δ_{v2} (mm)
IC10019	L/2	22.97	85.61	84.15
	L/3	22.91	87.09	87.39
	L/4	22.17	78.07	80.21
	L/6	20.70	73.45	75.20
IC15019	L/2	35.29	45.11	46.64
	L/3	38.39	53.14	55.40
	L/4	38.21	51.04	52.84
	L/6	37.63	48.35	49.98

**Figure 3. Influence of web height on (a) maximum loads, (b) deflection1, (c) deflection2**

deflection curves, load-strain curves, and failure modes are discussed to understand the structural behavior of the specimens.

Experimental Results and Discussions

The maximum loads, maximum deflections, strains at compression and tension parts, as well as the failure modes were obtained from 8 tested specimens under the loading stage, load failure, and unloading stage. Table 2 summarizes the experimental results of specimens IC10019 and IC15019 corresponding to each connection spacing of the same span length of $L_s = 3.8\text{m}$.

Influence of Web Height on Maximum Loads

From Figure 3(a), the increase of the section's web height leads to an increase in the maximum loads. When the web height increases 57%, the maximum load increases 54%, 68%, 72%, and 82% for the connection spacings L/2, L/3, L/4, and L/6, respectively. Moreover, when the connection spacing is smaller, the web height has more influence on the increase of the ultimate loads.

Influence of Web Height on Deflections

When the web height increases, it causes the maximum deflections' decrease due to the variation of the second moment. The maximum

deflection 1 reduces by 90%, 64%, 53%, 52% and the maximum deflection 2 decreases by 80%, 58%, 52%, 50% for the connection spacings of $L/2$, $L/3$, $L/4$, and $L/6$, respectively, when the web height increases 57% (Figures 3(b) and 3(c)). Additionally, when the connection spacings become smaller, the web height is less influential on the decrease of the maximum deflections.

Load-deflection Curves

The load-deflection curves of all specimens are plotted in 1 graph by separating as deflection 1, Δ_1 , and deflection 2, Δ_2 (Figure 4). Each section has 4 connection spacings represented by blue, red, black, and green for connection spacings $L/2$, $L/3$, $L/4$, and $L/6$, respectively. It is noticed that the relationship between the load and deflection has a similar tendency for all connection spacings during the loading stage. However, for the specimens of section IC10019, the maximum loads of the connection spacings $L/3$, $L/4$, and $L/6$ compared to $L/2$ increase or decrease interestingly in the range from 0.3% to 10%. For the specimens of section IC15019, the increases or decreases of the maximum loads of the connection spacings $L/3$, $L/4$, and $L/6$ compared to $L/2$ are in the range from 6% to 8%. According to these percentages, it can be illustrated that connection spacings are also influential on the maximum load. Moreover, all curves of the specimens dropped immediately after the maximum load was reached. It can be indicated that the collapse of the specimens

occurred suddenly. From Figure 4, it can be seen that when the section has the same thickness with different heights, the deflections of the higher sections are lower than the shorter sections, but the maximum loads of the high section are greater than the small section. From Table 2, it can be observed that the different percentages of deflection 1 and deflection 2 at the maximum load are in the range from 0.34% to 3% and from 3% to 4% for the specimens of section IC10019 and IC15019, respectively.

Load-strain Curves

Another parameter taken into account in this study is the strains of the cold-formed steel section at mid-span. Figure 5 shows all the longitudinal strain values considered at maximum loads. It can be observed that when the sections have the same thickness with a different height, the high sections provide greater maximum loads than the small sections, but the high sections seem to provide smaller tensile strains at maximum loads than the small sections. Moreover, the compressive strains of the specimens for all connection spacings $L/2$, $L/3$, $L/4$, and $L/6$ are always higher than the tension strains at the maximum load except for compression strain 2 (red curves) of C2 for specimen IC15019.

Failure Modes of Specimens

Two kinds of failure mode are shown in Table 3. Local (LB) and distortional (DB) buckling appeared on the specimens. It can be

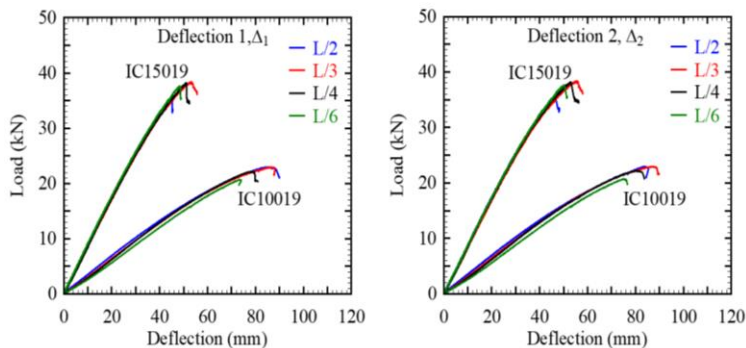


Figure 4. Load-deflection curves of all specimens

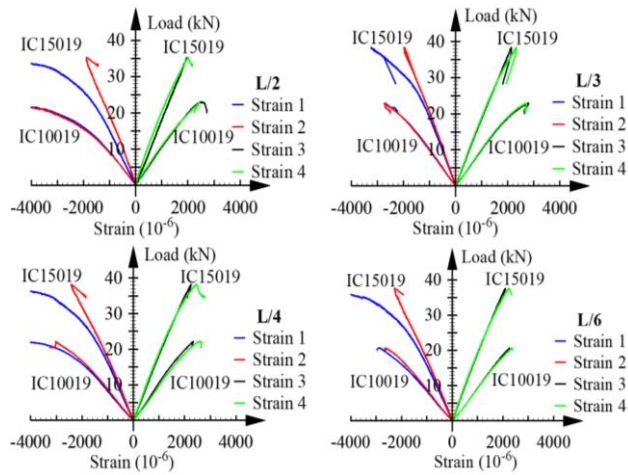


Figure 5. Load-strain curves of all specimens

Table 3. Experimental results of failure modes

Specimen	CS ^a	Point (A)		Mid-span and A/B		Point (B)	
		C2	C1	C2	C1	C2	C1
IC10019	L/2	-	-	DB ^c	-	-	-
	L/3	LB+DB	LB+DB	-	-	LB+DB	LB+DB
	L/4	-	-	-	DB	-	-
	L/6	LB ^b	LB+DB	-	DB	-	-
IC15019	L/2	-	-	-	LB+DB	-	-
	L/3	LB+DB	LB+DB	-	-	LB+DB	LB+DB
	L/4	-	-	-	LB+DB	-	-
	L/6	-	-	-	LB+DB	-	-

^a Connection spacing, ^b Local buckling, ^c Distortional buckling.

seen that there are 3 positions where failure modes occurred. They are at the load-bearing plate which is next to the pinned support (Point A), at the load-bearing plate that is next to the roller support (Point B), and at mid-span or between mid-span and the load-bearing plate depending on the types of the specimens. It is noticed that local or distortional buckling happens separately on some specimens; but a combination between local and distortional buckling occurred on some specimens. However, there was no failure mode that happened on specimens at mid-span for the connection spacing of L/3, but each web of the section separated noticeably from each other due to the absence of a bolt connection at mid-span. Some experimental pictures of failure modes are illustrated in Figure 6.

Conclusions

In this research, the web height section becomes the key parameter for improving the load capacity of cold-formed steel built-up I beams while the connection spacing improves the load capacity of beams by, at the most, 10%. The cold-formed steel built-up I beams failed through local and/or distortional buckling. The absence of a bolt connection at mid-span made the webs of the C-section separate noticeably from each other.

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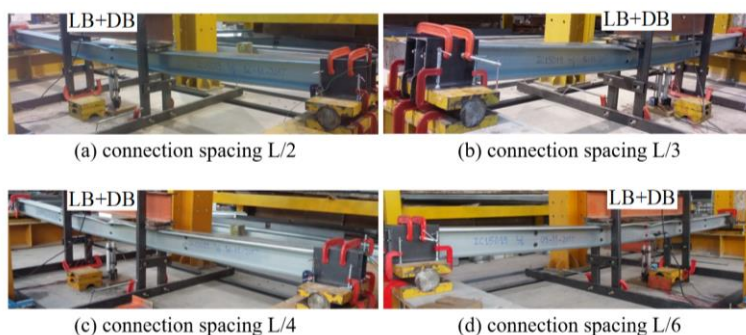


Figure 6. Failure mode of specimens IC15019

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