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WEB CRIPPLING BEHAVIOUR OF COLD-FORMED SIGMA CHANNEL SECTIONS WITH WEB OPENINGS: EXPERIMENTAL STUDY

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Abstract. *Over the past few years, Cold-Formed (CF) channel sections have received significant attention in the construction industry based on their inherent characteristics such as high strength-to-weight ratio, high dimensional accuracy and cost-effectiveness. These channel sections are often fabricated with web openings to facilitate service lines. With the inclusion of web openings, these web-perforated CF channel sections are susceptible to different types of buckling failure modes including web crippling. However, the web crippling response of CF carbon steel sigma channel sections with web openings has not been investigated yet. Bridging this knowledge gap, this paper presents an experimental analysis conducted on the web crippling behaviour of CF steel sigma channel sections with web openings. Experimental analysis was focused on CF Sigma channel sections subjected to Interior Two Flange (ITF) loading condition. Assessing the suitability of existing design guidelines, these experimental results were then compared with the web crippling capacity predictions from existing design guidelines.*

1 INTRODUCTION

With the recent developments in the construction industry, Cold-Formed Steel (CFS) sections are extensively used in structural steelwork, overruling their hot-rolled counterparts. Intrinsic characteristics of CFS including, high specific strength, high dimensional accuracy, ease of fabrication, transportability and installation simplicity, and cost-effectiveness, have resulted in this advancement. CFS sections, fabricated using cold rolling or press brake mechanisms, offer a wide range of section geometries to meet diverse industrial requirements (Figure 1). These sections frequently incorporate web openings, facilitating easy installation of electrical and plumbing lines. However, these web openings increase the risk of member failure through web crippling [1–4]. Depending on the location of the applied load or reaction, these web crippling failures can be categorized into four types: Interior One Flange (IOF), End One Flange (EOF), Interior Two Flange (ITF) and End Two Flange (ETF) loading conditions.

Davis [5] conducted one of the earliest experimental investigations on the web crippling behaviour of web perforated CFS lipped channel sections. The experimental study comprised of 20 tests conducted on the web crippling behaviour of CFS back-to-back channels or two-lipped channel sections (connected through the lips) with circular and square web openings,

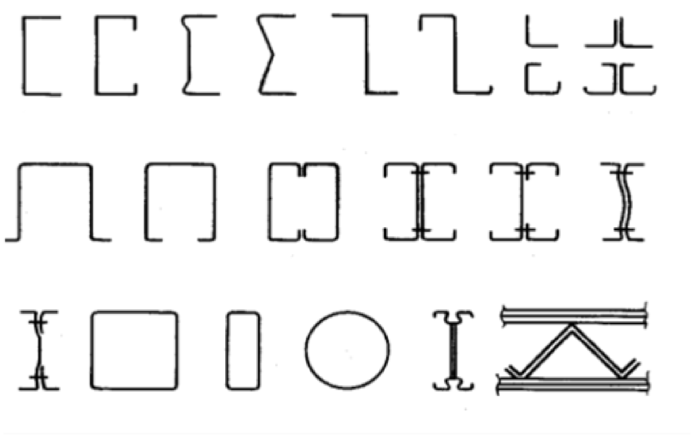


Figure 1: Different cold-formed section geometries [6]

under ITF loading condition. Openings were located at the mid-depth of the web centered beneath the bearing plates. Based on the experimental results Davis [5] proposed reduction factors to account for the web crippling strength reduction caused by the openings. Sivakumaran [7] and Sivakumaran and Zielonka [3] experimentally investigated the web crippling behaviour of CFS lipped channel sections with rectangular web openings under the IOF loading condition. Opening height to web height and the opening width to effective bearing length of the section were identified as the prominent parameters affecting the web crippling strength reduction [3]. Considering these parameters, a reduction factor equation was derived to predict the web crippling capacity of web perforated CFS lipped channel sections under IOF loading condition. Based on extensive experimental studies, Langan et al. [8] and LaBoube et al. [4] developed reduction factor equations to predict the web crippling capacity of CFS lipped channel sections with offset web openings under one flange loading conditions. Both Langan et al. [8] and LaBoube et al. [4] identified the ratio of the hole depth to the flat depth of the web and the ratio of the distance from the edge of the bearing to the flat depth of the web as the key parameters affecting the web crippling capacity of CFS lipped channel sections with offset web openings. Reduction factor equations developed by LaBoube et al. [4] were incorporated into the North American Specification for design of cold-formed steel structural members(AISI S100-07) [9] and Australian/New Zealand standard for cold-formed steel structures (AS/NZS 4600:2005) [10], and they remain effective to date.

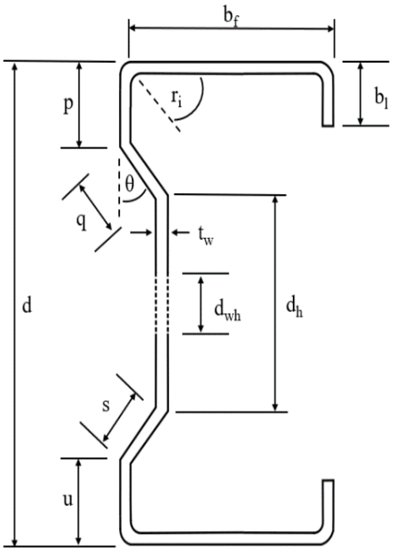


Figure 2: Definition of used symbols

Being dependent on empirical data, these reduction factor equations were identified to be limited to certain cross-sectional geometries and opening configurations. Hence, recently Uzzaman et al. [1,11–13] and Lian et al. [14–17] conducted combined experimental and numerical investigations on the web crippling reponse of CFS lipped channel sections with circular web openings under two flange and one flange loading conditions, respectively. These studies investigated both scenarios, where web openings were centered beneath the bearing plates [11,12,14–17] and located at a fixed offset distance from the bearing plate [1,13–17]. Based on these experimental and numerical results, a/h and N/h ratios were identified to be the primary factors affecting the web crippling strength of CFS lipped channel sections with centered web openings. The terms a, N and h refer to hole depth, bearing length and flat depth of the web, respectively. Resembling the findings of Langan et al. [8] and LaBoube et al. [4] , the ratios a/h and x/h were identified to be the main parameters affecting the web crippling response of CFS lipped channel sections with offset web openings. The terms a, x and h refer to hole depth, offset distance from the web opening to the bearing plate and flat depth of the web, respectively.

Despite numerous investigations conducted on the web crippling response of conventional CFS lipped channel sections [18–22], web crippling behaviour of web perforated CFS sections with advanced sectional geometries remains unexplored. Cold-formed steel Sigma section is one such advanced channel section geometry. Hence, an experimental investigation was conducted in this study to evaluate the effect of circular web openings on the web crippling response of CFS Sigma channel sections under the ITF loading condition. The experimental results were compared with existing design equations to assess their applicability in predicting the web crippling capacity of CFS Sigma channel sections with web openings.

2 EXPERIMENTAL INVESTIGATION

2.1 General

This section summarizes the experimental study conducted on the web crippling response of web perforated CFS Sigma sections under the ITF loading condition. Altogether six web crippling tests were conducted based on the test standard proposed by the American Iron and Steel Institute (AISI S909-17) [23]. Cross-section dimensions of the Sigma sections were selected based on the optimized sectional geometries proposed by Gatheeshgar et al. [24], while the specimen lengths were chosen as per the AISI S909-17 [23] test standard. These CFS Sigma sections were manufactured considering the press brake mechanism. Table 1 shows the measured dimensions of the specimens. Figure 2 illustrates the nomenclature used in Table 1.

The effect of opening diameter on the web crippling strength was assessed by considering three web opening ratios (d_{wh}/d_1= 0, 0.2, 0.6). Here, d_1 represents the clear web height of the section. These openings were located at the mid-depth of the web to be centered underneath the top bearing plate. Two bearing lengths (120 mm and 150 mm) were considered to evaluate the effect of bearing length on the web crippling behaviour of web perforated CFS Sigma sections. These bearing plates were manufactured considering high strength steel. Thicknesses of the bearing plates were maintained to be 25 mm, while the plate width was taken as b_f + 20 mm. Table 2 provides the summary of the web crippling tests conducted in this study.

2.2 Material tests

Initiating the experimental study, material tests were conducted to identify the mechanical properties of CFS Sigma sections. These tests were conducted as per the Australian Standard for metallic materials (AS 1391) [25]. Following AS 1391 [25] guidelines, tensile coupons were

Table 1: Measured dimensions of the Sigma sections

Specimen number	L	d	d_h	d_{wh}	b_f	b_l	p	q	s	u	r_i	t_w	θ
S25	1324	268	137	0	50.42	17.16	41	31	30	41	1.75	0.89	34°
S26	1324	268	138	0	49.53	16.75	41	30	30	41	1.75	0.91	34°
S27	1325	269	137	80.12	49.4	18.53	41	30	29	42	1.75	0.88	34°
S28	1324	268	138	80.13	50.03	17.55	41	30	29.5	41	1.75	0.89	34°
S29	1324	268	138	159.00	50.32	16.99	41	30	29	41	1.75	0.89	34°
S30	1325	268	137	159.00	49.98	16.53	41	30	29	41	1.75	0.88	34°

L is the length of the specimen, d_{wh} is the depth (diameter) of the web opening

fabricated from flat web regions (top web, middle web, bottom web, respectively) of three CFS Sigma sections, along their longitudinal direction. Altogether nine coupons were fabricated (three coupons from each section). To remove the top coating, these coupons were immersed in a diluted hydrochloric acid solution for 45 minutes. The coupon surfaces were then cleaned with fine-grade emery paper and an acetone solution [26]. The original width and thickness of each coupon were measured at three locations along the gauge length. These dimensions were used in calculating the mechanical properties.

Following coupon preparation, tensile tests were performed using a displacement-controlled Instron testing machine. The longitudinal strain of coupons was measured using an extensometer. Applied load and strain data obtained from the extensometer were automatically recorded using a data acquisition system and were used in determining the yield stress, ultimate tensile stress and elastic modulus of CFS. Table 3 summarizes the results of the tensile coupon tests. Material test results from two coupons were excluded due to inconsistency with other test results.

2.3 Test setup and procedure

Web crippling test setup (Figure 3) was designed based on the guidelines given in the AISI S909-17 [23] test standard. A transverse concentrated load was applied using a 600 kN Instron testing machine. Increasing the accuracy of measured load readings, an additional 50 kN load cell was used to measure the applied transverse load. Bearing plates were fastened to the loading arrangement with half rounds to simulate the pinned support condition. As shown in figures 3 and 4, two Linear Variable Displacement Transducers (LVDT’s) were used to record the lateral (web) and vertical (flange) deformations of the test specimen subjected to transverse loading. A data acquisition system was used to record the applied vertical loading and lateral and vertical displacements of the test specimen at regular time intervals throughout the testing period. Due to experimental limitations, vertical displacement directly under the loading plate was obtained by considering the displacement of the loading arm.

Table 2: Experimental plan

Loading condition	Specimen number	Section length (mm)	Bearing length, l_b (mm)	Opening diameter (mm)	d_{wh}/d_1	Number of sections tested
ITF	S25	1324	120	0	0	1
	S28	1324		80.13	0.2	1
	S29	1324		159.00	0.6	1
	S26	1324	150	0	0	1
	S27	1325		80.12	0.2	1
	S30	1325		159.00	0.6	1

d_1 is the clear web height of the section

Initiating the web crippling test, CFS Sigma specimen was positioned between the top and bottom bearing plates, ensuring that the bearing plates were located at the mid-span of the test specimen. A 50 N load was applied to achieve uniform settlement of the loading and support sytems on the bearing plates. After zero setting the data acquisition system, loading was initiated by maintaining a constant crosshead speed of 0.8 mm/min until the specimen failed.

2.4 Test results and analysis

Table 4 shows the web crippling capacities of the tested Sigma sections. All six sections exhibited web crippling failure, and no combined failure modes were observed. Figures 5 (a)-(f) show the observed web crippling failure modes. Figure 6 shows the applied load versus deflection (vertical and horizontal) curves generated for a tested CFS Sigma specimen. A gradual web crippling strength reduction was observed with the increase of the opening diameter. A similar behaviour was observed in past experimental studies conducted on web perforated CFS lipped channel sections [11]. In comparison to CFS Sigma sections without web openings, average web crippling strength reductions of 4.8% and 9.8% were observed for d_{wh}/d_1 ratios of 0.2 and 0.6, respectively. Similar to previous research findings [11,22], a gradual increase in web crippling strength was observed as the bearing length increased. Figure 7 depicts the web crippling strength variations observed with different d_{wh}/d_1 ratios and bearing length to flat web depth (l_b/d_1) ratios.

Table 3: Results of the tensile coupon tests

Specimen number	Average yield stress,fy (MPa)	Average ultimate tensile stress,fu (MPa)	Average elastic modulus, E (Pa)
Sigma 1	251	324.5	203477
Sigma 2	277.5	336.5	203368
Sigma 3	271.7	328.3	196190
Average material properties	266.7	329.8	201011

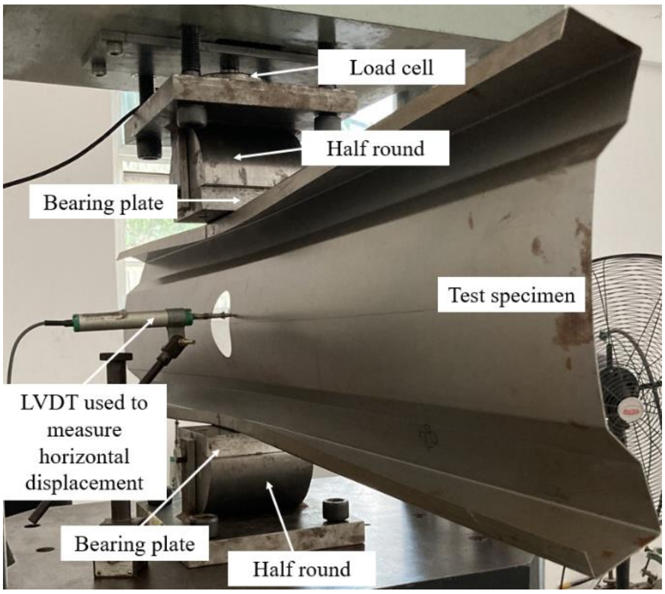


Figure 3: Web crippling test setup

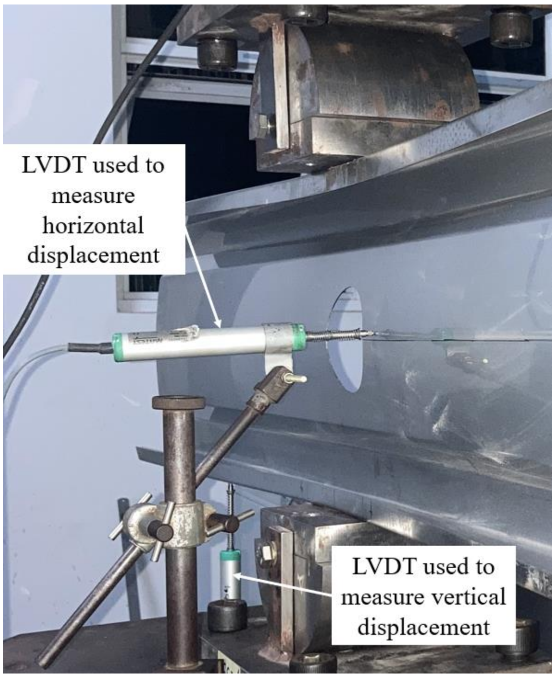


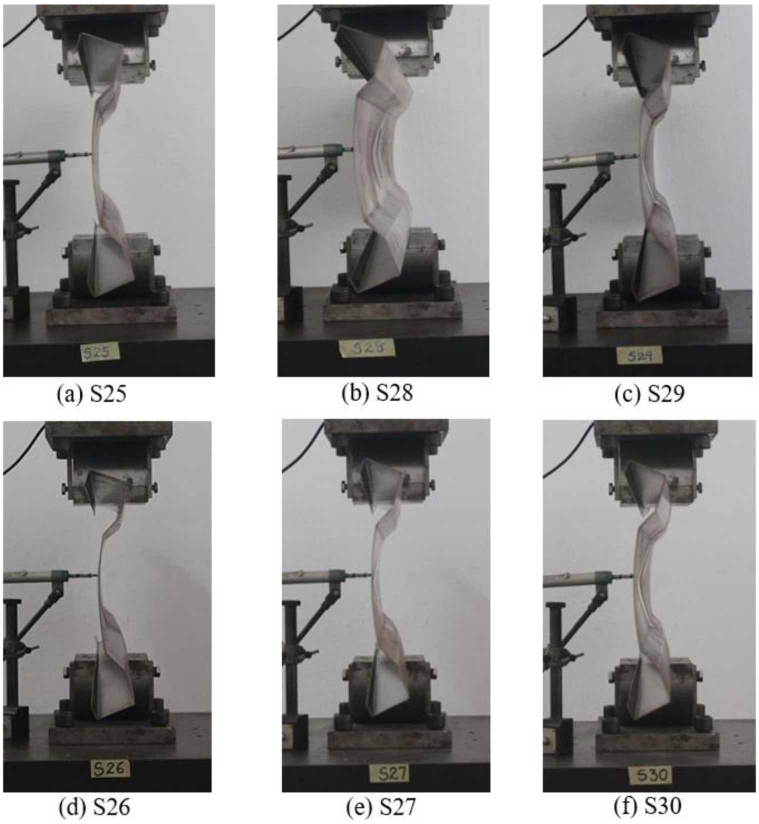
Figure 4: Arrangement of the LVDT's

3 APPLICABILITY OF EXISTING DESIGN GUIDELINES

Eurocode 3 Part 1-3 (EN1993-1-3) [27], Australian/New Zealand standard for cold-formed steel structures (AS/NZS 4600) [28] and the North American specification for the design of cold-formed steel structural members (AISI S100-16) [29] are the three main design standards used in predicting the web crippling capacities of CFS channel sections. EN1993-1-3 [27] provides web crippling design equations limited to CFS sections without web openings. Web crippling design guidelines provided in AS/NZS 4600 [28] and AISI S100-16 [29], developed based on the findings of LaBoube et al. [4], are limited to web perforated CFS sections under one flange loading conditions. Additionally, these design guidelines are only applicable to CFS sections with a flat web depth to thickness ratio of 200 or less. Web crippling design equations provided in EN1993-1-3 [27] are only applicable to sections having an inside bent radius to thickness (r_i/t_w) ratio of six or less. When considering the ITF loading condition and unfastened support conditions, web crippling design guidelines provided in AS/NZS 4600 [28] and AISI S100-16 [25] are limited to sections with a r_i/t_w ratio of three or less. Moreover, it was observed that none of the above standards provides web crippling design guidelines specific to advanced CFS sectional geometries.

Table 4: Web crippling test results

Specimen number	Bearing length (mm)	Opening diameter (mm)	d_{wh}/d_1	Average l_b/d_1	Average d_1/t_w	Web crippling strength (kN)
S25	120	0	0	0.46	295	2.172
S28		80	0.2			2.073
S29		159	0.6			1.980
S26	150	0	0	0.57	295	2.202
S27		80	0.2			2.089
S30		159	0.6			1.965


(a) S25 (b) S28 (c) S29

(d) S26 (e) S27 (f) S30

Figure 5: Deformation patterns

However, given the growing industrial demand, there is an urgent need to develop web crippling design guidelines for CFS Sigma sections, with and without web openings. Therefore, the authors intended to compare the experimental web crippling capacities with the design guideline predictions. Nonetheless, the flat web depth to thickness ratios of all the tested specimens were greater than 200 (Table 4). Yet the test results were compared with the existing design guideline predictions (Figure 8). It was observed that both AS/NZS 4600 [28] and AISI S100-16 [29] design guidelines overestimate the web crippling capacity of web perforated CFS Sigma sections, while EN1993-1-3 [27] underestimate the same. However, further investigations are required to determine the adequacy of existing design guidelines for CFS Sigma sections with d_1/t ratios less than 200. It is thus proposed to use these experimental data to validate a numerical model which can effectively be used to conduct a parametric study and assess the applicability of existing design guidelines.

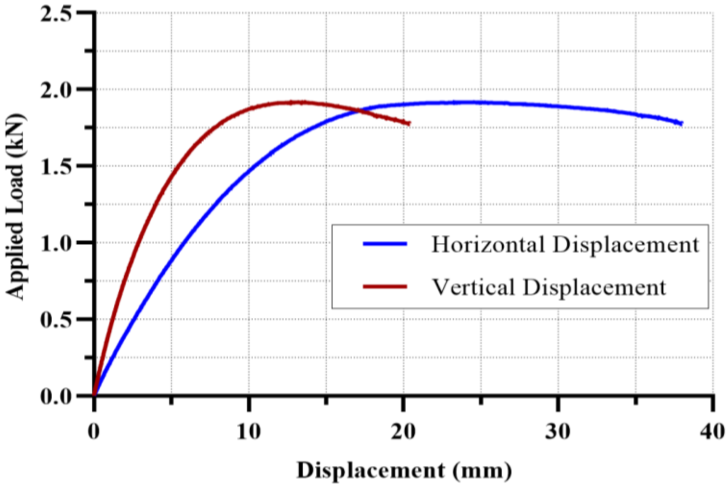


Figure 6: Applied load versus deflection curves for S29 specimen

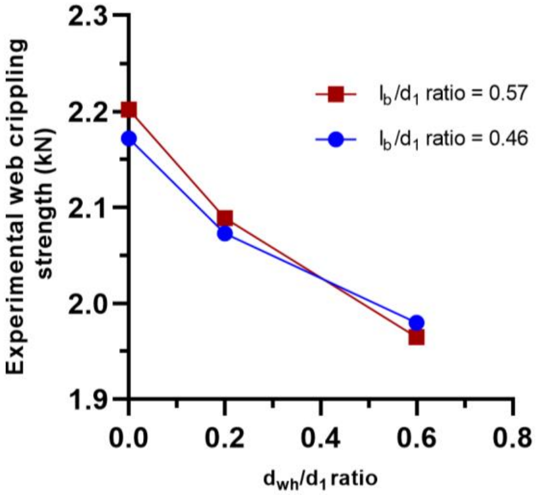


Figure 7: Web crippling strength variations with d_{wh}/d_1 and l_b/d_1 ratios

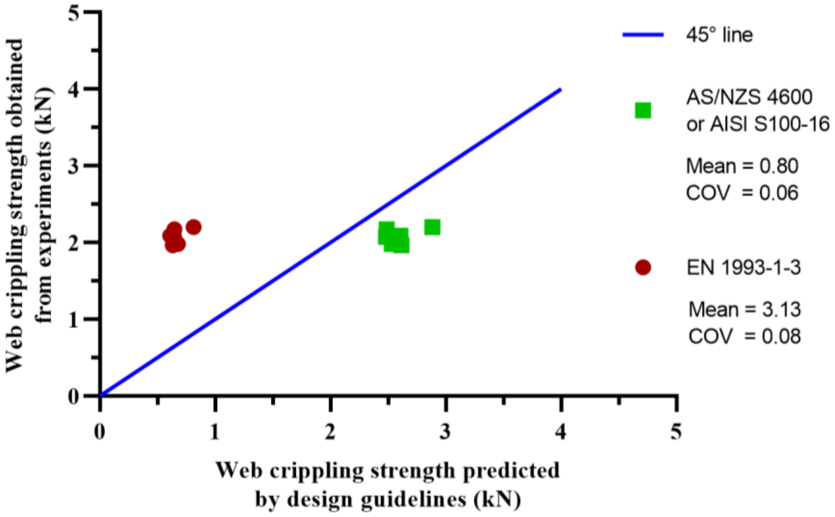


Figure 8: Comparison of experimental test results with design guideline predictions

4 CONCLUSION

This paper presents the details of an experimental study conducted on the web crippling behaviour of CFS Sigma sections with web openings under the ITF loading condition. Six Sigma sections (both with and without circular web openings) were tested considering two bearing lengths (120 mm and 150 mm). Three d_{wh}/d_h ratios (0,0.2 and 0.6) were considered to identify the effect of web openings on the web crippling strength. Tests were conducted as per the AISI S909-17 [23] test standard, considering the unfastened support conditions. The web crippling strength of CFS Sigma sections was found to decrease with increasing opening diameters. A considerable web crippling strength increment was observed in the sections tested under larger bearing lengths. Numerical studies are currently underway to further assess the applicability of existing design equations in predicting the ultimate web crippling strength of CFS Sigma sections with and without web openings.

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