An approach for the prediction of the load carrying capacity of thin-walled members under eccentric axial load.

Part 2: validation

Un approccio per la predizione della capacità portante di elementi con sezioni snelle soggetti ad azione assiale eccentrica.

Parte 2: la validazione

Claudio Bernuzzi, Paolo Rugarli

A companion paper describes a unified approach to evaluate the load carrying capacity of thin-walled cold-formed members under constant axial load and constant bending moments. In this paper the validation phase is presented, which has been developed to appraise the method's accuracy. In particular, the state-of-the-art of tests of thin-walled members under eccentric axial load has been considered and in total 229 experiments have been simulated to predict the specimen resistance.

In un lavoro precedente è stato descritto un approccio unificato per valutare la capacità portante di membrature formate a freddo in parete sottile soggette ad azione assiale e momenti flettenti costanti lungo lo sviluppo della membratura stessa. In questo lavoro è presentata la fase di validazione che è stata sviluppata per determinare l'accuratezza del metodo. In particolare sono stati considerati i risultati di ricerche sperimentali svolte su elementi in parete sottile compressi e presso-inflessi, simulando in totale 229 prove e raffrontando la capacità portante predetta con quella sperimentale.

Keywords: cold-formed, thin-walled, experimental test, specimen, angle, channel, hat section, prediction.

1. INTRODUCTION

An approach has been developed and proposed by the Authors [1] to evaluate the load carrying capacity of thin-walled cold-formed steel members under constant eccentric axial load. Local as well as overall buckling are taken directly into account by defining a unique effective cross section, which is assessed on the basis of the values of the actual stress acting on members.

This paper summarises the results of the validation phase, which has been carried out to appraise the degree of accuracy of the method. In particular, reference is made to three main types of cross section, i.e. angles, channels and hat sections, with and without simple as well as compound lips. The experiments [2-16] considered in the validation phase are in total 229 and they are related to mono-symmetrical cross-sections, owing to the cold-forming technique most frequently used to obtain beams and beam-columns. However, it should be noted that the unified approach is capable to predict the behaviour of members having a generic cross-section, despite the fact that to the Authors' knowledge, no experimental data are available.

It should be reminded that the effective parts of internal as well as outstanding elements have been assessed by using the criteria proposed in the European standard for steel structures [17], which are recommended only for cross sections characterised by a range of width-thickness ratio (b/t) inside the limits presented in table 1 [18]. In some cases, the considered specimens are characterised by values of b/t slightly outside these limits, while some available data have not been considered, being quite far out outside limits.

2. THE CONSIDERED RESEARCHES

The state-of-art of tests of cold-formed column and beam-column members under constant axial load has been considered, in order to assess the degree of accuracy of the approach proposed by the Authors. Attention has been focussed only on papers reporting sets of data which appear exhaustive and totally reliable to reproduce numerically the experimental specimen performance. However, it should be noted that the considered papers are not homogeneous for the level of details reported. In particular, remarks are necessary on the following features:

• *geometry of the cross section:* in some cases, authors present the measurement of the sizes of each specimen, while, in other papers only the mean value of the key sizes defining geometry are presented;

• *constraints of the specimen:* the simulations have been carried out

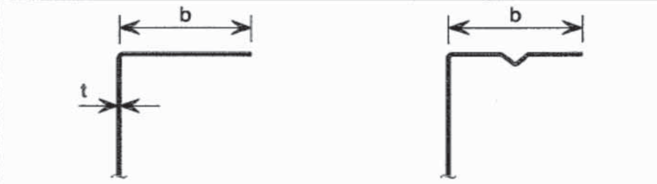
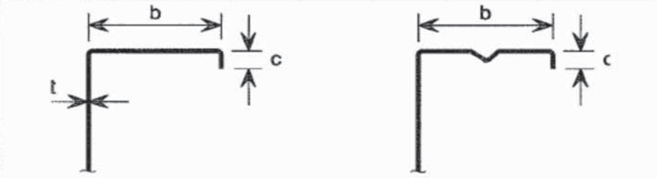
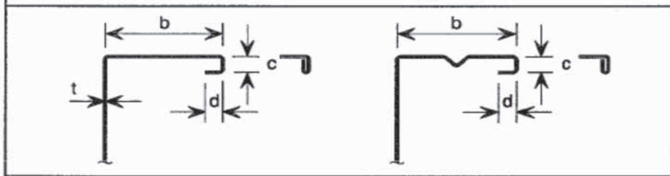
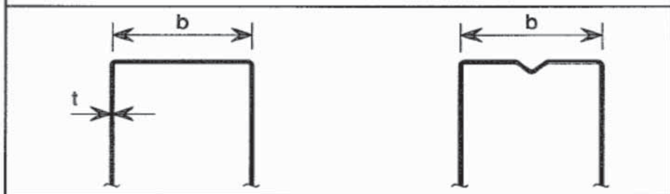
Element of cross-section	Maximum value
	b/t ≤ 50
	b/t ≤ 60 c/t ≤ 50
	b/t ≤ 90 c/t ≤ 60 d/t ≤ 50
	b/t ≤ 500

Table 1 - Maximum limits for width-to-thickness (b/t) ratio [18] for members

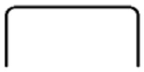
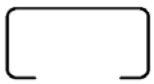
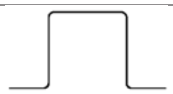
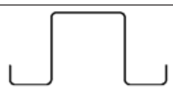
Section type		*Author(s) [Reference]*	*Number of tests and section type*
 Angles A	 Lipped Angles LA	Wilhoite et al. [4]	9 LA
		Popovic, Hancock and Rasmussen [12]	36 A
 Plain Channel PC		Young and Rasmussen [9]	22 PC
		Feng, Yang and Davies [15,16]	3 PC
 Lipped Channels LC		Lau and Hancock [2,6]	16 LC
		Young and Rasmussen [10]	21 LC
		Feng, Yang and Davies [15,16]	4 PC
		Pu, Godley, Beale and Lau [11]	9 LC
 Channels with Compound Lip CLP		Seah [2,7]	23 CLP
		Yan and Young [13,14]	30 CLP
 Hat Sections HS		Lim [2,5]	13 HS
		Lau and Hancock [2,6]	17 HS
 Hat Sections with Compound Lips HSCL		Seah [2,7]	26 HSCL

Table 2 - The considered experimental activities

by considering the specimen pinned at its ends and hence an appropriate length depending on the actual experimental constraints has been considered. Furthermore, load eccentricity, if present, is taken directly into account;

• *material properties:* the actual value of material yielding as well as of Young's modulus determined on tests on coils have been considered, despite in some papers both the corner sides and the flat sides material data are presented. Furthermore, in some researches, mechanical properties associated with each specimen are presented while in other papers mean values are given as representative for the whole set of tested specimens;

• *load carrying capacity:* some researches, for which exhaustive data were available, have not been considered since for nominally equal specimens the experimental ultimate values of the load were significantly different (even more than 10%) without any detail on the observed performances.

A preliminary check on the sensitivity of results to the use of mean values for geometry or material instead of actual values, showed moderate differences on the results.

The considered section types are presented in table 2. For each type of cross section, the author(s) and reference(s) to the experimental activities are reported together with the number of tests and the label used in the following to identify the cross-section type.

Wilhoite et al. [3,4] studied in 1984 the experimental response of cold-formed members by testing few types of cross section. In the present study, lipped angles (LA) data have been considered and the load-carrying capacity of 3 sets of series, which differ for the value of the nominal overall slenderness (60, 90 and 120), has been predicted for a total of 9 specimens.

In 1985 Lim [2,5] carried out a research on the response of hat sections (HS). In total 13 stub columns were tested for 3 different types of hat section differing in the lip length. It should be noted that the cross-sections are characterised by high slenderness values, with reference to the cold formed practice, up to 126 for doubly supported elements and 53 for outstanding compression elements.

In 1988, Lau and Hancock [2,6] studied the distortional buckling of cold-formed members by testing specimens related to some types of cross-sections, typically used as structural components. In the following, 16 lipped channel (LC) and 17 hat section (HS) tests have been considered for the validation phase. For each of these section types, 3 different values of the thickness of the material have been considered (i.e., 1.6 mm, 2.0 mm and 2.4 mm). Researchers included also the length as a key investigated parameter, testing specimens with a length varying between 300 mm and 1900 mm, corresponding to a maximum overall gross section slenderness varying between 5.1 and 79.4.

Seah [2,7] in 1989 researched the influence of a compound lip on the behaviour of cross-sections typically used for cold-formed members. In total 49 test data have been considered for 2 type of sections: lipped channels (CLP, 23 tests) and hat sections with compound lip (HSCL, 26 tests). For each of them stub column specimens have been tested differing for the geometry of the compound lips as well as for the thickness of material.

Young and Rasmussen [8,10] in 1999 carried out a study on the load carrying capacity of cold-formed channels. In particular, 4 cross section types: 2 plain and 2 lipped channels differing for the length of the flanges. In total 22 tests on plain channels (PC) and 21 tests on lipped channels (LC) have been simulated by means of the developed approach on specimens having different length. The overall slenderness, which is evaluated with reference to gross section, varies between 8.3 and 133.0.

Pu, Godley, Beale and Lau [11] in 1999 investigated the behaviour of perforated lipped channels (LC), focussing attention on the prediction of the ultimate load capacity. They tested several specimens differing for the presence and position of perforations as well as for their geometry. For the validation phase, test data of 9 specimens without perforation have been considered.

Popovic, Hancock and Rasmussen [12] in 1999 investigated the behaviour of cold-formed angles (A). Reference was made to equal edge angles for which three different nominal thicknesses were considered (2.4 mm, 4.0 mm and 5.0 mm). In total 36 specimens were considered for validation, differing for specimen length (gross-section slenderness values between 10.4 and 133.0) as well as for the value of the load eccentricity.

Yan and Young [13,14] in 2002 investigated the experimental response of two types of channels with double edge fold (CLP). For each of them, two different thicknesses have been considered and in total 30 tests were carried out by also varying the length of the specimens, investigating hence the response in the overall slenderness range between 7.3 and 51.9.

Specimen number, type and reference	Experimental / Numerical			
	minimum	maximum	mean	variance
9 LA [4]	0.705	1.319	0.982	0.056
36 A [12]	0.899	1.610	1.158	0.032
in total 45 tests (9 LA and 36 A)	0.705	1.610	1.123	0.041

Table 3 - Accuracy of the method applied to angles

In 2003, Feng, Yang and Davies [15,16] analysed the influence of temperature on the response of plain as well as lipped channel column. Test temperature ranged from ambient conditions to 700 °C. Only data related to ambient temperature tests were herein considered and in particular 3 tests on plain channel (PC) and 4 tests on lipped channels (LC).

As mentioned in the companion paper [1], the unified approach has been implemented by the software house Castalia srl in a computer programme [19], which has been used to obtain the results herein presented. In the following, data related to the validation phase are presented grouped by section type. In particular, attention has been paid to the ratio between the experimental load and the predicted one (Exp/Num), which has been considered as an index of error, and the results are presented in terms of minimum, maximum and mean value of exp/num. Furthermore, also the variance of the ratio Exp/Num is presented.

It should be noted that the approach defines the effective cross section depending on the values of the applied load. Furthermore, the whole set of effective geometric properties (area, second moment of area and section moduli) is directly available for design purposes.

3. PREDICTION OF THE LOAD CARRYING CAPACITY OF ANGLES

The ratio between the experimental value

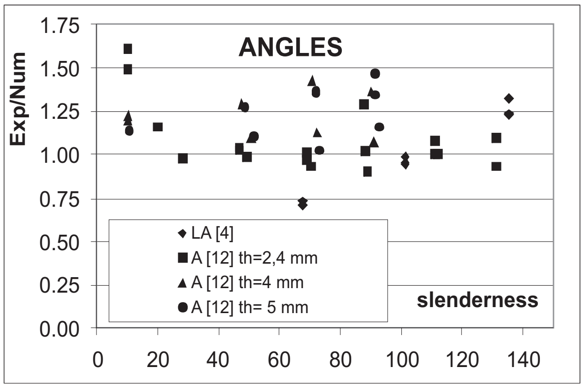


Figure 1 - Accuracy of the method for angles: error versus the specimen slenderness

of the ultimate load and the numerical one (Exp/Num) versus the specimen slenderness has been considered to appraise the method's accuracy. Data related to the considered angles are presented in figure 1. Furthermore, table 3 summarises these data divided also for research activity.

The prediction of the lipped angles tested by Wilhoite et al. [4] is extremely accurate for the case of medium slenderness. For the shorter specimens the method overestimates resistance up to 30% while for the longer specimens the predicted load carrying capacity is approximately 30% less than the experimental one. Overestimation is probably due to distortional buckling, which is not taken into account yet by the method.

The method applied to the simple angles tested by Popovic et al. [12] underestimates the resistance for the medium and high-thickness specimens, ranging the exp/num ratio from 1.02 to 1.42. In case of thinner angles, resistance is slightly overestimated (up to 10%). However it has to be pointed out that, as it appears from figure 1, specimens with very moderate differences in geometry or material have been considered. For these specimens ultimate

Specimen number, type and reference	Experimental / Numerical			
	minimum	maximum	mean	variance
22 PC [9]	0.985	1.599	1.283	0.038
3 PC [15,16]	1.161	1.323	1.244	0.007
16 LC [2,6]	0.924	1.534	1.140	0.034
21 LC [10]	0.874	1.254	1.053	0.010
4 LC [15,16]	0.731	0.771	0.753	0.0003
9 LC [11]	0.788	1.043	0.989	0.007
23 CLP [2,7]	0.703	0.950	0.833	0.005
30 CLP [13,14]	0.754	1.099	0.917	0.010
in total 128 tests (25 PC, 50 LC, and 53 CLP)	0.703	1.599	1.023	0.042

Table 4 - Accuracy of the method applied to channels

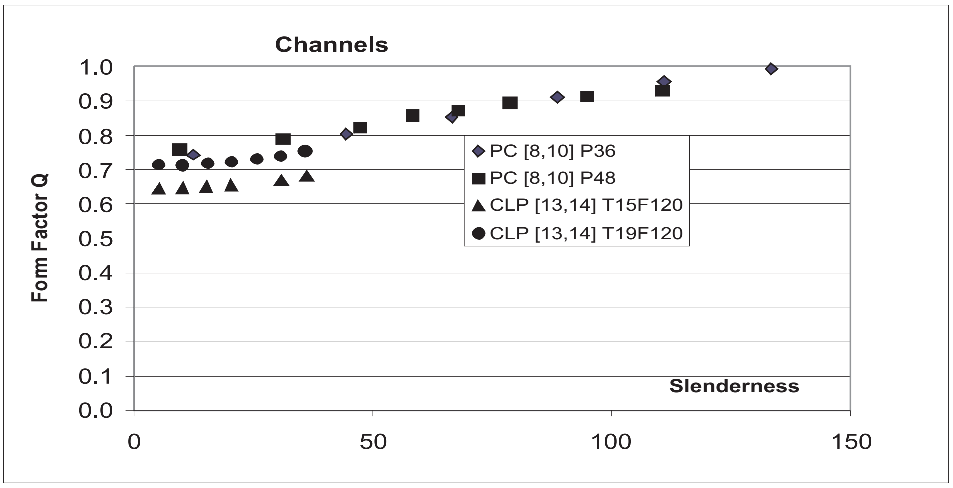


Figure 2 - Form factor versus slenderness for some channels specimens

Specimen number, type and reference	Experimental / Numerical			
	minimum	maximum	mean	variance
13 HS [2,5]	0.760	0.982	0.851	0.006
17 HS [2,6]	0.907	1.315	1.133	0.014
26 HSCL [2,7]	0.794	1.247	0.994	0.017
in total 56 tests (32 HS and 26 HSCL)	0.760	1.315	1.003	0.024

Table 5 - Accuracy of the method applied to hat sections

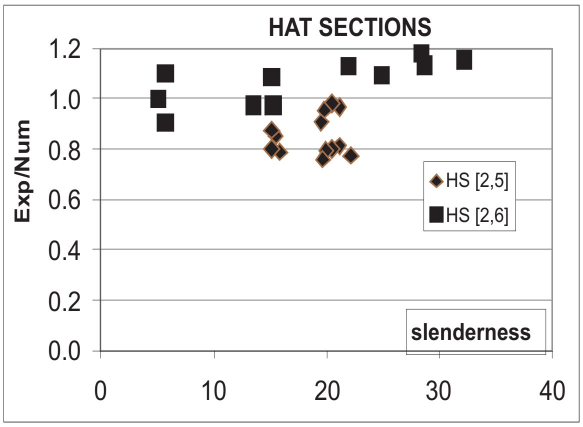


Figure 3 - Accuracy of the method for hat sections: error versus the specimen slenderness

loads differs up to 7%, while the theoretical ones are practically coincident. Overall mean value and variance of Exp/Num are quite good (1.123 and 0.041, respectively).

4. PREDICTION OF THE LOAD CARRYING CAPACITY OF CHANNELS

The method has been applied to 128 channels specimens related to three different section types, i.e., plain channels, lipped channels and lipped channels with compound lips. Table 4 presents key information related to the method's accuracy.

If plain channels are considered, the method underestimates the experimental failure load with a mean value of the error of 28%, except than for one specimen for which the exp/num ratio is equal to 0.985. As to lipped short channels, the method predicts a value of the load carrying capacity up to 27% greater than the experimental one, while, in many other cases, exp/num ratio is greater than unity up to 1.53. Overestimation of the ultimate load for short LC can be explained once more by the lack of distortional buckling in the proposed method. Finally, with reference to compound lipped channels, it has to be pointed out that the method is unconservative for only few tests, where distortional buckling mode, which is currently not included in the unified approach, caused failure of specimens.

The overall mean value and variance of Exp/Num are once more quite good (1.023 and 0.042, respectively).

Figure 2 presents the relationship between the form factor (i.e., the ratio between collapse effective section area and gross-section area) versus the slenderness evaluated with reference to the gross-section for some set of experiments where the influence of the specimen length was investigated by the Authors. These curves are characterised by similar trends, which differ from each other by the initial Q value, strictly depending on the cross section geometry. As introduced also in the numerical examples in the companion paper [1], while increasing the high values of the specimen slenderness, the area loss decreases, and for high value of slenderness the section tends to become fully effective.

5. PREDICTION OF THE LOAD CARRYING CAPACITY OF HAT SECTIONS

Results related to the method's accuracy for hat sections are presented in figure 3, where the data related to hat sections with compound lips are omitted, being related substantially to stub column test. Furthermore, table 5 summarises these data divided also for research.

The load carrying capacity in Lim's tests [2,5] is always overestimated, with an error ranging between 2% and 24 %. In the case of the hat sections tested by Lau and Hancock [2,6], the method predicts quite well the experimental results. In particular, only for three specimens the method is slightly unconservative while in the other cases the ultimate load is under-estimated up to 31%.

As to hat sections with compound lips [2,7], it can be noted that on average the method is slightly unconservative, with errors ranging between 0.79 and 1.25.

The overall mean value of Exp/Num and variance are quite good, 1.003 and 0.024, respectively.

6. GENERAL REMARKS ON THE ACCURACY OF THE APPROACH

The whole set of data for the validation phase is considered in the following so as to allow a general appraisal of the degree of accuracy of the proposed approach. It can be seen that, on average, the method slightly underestimates the experimental ultimate load, being the mean exp/num ratio equal to 1.04. Furthermore, it can be seen that in some cases the predicted ultimate load is greater than the experimental one up to 30%, while in very few other cases, the method is conservative up to 60%.

Table 6 summarizes the main information related to the values of Exp/Num ratio for all types of considered cross-section as well as for the whole set of data (in total 229 specimens).

Figure 4 presents the frequency versus the ratio exp/num, while figure 5 presents the cumulated frequency (both relative and absolute) versus the error (exp/num).

Grand overall mean value of Exp/Num is 1.0375, while variance is 0.0389.

Figure 6 presents the whole set of data in a diagram where the predicted load is reported versus the experimental one. A sol-

Specimen number, type and reference	Experimental / Numerical			
	minimum	maximum	Mean	variance
45 tests on angles	0,705	1,610	1,123	0,041
128 tests on channels	0.703	1.599	1.023	0.042
56 tests on hat sections	0.760	1.315	1.003	0.024
in total 229 tests on thin-walled specimens	0.7030	1.6097	1.0375	0.0389

Table 6 - Accuracy of the method applied to the considered specimens

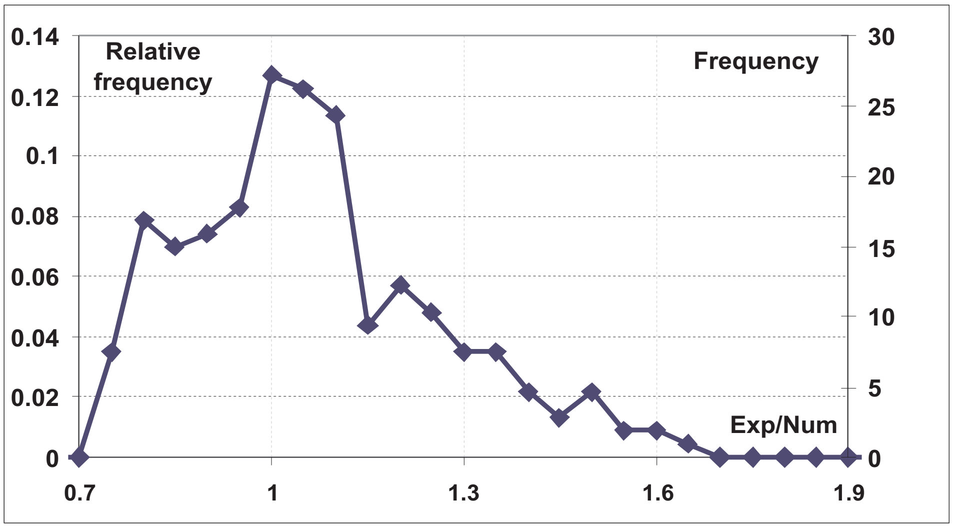


Figure 4 - Relative frequency versus ratio exp/num

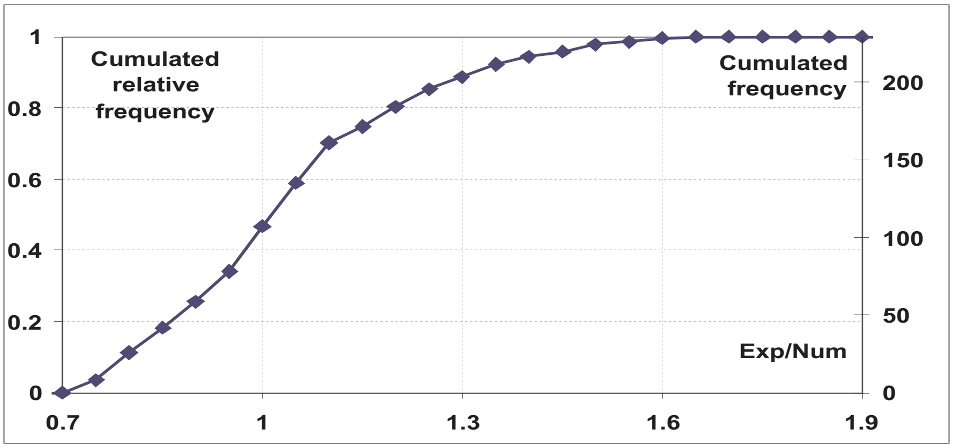


Figure 5 - Cumulated relative frequency versus ratio exp/num

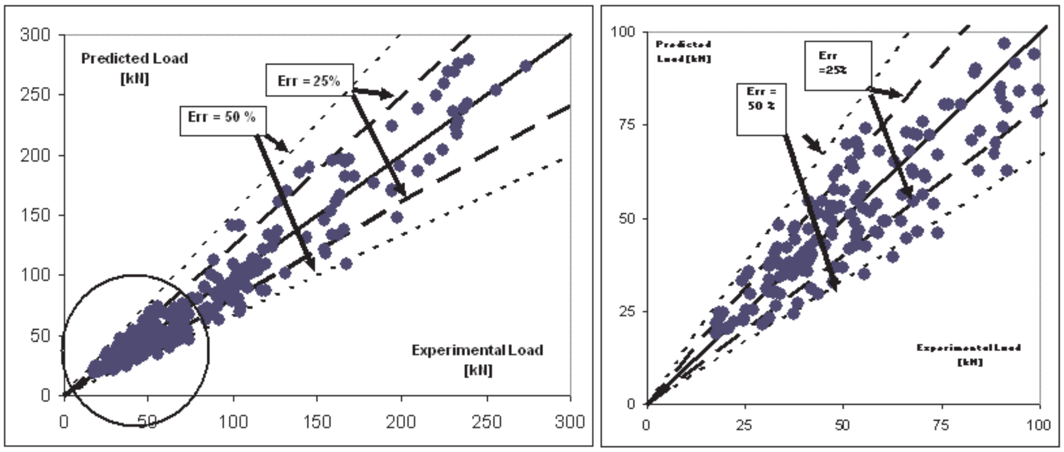


Figure 6 - Predicted load versus experimental load

id line corresponds to the case of zero error while dashed lines are related to the to errors of ±25% and ±50%. The number of cases where the error is greater than ±25% is relatively limited. A large amount of data is very close to unity, confirming the good accuracy of the method.

Under estimate of load-carrying capacity is due to plastic resistance of effective section (presently neglected), interaction formulae used to evaluate load-carrying capacity of effective member and post-buckling resistance of uneffective parts.

7. CONCLUSIONS

The approach for the design of cold formed member under axial as well as axial and bending loads, which has been presented in the companion paper [1], has been here validated. Despite the proposed approach is capable of evaluating the ultimate load of members with a generic cross section, the data available in literature are related only to mono-symmetrical sections.

The validation phase has been referred to 229 tests, related to 3 different types of section, also considering simple lips as well as compound lips. The results indicate that the present approach is generally characterised by a more than satisfactory degree of accuracy. In few cases the methods overestimated the load-carrying capacity up to 30%. Neglecting the reliability of the input data, it should be pointed out that failure for distortional mode experimentally occurred, which is currently not yet included in the proposed approach and this explains many occurences in which the method is unconservative. The method underestimated the experimental ultimate load up to a peak of 60% while the mean value of the ratio between experimental and numerical ultimate load is approximately 1.04, which is nearly 1. These results seem quite good also taking into account that experimental results are themselves affected, necessarily, by many uncertainties and possible problems (as sometimes it appears by examining the data), and that the method does not yet take into account distorsional buckling.

Furthermore, it should be noted that the degree of accuracy of the approach is quite similar to that of cold formed codes [2], being however very much simpler.

ACKNOWLEDGEMENTS

The approach has been implemented in a computer programme by the software house Castalia s.r.l. (www.castaliaweb.com).

Prof. dr. ing. Claudio Bernuzzi*,*
Department of Structural Engineering,
Politecnico di Milano, Milano
Dr. ing. Paolo Rugarli*,*
Structural Engineer, Castalia s.r.l., Milano

REFERENCES

[1] Bernuzzi C., Rugarli P., Prediction of the load carrying capacity of slender cross section members under eccentric axial load. Part 1: the approach.

[2] Chou S. M., Seah L. K., Rhodes J., The accuracy of some codes in predicting the load capacity of cold-formed columns, Journal of Constructional Steel Research, Vol. 37, No. 2, pp.137-172, 1996.

[3] Wilhoite G., Zandonini R., Zavelani A., Behaviour and strength of T-Shapes in compression: an experimental investigation, ASCE Annual Convention and Structures Congress, San Francisco (U.S.A.), october, 1984.

[4] Wilhoite G., Zandonini R., Zavelani A., Behaviour and strength of angles in compression: an experimental investigation, ASCE Annual Convention and Structures Congress, San Francisco, 1984.

[5] Lim B.S., Buckling behaviour of asymmetric edge stiffened plate, PhD Thesis, University of Strathclyde, Glasgow (1985).

[6] Lau S.C.W., Hancock G.J., Distortional buckling tests of cold-formed channel sections, Ninth international specialty conference on cold-formed steel structure, p. 45-73, ed. by W. W. Yu & J. H. Senne, nov. 1988.

[7] Seah L. K., Buckling behaviour of edge stiffeners in thin walled sections, PhD Thesis, University of Strathclyde, Glasgow (1989).

[8] Young B. and Rasmussen J.R., Tests of fixed–ended plain channel columns, Journal of Structural Engineering, vol. 124, nr. 2, February 1998, pp. 131-139.

[9] Young B. and Rasmussen J.R., Design of Lipped Channels Column, Journal of Structural Engineering, vol 124, nr.2, May 1998, pp. 140-148.

[10] Young B. and Rasmussen J.R., Behaviour of cold formed singly symmetric columns, Thin-Walled Structures vol. 33,1999 pp. 83 – 102.

[11] Pu Y., Godley R. M. H. R., Beale G., Lau H.H., Prediction of the ultimate capacity of perforated lipped channels, ASCE Journal of Structural Engineering, May 1999, pp. 510-514.

[12] Popovic, G. J. Hancock and K.J. Rasmussen, Axial compression tests of cold formed angles, ASCE Journal of Structural Engineering, May 1999, pp. 515-523.

[13] Yan Y. and Young B., Column tests of cold-formed steel channels with complex stiffeners, ASCE Journal of Structural Engineering, June 2002, pp. 737-745.

[14] Yan Y. and Young B, Numerical investigation of channel columns with complex stiffeners – Part I: test verification, Thin – Walled Structures 42 , 2004, pp. 883 – 893.

[15] M. Feng, Y.C. Wang, J.M. Davies, Structural behaviour of cold-formed thin walled short steel channel columns at elevate temperature. Part 1: experiments, Thin-Walled Structures 41 (2003) pp.543-570.

[16] M. Feng, Y.C. Wang, J.M. Davies, Structural behaviour of cold-formed thin walled short steel channel columns at elevate temperature. Part 2: Design calculations and numerical analysis, Thin-Walled Structures 41 (2003) pp.571-594.

[17] CEN, pr EN 1993-1-5:2006: Eurocode 3: Design of steel structures, Part 1-5: Plated structural elements, (Draft February 2006) European Committee for Standardisation.

[18] CEN, pr EN 1993-1-3:2005: Eurocode 3: Design of steel structures, Part 1-3: General rules-Supplementary rules for cold-formed members and sheeting, (Draft February 2006) European Committee for Standardisation.

[19] Sargon© by Castalia srl (www.castaliaweb.com).