Nov 9th, 12:00 AM - 12:00 AM

DSM for Web Crippling under Two-Flange Conditions

Pedro Natário

Nuno Silvestre

Dinar Camotim

Wei-Wen Yu International Specialty Conference on Cold-Formed Steel Structures
Baltimore, Maryland, U.S.A, November 9 & 10, 2016

DSM for Web Crippling under Two-Flange Conditions

Pedro Natário[1], Nuno Silvestre[2], and Dinar Camotim[1]

Abstract

This paper summarizes recent investigations on the development of Direct Strength Method (DSM) for the design of cold-formed steel beams under two-flange (TF) loading against web crippling failure. Recently, the authors proposed a new approach to predict the web crippling failure load of cold-formed steel beams under External Two Flange (ETF) and Internal Two Flange (ITF) loadings using DSM. Firstly, existing experimental test data are summarized and then the accuracy of North-American Specification (AISI 2012) and Eurocode 3 (CEN 2006) provisions is briefly assessed. In order to obtain additional information on the web crippling behavior of each test specimen, non-linear numerical results are obtained. Since the calibration of the DSM-based formula involves the previous calculation of (i) elastic buckling load and (ii) plastic load, two procedures are presented. Buckling loads are determined using the GBTWEB software, intentionally developed for this purpose, while plastic loads are calculated using analytical expressions based on yield-line models. By adopting a non-linear regression, the coefficients of DSM-based formulae are determined using a set of 128 (ETF) and 130 (ITF) test results and the corresponding estimates of buckling and plastic loads. The DSM-based formulas for ETF and ITF web crippling design are successfully proposed and the resistance factors (LRFD) obtained are φ=0.81 (ETF) and φ=0.75 (ITF).

Introduction

The Direct Strength Method (DSM) is a reliable, consistent and well established design approach for cold-formed steel structures, which has been adopted by the NAS (AISI 2012). Despite being increasingly used, the method is still limited to structural problems involving (i) longitudinal normal stresses (global, distortional and local buckling) and (ii) shear stresses (shear buckling). In light of the previous

[1] DECivil, ICIST, IST, Universidade de Lisboa, Av. Rovisco Pais, 1049-001 Lisboa, Portugal.
[2] DEM, IDMEC, IST, Universidade de Lisboa, Av. Rovisco Pais, 1049-001 Lisboa, Portugal.

considerations, a DSM-based approach for web crippling should be sought. Following the DSM philosophy, the calibration of a formula (design curve) requires the use of three sets of data: (i) experimental ultimate loads (P_{test}), (ii) elastic critical loads associated with the appropriate buckling mode (P_{cr}) and (iii) plastic loads based on idealized failure mechanisms (P_y). The calibration of the DSM-based formula for the web crippling design of cold-formed steel beams subjected Two Flange (TF) loading is based on a non-linear regression model applied to the distribution of calculated data points (λ,χ), where χ stands for the web crippling strength reduction factor and λ is the slenderness parameter associated with the web failure. They depend on P_{test}, P_y and P_{cr}, being given by

$$\chi = \frac{P_{test}}{P_y} \qquad\qquad \lambda = \sqrt{\frac{P_y}{P_{cr}}} \tag{1}$$

Both P_y and P_{cr} could be obtained from Shell Finite Element (SFE) analyses, using elastic buckling analyses (no plasticity) for P_{cr} and elastic-plastic 1st order analyses (no 2nd order effects) for P_y. However, the critical load P_{cr} is determined through the use of Generalised Beam Theory – GBT (Natário *et al.* 2012) and the plastic load P_y is calculated through formulae derived from classical Yield-Line Theory (YLT). Additionally, SFE models were developed to link ("bridge") qualitatively the three data sets: P_{test} (experimental), P_{cr} (GBT) and P_y (YLT). The three objectives of SFE analyses are: (i) the validation of SFE ultimate loads through comparison with P_{test} values (test vs. SFE), (ii) the validation of GBT-based P_{cr} values through comparison with SFE critical loads (SFE vs. GBT), and (iii) the identification of plastic mechanisms to use for the YLT-based derivation of P_y formulae (SFE vs. YLT). Therefore, the aim of this paper is to propose new DSM-based formulas to estimate web crippling failure loads for the case of TF loadings. Further details should be found in Natário (2015) and Natário *et al.* (2016a,b).

Ultimate Strength - Existing Experimental Results

A literature survey of the existing experimental studies on beams under TF loading conditions was completed and the DSM-based formula was calibrated using these experimental results. The database includes 128 (ETF) / 130 (ITF) tests and a summary is provided in Table 1. Test data was reported by:

- Hetrakul and Yu (1978) (*Groups (i)-(ii)* – Figs. 1-2)
- Young and Hancock (1999, 2001) (*Group (iii)* – Fig. 3)
- Beshara and Schuster (2000) (*Group (iv)* – Fig. 4)
- Macdonald *et al*. (2008, 2011) (*Group (v)* – Fig. 5)

Tables 1 and 2 shows a brief characterization of the 5 groups of tests and the ranges of geometrical and material data.

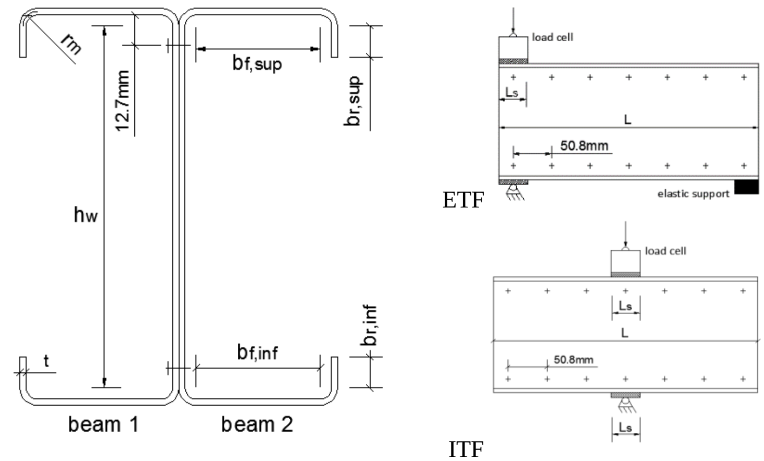


Fig 1: *Group (i)* by Hetrakul and Yu (1978)

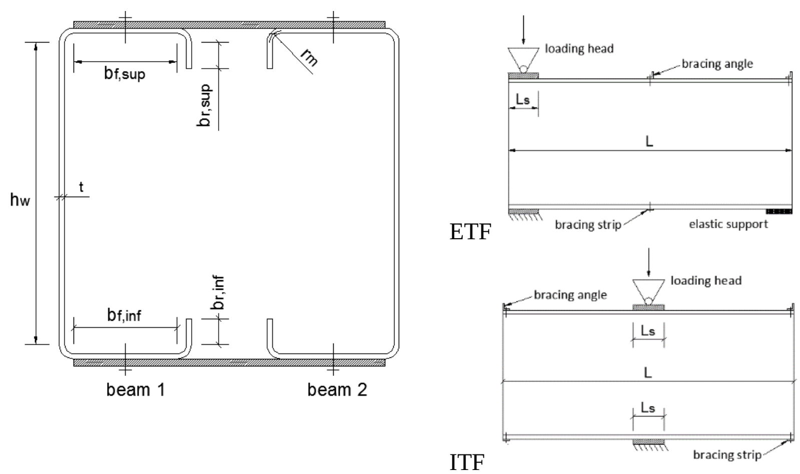


Fig. 2. *Group (ii)* by Hetrakul and Yu (1978)

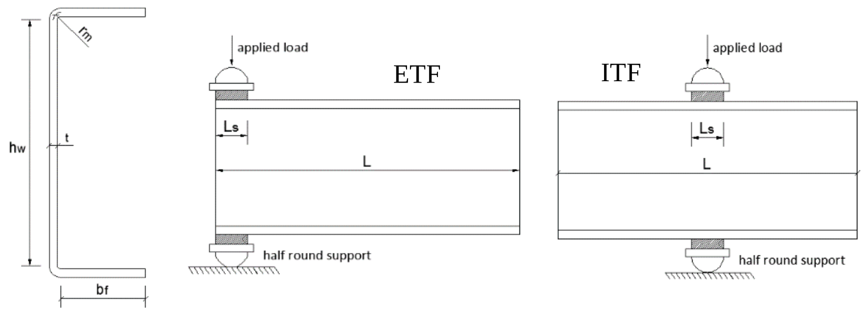


Fig. 3. *Group (iii)* by Young and Hancock (1999, 2001)

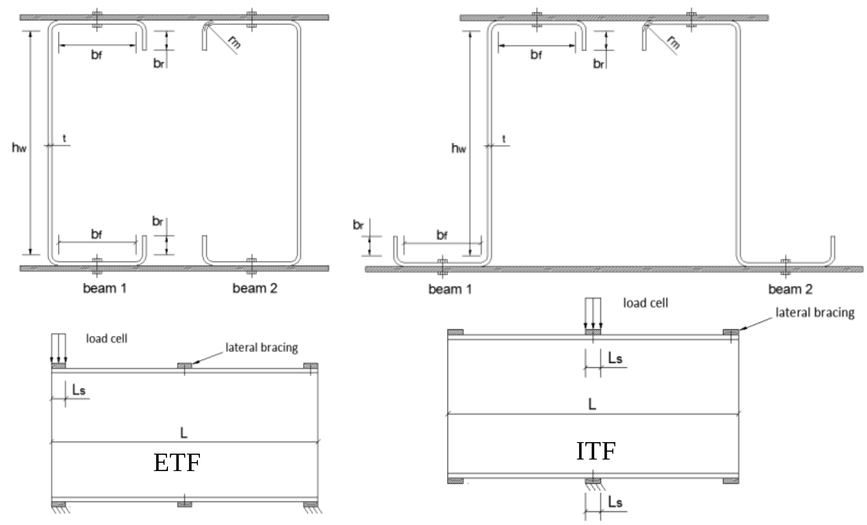


Fig. 4. *Group (iv)* by Beshara and Schuster (2000)

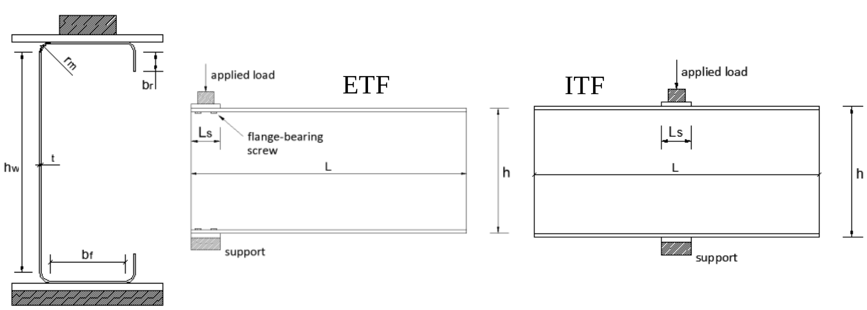


Fig. 5. *Group (v)* by Macdonald et al. (2008, 2011)

Table 1: Summary of the ETF test data for calibration of DSM-based formula

Group	#	t [mm]	h_w [mm]	b_f [mm]	r_m [mm]
(i)	28	1.17 – 2.74	129.2 – 305.2	27.8 – 90.5	2.97 – 4.15
(ii)	30	1.17 – 1.31	117.4 – 304.7	9.8 – 73.4	1.81 – 3.80
(iii)	16	3.83 – 6.01	58.8 – 269.7	31.9 – 76.8	5.82 – 11.40
(iv)	18	1.16 – 1.45	87.1 – 283.1	45.6 – 61.0	7.58 – 14.73
	18	1.16 – 1.45	89.1 – 283.1	44.8 – 60.7	7.58 – 14.73
(v)	18	0.78	65.2 – 98.2	26.8 – 46.7	1.99 – 5.39

Table 2: Summary of the ITF test data for calibration of DSM-based formula

Group	#	t [mm]	h_w [mm]	b_f [mm]	r_m [mm]
(i)	28	1.17 – 2.74	128.3 – 304.2	28-0 – 90.1	2.92 – 4.15
(ii)	30	1.19 – 1.33	117.0 – 305.2	10.1 – 73.8	1.82 – 3.79
(iii)	18	3.78 – 6.01	59.0 – 270.0	31.9 – 76.6	5.82 – 11.40
(iv)	18	1.16 – 1.45	87.1 – 283.1	45.1 – 61.0	7.58 – 14.73
	18	1.16 – 1.45	89.1 – 283.1	44.4 – 60.1	7.58 – 14.73
(v)	18	0.60	68.8 – 73.8	30.8 – 35.3	1.30 – 3.30

Ultimate Strength – NAS and EC3 Design Approaches

Before proposing the new DSM-based approach for the web crippling design of cold-formed steel members, it is deemed relevant to assess the applicability and accuracy of the existing design approaches. For this purpose, both the EC3 (CEN 2006) and NAS (AISI 2012) methodologies are considered. Figures 6 and 7 show comparisons between the nominal web crippling strength prediction (P_n) determined with the EC3 (Fig. 6) and NAS (Fig. 7) formulae, and the test failure loads (P_{test}). These plots provide clear information about the relative accuracy of each design method.

Overall, the current EC3 formulae may lead to significant errors, often on the unsafe side (data above the 1:1 line). This is particularly notorious for the (i) fastened C- and Z-sections tested by Beshara and Schuster (2000) and (ii) unfastened C-sections reported by Young and Hancock (1999, 2001), for which the errors are extremely large. Conversely, the current NAS formula leads to a better agreement, mainly due to the fact that many of these experimental test results were included in its calibration. However, its application to a new test data set (*Group (v)*) yields quite poor results. Furthermore, the EC3 approach lacks an appropriate distinction between C- and Z-sections, which have been proven to exhibit different web crippling strengths. Finally, despite the clause regarding the rotational restraint imposed to the web, the distinction between fastened and unfastened flanges is not explicitly addressed in EC3. In view of the above assessment, it can be easily concluded that the development of a novel DSM-based formula for the design against web crippling failure would be useful.

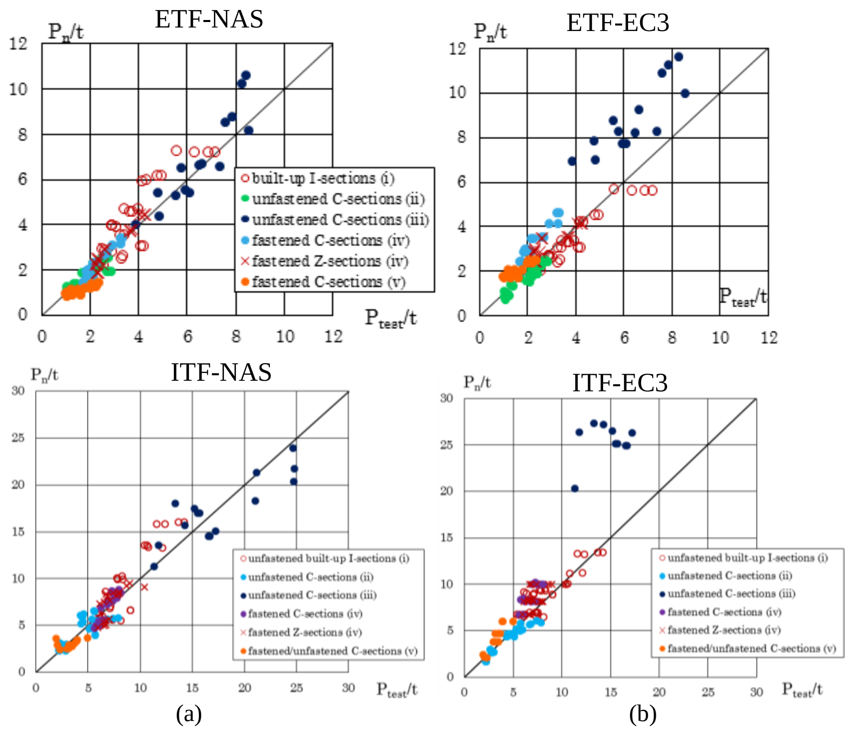
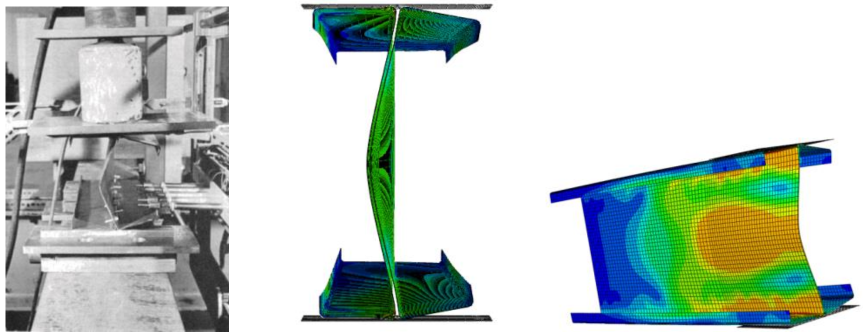


Fig. 6. Ultimate strength: (a) NAS vs. tests and (b) EC3 vs. tests – values divided by t

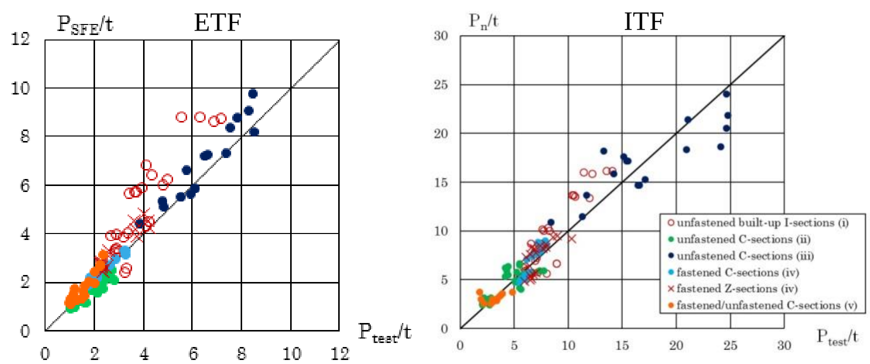
Ultimate Strengths – SFE Analyses

In the context of the ABAQUS (Simulia 2010) finite element software, an in-depth explanation of the advantages of quasi-static analysis was given in Natário et al. (2014a,b) and the selection of the different parameters involved in performing non-linear SFE analyses was addressed. In this work, SFE models accounting for several cross-section types and supporting/fastening conditions were implemented (see Figure 7). The full description of the SFE model implemented is presented in Natário et al. (2014a,b). Figure 8 summarizes the comparison between the ultimate loads obtained from quasi-static SFE analyses (P_n) with test results (P_{test}).



(a) (b)

Fig. 7: (a) Failure of I- 6-ETF-1 – *Group (i)* (Hetrakul and Yu 1978), (b) SFE model



(a) (b)

Fig. 8. Ultimate strength (SFE vs. tests): (a) ETF and (b) ITF – values divided by t

Overall, there is a good agreement between the numerical and experimental ultimate strength estimates, as well as between the failure modes (plastic mechanisms) obtained from SFE analyses and experimental tests (i.e., those visible in photos appearing in the source publications). The main differences occurred for the specimens belonging to *Group (iii)*, which failed in either web crippling (Natário et al. 2014a) or flange crushing (Natário et al. 2014b). It was generally observed that web crippling occurs for wider bearing plates, whereas flange crushing becomes prevalent when such plates are narrower. In certain cases, the experimental ultimate strength was higher for a narrower bearing plate, perhaps due to the development of flange crushing collapse. Usually, the web crippling strength capacity increases with the bearing plate size.

Buckling Loads - GBT Analyses

In this work, the buckling loads are determined by means of the GBTWEB freeware (Natário et al. 2016c), based on a GBT formulation previously developed by the authors (Natário et al. 2012). The GBT model for the buckling analysis is detailed in Natário (2015). In order to validate the GBT results, the SFE models developed to carry out the non-linear analyses (previously presented) were adapted to perform the corresponding elastic buckling analyses. In general, the GBT and SFE buckling analyses yielded similar results, not only in terms of the web buckling mode configuration but also concerning the buckling load (P_{cr}) values, as shown in Fig. 9. The exceptions are some specimens belonging to *Groups (i)* and *(iv)*. It is observed that GBT yields consistently lower buckling loads for the built-up I-section specimens (*Group (i)*), as had already been observed in the ETF case – most likely, these underestimations stem from the oversimplified model adopted. Moreover, some very significant discrepancies occur for specimens belonging to *Group (iv)*, due to the modelling of the corner: it is arguable that the buckling loads of specimens with large corner bend radii (with respect to the web size) will be less accurate. Nevertheless, it is possible to conclude that both models are quite performing in terms of capturing the influence of other geometrical parameters (e.g., thickness, web height and bearing plate width) on the value of P_{cr}.

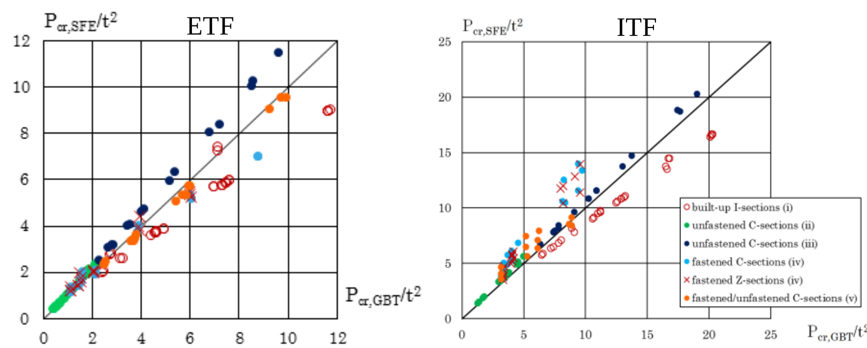


Fig. 9. Buckling loads (GBT vs. SFE): (a) ETF, (b) ITF – values divided by t^2

Plastic Loads - YLT Analyses

Besides P_{cr}, P_y (plastic load) is the other key ingredient of the proposed DSM design approach. A rational basis to calculate P_y is to view it as the load associated with the idealized plastic mechanism, akin to the true failure mode. For this purpose, rigid plastic analysis, namely the Yield-Line Theory (YLT), must be employed. The selected yield-line mechanism for the derivation of a P_y formula depends on the observation of experimental (if available) and/or numerical (non-linear SFE) results. Both are instrumental to the definition of the failure mechanism. The non-linear analyses were particularly important in describing the progressive development of the mechanism, from the formation of the first yield line until the post-failure regime (e.g. see Fig. 10).

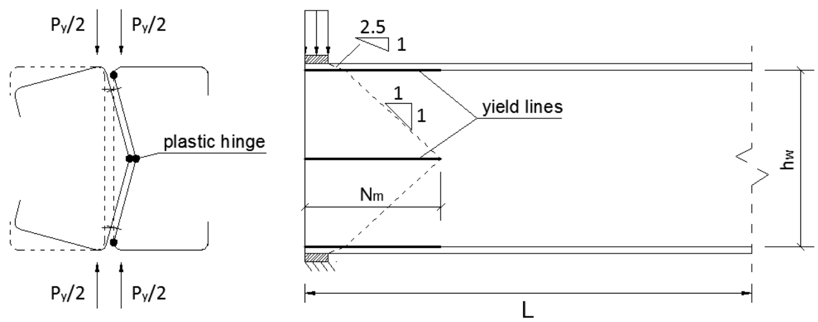


Fig. 10: Example of an yield-line mechanism (built-up I-section beams subjected to ETF loading conditions – *Group (i)*)

Naturally, the yield-line method leads to a P_y value that is an upper bound of the real plastic load – this fact is crucial for the validation of the proposed analytical models. The derivation of these P_y formulae has been reported in Natário (2015) and Natário et al. (2016a,b). The formulae to calculate P_y are briefly presented:

• *Group (i)*:

$$P_y = \frac{2}{3} f_y N_m \left(\sqrt{4r_m^2 + 9t^2} - 2r_m\right) \qquad N_m = \min\{L\ ;\ L_s + a \cdot r_{ext} + 0.5h_w\} \qquad (2)$$

$$a = 2.5 \text{ (ETF)};\ a = 5.0 \text{ (ITF)}$$

• *Group (ii)*:

$$P_y^{ETF} = f_y\, N_m \left(\sqrt{4\, r_m^2 + t^2 N_*/N_m} - 2r_m\right) \qquad N_* = 2N_m + \frac{4}{\sqrt{3}}(h_w + 2\, r_m) \qquad (3)$$

$$N_m = L_s + 2.5\, r_{ext} + 0.5h_w$$

$$P_y^{ITF} = f_y L \left(\sqrt{4r_m^2 + t^2} - 2r_m\right) \qquad (4)$$

• *Group (iii)*:

$$P_y = f_y N_m \left(\sqrt{4r_m^2 + t^2} - 2r_m\right) \qquad N_m = \min\{L\ ;\ L_s + a \cdot r_{ext} + b \cdot h_w\} \qquad (5)$$

$$a = 2.5;\ b = 0.5 \text{ (ETF)};\ a = 5.0;\ b = 1.5 \text{ (ITF)}$$

• *Group (iv)*:

P_y^{ETF} for Cs: use Group (ii) formula (3); P_y^{ETF} for Zs: use

$$P_y^{ETF} = \frac{2}{3} f_y N_m \left(\sqrt{r_m^2 + t^2 N_*/N_m} - r_m\right) \qquad N_m = L_s + 2.5\, r_{ext} + h_w/3 \qquad (6)$$

$$N_* = 4.5N_m + 5(h_w + 2r_m)$$

$$P_y^{ITF}=f_y N_m\left(\sqrt{4r_m^2+1.5t^2}-2r_m\right) \qquad N_m = \min\{L\ ;\ L_s+5r_{ext}+3h_w\} \qquad (7)$$

- *Group (v)*:

P_y^{ETF}: use Group (ii) formula (3)

P_y^{ITF} for fastened/unfastened sections: use *Group (iv)/Group (iii)* formula (7)/(5)

Unlike the determination of critical loads (P_{cr}), which was based on the consideration of sharp corners, the calculation of plastic loads (P_y) always considers explicitly the influence of the rounded corners, through the incorporation of r_{ext}. In fact, previous investigations by the authors have shown that rounded corners affect much more the plastic load values obtained from 1st order SFE analyses than the critical load values obtained from elastic buckling SFE analyses. In summary, this section presented yield-line models for the different web buckling failure mechanisms observed. Upon investigating the different test groups considered in the calibration of design expressions for TF web crippling load conditions, from a YLT perspective, it was concluded that there are substantial peculiarities in the collapse behavior, which limit the accuracy of the proposed yield-line models. In order to simplify the application of the DSM methodology, easy yield-line models were proposed, mostly grounded on the observation of numerical results (quasi-static analyses). Moreover, it should be noted that expression (6) has been simplified from a more complex equation presented by Natário (2015) and Natário *et al*. (2016a), which is acceptable for h_w/r_m ratios higher than 20.

Calibration of DSM-based formulas

The current DSM design formulas (NAS 2012) for the design of columns, beams and beam columns have a general format, which is also considered herein for web crippling design,

$$\frac{P_n}{P_y} = k_1\left[1 - k_2\left(\frac{P_{cr}}{P_y}\right)^{k_3}\right]\left(\frac{P_{cr}}{P_y}\right)^{k_3} \quad , \quad (8)$$

where (i) P_{cr} is the elastic buckling load, calculated using GBTWEB software, (ii) P_y is the plastic load, estimated using the YLT formulas previously presented and (iii) P_n is the nominal value of the web crippling strength. The calibration of the k_1, k_2 and k_3 coefficients was achieved through a non-linear regression, fitting the ratio P_{test}/P_y and the right hand side of Eq. (8), and using the computed results of P_{cr} and P_y for the tested specimens contained in *Groups (i)*-

(v). The coefficients k_1, k_2 and k_3 were calculated via the minimization of the sum of squared differences.

ETF conditions

The DSM-based formula to calculate the web crippling strength of section under External Tow Flange loading is given by

$$P_n = \begin{cases} P_y & \text{for } \lambda \leq 0.415 \\ 0.474 P_y \left[1 - 0.115\left(\frac{P_{cr}}{P_y}\right)^{0.728}\right]\left(\frac{P_{cr}}{P_y}\right)^{0.728} & \text{for } \lambda > 0.415 \end{cases} , \quad (9)$$

and a coefficient of determination R^2=0.928 was obtained. Fig. 11 shows the DSM-based curve and all test data points used for its calibration. According to the graphical results, it is possible to confirm that the different *Groups* included in this calibration exhibit a clear trend that is captured by the DSM-based formula. There is some dispersion for low web crippling slenderness values (up to 2). Also, there are specimens with very high slenderness, particularly those corresponding to fastened cases, due to the large value of the yield-to-buckling load ratio.

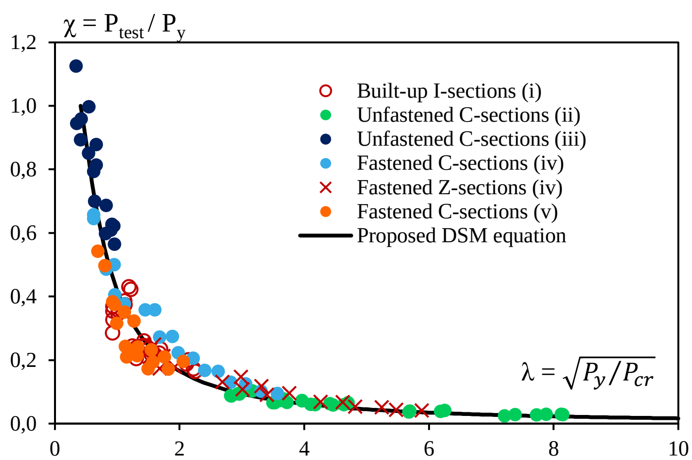


Fig. 11: Comparison between the proposed DSM-based formula and ETF test data

It was also considered important to evaluate the resistance factor φ associated with the proposed DSM formula. The load and resistance factor design (LRFD) design methodology adopted in the NAS (2012) adopts the condition, $\phi P_n \geq P_u$, where P_n stands for the nominal strength capacity and P_u is the factored load. The calculated resistance factor ϕ=0.81 is located within the range of the coefficients that are proposed in the NAS for web crippling design (0.75-0.90).

ITF conditions

In the calibration of the DSM-based formula for the web crippling strength of sections under Internal Two Flange (ITF) loading conditions, specimens failing by flange crushing (verified from quasi-static SFE analysis) were not considered. The expression obtained is

$$P_n = \begin{cases} P_y & \text{for } \lambda \leq 0.517 \\ 0.732P_y\left[1 - 0.156\left(\frac{P_{cr}}{P_y}\right)^{0.516}\right]\left(\frac{P_{cr}}{P_y}\right)^{0.516} & \text{for } \lambda > 0.517 \end{cases} \quad , \quad (10)$$

In the Figure 12, the proposed curve is compared with every experimental test result, including both web buckling and flange crushing data.

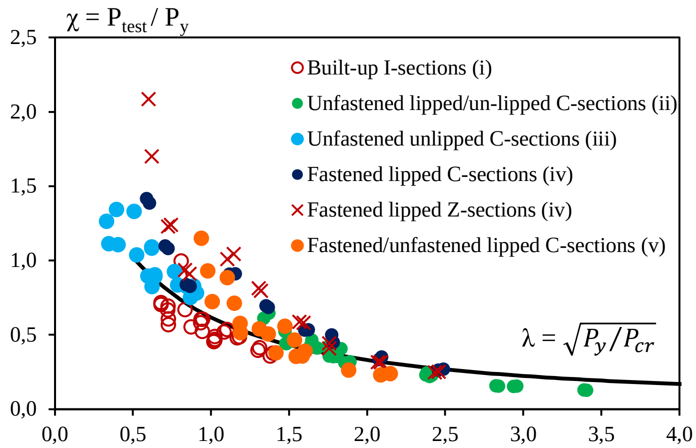


Figure 12: Comparison between the proposed DSM-based formula and ITF test data

According to these results, there is a non-negligible dispersion of the data points. Overall, it may be noticed that the method is overly conservative for a large number of test data, where a majority of the test specimens failing by flange crushing are included. From a more detailed observation, the points corresponding to the built-up I-sections (*Group (i)*) are systematically below the proposed curve, while those concerning *Groups (ii)*, *(iv)* and *(v)* are mostly above it. Despite the previous considerations, a well-defined trend regarding the relationship between the slenderness λ and the strength reduction factor χ is still clearly visible. These results evidence that there is great potential in the adopting the DSM approach to estimate the web crippling strength under ITF loading – nevertheless, it is also observed that there is a non-negligible spread in the data point distribution, which likely stems from the adoption of less consistent YLT models, particularly when applied to specimens where flange crushing is predicted. In fact, there is a number of data points for which P_{test} (ultimate load obtained from tests) exceeds P_y, thus leading to $\chi>1$ – this means that, in such cases, the P_y value (and plastic mechanism) predicted by the YLT model might not fit well the actual collapse mechanism. The calculated resistance factor for LFRD design was $\phi=0.75$, which is still within the range proposed in the NAS for web crippling design.

Conclusion

This paper presented a new approach to estimate the web crippling failure load of cold-formed steel beams under Two Flange (TF) loading using the Direct Strength Method (DSM). First, existing experimental data were reviewed and the current design formulas available in NAS and EC3 were applied to all test data to assess their accuracy. Quasi-static non-linear Shell Finite Element (SFE) analyses were performed to obtain additional information on the web crippling behavior of each test specimen. Then, the calibration of the DSM-based design curve involved the calculation of (i) elastic buckling loads, using the GBTWEB software (specifically developed for this purpose), and (ii) plastic loads, using analytical expressions based on Yield-Line Theory (YLT) models. Despite the different cross-section types, several fastening conditions, and distinct experimental set-ups considered in the calibration of the DSM formula, it was possible to find a clear relationship between the web crippling slenderness and the strength reduction factor. Some scatter exhibited by the results, particularly in the ITF case, was attributed to the less accurate prediction of plastic loads given by the developed YLT-based formulae. However, an increase in the accuracy of YLT-based formulas would entail an increased complexity, which is a feature that should be avoided in design practice. Furthermore, it was identified that several beams under ITF loading conditions were prone to flange crushing collapse, a phenomenon that should not be confused with the typical web buckling, commonly referred to as web crippling. Applying the expression calibrated with web buckling test data to the flange crushing test data, yielded the conclusion that while the proposed DSM formula reached safe estimates for the ultimate strength, the computed values may also be overly conservative. Finally, it should be mentioned that any beam is pre-qualified to be designed using the above DSM-based formula if it satisfies a given set of geometrical and material conditions/limits. These limits, given in Natário (2015) and Natário et al. (2016a,b), might be extended whenever additional test data becomes available. Despite the undeniable potential evidenced in this study, the proposal should be validated and enhanced through extension to different cross-section types (single hats, multi-web). In light of the promising results of this study, the methodology may also be easily extended to One Flange conditions (EOF and IOF) in the future, by following similar calibration procedures.

References

AISI (2012). American Iron and Steel Institute. *North American Specification for the design of cold-formed steel structural members*, S100-12, Washington.

Beshara B., Schuster R.M. (2000). *Web crippling data and calibrations of cold formed steel members*, Research Report RP00-2, Canadian Cold Formed Steel Research Group, University of Waterloo (AISI Report, revised 2006), Canada.

CEN (2006). Comité Européen de Normalisation. *Eurocode 3, Design of steel structures – Part 1-3: General rules, Supplementary rules for cold-formed members and sheeting*, Brussels.

Heiyanthuduwa M. (2008). *Web crippling behaviour of cold-formed thin-walled steel lipped channel beams*, Ph. D. Thesis, School of Engineering & Computing, Glasgow Caledonian University, Scotland, 2008.

Hetrakul N., Yu W. (1978). *Webs for cold-formed steel flexural members; Structural behaviour of beam webs subjected to web crippling and a combination of web crippling and bending*, University of Missouri-Rolla, Missouri, USA.

Macdonald M., Heiyantuduwa M.A., Kotelko M., Rhodes J. (2011). Web crippling behaviour of thin-walled lipped channel beams, *Thin-Walled Structures*, 49, 682-690.

Natário P. (2015). *Localized failure of thin-walled steel members subjected to concentrated loads: analysis, behaviour and design*. PhD Thesis in Civil Engineering, Instituto Superior Técnico – IST, Universidade de Lisboa, Portugal.

Natário P., Silvestre N., Camotim D. (2012). Localized web buckling analysis of beams subjected to concentrated loads using GBT, *Thin-Walled Structures*, 61, 27-41.

Natário P., Silvestre N., Camotim D. (2014a). Web crippling failure using quasi-static FE models, *Thin-Walled Structures*, 84, 34-49.

Natário P., Silvestre N., Camotim D. (2014b). Computational modelling of flange crushing in cold-formed steel sections, Thin-Walled Structures, 84, 393-405, 2014.

Natário P., Silvestre N., Camotim D. (2016a). Direct strength prediction of web crippling failure of beams under ETF loading, *Thin-Walled Structures*, 98(B), 360-374.

Natário P., Silvestre N., Camotim D. (2016b). Web Crippling of Beams under ITF Loading: a Novel DSM-Based Design Approach, *Submitted for publication*.

Natário P., Silvestre N., Camotim D. (2016c). *GBTWEB, GBT-based code for web buckling analysis of members under localised loads*, soon available at http://www.civil.ist.utl.pt/gbtweb/.

Simulia (2010). Dassault Systèmes. Abaqus User's Manual and Abaqus Theory Manual (version 6.10).

Young B., Hancock G.J. (1999). *Design of cold-formed unlipped channels subjected to web crippling*, Research Report No R794, The University of Sydney, Australia.

Young B., Hancock G.J. (2001). Design of cold-formed channels subjected to web crippling, *Journal of Structural Engineering ASCE*, 127 (10), 1137-1144.