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Article

Web Crippling Behaviour of Cold-Formed Carbon Steel, Stainless Steel, and Aluminium Lipped Channel Sections with Web Openings

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Abstract: This paper reviews the research advancements and design practices related to the structural web crippling response of lipped Cold-Formed (CF) carbon steel, stainless steel, and aluminium channels with web perforations. The web crippling response differs among each material based on the non-linear stress-strain characteristics and degree of strain hardening. Therefore, the reduction in the web crippling strength of web-perforated CF channel sections made of different materials may not be equivalent. The research activities surrounding the web crippling response of CF channels with and without web openings were reviewed initially. Despite the limited design provisions given in the international specifications for the web crippling design of lipped CF channels with web openings, web crippling studies conducted across the world have developed suitable design equations in the form of reduction factors. Past research studies have substantially captured the web crippling response of carbon steel channels with web openings while that of stainless steel and aluminium are limited, as identified in this paper. Lastly, numerical models were developed for simulating the web crippling behaviour of lipped CF carbon steel, stainless steel, and aluminium channels with web opening and validated with past experimental data, with a view for developing unified design guidelines.

Keywords: Cold-formed lipped channel sections; web crippling; web openings; unified design guidelines

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1. Introduction

Cold-Formed (CF) sections are structural products formed by cold roll-forming or press braking of metal sheets into different shapes at ambient temperature [1]. Over the past few decades, these CF sections have been extensively used in the modern construction industry both as primary and secondary structural members, by overruling their hot-rolled counterparts [1–4]. High specific strength, ease of fabrication, transportation, installation, and handling, and high dimensional accuracy observed in CF sections have triggered this advancement [1–3].

With this increasing popularity, CF sections have been made available from a range of materials such as carbon steel, stainless steel, and aluminium, and from an array of geometries as shown in Figure 1. Among these sections, lipped channel sections (Figure 1(aii)), are commonly used in many structural applications such as floor joists, roof purlins, and wall studs. These Lipped Channel Sections (LCSs) are often fabricated with web openings to facilitate for easy installation of electrical and plumbing services [5–8].

However, when subjected to concentrated loading, these perforations increase the tendency for web crippling [8].

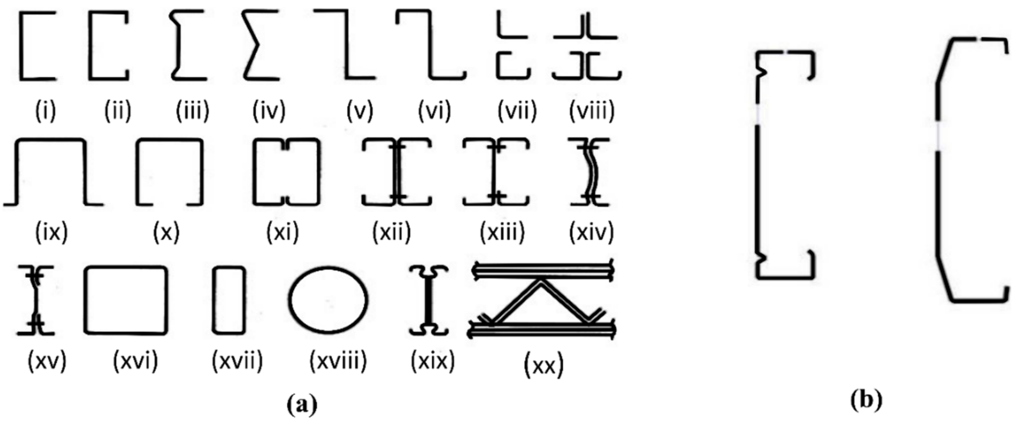


Figure 1. Cold-formed section geometries (**a**) Typical CF sections [9], (**b**) Optimized CF sections [10].

Web crippling is among the most critical failure mechanisms to be considered in the design of CF sections. It is defined as the localized failure of web elements of a member subjected to transverse concentrated loading [11]. Local yielding of the flange to web intersection (web yielding), web buckling and flange crushing (Figure 2), or a combination of the aforementioned failure modes are the four mechanisms through which a member subjected to web crippling may fail [12,13]. According to the test standards proposed by the American Iron and Steel Institute (AISI S909-17) [14], these web crippling failures fall under four categories depending on the location of the applied loading or the reaction force. Those four loading conditions are End-One-Flange (EOF) loading, Interior-One-Flange (IOF) loading, End-Two-Flange (ETF) loading, and Interior-Two-Flange (ITF) loading.

Apart from the loading conditions, flat web depth to thickness ratio, corner radius to thickness ratio, opening depth to web height ratio, ratio of the clear distance to the web holes from the nearest edge of the bearing plate to flat depth of the web, nature of the support (fastened or unfastened), bearing length and yield strength of the section material have been identified as the major parameters affecting the web crippling strength of web perforated CF sections [7,15–18].

This paper aims to provide a comprehensive review on the web crippling response of CF steel, stainless steel, and aluminium LCSs with web openings. Beginning with a short introduction in Section 1, different types of web crippling studies are discussed in Section 2. Section 3 discusses web crippling investigations on CF steel, stainless steel, and aluminium LCSs with web openings. Existing web crippling design guidelines are discussed under Section 4. Based on the research gaps identified via the literature review, Section 5 describes the finite element model developed and validated for simulating the web crippling response of web perforated CF steel, stainless steel, and aluminium LCSs, under ETF loading condition. Finally concluding remarks on the overall investigation along with the identified research gaps are presented in Section 6.

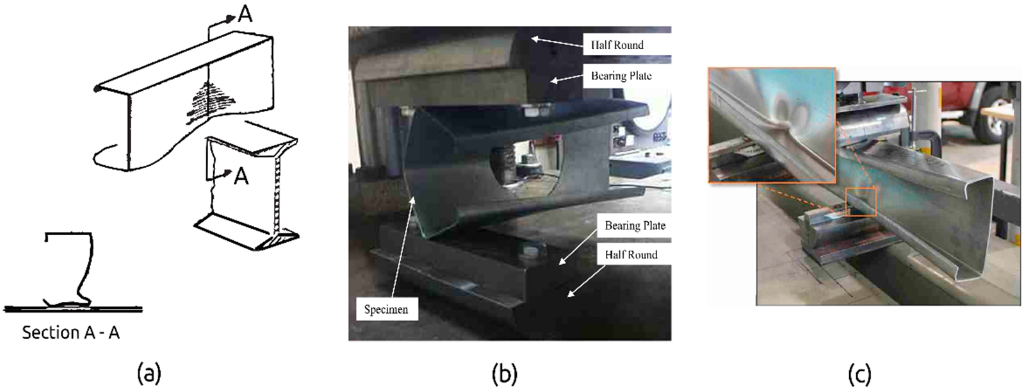


Figure 2. Failure mechanisms (**a**) web yielding [18], (**b**) web buckling [19], (**c**) flange crushing [20].

2. Different Approaches for Studying Web Crippling Behaviour

Depending on the critical nature of web crippling as a failure mode, the study of web crippling of CF sections has been in the spotlight since the 1940s. Most of these studies are based on experimental investigations, while some unveil the mechanics of web crippling theoretically. However, over the past few years, numerical studies on web crippling have become more popular than theoretical and experimental web crippling studies.

2.1. Theoretical Investigations

Conducting theoretical investigations on the web crippling response of CF sections is highly complicated as it involves several factors including non-uniform stress distribution under the applied concentrated load, elastic and inelastic behaviour of the web element, localized yielding in the web region under direct loading, and initial out of plane imperfections of the web region [5,21]. Considering this complexity, theoretical investigations on the web crippling behaviour have been conducted by idealizing webs as thin rectangular plates, simply supported along the four corners [22–24]. However, the web element of a CF channel section is hardly identical to a rectangular thin plate simply supported over the edges [11,25]. This idealization of webs also results in omitting the effect of web flange interaction in web crippling capacity predictions proposed by theoretical studies. Moreover, the prediction of post-buckling strength via the theoretical approach is quite complex [15]. To overcome these issues, most of the web crippling studies follow an experimental approach.

2.2 Experimental Investigations

In the year 1946, Winter and Pian [26] conducted the earliest experimental investigation on the web crippling capacity of CF sections. In this study, the authors developed an equation for predicting the ultimate web crippling strength of unpunched Cold-Formed Steel (CFS) sections. This equation was later considered as the basis for early design specifications [5]. These specifications were later on modified with the findings of Hetrakul and Yu [27]. Since then, a number of experimental studies have been carried out to assess the web crippling behaviour of CF sections [5,12,28–31]. Most of these research studies have led to the development of novel design regulations for predicting the web crippling strength of CF sections [28,29,31].

Succeeding many studies conducted on conventional CF sections, Keerthan et al. [32] and Keerthan and Mahendran [33] conducted experimental studies on LiteSteel Beams (LSBs), initiating web crippling investigations on unconventional CF sections (Figure 3). In these studies, authors proposed new design rules unique for LSBs. These design guidelines were developed based on the Direct Strength Method (DSM). Steau et al. [34-36] conducted experimental studies on the web crippling behaviour of rivet-fastened Rectangular Hollow Flange Channel Beams (RHFCBs) subjected to all four loading conditions. Based on these experimental investigations the authors developed new web crippling design equations for rivet-fastened RHFCBs considering both flange fastened and unfastened conditions. Subsequently, Sundararajah et al. [37–39], Gatheeshgar et al. [40,41] and Thirunavukkarasu et al. [42] conducted combined empirical and numerical investigations on the web crippling response of SupaCee sections, optimized CF sections and modular construction optimized beams, covering the full range of unconventional cold-formed sections. Based on each of these studies authors have developed new web crippling design guidelines appropriate for each sectional geometry.

2.3 Numerical Investigations

Being dependent upon empirical formulae, design guidelines developed via experimental studies, are restricted to certain cross-sectional geometries, loading conditions, and material properties [15]. To overcome this issue experimental investigations are often followed by numerical investigations, which enable the coverage of a broader spectrum of section geometries, loading conditions, and material properties [7]. With the increasing developments in the field of technology, numerical investigations have become a reliable alternative for experimental tests, provided that adequate validation of the numerical models is being carried out [43]. Finite Element Analysis (FEA) is frequently regarded as the most widely used numerical investigation technique. The study conducted by Sivakumaran [44] is considered to be one of the pioneering finite element-based web crippling studies conducted on lipped CF channel sections. The ADINA [45] software was used by the author to simulate the web crippling response of CF sections subjected to IOF loading condition. There the author was able to achieve satisfactory agreement in between Finite Element (FE) predictions and experimental results, thus proving the reliability of ADINA software in predicting web crippling capacities. Since then, numerical investigations conducted using shell FE models were extensively used to model the web crippling behaviour of CF sections. ABAQUS [46] and ANSYS [47] are some such commercial and general-purpose FE programs that are commonly used in analyzing the web crippling behaviour of CF sections [7,37,38,48–51]. Comparison of the failure modes between these numerical studies and experimental studies demonstrates the high reliability of numerical investigations, in simulating actual web crippling behaviour observed under experimental conditions (Figure 4).

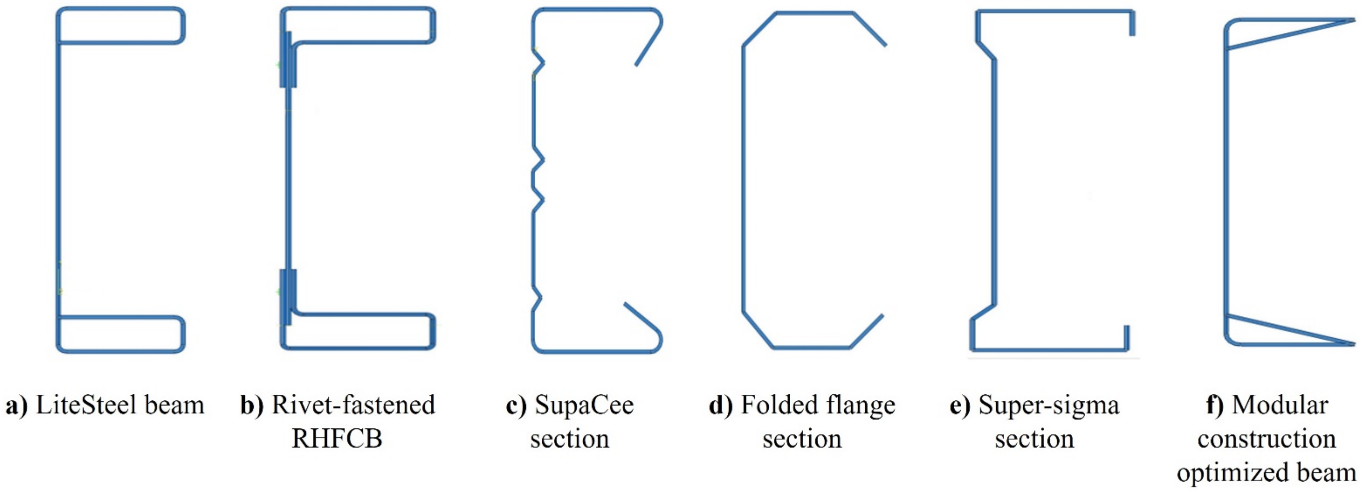


Figure 3. Section geometries of unconventional cold-formed sections.

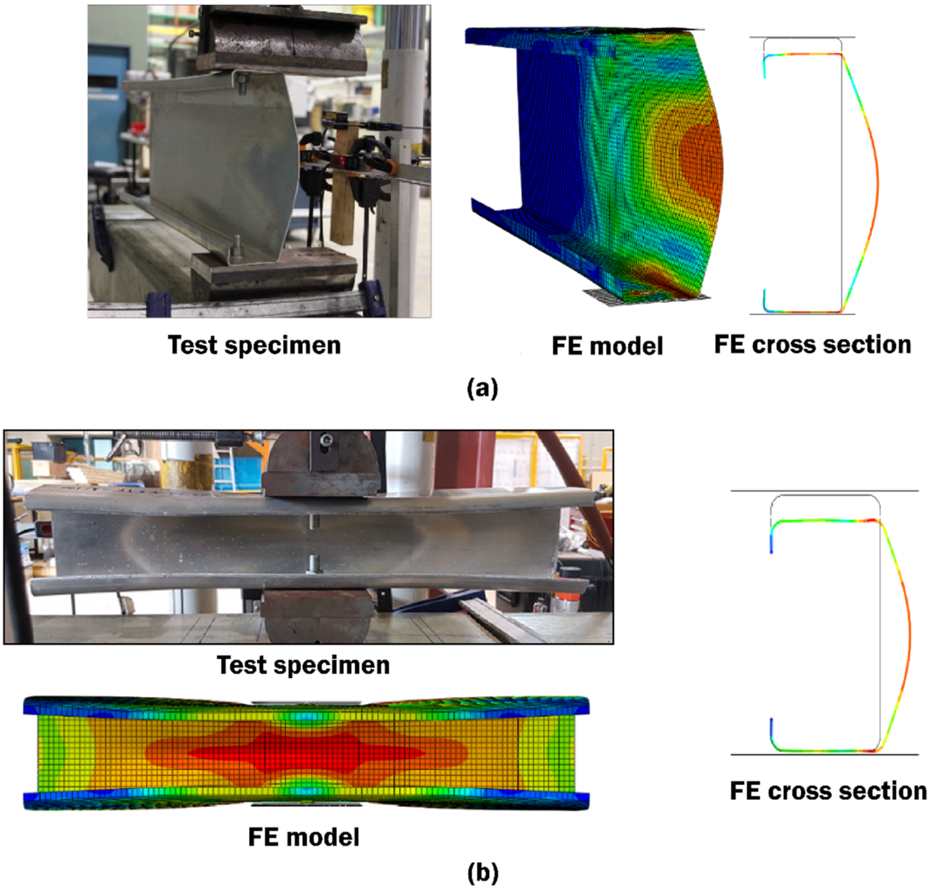


Figure 4. Failure patterns observed in experimental and numerical approaches (**a**) for a LCSs under ETF loading condition, (**b**) for a LCSs under ITF loading condition [52].

3. Web Crippling Studies on Lipped CF Channel Sections with Web Perforations

3.1. CF Steel Sections

Web crippling studies on lipped CFS channel sections dates back to late 1940s where Winter and Pian [26] experimentally investigated the web crippling behaviour of 136 unpunched I sections made of welded channel sections. Since then, numerous web crippling investigations have been conducted on CFS sections [11,29,39,43,53]. Results of these studies have been utilized in deriving web crippling design guidelines for CF sections without web perforations [28,29,31,54]. A summary of these web crippling studies is provided in Table 1.

However, as evidently seen in this summary, only a few research studies have evaluated the web crippling response of lipped web perforated CFS sections. As a result, there are only a few design principles for predicting the web crippling behaviour of CFS sections with web perforations. Research study conducted by Davis [55] is reported to be one of the pioneering experimental investigations conducted on web perforated lipped CF channel sections. The effect of circular and square web perforations on web crippling strength was investigated in this study. Twenty web perforated CF sections formed out of either two back-to-back unlipped channels or two-lipped channel sections connected via the lips were considered for this study. Each web perforation was centered beneath the bearing plate. Reduction factors developed through this experimental analysis were used to modify the North American specifications on web crippling of CF sections.

Sivakumaran [30], and Sivakumaran and Zielonka [12] described the web crippling response of web perforated lipped CFS channel sections considering 103 web crippling tests conducted on steel LCSs with rectangular or oval web openings, under IOF loading condition. All web perforations were fabricated at the mid-depth of the specimen and were located directly under the bearing plate. Considering the load dispersion angle to be 45°, this research study proposed an equation for predicting the web crippling strength of lipped CFS channel sections.

Accommodating the strength reduction caused by web openings, Langan et al. [56] derived reduction factors to modify the existing web crippling equations. Authors derived these reduction factors based on a comprehensive experimental study conducted on 168 steel LCSs with offset rectangular openings. Based on these data, authors identified the ratio of the hole depth to web depth, and the ratio of clear distance from the hole to the edge of the bearing to flat depth of the web as the main parameters governing the web crippling capacity of web perforated CF sections. Strengthening the above research work, LaBoube et al. [5] conducted 108 tests on steel LCSs with offset circular openings positioned at the mid-depth of the web. In this study, the authors used the bivariate linear regression analysis to develop reduction factor equations, considering both EOF and IOF load cases. The North American Specifications for CFS sections later adopted these empirical equations [57]. However, these reduction factor equations are only applicable to CFS sections of 0.83 mm to 1.42 mm thickness [57].

Similar research studies were conducted by Uzzaman et al. [7,19,58,59] and Lian et al. [6,57,60,61]. In these studies, authors investigated the web crippling strength reduction caused by offset and centered circular web holes. Most of these studies are limited to conventional lipped CFS channel sections with circular openings, necessitating web crippling studies on innovative CF channel sections with diverse web opening configurations. Aside from that, the authors identified a lack of investigations on the web crippling response of web perforated CFS sections at elevated temperatures. Bridging this research gap Fang et al. [62] recently conducted a numerical study on the web crippling behaviour of web perforated lipped CFS channel sections at elevated temperatures. Under this study authors derived new design rules for predicting the web crippling response of web perforated lipped CFS channel sections under IOF loading. However, web crippling response of web perforated CFS sections under ITF, ETF and EOF loading conditions at elevated temperatures is yet to be studied.

3.2 CF Stainless Steel Sections

Cold-Formed Stainless-Steel (CFSS) sections are popular in the construction sector for a variety of reasons such as recyclability, durability, heat resistance, and corrosion resistance [63,64]. This has resulted in its high popularity over CFS sections. However, CFSS sections have some drawbacks, such as their proneness to web crippling.

Web crippling investigation conducted by Korvink et al. [65] is considered to be the first web crippling study conducted on lipped CFSS sections. In this study, authors have compared the results of an extensive empirical investigation conducted on lipped CFSS sections, with the theoretically predicted web crippling data given in the 1991 edition of the Specification for the Design of Cold-Formed Stainless Steel Structural Members. This study has been followed by a series of studies conducted by Talja and Salmi [66] and Gardner et al. [67]. In these studies, authors have considered the web crippling behaviour of Rectangular Hollow Sections (RHSs) under IOF loading condition. Zhou and Young [68–71] continued these research studies by conducting theoretical and numerical investigations on the web crippling behaviour of tubular stainless-steel sections under all four loading conditions. These research studies have been the basis in developing web crippling design guidelines for CFSS sections without web openings.

However, in comparison to carbon steel, web crippling studies on CFSS sections are lacking. Moreover, as apparently seen in Table 1, relatively few studies have been conducted on the web crippling response of web perforated lipped CFSS sections. Combined empirical and numerical investigations conducted by Yousefi and Uzzaman [72–74] are some such studies. In these studies, authors have examined the web crippling response of web perforated lipped duplex, austenitic and ferritic stainless-steel sections under all four load cases. In each study bivariate linear regression analysis principles have been adopted to derive unified reduction factor equations covering all three stainless steel types. Yet, these research studies have only focused on the influence of circular web perforations.

Fareed et al. [75] addressed this research gap by developing web crippling strength reduction factors for CFSS channel sections with square and rectangular web openings. However, these reduction factor formulae are only applicable to unlipped CF ferritic stainless-steel sections. Moreover, web crippling studies on lipped CFSS channel sections with non-circular web openings are lacking. Furthermore, to the best of the author's knowledge, very limited research has been conducted on the web crippling response of unconventional CFSS sections with web openings.

3.3 CF Aluminum Sections

Use of CF aluminium sections has accelerated in the recent years due to many reasons such as high specific strength, excellent thermal conductivity, simple fabrication process and superior resistance for corrosion. However, as shown in Figure 5, in comparison to carbon steel, aluminium alloys have a relatively low elastic modulus. Thus, CF aluminium sections are vulnerable to a number of failure modes, including web crippling. This is evidently scene in the research findings of McIntosh et al. [76,77], where CF aluminium sections show low web crippling strength values in comparison to CFS and CFS sections of the same grade. Yet, over the years web crippling behaviour of CF aluminium sections has not been studied sufficiently, in comparison to the same of CFS and CFSS sections. This is evidently seen in the comparison of web crippling studies provided in Table 1.

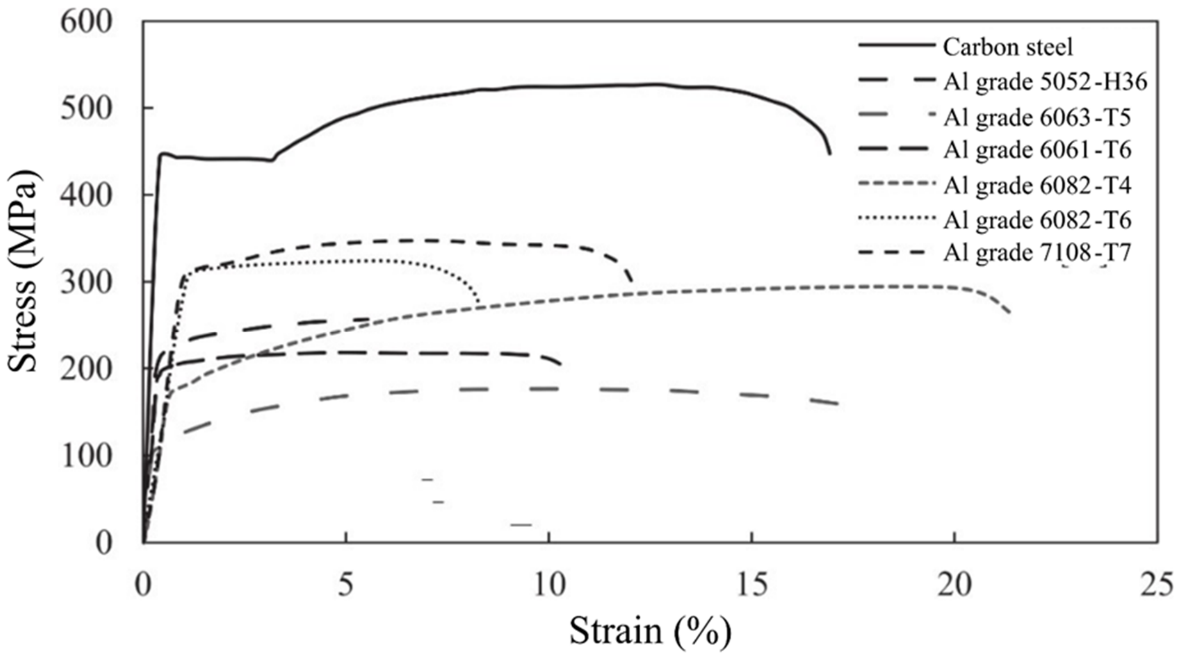


Figure 5. Stress strain curve corresponding to Carbon steel and Aluminium alloys [78].

The experimental and numerical study carried out by Zhou and Young [79] on CF aluminium Square Hollow Sections (SHSs) and RHSs is reported to be one of the first few studies conducted on the web crippling response of CF aluminium sections. Further to this, Young and Zhou [80] derived design equations for determining the web crippling response of CF aluminium SHSs and RHSs subjected to ETF and ITF load cases. However, these equations are only valid for tubular CF aluminum sections with unfastened flanges.

Zhou and Young [81] investigated the web crippling behaviour of CF aluminium SHSs and RHSs with web openings. The aforementioned experimental and numerical study proposed a unified web crippling equation limited for CF aluminium SHSs subjected to ETF and ITF loading conditions. Chen et al. [82] conducted a combined numerical and experimental investigation to identify the web crippling behaviour of aluminium SHSs under all four loading conditions. Depending on the results of this investigation, new design equations were derived for calculating the ultimate web crippling response of CF aluminium SHSs under each loading condition.

More recently Alsanat [20,52,83–85] conducted a series of experimental and numerical studies on the web crippling behaviour of lipped CF aluminium channel sections under two flange loading conditions. In these research studies, authors have proved the inadequacy of existing design guidelines in predicting the web crippling response of lipped CF aluminium channel sections. Hence, new design equations were developed considering both flange fastened and unfastened conditions. However, the web crippling response of web perforated lipped CF aluminium sections has been rarely studied. Identifying this research gap, Alsanat et al. [86] investigated the web crippling behaviour of lipped CF aluminium sections with circular openings, under ETF loading conditions. Nonetheless, the web crippling behaviour of web perforated lipped CF aluminum sections under ITF, IOF, and EOF loading conditions are yet to be explored. Moreover, the web crippling response of unconventional CF aluminium sections is yet to be investigated.

Table 1. Summary of web crippling studies conducted on CF carbon steel, stainless steel and aluminium sections.

Without Web Opening				
Loading/Support Condition		**Carbon Steel**	**Stainless Steel**	**Aluminium**
ETF	Unfastened	Winter and Pian [26] * Hetrakul and Yu [27] * Young and Hancock [31] * Keerthan et al. [32] * Steau et al. [34] * Gatheeshgar et al. [41] *# Thirunavukkarasu et al. [42] *# McIntosh et al. [76] # Gunalan and Mahendran [87] * Sundararajah et al. [13,37,38,88] *#	Li and Young [63] *# Zhou and Young [68–71] ¤# McIntosh et al. [76] #	Alsanat et al. [20] *# McIntosh et al. [76] # Young and Zhou [80] #¤ Zhou and Young [79,89] *# Chen et al. [82] *# Alsanat et al. [83] *# Alsanat et al. [90] #
	Fastened	Steau et al. [36] *	-	Alsanat et al. [52] *# Alsanat et al. [84] *# Alsanat et al. [85] *#
ITF	Unfastened	Winter and Pian [26] * Hetrakul and Yu [27] * Young and Hancock [31] * Keerthan et al. [32] * Steau et al. [34] * Gatheeshgar et al. [40] *# McIntosh et al. [77] # Gunalan and Mahendran [87] * Sundararajah et al. [13,37,38,88] *#	Li and Young [63] *# Zhou and Young [68–71] ¤# McIntosh et al. [77] #	Alsanat et al. [20] *# McIntosh et al. [77] # Young and Zhou [80] #¤ Zhou and Young [79,89] *# Chen et al. [82] *# Alsanat et al. [83] *# Alsanat et al. [90] #
	Fastened	Steau et al. [36] *	-	Alsanat et al. [52] *# Alsanat et al. [84] *# Alsanat et al. [85] *#
EOF	Unfastened	Winter and Pian [26] * Hetrakul and Yu [27] * Young and Hancock [31] * Keerthan et al. [32] * Steau et al. [35] *	Li and Young [63] *# Zhou and Young [68–71] ¤# Bock et al. [92] #	Chen et al. [82] *# Alsanat et al. [93] *#

		Sundararajah et al. [39,91] *#		
	Fastened	Bhakta et al. [17] * Cain et al. [28] * Gerges and Schuster [29] * Steau et al. [35] * Sundararajah et al. [39,91] *#	-	-
IOF	Unfastened	Winter and Pian [26] * Hetrakul and Yu [27] * Young and Hancock [31] * Keerthan et al. [32] * Steau et al. [35] * Sundararajah et al. [91] *#	Li and Young [63] *# Talja and Salmi [66] * Gardner et al. [67] *# Zhou and Young [68–71] ¤#	Chen et al. [82] *# Alsanat et al. [93] *#
	Fastened	Bhakta et al. [17] * Cain et al. [28] * Gerges and Schuster [29] * Steau et al. [35] * Sundararajah et al. [91] *#	-	-
With Web Openings				
Loading/Support Condition		**Carbon Steel**	**Stainless Steel**	**Aluminium**
ETF	Unfastened	Uzzaman et al. [19,58,59] *#	Yousefi et al. [8] *# Fareed et al. [75] #	Zhou and Young [81] *# Alsanat et al. [86] *
	Fastened	Uzzaman et al. [19,58,59] *#	Yousefi et al. [8] *# Yousefi et al. [64] *#	Alsanat et al. [86] *
ITF	Unfastened	Davis [55] *¤ Uzzaman et al. [7,58,59] *#	Yousefi et al. [74] *# Fareed et al. [75] #	Zhou and Young [81] *#
	Fastened	Uzzaman et al. [7,58,59] *#	-	-
EOF	Unfastened	LaBoube et al. [5] * Langan et al. [56] * Lian et al. [6,57] *# Gatheeshgar et al. [94] #	Yousefi et al. [73] *#	-
	Fastened	Lian et al. [6,57] *#	Yousefi et al. [73] *#	-
IOF	Unfastened	LaBoube et al. [5] * Sivakumaran and Zielonka [12] * Sivakumaran [30] * Langan et al. [56] * Lian et al. [6,57] *# Fang et al. [62] # Gatheeshgar et al. [95] #	Yousefi et al. [72] *# Yousefi et al. [96] #	-
	Fastened	Lian et al. [60,61] #,*# Fang et al. [62] #	Yousefi et al. [72] *# Yousefi et al. [96] #	-

¤—Theoretical study, *—Experimental study, #—Numerical study, ¤*—Combined theoretical and experimental study, ¤#—Combined theoretical and numerical study, *#—Combined experimental and numerical study.

4. Current Design Guidelines

Based on the critical nature of web crippling as a failure mode, web crippling design guidelines have been proposed by many international design standards. North American specification for design of cold-formed steel structural members (AISI S100-16) [97] which is based on the Australian/New Zealand standard for cold-formed steel structures (AS/NZS 4600) [98], American specification for the design of cold-formed stainless steel structural members (SEI/ASCE 8-02) [99], Australian/New Zealand standard for cold-formed stainless steel structures (AS/NZS 4673) [100], Australian/New Zealand standard for aluminium structures (AS/NZS 1664) [101], Eurocode 3 Part 1-3 (EN1993-1-3) [102], Eurocode 3 Part 1-4 (EN1993-1-4) [103] and Eurocode 9 Part 1-4 (EN1999-1-4) [104] are the most prominent design standards used in predicting the web crippling response of CF sections. Table 2 provides a detailed summary of these guidelines.

AISI S100-16 [97] and AS/NZS 4600 [98] provides web crippling design guidelines for common industrially used CFS sections with or without web openings. Both these design standards consider the influence of circular and non-circular web openings centered at the mid height of the web. However, design guidelines for web perforated CF channel sections provided in the North American specification [97] are limited to EOF and IOF loading conditions. Hence, extensive numerical and experimental investigations covering all four loading conditions should be conducted to evaluate the web crippling response of web perforated CFS sections with varying section geometries. Apart from these two design guidelines, EN1993-1-3 [102] is also commonly used in designing CFS sections. Unlike the other two standards, Eurocode 3 [102] does not provide design guidelines for predicting the web crippling resistance of web perforated CFS sections. However, in a recent study conducted, McIntosh et al. [76] claim that each of the above design guidelines overestimate the web crippling strength of lipped CFS sections.

SEI/ASCE 8-02 [99], AS/NZS 4673 [100] and Eurocode 3 part 1-4 [103] are the three main design guidelines used in designing CFSS sections. Web crippling design guidelines provided in AS/NZS 4673 [100] have been extracted from SEI/ASCE 8-02 [99] standard. Hence, the two design standards were identified to be identical. Due to the lack of experimental data, web crippling design guidelines provided in the above standards, have been developed based on the test results on CFS sections rather than those of CF stainless steel sections [70]. These guidelines provide design equations for predicting web crippling capacity of CFSS sections with single webs (C and Z sections) and for I sections made of two back-to-back channel sections. However, web crippling design guidelines provided under these standards are limited to CFSS sections without web openings. Moreover, the results of a number of recent empirical and numerical studies conducted on web crippling behaviour of CFSS sections depict inconsistencies between values predicted by the design standards. These inconsistencies are expected to be an outcome of the clear difference between the yield strength values of CF stainless steel and CF carbon steel sections, which were utilized in the derivation of design guidelines [70]. Moreover, in a recent study McIntosh et al. [76,77], identified a significant variation between the web crippling strengths of CFS and CFSS sections of the same grade. Henceforth, authors believe existing design guidelines should be further modified by considering experimental and numerical tests conducted on CFSS sections with and without web perforations.

Web crippling capacities of CF aluminium sections are often predicted by considering AS/NZS 1664 [101] and Eurocode 9 Part 1-4 [104]. AS/NZS 1664 [101] provides design guidelines for aluminium structural sheeting while design guidelines provided in Eurocode 9 Part 1-4 [104] are limited to CF aluminium sections with two or more webs. Hence, when used for CF lipped channel sections, both aforementioned guidelines tend to predict web crippling capacities with major discrepancies, when compared to the experimental and numerical test values [20,76]. Moreover, none of the above standards provide guidelines for predicting the web crippling capacity of web perforated CF aluminum sections. With reference to past literature, it is also evident that no unified design guideline has been derived so far, to predict web crippling capacities of all commercially available CF sections.

Apart from the above-mentioned design guidelines, many authors have developed web crippling design guidelines based on the DSM. Instead of the effective section modulus, DSM considers elastic buckling behaviour and the yield loads acting upon the entire CF section in predicting the nominal strength of the member [105]. Web crippling being a failure mode dependent upon the combined effect of buckling and yielding of the section can easily be predicted based on the DSM. A summary of the past research studies conducted on the web crippling behaviour CF sections based on DSM is provided in Table 3. When referring to past literature, it is evident that the web crippling capacity of CF stainless-steel and aluminium sections has poorly been studied via DSM, while no DSM-based design guidelines have been developed for predicting web crippling response of web perforated CF carbon steel, stainless-steel and aluminium channel sections.

Table 2. Summary of web crippling design guidelines.

Design Guideline	Material	Summary
AISI S100-16 [97]	Steel	• Applicable to web perforated cold-formed C sections • Restricted to sections exposed to IOF and EOF loading conditions • Limited to web perforations located at mid-depth of the web • Confined to offset web openings • Consider both circular and non-circular web openings • Covers both flanges stiffened and unstiffened conditions • Limited for following bearing lengths(N) • For IOF loading N ≥ 25.4 mm • For EOF loading N ≥ 76.2 mm
AS/NZS 4600 [98]	Steel	• Applicable to web perforated cold-formed C sections • Provides guidelines for all four-loading condition • Limited to web perforations located at mid-depth of the web • Confined to offset web openings • Consider both circular and non-circular web openings • Covers both flanges stiffened and unstiffened conditions
EN1993-1-3 [102]	Steel	• Applicable to I sections and both single and multi-web • Limited for sections without web openings
SEI/ASCE 8-02 [99] and **AS/NZS 4673** [100]	Stainless steel	• Applicable to C, Z, and I sections • Limited for sections without web openings • Provides guidelines for all four-loading condition • Covers both flanges stiffened and unstiffened conditions
EN1993-1-4 [103]	Stainless steel	• Suggests to use design guidelines provided in Eurocode 3 Part 1-3

AS/NZS 1664 [101]	Aluminium	• Web crippling design guidelines for flat web sections subjected to interior reactions and end reactions is provided • Limited for sections without web openings
EN1999-1-4 [104]	Aluminium	• Web crippling design guidelines for sections with stiffened and unstiffened webs is provided • Limited for sections without web openings

According to the reviewed literature it was evident that most of the past literature focuses on the web crippling response of web perforated lipped CF steel channel sections, and only a handful of studies have explored the web crippling response of web perforated CF stainless steel and CF aluminium channel sections. As a result, only a limited number of design guidelines are available for predicting web crippling capacities of web perforated CF stainless steel and aluminium sections. Moreover, it was understood that most of the existing design guidelines overestimate the web crippling capacities of CF lipped channel sections with web openings. Furthermore, no previous study has developed unified design guidelines for predicting the web crippling capacities of lipped CF steel, stainless steel and aluminium channel sections with web openings.

Laying the initial step for developing unified design guidelines via numerical investigations, this paper intends to develop a FE model for simulating the web crippling behaviour of CF steel, stainless steel and aluminium lipped channel sections with web openings, under the ETF loading condition. General-purpose FE program ABAQUS was used for developing the model. Developed FE models were then validated using past experimental data. Steps followed in the model development and validation is described under the section 5.

Table 3. Web crippling studies conducted on CF carbon steel, stainless steel and aluminium sections based on the direct strength method.

Loading Condition	Support Condition	Carbon Steel	Stainless Steel	Aluminium
ETF	Unfastened	Duarte and Silvestre [106]—Unlipped Channel Sections (UCSs) without web openings Choy et al. [105]—C and Z channel sections without web openings Keerthan et al. [32]—Hollow flange channel sections without web openings Gunalan and Mahendran [87]— UCSs without web openings Janarthanan et al. [16]—C and SupaCee sections without web openings Qiao et al. [107]—LCSs without web openings	Li and Young [63]—SHSs and RHSs without web openings	Alsanat et al. [90]—LCSs without web openings

	Fastened	Janarthanan et al. [16]—C and SupaCee sections without web openings	-	Alsanat et al. [52]—LCSs without web openings
ITF	Unfastened	Duarte and Silvestre [106]—UCSs without web openings Choy et al. [105]—C and Z channel sections without web openings Keerthan et al. [32]—Hollow flange channel sections without web openings Gunalan and Mahendran [87]— UCSs without web openings Janarthanan et al. [16]—C and SupaCee sections without web openings Qiao et al. [107]—LCSs without web openings	Li and Young [63]—SHSs and RHSs without web openings	Alsanat et al. [90]—LCSs without web openings
	Fastened	Janarthanan et al. [16]—C and SupaCee sections without web openings	-	Alsanat et al. [52]—LCSs without web openings
EOF	Unfastened	Duarte and Silvestre [106]—UCSs without web openings Dara and Yu [108]—C and Z sections without web openings Keerthan and Mahendran [33]—Hollow flange channel sections without web openings Sundararajah et al. [91]—LCSs without web openings Heurkens et al. [109]—LCSs without web openings Janarthanan et al. [16]—C and SupaCee sections without web openings	Li and Young [63]—SHSs and RHSs without web openings	-
	Fastened	Dara and Yu [108]—C and Z sections without web openings Janarthanan et al. [16]—C and SupaCee sections without web openings	-	-
IOF	Unfastened	Duarte and Silvestre [106]—UCSs without web openings Dara and Yu [108]—C and Z sections without web openings Keerthan and Mahendran [33]—Hollow flange channel	Li and Young [63]—SHSs and RHSs without web openings	-

	sections without web openings Sundararajah et al. [91]—LCSs without web openings Heurkens et al. [109]—LCSs without web openings Janarthanan et al. [16]—C and SupaCee sections without web openings		
Fastened	Dara and Yu [108]—C and Z sections without web openings Janarthanan et al. [16]—C and SupaCee sections without web openings	-	-

5. Numerical Model

In this study, non-linear elasto plastic FE software package ABAQUS, version 6.14 [46] was used to simulate web crippling behaviour of web perforated lipped CF carbon steel, stainless steel and aluminum channel sections. The bearing plates, web perforated LCS and the connection between the LCS and the bearing plates were modelled. Centerline dimensions were considered in modelling the cross-sections. ABAQUS/Explicit solver and nonlinear quasi-static analysis and were considered in simulating the slow movement of the bearing plates and to solve contact and convergence issues observed when using ABAQUS/Implicit solver [52].

5.1. Element Type and Mesh Control

Considering the thin-walled nature of the CF lipped channel sections, four-node general-purpose deformable shell element S4R was used to model the channel sections. Adequacy of the S4R element in simulating the web crippling response of CF sections has been proved in many past studies [8,76]. Considering the relatively stiff nature, top and bottom bearing plates were modelled as rigid bodies. Three-dimensional quadrilateral rigid element (R3D4) was used in modelling the bearing plates. Mesh sizes were appropriately selected to increase the accuracy of the numerical results, while keeping the computational time to a minimum. Based on the numerical studies conducted by Sundararajah et al. [88], web perforated lipped channel sections were modelled using a 5 mm × 5 mm mesh size. Ensuring proper transfer of stresses at the web flange juncture, a finer mesh size (5 mm × 1 mm) was used around the corner regions of the section. A mesh size of 10 mm × 10 mm was used for the bearing pates. Figure 6 shows the mesh sizes and element types used in the FE model.

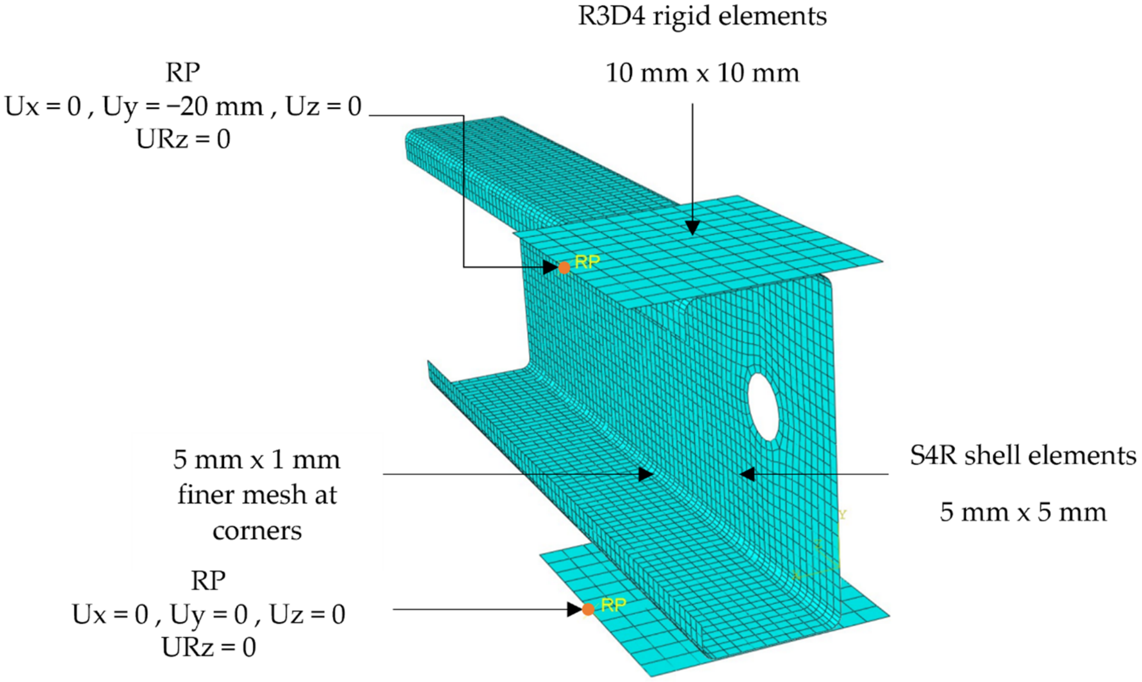


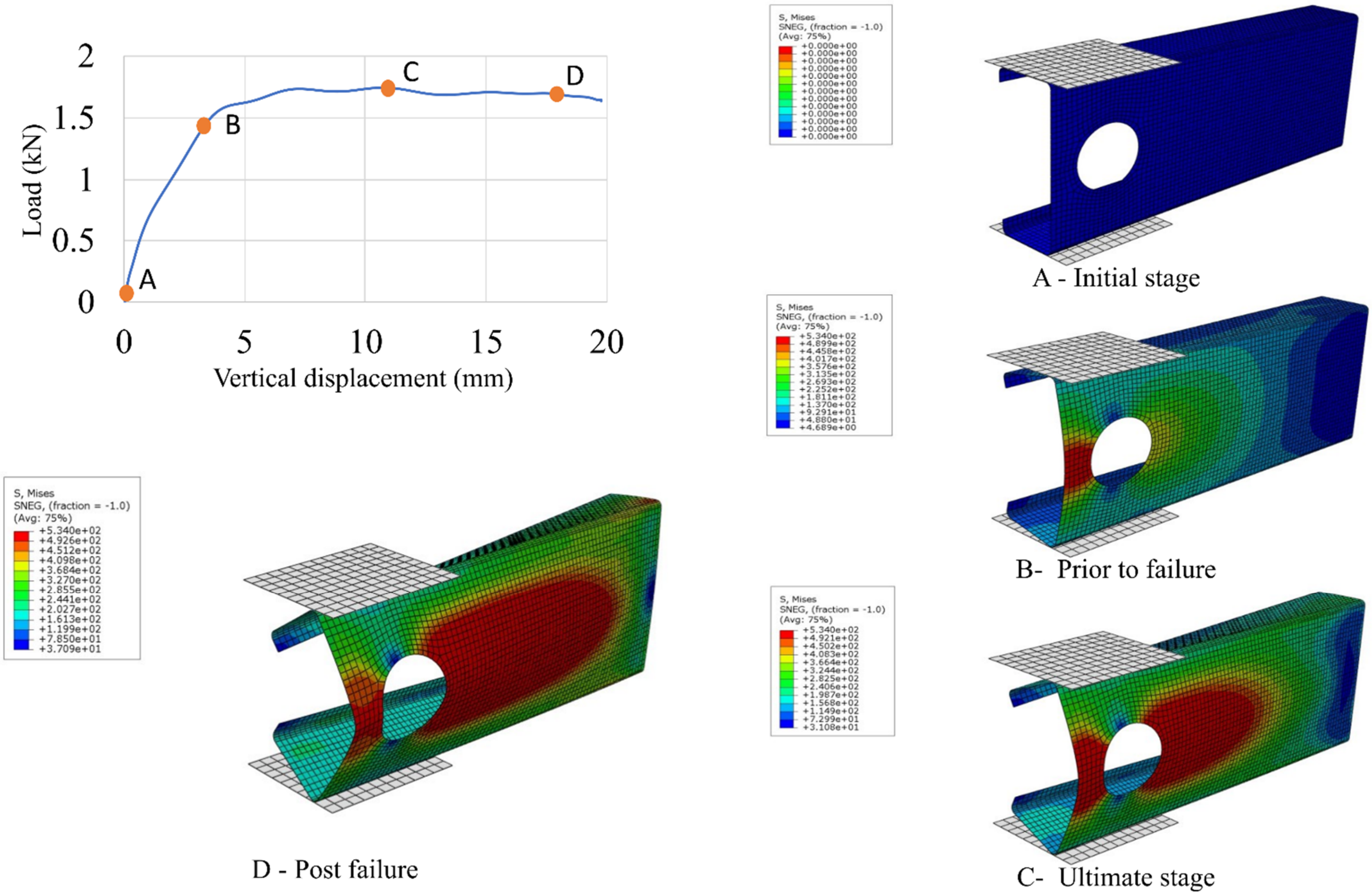
Figure 6. Element types, mesh sizes and boundary conditions used in the FE model.

5.2. Material Properties

In this study material properties of CF carbon steel, stainless steel, and aluminium sections were simulated considering the true stress-strain behaviour. Based on the web crippling studies conducted by Sundararajah et al. [88] an elastic-perfectly plastic model with nominal yield strength was used to model CFS sections. Modified two stage Ramberg-Osgood material model was used to simulate the non-linear stress-strain behaviour of CFSS sections. Considering the strain hardening nature of CF aluminium, Continuous Strength Method (CSM) was applied to model the material behaviour of CF aluminium sections. In this study, similar material properties were considered for the whole model, despite the variation of the material properties at corners of the LCS due to the plastic deformations caused via the cold working process [58,86].

5.3. Contact Behaviour, Boundary Conditions and Loading

Simulating the experimental setup, contact between the top and bottom bearing plates and the CF lipped channel section was modelled considering surface to surface contact technique. Contact surfaces of the bearing plates were considered as the master surface, while the contact surface of the channel section was considered as the slave surface. In simulating the contact behaviour penetration of the slave surface into the master surface was prevented by adhering the “hard” contact relationship. In each model, a coefficient of friction of 0.4 was used to account for the friction between contact surfaces [76,88]. Boundary conditions were carefully assigned to replicate the experimental behaviour. Simply supported behaviour of the top bearing plate was simulated by restraining it against translational movements in the X and Z directions and rotations about Z axis. Simulating the displacement-controlled loading conditions, translations movements in the Y axis were enabled. To simulate the experimental behaviour all translational movements and rotational movements about Z axis were restricted at the bottom bearing plate. These boundary conditions were applied to the bearing plates through a reference point (Figure 6). Furthermore, “smooth step amplitude” was considered in modelling the effect of the transverse load on the channel section. Figure 7 shows the failure mode progression observed during the FEA of this study along with the respective load-displacement plot.



A - Initial stage

B- Prior to failure

C- Ultimate stage

D - Post failure

Figure 7. Failure mode progression of the 172x65x13-t1.3N120A0.4FR CFS section.

5.4. Model Validation

Past experimental data on the web crippling behaviour of lipped CF steel, stainless steel, and aluminium sections under ETF loading condition were considered in validating the developed FE model. Test data on the web crippling response of web perforated lipped CF steel (reported in [58]) and aluminium (reported in [86]) channel sections subjected to ETF loading were respectively used in validating the models developed for CF steel and aluminum materials. Considering the unavailability of experimental test data CFSS channel sections, web crippling test data of web perforated lipped CFS channel sections under ETF loading (reported in [58]) were used to validate the model developed for CFSS sections. Tables 4–6 presents the comparison of the FE test results with experimental test data for CF steel, stainless steel and aluminium sections respectively.

Table 4. Comparison of web crippling capacities of lipped CFS channels with web openings under ETF loading condition [58].

Specimen	**Lipped Channel Dimension (mm)**							**Bearing Length (mm)**	**Yield Strength (Mpa)**	**Experimental Web Crippling Strength (kN)**	**Web Crippling Strength from FEM (kN)**	**Exp/FEM**
	Depth of the Web	**Flange Width**	**Lip Width**	**Web Thickness**	**Corner Radius**	**Opening Diameter**	**Length**					
142x60x13-t1.3N90A0.2FR	142.2	58.6	15.90	1.23	4.8	27.9	337.5	90	455	1.98	1.97	1.01
142x60x13-t1.3N90A0.4FR	142.2	59.5	16.30	1.25	4.8	55.8	337.5	90	455	1.62	1.73	0.94
142x60x13-t1.3N90A0.6FR	142.2	59.5	16.30	1.25	4.8	83.6	337.5	90	455	1.32	1.44	0.92
142x60x13-t1.3N120A0.2FR	141.8	58.9	15.60	1.24	4.8	27.9	350	120	455	1.95	2.2	0.89
142x60x13-t1.3N120A0.4FR	141.3	58.8	16.30	1.24	4.8	55.7	350	120	455	1.78	1.88	0.95
172x65x13-t1.3N120A0.4FR	172.3	63.6	15.50	1.27	5	67.6	400	120	534	1.7	1.74	0.98
172x65x13-t1.3N120A0.6FR	172.6	64.3	15.30	1.28	5	101.6	400	120	534	1.36	1.46	0.93
202x65x13-t1.4N120A0.4FR	202.4	64.2	16.50	1.45	5	79.5	425	120	513	1.88	1.99	0.94
262x65x13-t1.6N120A0.4FR	262.8	63.4	14.70	1.55	5.5	103.4	525	120	525	1.77	1.86	0.95
262x65x13-t1.6N150A0.4FR	262.8	63.4	14.70	1.55	5.5	103.4	550	150	525	2.04	1.98	1.03
Mean value												0.95
COV												0.04

Table 5. Comparison of web crippling capacities of lipped CFSS channels with web openings under ETF loading condition [58].

Specimen	**Lipped Channel Dimension (mm)**							**Bearing Length (mm)**	**Yield /Ultimate Strength (Mpa)**	**Experimental Web Crippling Strength**	**Web Crippling Strength from FEM**	**Exp/FEM**
	Depth of the Web	**Flange Width**	**Lip Width**	**Web Thickness**	**Corner Radius**	**Opening Diameter**	**Length**					
142x60x13-t1.3N90A0.2FR	142.2	58.6	15.90	1.23	4.8	27.9	337.5	90	455/532	1.98	2.01	0.99
142x60x13-t1.3N90A0.4FR	142.2	59.5	16.30	1.25	4.8	55.8	337.5	90	455/532	1.62	1.67	0.97
142x60x13-t1.3N120A0.2FR	141.8	58.9	15.60	1.24	4.8	27.9	350	120	455/532	1.95	2.01	0.97
172x65x13-t1.3N120A0.4FR	172.3	63.6	15.50	1.27	5	67.6	400	120	534/566	1.7	1.69	1.01
202x65x13-t1.4N120A0.2FR	202.4	64.3	16.30	1.45	5	39.8	425	120	513/552	2.41	2.51	0.96
202x65x13-t1.4N120A0.4FR	202.4	64.2	16.50	1.45	5	79.5	425	120	513/552	1.88	2.05	0.92
Mean value												0.97
COV												0.03

Table 6. Comparison of web crippling capacities of CF aluminium lipped channels with web openings under ETF loading condition [86].

Specimen	Lipped Channel Dimension (mm)							Bearing Length (mm)	Yield Strength (Mpa)	Experimental Web crippling Strength (kN)	Web Crippling Strength from FEM (kN)	Exp/FEM
	Depth of the Web	Flange Width	Lip Width	Web Thickness	Corner radius	Opening Diameter	Length					
U-ETF-250-3-A0.2(a)	252.4	76.7	24.90	2.94	4.8	47.384	716	100	210	4.8	4.7	1.02
U-ETF-250-3-A0.2(b)	252.3	76.9	23.70	2.94	5	47.284	714	100	210	4.7	4.63	1.02
U-ETF-250-3-A0.5	253.5	77.2	23.60	2.97	4.8	118.98	715	100	206	3.9	3.6	1.08
U-ETF-250-3-A0.8(a)	254	77.7	25.60	2.94	4.8	190.816	714	100	206	3	2.94	1.02
U-ETF-250-3-A0.8(b)	262.1	76.2	22.70	2.44	4.8	198.096	715	100	206	3.1	2.6	1.19
Mean value												1.06
COV												0.06

When considering the validation for CFS, the mean value was observed to be 0.95, while the coefficient of variation (COV) is 0.04. Validation of the FE model developed for CFSS sections showed a mean value of 0.97 with a COV of 0.03. Validation of the FE model developed for CF aluminium sections resulted in a mean value of 1.06 with a COV of 0.06. Further, as shown in Figures 8 and 9, load-deflection plots comparing the experimental test results and the FE results were developed for CF carbon steel and aluminium sections. Based on this comparison, it is possible to conclude that there is a decent agreement between experimental and finite element results. Based on these findings, it is possible to conclude that the FE models developed for CF carbon steel, stainless steel and aluminium sections can be successfully used to simulate the web crippling behaviour of lipped CF channel sections with web openings under ETF loading condition. Hence, these models can be successfully used in developing unified design equations for predicting the web crippling response of web perforated CF lipped channel sections.

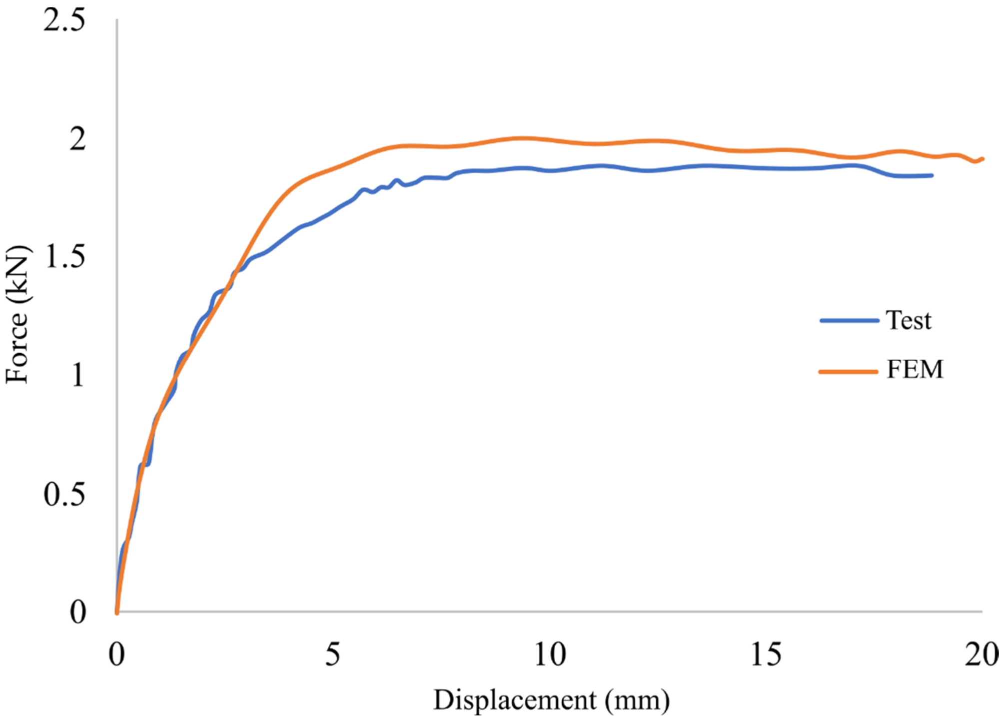


Figure 8. CF Carbon steel specimen; 202x65x13-t1.4N120A0.4FR.

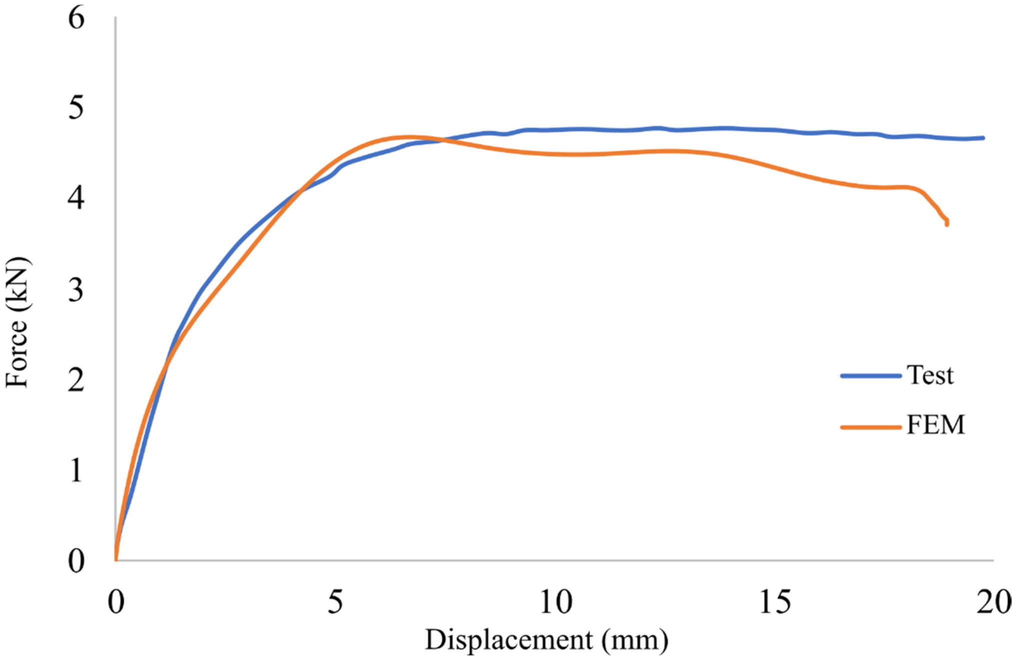


Figure 9. CF Aluminium specimen; U-ETF-250-3-A0.2(a).

6. Conclusions

This paper provides a detailed review of the past literature on the web crippling behaviour of lipped cold-formed (CF) steel, stainless steel, and aluminium channel sections with web openings. All these investigations were found to have followed one of three basic approaches: theoretical, experimental, or numerical. However, there were many instances in the literature where combined studies of theoretical and experimental and experimental and numerical have been conducted. Among them, combined numerical and experimental studies were identified to be the most reliable and commonly used type of study.

Even though web openings play a vital role in reducing the web crippling capacity of CF sections, only a few studies have been conducted to evaluate the web crippling strength of web perforated CF sections. Most of the past literature investigates the web crippling behaviour and strength of web perforated CF steel channel sections, while only a few studies have focused on the web crippling behaviour of CF stainless steel and aluminium sections with web openings. This has ultimately resulted in the limited availability of design guidelines for predicting the web crippling behaviour of CF stainless steel and aluminium sections with web openings. Moreover, it was understood that most of the existing design guidelines are incapable of providing adequate web crippling strength predictions for CF-lipped channel sections with web openings. Furthermore, to date no unified design guideline has been derived to predict the web crippling capacities of CF channel sections with web openings. Hence, unified design guidelines should be developed for predicting the web crippling capacities of all commercially available web perforated lipped CF steel, stainless steel, and aluminium channel sections.

To bridge this research gap, a combined experimental and numerical investigation should be conducted on the web crippling behaviour of web perforated CF sections, under all four loading conditions. Initiating the numerical investigation, under the present study a finite element model was developed for predicting the web crippling behaviour of lipped CF steel, stainless steel and aluminium channel sections with web openings under end two flange loading condition. Based on past experimental data, developed finite element models have been proved to successfully simulate the web crippling response of CF lipped channel sections with web openings. Hence, the FE model developed under this study can be used to develop unified design guidelines for predicting the web crippling behaviour of lipped CF steel, stainless steel and aluminium sections with web openings.

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