Reliability of cold-formed sections with web holes susceptible to failure by web crippling due to concentrated force

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Abstract.

This study evaluate the reliability of cold-formed profiles with perforated webs subjected to concentrated loads in sections without transverse stiffeners, susceptible to web crippling failure using the First-Order Reliability Method (FORM). A database was created with experimental results extracted from the literature, contemplating the four loading cases (End One Flange Loading - EOF, Interior One Flange Loading - IOF, End Two Flanges Loading - ETF, Interior Two Flanges Loading - ITF) addressed by the standards used as references, NBR 14762 [1], AISI [2], and EN 1993-1-3 [3]. To obtain statistical data for the professional factor, one of the variables in the reliability problem, experimental results were compared with theoretical results obtained from standard equations. Only the AISI standard [2] provides a criterion for considering openings in the web, in other words, equations for specified reduction factors for EOF and IOF. The results showed that web perforations significantly reduce the strength of sections when subjected to the EOF loading case, while they reduce to a lesser extent in sections exposed to the IOF loading case. The specimens groups subjected to ETF and ITF loading cases did not reach the target reliability index values for any of the reference standards.

Key words: Web crippling, Reliability, Cold-formed profile.

1 Introduction

Cold-formed steel members are structural elements widely used in the construction industry due to their high strength-to-weight ratio and ease of installation. Despite reducing the profile's strength in various situations, the perforation of the web is often a design necessity to accommodate the passage of ducts, wires, and pipes.

One of the main characteristics of cold-formed profiles is their small thickness, making them prone to web crippling due to high local stress concentrations. Furthermore, the presence of perforations in the web can increase susceptibility to this effect, especially if the holes are located near supports or where concentrated loads are applied.

The study of web crippling is complex, and its occurrence is influenced by many factors, such as geometric characteristics of the member, steel properties, and the loading case to which it is subjected, making it difficult to develop an appropriate theoretical formulation.

The first publication of the design specification for Cold-Formed Steel Design (CFSD) by AISI occurred in 1946. After several revisions, the first edition based on the Load and Resistance Factor Design (LRFD) method was published in 1991 (BESHARA and SCHUSTER, [4]). Misiek and Belica [5] mention that the specifications for web crippling in the EN 1993-1-3 standard [3] were derived from the AISI 1996 specification, although some provisions were modified.

The formulations used in this study follow the guidelines established by standards NBR 14762 [1], AISI [2], and EN 1993-1-3 [3], which are limited to certain situations. For instance, NBR 14762 [1] and EN 1993-1-3 [3] do not provide any specific formulations for the design of profiles with web perforations. Additionally, AISI [2] does not cover all loading cases in its considerations, limiting itself to End One Flange Loading (EOF) and Interior One Flange Loading (IOF). Melo et al. [6] mentions that current standardization, as it is based on empirical formulations, limited by the properties of the specimens tested, results in low safety levels.

These formulations were used to calculate the theoretical values of nominal web crippling strength (resistance) in specimens from a database extracted from the literature. With these theoretical resistance force values, it was possible to compare them to the experimental resistance force values provided by the authors, obtaining the model error (professional factor) for each specimens group in the database. The following studies were used to compile the database: Langan et al. [7], Deshmukh et al. [8], Uphoff et al. [9], Lian et al. [10], Lian et al. [11] Uzzaman et al. [12], Uzzaman et al. [13], Uzzaman et al. [14].

For the reliability analysis, the FORM method were applied to obtain the reliability index values (β), which were then compared with the target reliability index (β_0) adopted in each standard. Finally, resistance factors (ϕ ou γ) were calibrated.

2 Design criteria

The NBR 14762 [1], as well as the AISI [2], mentions four types of loading to be analyzed that depend on the position of the concentrated force on the profile flanges:

- EOF, End One Flange loading;
- IOF, Interior One Flange loading;
- ETF, End Two Flange loading;
- ITF, Interior Two Flange loading.

The situation that characterizes a loaded flange occurs when the free distance between concentrated forces applied to opposite flanges corresponds to 1.5 h (where h is the depth of the web) of the profile or higher values. Other cases are classified as both flanges loaded. Regarding the location of the concentrated force on the profile, it is classified as an end force when the distance from its application to the end of the beam corresponds to 1.5 h or lower values. Higher values classify it as an interior force. The support condition of the flange at the region of force application, establishing a restriction on rotation, is a factor that complements the analysis of loading cases. This condition classifies the flange as fastened (F) or unfastened (UF).

The nominal web crippling resistance is determined from Equation 1, which is provided similarly in the standards NBR 14762 [1] and AISI [2], differing only in terminology and presentation of resistance factors. The European standard EN 1993-1-3 [3] provides an equation for each loading case (Equations 2 to 8). For this study, the terms of the standard equations that have the same meaning were standardized.

The AISI [2] standard presents guidelines with reduction factor formulas for the EOF (Equation 9) and IOF (Equation 10) loading cases to be applied to the web crippling resistance obtained from Equation 1. For this study, the reduction factors obtained from the AISI [2] specifications were also applied to the resisting forces obtained from NBR 14762 [1] and EN 1993-1-3 [3], since these standards do not provide their own reduction factor formulas. For the ETF and ITF loading cases, equations presented by the authors in their studies were used (Equations 11 to 14).

In both equations, P_n is the nominal web crippling resistance; θ is the angle between the web and bearing surface planes, in degree (45°≤ θ ≤ 90°); R is the inside bend radius; N is the bearing length; h is the flat dimension of the web measured in the web plane; t is the web thickness; C is a coefficient associated with web crippling; C_R is a coefficient associated with the inside bend radius; C_N is a coefficient associated with is the bearing length; C_h is a coefficient associated with web slenderness; F_y is the design yield stress.

In EN 1993-1-3 [3], h_w is the height of the web between the midlines of the flanges, and the coefficients are given by: $k_1 = 1.33 – 0.33$ k; $k_2 = 1.15 – 0.15$ R/t, however $0.5 \leq k_2 \leq 1$; $k_3 = 0.7 + 0.3 (\theta /90)^2$; $k_4 = 1.22 – 0.22$ k; $k_5 = 1.06 – 0.06$ R/t, however $k_5 \leq 1$; k = F_y/228 with F_y in N/mm².

In Equations 9 and 14, used to calculate the reduction factors (R_c), d_h is the diameter of the hole in the web; h is the flat dimension of the web measured in the web plane; x is the closest distance between the hole in the web and the end of the beam; r_q represents inside fillet radius between web and hole edge-stiffener; q is the length of web holes edge-stiffener, if it exists specimens with web holes edge-stiffener.

The NBR 14762 [1] presents the resistance factor (γ), while the AISI [2] presents different resistance factor values (ϕ) for different loading cases, support conditions of the specimens, and methodology (LSD and LRFD). γ corresponds to 1/ϕ.

Table 1 presents the formulations for web crippling resistance and reduction factors.

Table 1. Formulations for web crippling resistance

Reference	Equation	Notes
[1]	$P_n = Ct^2F_y sen\theta\left(1 - C_R\sqrt{\frac{R}{t}}\right)\left(1 + C_N\sqrt{\frac{N}{t}}\right)\left(1 - C_h\sqrt{\frac{h}{t}}\right)$ (1)	
[3]	$P_n = k_1k_2k_3\left[9.04 - \frac{\frac{h_w}{t}}{60}\right]\left[1 + 0.01\frac{N}{t}\right]t^2F_y$ (2)	EOF. A section, stiffened flanges.
[3]	$P_n = k_1k_2k_3\left[5.92 - \frac{\frac{h_w}{t}}{132}\right]\left[1 + 0.01\frac{N}{t}\right]t^2F_y$ (3)	EOF. A section, unstiffened flanges. N/t ≤ 60
[3]	$P_n = k_1k_2k_3\left[5.92 - \frac{\frac{h_w}{t}}{132}\right]\left[0.71 + 0.015\frac{N}{t}\right]t^2F_y$ (4)	EOF. A section, unstiffened flanges. N/t >60
[3]	$P_n = k_3k_4k_5\left[14.7 - \frac{\frac{h_w}{t}}{49.5}\right]\left[1 + 0.007\frac{N}{t}\right]t^2F_y$ (5)	IOF. N/t ≤ 60
[3]	$P_n = k_3k_4k_5\left[14.7 - \frac{\frac{h_w}{t}}{49.5}\right]\left[0.75 + 0.011\frac{N}{t}\right]t^2F_y$ (6)	IOF. N/t >60
[3]	$P_n = k_1k_2k_3\left[6.66 - \frac{\frac{h_w}{t}}{64}\right]\left[1 + 0.01\frac{N}{t}\right]t^2F_y$ (7)	ETF
[3]	$P_n = k_3k_4k_5\left[21.0 - \frac{\frac{h_w}{t}}{16.3}\right]\left[1 + 0.0013\frac{N}{t}\right]t^2F_y$ (8)	ITF
[2]	$R_c = 1.01 - \frac{0.325d_h}{h} + \frac{0.083x}{h} \leq 1.0$ (9)	EOF
[2]	$R_c = 0.90 - \frac{0.047d_h}{h} + \frac{0.053x}{h} \leq 1.0$ (10)	IOF
[13]	$R_c = 1.01 - 0.16\left(\frac{d_h}{h}\right) + 0.06\left(\frac{x}{h}\right) + 0.04\left(\frac{r_q}{t}\right) + 0.31\left(\frac{q}{h}\right)$ (11)	ITF Offset to the bearing plates web holes.
[13]	$R_c = 1.02 - 0.39\left(\frac{d_h}{h}\right) + 0.02\left(\frac{N}{h}\right) + 0.04\left(\frac{r_q}{t}\right) + 0.49\left(\frac{q}{h}\right)$ (12)	ITF Down the bearing plates web holes.
[14]	$R_c = 0.98 - 0.11\left(\frac{d_h}{h}\right) + 0.01\left(\frac{x}{h}\right) + 0.05\left(\frac{r_q}{t}\right) + 0.41\left(\frac{q}{h}\right)$ (13)	ETF Offset to the bearing plates web holes.

[14]	$R_c = 0.92 - 0.35\left(\frac{d_h}{h}\right) + 0.12\left(\frac{N}{h}\right) + 0.21\left(\frac{r_q}{t}\right) + 0.22\left(\frac{q}{h}\right)$	(14)	ETF Down the bearing plates web holes.

3 Limit State Function and Professional Factor

The limit state distinguishes the desirable behavior from the undesirable behavior of a structure. This concept is fundamental in determining the failure of a structural component in reliability analysis. Mathematically, the limit state is expressed as a function relating structural resistance to applied actions:

$$G\,(.) = R_n\,(MFP) - c(D + L) \tag{15}$$

where M is the material factor; F is the fabrication factor; P is the model error or professional factor; R_n is the nominal resistance determined in design; c is a deterministic coefficient; D represents the dead load and L represents the live load. Table 2 presents the statistical parameters and probability distributions of the variables.

The model error (P) is a random variable that can be obtained by the ratio between the experimental strength determined through tests and the theoretical strength calculated using the formulations proposed by the standards. The variable P reflects uncertainties arising from analysis methods, and as a result of its statistical analysis, the mean (P_m), the standard deviation (σ_P), the coefficient of variation (V_P), and the Probability Density Function (PDF) are obtained. These parameters are used to obtain the reliability index. Table 3 presents geometric characteristics of the specimens groups used in this study. All specimens are of stiffened C-section profiles. The number of specimens is represented by n.

The specimens from the IOF and EOF loading cases were separated into groups considering two factors: the time when the tests were conducted and the yield strength of the steel (F_y). The studies conducted by Langan et al. [7], Deshmukh et al. [8] and Uphoff et al. [9] are older and precede the formulations available in current editions of the reference standards, even serving as sources for updates in earlier versions of AISI. Therefore, they were based on parameters different from more recent studies.

The separation into groups according to F_y is due to the influence that its values exert on the results of the nominal web crippling resistance calculated using the formulations of EN 1993-1-3 [3], since it is applied twice in the formulas, multiplying the other parameters, as in NBR 14762 [1] and AISI [2], and in its coefficient k, which also determines other coefficients. In the study conducted by Langan et al. [7], the author describes that for the IOF loading case, the maximum web crippling resistance was obtained for F_y = 630 MPa, and for EOF it was F_y = 458 MPa. Therefore, these values were used as a basis for dividing the groups. Samples from the ETF and ITF loading cases were not divided into groups due to their limited amount of data.

Table 2. Statistical parameters and probability distributions

Variables	Mean value / nominal value	Coefficient of variation	Probability distribution
M	1.10	0.10	Lognormal
F	1.00	0.05	Lognormal
D	1.05	0.10	Normal
L	1.00	0.25	Largest Extreme Value

Table 3. Experimental data groups

Reference	Year	n	t	N/t	h/t	R/t	Fy (MPa)
[11] [12]	2017	27	1.27-2.49	20.08-117	109.02-151.06	1.20-3.78	263.39-479
[11]	2017	22	1.28-1.96	52.36-117.19	108.28-157.71	2.19-3.75	457-479
[7] [8]	1994/1996	130	0.81-2.49	30.61-181.82	46.36-220.85	1.59-5.21	248.21-641.21
[7] [8]	1994/1996	124	0.81-2.49	30.61-181.82	46.36-220.85	1.59-5.21	248.21-510.21
[7]	1994	6	0.84	91	179	4.73	641.21
[10] [12]	2016/2017	32	1.23-2.46	20.33-121.95	111.82-157.72	1.22-3.90	263.39-479
[12]	2017	6	1.96-2.46	20.33-50.51	115.94-118.78	1.22-1.53	263.39-332.81
[10]	2016	26	1.23-1.90	52.63-121.95	111.82-157.72	2.63-3.90	457-479
[7] [9]	1994/1996	124	0.84-1.96	12.99-90.91	33.55-220.85	2.03-5.21	234.42-641.21

[7] [9]	1994/1996	102	0.84-1.96	12.99-90.91	33.55-220.85	2.03-5.21	234.42-441.26
[7]	1994	22	0.84-1.80	14.09-30.30	44.79-168	2.20-4.73	496.42-641.21
[14]	2020	12	1.96-2.48	25-51	114.53-118.41	1.21-1.53	263.40-332.80
[13]	2020	12	1.96-2.48	20-51	114.53-118.41	1.21-1.53	263.40-332.80

4 Results

Table 4 presents the results related to the model error variable.

Table 4. Results of the statistical analysis of the model error variable

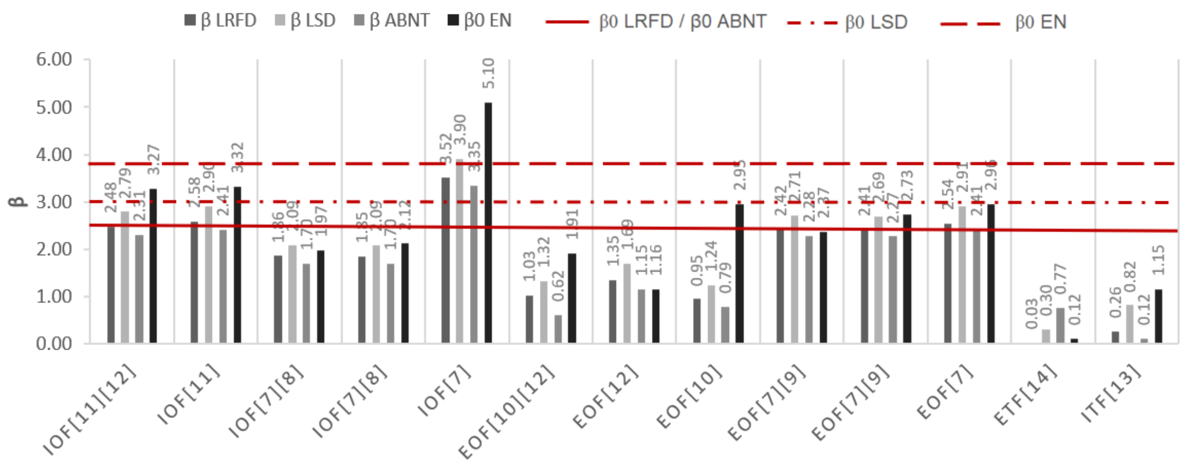
Reference	n	Load case	Support condition	Standard	P_m	V_P	Probability distribution
[11] [12]	27	IOF	UF	EN 1993-1-3 (2006)	1.17	0.07	Lognormal
				AISI (2016)	1.02	0.09	Normal
				NBR 14762 (2010)	0.84	0.08	Normal
[11]	22	IOF	F	EN 1993-1-3 (2006)	1.20	0.09	Normal
				AISI (2016)	1.03	0.07	Normal
				NBR 14762 (2010)	0.85	0.06	Normal
[7] [8]	130	IOF	UF	EN 1993-1-3 (2006)	1.00	0.28	Largest Extreme Value
				AISI (2016)	0.95	0.19	Lognormal
				NBR 14762 (2010)	0.78	0.15	Lognormal
[7] [8]	124	IOF	UF	EN 1993-1-3 (2006)	0.96	0.19	Lognormal
				AISI (2016)	0.93	0.17	Lognormal
				NBR 14762 (2010)	0.77	0.14	Lognormal
[7]	6	IOF	UF	EN 1993-1-3 (2006)	1.96	0.07	Largest Extreme Value
				AISI (2016)	1.35	0.05	Largest Extreme Value
				NBR 14762 (2010)	1.11	0.04	Largest Extreme Value
[10] [12]	32	EOF	UF	EN 1993-1-3 (2006)	1.05	0.25	Weibull
				AISI (2016)	0.62	0.08	Lognormal
				NBR 14762 (2010)	0.57	0.07	Lognormal
[12]	6	EOF	UF	EN 1993-1-3 (2006)	0.64	0.03	Normal
				AISI (2016)	0.65	0.04	Lognormal
				NBR 14762 (2010)	0.60	0.04	Lognormal
[10]	26	EOF	UF	EN 1993-1-3 (2006)	1.15	0.17	Largest Extreme Value
				AISI (2016)	0.61	0.08	Largest Extreme Value
				NBR 14762 (2010)	0.57	0.08	Largest Extreme Value
[7] [9]	124	EOF	UF	EN 1993-1-3 (2006)	1.56	0.61	Largest Extreme Value
				AISI (2016)	0.97	0.15	Normal
				NBR 14762 (2010)	0.90	0.14	Normal
[7] [9]	102	EOF	UF	EN 1993-1-3 (2006)	1.40	0.30	Normal
				AISI (2016)	0.98	0.16	Normal
				NBR 14762 (2010)	0.91	0.15	Normal
[7]	22	EOF	UF	EN 1993-1-3 (2006)	2.28	1.02	Lognormal
				AISI (2016)	0.93	0.09	Lognormal
				NBR 14762 (2010)	0.87	0.08	Lognormal
[14]	12	ETF	UF	EN 1993-1-3 (2006)	0.51	0.07	Largest Extreme Value
				AISI (2016)	0.47	0.04	Lognormal

				NBR 14762 (2010)	0.38	0.03	Lognormal
[13]	12	ITF	UF	EN 1993-1-3 (2006)	0.66	0.08	Lognormal
				AISI (2016)	0.50	0.06	Lognormal
				NBR 14762 (2010)	0.47	0.05	Lognormal

NBR 14762 [1] does not define calibration parameters such as β_0 and L_n/D_n, instead, it applies a single resistance factor for all load cases, $\gamma = 1.35$, EN 1993-1-3 [3] uses $\gamma = 1.25$, and AISI [2] employs variable resistance factors depending on loading cases, profile types, and flange support conditions. Table 5 provides some information used in the reliability analysis.

Figure 1 presents the β values obtained using the FORM method.

Table 5. Calibration data



Standard	$\gamma_D D_n + \gamma_L L_n$	L_n/D_n	ϕ	γ	β_0
AISI (2016) - LRFD	$1.2D_n + 1.6L_n$	5	0.8-0.9	1.25-1.11	2.5
AISI (2016) - LSD	$1.25D_n + 1.5L_n$	3	0.65-0.8	1.54-1.25	3.0
NBR 14762 (2010)	$1.25D_n + 1.5L_n$	5	0.74	1.35	2.5
EN 1993-1-3 (2006)	$1.35D_n + 1.5L_n$	5	0.80	1.25	3.8

Note: the subscript n refers to nominal value.

Figure 1. Reliability indices

Observing Figure 1, it is possible to see that for IOF loading cases, the groups with more uniform ranges of F_y values achieved or closely approached the target reliability indices. The specimens analyzed for the EOF loading case showed greater loss of resistance due to the presence of holes in the web compared to the specimens subjected to the IOF loading case. However, they did not suffer significant influence from the ranges of F_y values.

The specimens groups subjected to the ETF and ITF loading cases did not reach the target reliability index values for any of the reference standards. It should be noted that AISI [2] does not include these loading cases in its guidelines for determining resistance factors.

The variable P significantly influences reliability. If the P_m increases, to a value well above 1, β increases. In cases of low dispersion or when P_m is high together with low V_P, there is a high β. However, if P_m is low and at the same time V_P is high, we have a very low β.

The high variation in the values of β obtained in this study is primarily due to the dispersion among the data within each sample group. Although the samples were divided into groups based on the authors, the timing of the tests, and the limits of F_y, other factors also impact the results, such as h/t and N/t, the type and position of holes in the web, for example.

5 Conclusions

This study presents the reliability analysis of cold-formed steel members with perforations in the web subjected to concentrated force in sections without transverse stiffeners, susceptible to web crippling failure. For the IOF loading case, 179 specimens divided into 5 groups were analyzed. For EOF, 156 specimens divided into 6 groups were analyzed. For ETF and ITF, 12 specimens were analyzed for each case, with only one group in each case.

For IOF, the groups of specimens that reached β_0 have low dispersion and P_m above 1, in addition to F_y values in a range with less variation. For EOF, the groups of specimens that came closest to β_0 have P_m above 1, but significant dispersion, therefore approaching, but not reaching β_0.

Overall, observing the sample groups, the EOF loading case showed greater sensitivity to the presence of holes in the web compared to the IOF case. The ITF and ETF cases showed the worst results; however, the calculations of reduction factors were based on studies developed by other authors rather than on standards.

The reliability analysis of the specimens groups subjected to different loading cases showed that the LRFD approach yielded more satisfactory results, as more groups achieved the target reliability index. In cases where the target reliability index was not achieved, more conservative values for resistance factors would be necessary than those currently specified by the standards. Therefore, it would be necessary to extend and deepen the study to establish a code safety scenario for web crippling, encompassing sections with perforations in the web.

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References

[1] ABNT - Associação Brasileira de Normas Técnicas, "ABNT NBR 14762: Dimensionamento de estruturas de aço constituídas por perfis formados a frio". Rio de Janeiro, Brasil, 2010.

[2] American Iron and Steel Institute, "Specification for the Design of Cold-formed Steel Structural Members, Cold-formed Steel Design Manual". Washington, USA; 2016. AISI S100-16 Standard.

[3] European Committee for Standardization, "Eurocode 3 - Design of steel structures - Part 1-3: General rules - Supplementary rules for cold-formed members and sheeting". Brussels, Belgium, 2006.

[4] B. Beshara and R.M. Schuster, "Web Crippling Data and Calibrations of Cold Formed Steel Members". 2000. (*Research report RP00-2*).

[5] T. Misiek and A. Belica, "Calibration of European web-crippling equations for cold-formed C- and Z-sections". *Steel Construction*, 2019. doi: 10.1002/stco.201800006.

[6] N.B. Melo, M.S.R. Freitas, and A.L.R. Brandão, "Reliability of Cold-Formed Steel Sections Subjected to Web Crippling". *Structural Engineering International*, vol. 34:2, 196-202, 2024, doi:10.1080/10168664.2023.2249494.

[7] J.E. Langan, R.A. LaBoube and W.W. Yu, "Structural Behavior of Perforated Web Elements of Cold-Formed Steel Flexural Members Subjected to Web Crippling and a Combination of Web Crippling and Bending". Rolla (MO): University of Missouri-Rolla, 1994.

[8] S.U. Deshmukh, R.A. LaBoube and W.W. Yu, "Behavior of cold-formed steel web elements with web openings subjected to web crippling and a combination of bending and web crippling for interior-one-flange loading". Rolla (MO): University of Missouri-Rolla, 1996.

[9] C. Uphoff, R.A. LaBoube and W.W. Yu, "Structural behavior of circular holes in web elements of cold-formed steel flexural members subjected to web crippling for end-one-flange loading". Rolla (MO): University of Missouri-Rolla, 1996.

[10] Y. Lian, A. Uzzaman, J.B.P. Lim, G. Abdelal, D. Nash and B. Young, "Effect of web holes on web crippling strength of cold-formed steel channel sections under end-one-flange loading condition – part I: tests and finite element analysis". *Thin-Walled Struct*, vol. 107, 443– 452, 2016. doi:10.1016/j.tws.2016.06.025.

[11] Y. Lian, A. Uzzaman, J.B.P. Lim, G. Abdelal, D. Nash and B. Young, "Web crippling behaviour of cold-formed steel channel sections with web holes subjected to interior-one-flange loading condition - part I: experimental and numerical investigation". *Thin-Walled Struct*, vol. 111, 103–112, 2017. doi:10.1016/j.tws.2016.10.024.

[12] A. Uzzaman, J.B.P. Lim, D. Nash and B. Young, "Effects of edge-stiffened circular holes on the web crippling strength of cold-formed steel channel sections under one-flange loading conditions". *Engineering Structures*, vol. 139, 96-107, 2017. doi: 10.1016/j.engstruct.2017.02.042.

[13] A. Uzzaman, J.B.P. Lim, D. Nash and R. Krishanu, "Web crippling behaviour of cold-formed steel channel sections with edge-stiffened and unstiffened circular holes under interior-two-flange loading condition". *Thin-Walled Struct*. vol. 154, 2020. doi: 10.1016/j.tws.2020.106813.

[14] A. Uzzaman, J.B.P. Lim, D. Nash and R. Krishanu, "Cold-formed steel channel sections under end-two-flange loading condition: Design for edge-stiffened holes, unstiffened holes and plain webs". *Thin-Walled Struct*. vol. 147, 2020. doi: 10.1016/j.tws.2019.106532.