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LITERATURE SURVEY OF WEB CRIPPLING EXPERIMENT ON CEE-SHAPED SPECIMENS WITHOUT PERFORATIONS

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Abstract— **Cold-Formed Steel (CFS) products are widely used in the field of building construction due to their inherent characteristics such as high material strength and design versatility. Depending upon their application and loading configuration, these structures are prone to different types of failures. Web crippling is a type of localized failure mode observed in CFS beam structures due to concentrated loading over them. The web crippling behavior in CFS products are influences by various factors including geometric, material, loading and environmental properties, making it a complex failure phenomenon.**
This literature survey investigates ten research studies performed on Cee-shaped CFS specimen, focusing on various dimensions and loading configurations. By examining the experimental and analytical methodologies considered across various studies, the paper attempts to consolidate the key findings which could propose future researches. The survey offers an insight into discrepancies in the design practices for predicting the ultimate web crippling strength in Cee-shaped Cold-Formed Steel specimens.

Keywords— **Cold-Formed Steel (CFS), Floor beams, Web crippling, Cee-shaped, Thin-walled, Failure mode, Local buckling**

I. INTRODUCTION

The use of cold-formed steel (CFS) structures has been prevalent in the construction industry since the 1850s. the lightweight and high strength properties of CFS products facilitated the growth of metal manufacturing industries in both the United States and Great Britain for over a century. However, during the 1930s, the utilisation of this innovative construction material was somewhat restricted. During the World War II, CFS structures were employed for the construction of military facilities including hangars and barracks [1]. The use of CFS in structural building applications commenced in 1940, as shown in Figure 1.
Cold-formed steel (CFS) exhibits greater strength than hot-rolled steel due to strain hardening, a property that develops during manufacturing processes such as press braking and roll forming. Thin sheets of raw steel are transformed into various shapes including Cee, Zee, I-channel and angle sections, based on design specifications. CFS is characterised by design versatility, high strength and stiffness, ease of mass production and installation, cost effectiveness and recyclability distinguishing it from other construction materials [2].

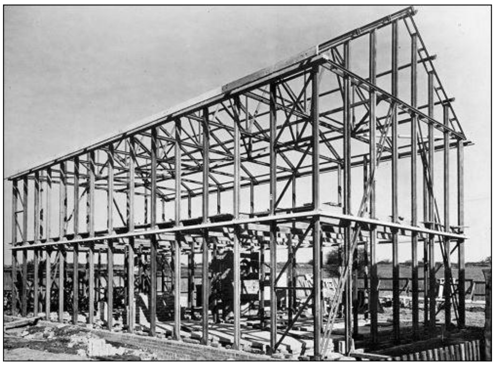

Fig. 1. CFS frame house manufactured during 1940 [3]

CFS products are utilized in a range of applications, including manufacturing equipment, automotive bodies, railway tracks, highway products, transmission towers and poles, drainage systems and bridge construction. However, the use of CFS in building construction, for elements such as wall covering, floor decks, roof panels, purlins, stud headers and attaching components, have been limited due to certain failure modes observed, when subjected to concentrated or distributed loading [4].

II. FAILURE MODE

Cold-formed steel (CFS) floor beams in building constructions exhibit several types of failure modes, when subjected to concentrated or distributed loadings as represented in Figure 2. The most common modes include local buckling, where individual elements buckle under compressive stress, distortional buckling involving deformation of the flanges and web together and lateral-torsional buckling where beam twists and displaces laterally due to bending [5,6,7].

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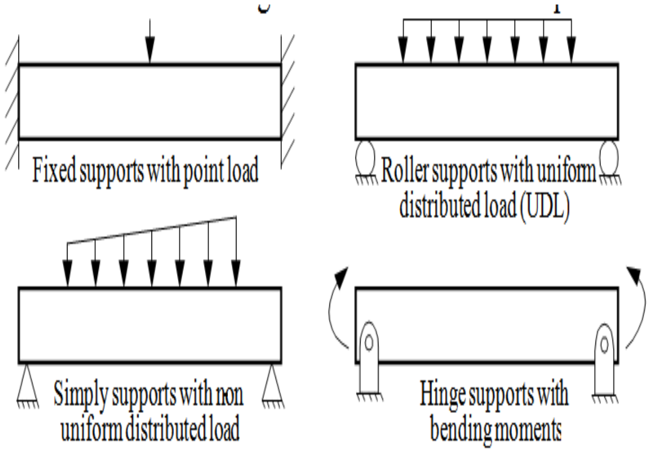

Fig. 2. Support and loading on beam structures [8]

Web crippling in CFS beams refers to the local buckling or crushing of the web under concentrated loads, typically observed in joist beam members as shown in Figure 3. The failure mode is influenced by load or reaction forces acting through one or both flanges and occurs when the web experiences intense localised stress concentration [9]. The American Iron and Steel Institute (AISI) classifies web crippling into four loading conditions; End-One-Flange (EOF), Interior-One-Flange (IOF), End-Two-Flange (ETF) and Interior-Two-Flange (ITF) [9]. IOF and ITF involves mid-span loading while EOF and ETF apply concentrated loads towards to the end of the beam, as shown in Figure 3.

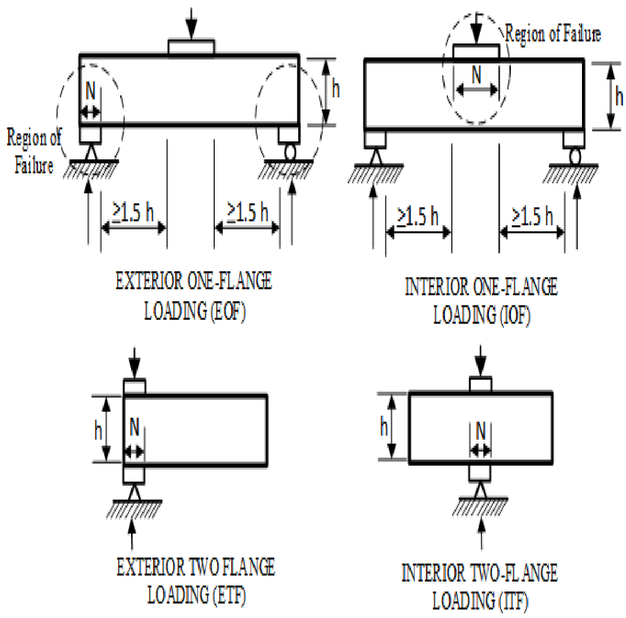

Fig. 3. Types of loading configuration for web crippling [10]

III. METHODOLOGY

In conducting a literature survey on web crippling in Cee-shaped specimens without perforations, a chronological review methodology is particularly advantageous. This approach facilitates a structured examination of various research studies allowing a clear understanding of the parameters affecting web crippling strength. By organizing studies based on their publication dates, the chronological review highlights significant advancements, including foundational experiments, emerging design codes and methodological refinements. Consequently, this methodology fosters a comprehensive understanding of trends and shifts in focus, ultimately enhancing the relevance and applicability of the review within the broader context of cold-formed steel beam structures.

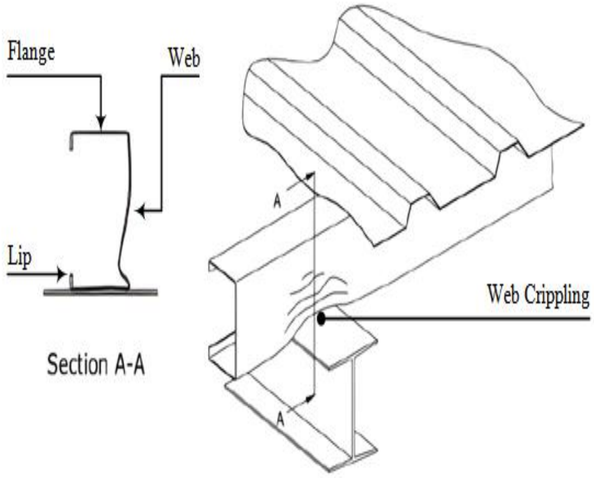

Fig. 4. Web crippling deformation observed in CFS beams [11]

IV. SURVEY

CFS products characterised by their wide and thin flanges, exhibit a high width-to-thickness ratio, which makes them susceptible to local instability. This vulnerability is significantly affected by the ratio of the web height to thickness, leading to a phenomenon known as web crippling [12]. The exploration of web crippling began with Winter and Puan at Cornell University, who pursued to derive a formula for determining the web crippling strength of I-section members.

Research conducted by Hetrakul, et al., (1978) and colleagues at the University of Missouri-Rolla, along with the contributions form Wing (1981) and Prabakaran, et al., (1993) culminated in the development of a unified design equation for both stiffened and unstiffened CFS sections which was adopted by AISI. Despite these advancement, numerous factors, such as cross-sectional geometry, presence of web perforations and various loading conditions impacted web crippling resistances of Cee-shaped specimens. This ongoing complexity has prompted further research focussing on alternative design guidelines tailored for different CFS products.

A. Early Research (1978-2000)

Yu, W.W. and Hetrakul, N., (1978) conducted one of the earliest web crippling experiments on Cee-shaped specimens with and without lips. 140 beam specimens with web height (D) ranging from 36.52 mm to 101.60 mm was considered for the web crippling experiments under IOF, ITF, EOF and ETF loading configurations, as shown in Table Loads were applied in increments of 15% of the expected ultimate web crippling strength, with results compared to the AISI 1968 edition. For beams with height-to-thickness ratios (h/t) less than 150, the end loading condition revealed that design equations overestimated web crippling loads for end two-flange loading, yielding test values approximately 15% lower than predictions, while underestimating loads for end one-flange loading (average ratio of 1.137). Under interior loading, the equations matched results for two-flange loading (0.988) but were conservative for one-flange loading (1.125). For h/t ratios between 200 and 250, the end one-flange ratio was 1.319 and the two-flange ratio was 1.076. In interior scenarios, the two-flange ratio was 0.782 and the one-flange ratio was 1.223. The flange type did not influence loads for interior one-flange loading but caused a 10% reduction in other loading conditions with unstiffened flanges [13].

Table -1 Experiment Result

Parameters	Range	
	Minimum (mm)	Maximum (mm)
Web Height	100.08	307.85
Flange Width	36.53	101.6
Lip Height	12.7	25.4
Thickness	1.17	2.66
Total Length	3048	4876.8

Bhakta, B. H., et al (1992) conducted an experimental investigation into the behavior of CFS members subjected to web crippling under End-One-Flange (EOF) loading conditions. The study included twelve Cee-shaped channel specimens with web height ranging from 199.39 mm to 229.12 mm along with thickness varying from 1.60 mm to 2.77 mm. The channel sections which were categorized based on the web slenderness ratio (h/t), with the specimens both fastened and unfastened with the bearing plate of width 66.67 mm. The web crippling strength for fastened specimens ranged from 6.61 MPa to 20.92 MPa, while for unfastened specimens, it ranged from 6.64 MPa to 18.98 MPa. The results showed that the fastened specimens exhibited higher web crippling resistance particularly with higher h/t ratio, than the unfastened specimens with the highest value of 18.98 MPa. The findings indicated that the web crippling strength when evaluated against the AISI design specifications, overestimated approximately by 18% for h/t ratio of 115 and conservative by 58% for h/t ratio of 131 [14].

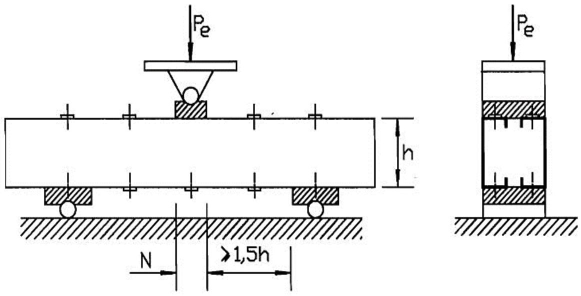

Fig. 5. Interior-One-Flange loading setup used by Korvink, S. A [15]

Korvink, S. A., et al., (1995) performed the experimental investigation on the Cee-shaped specimens under Interior-One-Flange (IOF) loading as represented in Figure 5, considering variations in web height and bearing plate width. The specimens, fabricated from Type 430 stainless steel and modified Type 409 steel maintained a constant thickness of 1.6 mm, while the web heights ranged from 100 mm to 325 mm in 25 mm increments. Testing was carried out using an Avery-Denison loading apparatus at a constant loading rate of 5kN/min with failure loads recorded digitally. To prevent lateral instability, small plates were bolted to the top and bottom flanged during some tests. The experimental results revealed reasonable agreement with the American Society of Civil Engineers (ASCE/AISI 1991) design specifications for CFS though the formula was conservative for longer bearing widths. Both beam webs exhibited buckling at load application points prior to failure and for beams with larger web depths, significant and permanent deformation were observed at failure [15].

Young, Ben and Hancock, Gregory J., (1998) studied on the web crippling behavior of cold-formed unlipped channels using three series of materials. While series S1 and S2 were fabricated with web thickness ranging from 4 mm to 5 mm, web depths between 80 mm and 200 mm, series S3 specimens had thinner web thickness of 1.5 mm and web height of 96 mm. The experimental testing was carried out under all the four loading configurations. The results were compared again the AISI 1996 design specification for predicting web crippling strength, along with Australian/ New Zealand Standard (AS/NZS 4600). The research revealed that existing specifications for web crippling were generally unconservative across various loading conditions. Under EOF loading, predictions for series S1 and S2 aligned closely with test results. In contrast, for IOF and ETF conditions in Series S1, the experimental web crippling strengths were approximately 72% of the predicted values, while for ITF loading, they were about 60%. Series S3, with higher web slenderness ratios (60.9 and 62.7), showed more accurate predictions for ETF and ITF conditions compared to Series S1 and S2, which had slenderness ratios of 38.3 or less. Notably, one ITF condition in Series S2 recorded a web crippling strength of only 37% of the predicted value [16].

Beshara and Schuster (2000) examined the web crippling behavior of cold-formed steel (CFS) members subjected to two-flange loading conditions, specifically focusing on Cee and Zee-shaped specimens. The study involved overall section depths of 120 mm, 200 mm, and 300 mm, with varying inside bend radii of 7 mm, 10 mm, and 14 mm. The web thicknesses were set at 1.45 mm and 1.16 mm, while the bearing plate lengths ranged from 30 mm to 101 mm to evaluate their impact on web crippling performance. The test results revealed that the web crippling load was more than 50% greater under interior two-flange (ITF) loading conditions compared to other loading scenarios, with approximately a 5% increase noted for exterior two-flange (ETF) loading. Additionally, it was observed that Zee-sections demonstrated superior load-bearing capacity relative to Cee-sections, indicating a significant influence of section geometry on web crippling resistance. This study contributes valuable insights into the design and optimization of CFS members, highlighting the critical parameters affecting their structural performance under varying loading conditions [17].

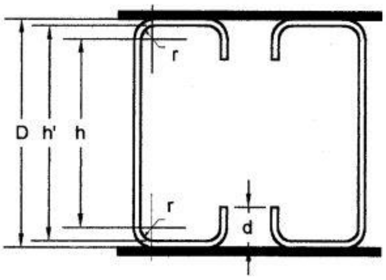

Fig. 6. Cross-sectional shape for the Cee-shaped specimens under two flange loading [17]

B. Recent Research (2001-2023)

Macdonald et al. (2011) conducted an investigation into the web crippling behavior of cold-formed steel lipped channel beams subjected to End-One-Flange (EOF) and End-Two-Flange (ETF) loading setups, as shown in Figure 7. The experimental program involved testing thirty-six specimens to evaluate their load-deformation characteristics under these conditions, which included both fastened and unfastened boundary scenarios. The results demonstrated that the American and European design standards were often overly conservative, particularly highlighting that the mean test-to-predicted web crippling capacities for ETF loading were 1.41 and 1.45, with coefficients of variation (COV) of 0.18 and 0.14, respectively. For EOF loading, mean values of 1.27 and 1.56, alongside COVs of 0.07 and 0.29, indicated similar trends. The experimental web crippling loads for EOF and ETF conditions ranged from 0.46 kN to 2.61 kN and 0.77 kN to 1.90 kN, respectively with means of approximately 1.59 kN for EOF and 1.27 kN for ETF loadings [18].

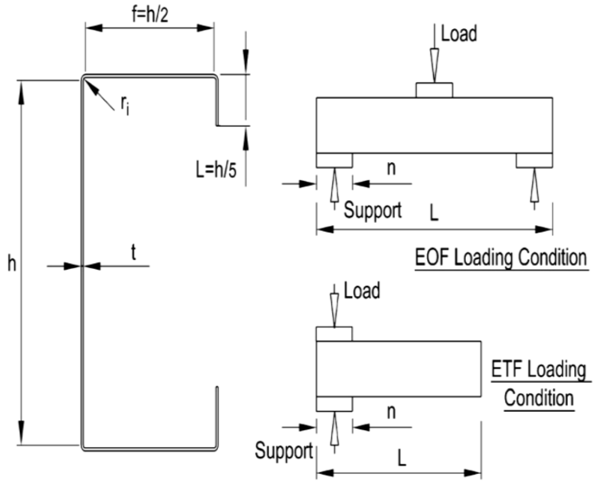

Fig. 7. Specimen shape and loading configuration for web crippling investigation [18]

Research conducted by **Sundararajah et al. (2015**) focused on the shortcomings of established design standards, such as AISI S100, AS/NZS 4600, and EN 1993-1.3, which often inadequately predicted web crippling strength under Exterior-Two-Flange (ETF) and Interior-Two-Flange (ITF) loading scenarios for lipped channel beams (LCB). The study involved 36 specimens to assess how varying bearing plate sizes (25 mm, 50 mm, and 100 mm) affected web crippling resistance. These specimens were constructed with thicknesses ranging from 1.03 mm to 2.41 mm, inside bend radii from 3.5 mm to 5.0 mm, and flange widths between 50.5 mm and 76.4 mm. Experimental findings revealed that the design equations from AS/NZS 4600 and AISI S100 were generally non-conservative for ETF loading, while being conservative for ITF loading. An analysis of the experimental strength ratios indicated mean values of 1.63 for ETF and 1.32 for ITF loading conditions, suggesting that the experimental strengths tended to exceed the predictions made by the design standards. These results highlighted the necessity for revised design equations specifically aimed at improving the accuracy of web crippling evaluations for LCBs [19].

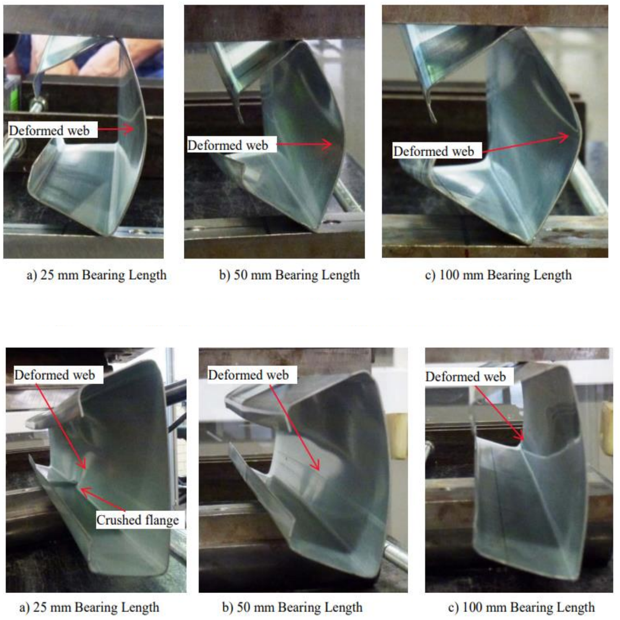

Fig. 8. ETF and ITF specimen failure mode observed in Cee-shaped specimens [19]

In the study conducted by **Gunalan et al. (2015),** a comprehensive experimental investigation was carried out to evaluate the web crippling behavior of cold-formed steel unlipped channels under End-Two-Flange (ETF) and Interior-Two-Flange (ITF) loading conditions. A total of 42 tests were performed using DuraGal steel sections with a nominal yield strength of 450 MPa, varying web slenderness, and bearing lengths. The tests were conducted based on the AISI standard test method, ensuring specimen lengths were appropriate for the loading conditions—three times the clear web height for ETF and five times for ITF. Specimens ranged in thickness from 4 mm to 8 mm, and bearing lengths of 25 mm to 150 mm were applied. The ultimate loads recorded for the ETF case ranged from 21.0 kN to 53.9 kN, while ITF tests showed values between 59.0 kN and 164.9 kN. The results revealed that web crippling strength generally increased with specimen length, consistent with the findings from previous studies by Young and Hancock. A comparison of experimental results with predictions from current design codes indicated that the test-to-predicted ratios ranged from 0.73 to 1.19 for ETF and from 0.87 to 1.10 for ITF, depending on the design rule used. This highlighted the need for adjustments to existing design codes, particularly in cases of combined flange crushing and web crippling. The study ultimately proposed modifications to the existing design rules and introduced a new design methodology to better predict web crippling capacities in these loading scenarios [20].

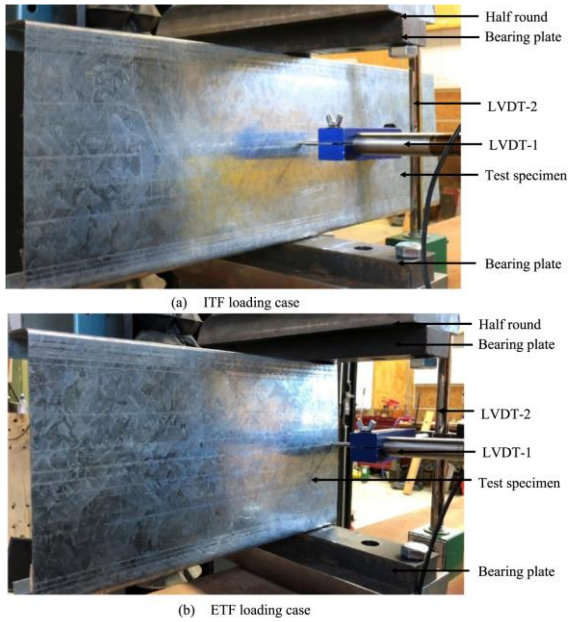

Fig. 9. Two flange loading experimental setup considered by Chen, B. [21]

Chen, B., et al. (2021) conducted an experimental investigation on the web crippling behavior of cold-formed steel (CFS) channels featuring edge-stiffened web holes, specifically examining their performance under fastened support in both Exterior-Two-Flange (ETF) and Interior-Two-Flange (ITF) loading configurations, as shown in Figure 9. A total of 36 tests were carried out, comparing specimens with edge-stiffened web holes to those with unperforated and unstiffened webs. The results indicated that the web crippling capacity of fastened flanges was significantly enhanced, showing increases of 71% and 33% under ETF and ITF loading, respectively. Additionally, the study developed and validated finite element (FE) models against the experimental outcomes, which facilitated a comprehensive parametric analysis involving 912 FE models that explored variations in web thickness, hole size, bearing plate length, and edge-stiffener length. The experimental findings were compared to predictions from Uzzaman et al. (2020) and current design standards, including the American Iron and Steel Institute (AISI, 2016) and AS/NZS (2018), revealing a mean ratio of predicted to experimental capacities of 1.05 for ETF and 1.03 for ITF loading scenarios. Notably, Uzzaman's reduction factor provided accurate predictions for channels with edge-stiffened web holes, underscoring the need for updated design guidelines that consider the influence of web perforations on crippling strength [21].

Yousefi, A. M., et al. (2023) conducted both experimental and numerical studies to examine the web crippling behavior of unlipped channel sections. The investigation involved 21 specimens with web heights between 100 mm and 250 mm and web slenderness ratios (h/t) ranging from 60.9 to 82.6. Experimental tests showed that the ultimate web crippling forces ranged from 5.23 kN to 27.10 kN. Finite Element Models (FEM) were created for cold-formed austenitic stainless steel under Interior-Two-Flange loading conditions and were validated against existing design standards from the American (ASCE 2002) and European (EN 1993-1.3) codes. The analysis revealed that these design equations were inaccurate and overly conservative for cold-formed austenitic stainless steel channels, underestimating the web crippling strength by up to 41%. This study emphasizes the necessity for updating current design equations to better account for the structural performance of modern materials [22].

IV.CONCLUSION

The body of literature on web crippling behavior in cold-formed steel (CFS) structural members spans several decades and offers a deep understanding of how factors such as web slenderness, loading configurations, and section geometries influence web crippling resistance. Pioneering work by Yu and Hetrakul (1978) examined Cee-shaped specimens under various loading conditions, highlighting that for beams with height-to-thickness (h/t) ratios below 150, the AISI 1968 equations overpredicted web crippling loads for two-flange end loading, while underestimating those for one-flange end loading. Bhakta et al. (1992) further explored CFS members subjected to End-One-Flange (EOF) loading, showing that fastened specimens displayed greater web crippling resistance compared to unfastened ones, particularly with higher h/t ratios, and identifying inaccuracies in AISI specifications, which either overestimated or underestimated web crippling strength depending on the web's slenderness.

Korvink et al. (1995) investigated web crippling in Cee-shaped stainless steel sections under Interior-One-Flange (IOF) loading and found that while ASCE/AISI standards generally aligned with the results, predictions were conservative for longer bearing plates. Similarly, Young and Hancock (1998) studied unlipped channels under multiple loading scenarios, revealing that the AISI 1996 predictions were mostly unconservative, particularly under ITF loading, where experimental results achieved only 60% of the predicted values. Beshara and Schuster (2000) demonstrated that Zee-shaped sections had higher web crippling resistance than Cee-shaped ones, especially under two-flange interior loading, which provided a 50% increase in capacity compared to other conditions.

More recent studies emphasize the need for updated design standards. Macdonald et al. (2011) identified that American and European design standards were often overly conservative, particularly for ETF and EOF loading conditions. Sundararajah et al. (2015) reported that established design codes underestimated web crippling strength for ETF loadings but were conservative for ITF cases. Gunalan et al. (2015) also noted discrepancies between experimental outcomes and design code predictions, leading to the suggestion of new methodologies to improve web crippling accuracy. Chen et al. (2021) explored the effect of edge-stiffened web holes, revealing that flange fastening considerably improved web crippling capacity. Lastly, Yousefi et al. (2023) showed that existing design equations for austenitic stainless steel underestimated web crippling strength, emphasizing the need for revised equations that more accurately represent modern materials and geometries.

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