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# Strength and Behavior of Cold Formed Steel Stiffened Sections under Interaction of Local, Distortional and Lateral Torsional Buckling: A Review

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***Abstract:*** **The aim of this report is to give a review of the progress in field of cold formed steel sections. Particular emphases are given to the study of strength and behaviour of different cold formed steel sections with flange or web stiffeners. Cold formed steel members can be plain in simple applications, but if provided with flange or web stiffeners, their performance and resistance to local, distortional and lateral torsional buckling improves. The idea behind cold-formed steel members is to use shape rather than thickness to support load. Due to the relatively easy method of manufacturing, a large number of different configurations can be produced to fit the demands of optimized design for both structural and economical purposes.**

***Keywords:*** **Local, distortional, flexural buckling, stiffened elements.**

## 1. INTRODUCTION

Cold-formed steel structures are steel structural products that are made by bending flat sheets of steel at ambient temperature into shapes which will support more than the flat sheets themselves. They have been produced for more than a century since the first flat sheets of steel were produced by the steel mills. However, in recent years, higher strength materials and a wider range of structural applications have caused a significant growth in cold-formed steel relative to the traditional heavier hot-rolled steel structural members. Cold-formed steel members have been widely used in building applications as the secondary cladding and purlin applications as well as the primary applications as beams and columns of industrial and housing systems. Consumption rate of cold-formed steel products is growing steadily. The reasons behind the growing popularity of these products include their ease of fabrication, high strength/weight ratio and suitability for a wide range of applications. These advantages can result in more cost-effective designs, as compared with hot-rolled steel, especially in short-span applications [1]. Cold-formed members can be produced in a wide variety of sectional profiles. The commonly used open cold formed sections are the “C” channels and, to a lesser extent, the “Z” sections shown in Fig. 1. While plain sections are finding applications as secondary members, the sections are usually enhanced with flange end stiffeners (e.g. the lipped channels) and/or web stiffeners in primary structural applications [2, 3]. With stiffeners, the members benefit from a larger cross-sectional effective area and are therefore expected to become better able to resist local and overall buckling.

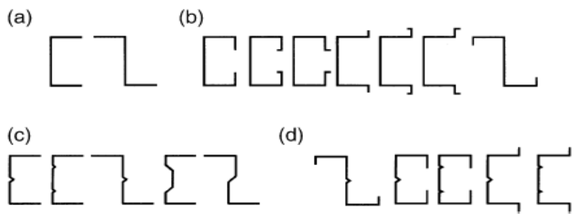


**Fig.1. Channel and Z cold-formed sections (a) Plain sections; (b) Sections with flange stiffeners; (c) Sections with web stiffeners; (d) Sections with flange and web stiffeners**

## 2. PARAMETRIC STUDIES

El-Sheikh et al [1] worked on a wide parametric study to cast light onto the behaviour of stiffened and unstiffened channel members as shown in Fig. 2 in various conditions of use, in which channel members with various aspect ratios (b/h),effective cross sectional area($A_{eff}$), stiffeners' sizes(d/h) and slenderness ratios are analysed.

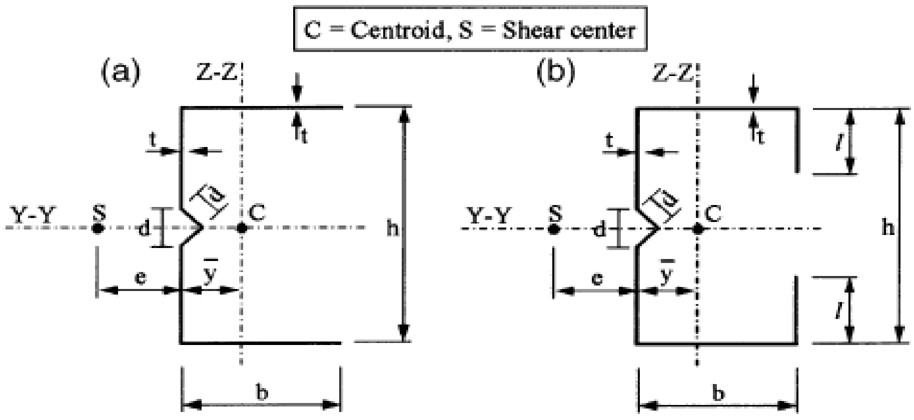


**Fig.2. Stiffened channel sections. (a) Plain channel section; (b) Lipped channel section.**

Mohan SJ et al [4] discussed the importance and use of equivalent radius of gyration method and necessary expressions were derived. The limiting values of slenderness ratio for the equivalent radius of gyration with the least radius of gyration were discussed to establish the buckling behaviour of lipped angles as shown in Fig.3.

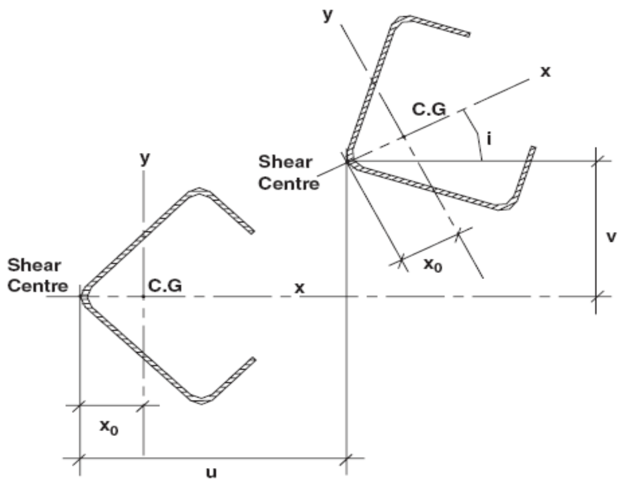


**Fig.3. Torsional–flexural buckling deformations of lipped angles**

Young and Ellobody [5] carried out an extensive parametric study using the finite element model to study the effects of cross section geometries on the strength and behavior of lipped angle columns.

Schafer and Pekoz [6] presented a new procedure for calculating the effective width of stiffened elements with multiple longitudinal intermediate stiffeners as shown in Fig.4.

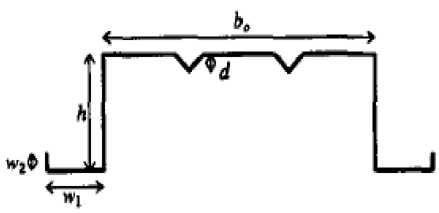


**Fig.4. Stiffened channel with multiple longitudinal intermediate stiffeners**

Schafer BW et al [7] state that, for an equivalent amount of material, complex stiffeners only provide advantages for specific stiffener lengths, though global optimal designs (maximum strength while minimizing material) still favor complex stiffeners over simple stiffeners in the investigated examples. Yong Ben [8] presented design and numerical investigations of cold-formed steel channel columns with inclined edge stiffeners compressed between fixed ends. A finite element model including geometric and material non-linearities had been developed and verified against experimental results. It was shown that the ultimate loads of the columns predicted using the finite element analysis are generally in good agreement with the experimental ultimate loads. A parametric study of cross-section geometries had been performed using the developed finite element model. Young and Yan [9] presented a parametric study and design of cold-formed steel channel columns with complex stiffeners as shown in Fig.5. The parametric study was performed using finite element analysis. The column strengths obtained from the finite element analysis were compared with the unfactored design column strengths calculated using the American Specification and the Australian/New Zealand Standard [10,11,12] for cold-formed steel structures.

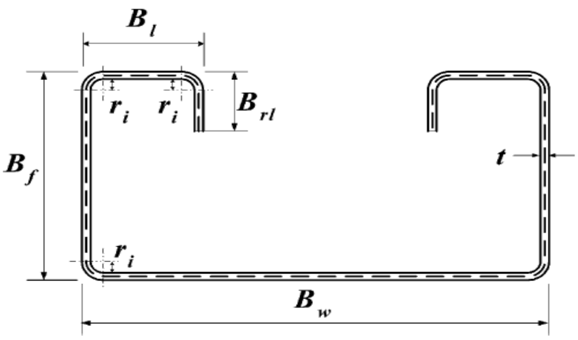


**Fig.5. Channel with complex stiffeners**

Dabaon et al [13] presented a test programme of stainless steel tubular stub columns. Comparison of results between five hollow-section unstiffened stainless steel columns as shown in Fig.6 and five hollow section stiffened stainless steel columns as shown in Fig.7 had been reported.

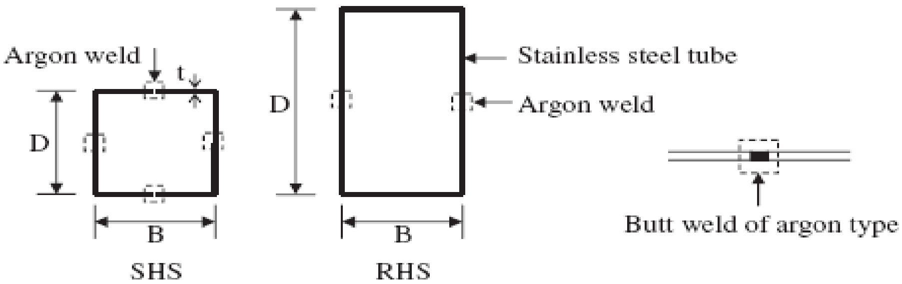


**Fig.6. Unstiffened stainless steel columns**

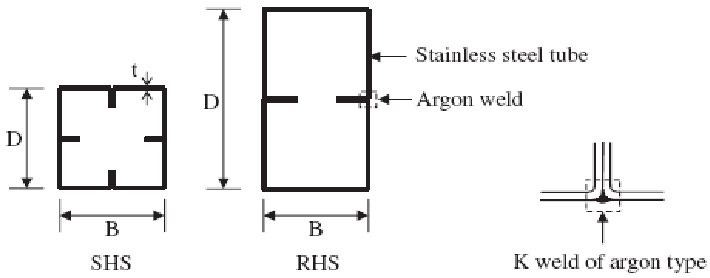


**Fig.7. Stiffened stainless steel columns**

The test strengths ($P_{Test}$) were compared with the design rules from the EN1993-1-4[16] and ASCE [15]. The tests results as shown in Fig.8 shown that using stiffeners in the stainless steel stub columns, the shape of the local buckling has been changed and the capacity has been increased.

**Fig.8. Deformed shape of square hallow section.**

Osama Bedair [16] presented a cost-effective procedure that can be utilized in the North American steel industry for efficient design of cold-formed lipped channels. An efficient modeling strategy that stimulates the ‘‘actual’’ boundary conditions between the channel components was presented. The influence of the lip and flange sizes on the buckling and post-buckling strength of the web and the flange was highlighted. Comparisons with the existing AISI [17] and CSA-S136-07[18] provisions were also made. Long-yuan Li [19] presented a parametric study on the calculation of the critical stress of distortional buckling of cold-formed sigma purlins using EN1993-1-3. The influence of support conditions as shown in Fig.9 at both the tension and compression ends of the web on the critical stress of distortional buckling of sigma sections had been investigated.

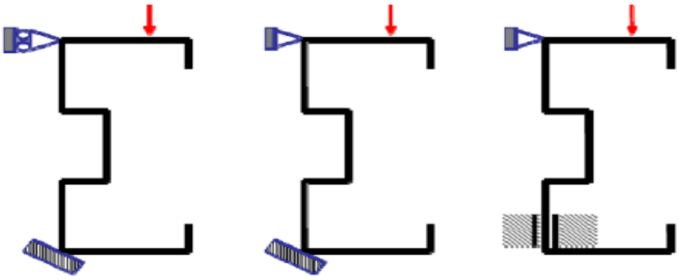

**Fig.9. Boundary conditions of CFS sigma sections**

Schafer BW et al [20] investigated the behavior, and provide recommendations on, the design of open cross-section thin-walled cold-formed steel members that employ complex stiffeners as shown in Fig.10. Nonlinear finite element analysis had been used to examine the post-buckling and ultimate strength regime. The direct strength method has been recommended for design and optimization of members with complex stiffeners.

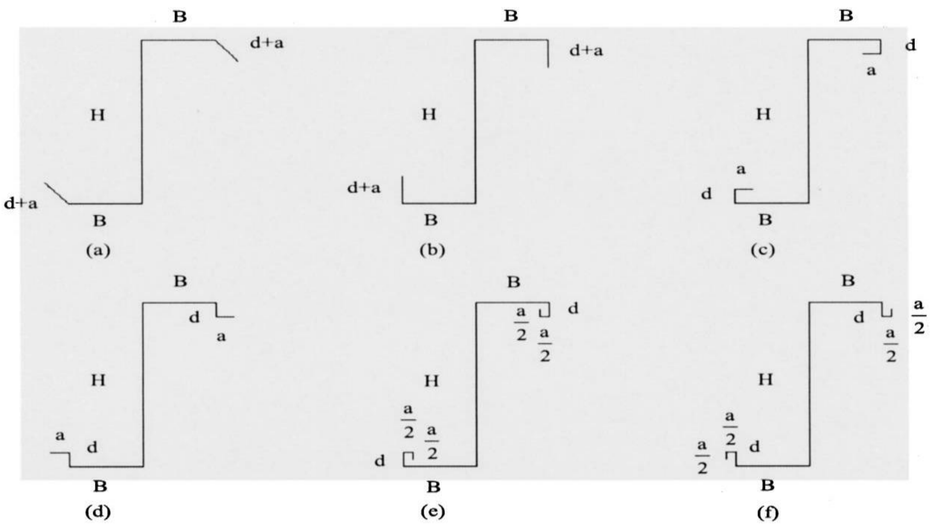


**Fig.10. Z sections with complex stiffeners**

Ben Young et al [21] presented a test program on cold-formed channels with inclined simple edge stiffeners at different angles for both outwards and inwards as shown in Fig.11.

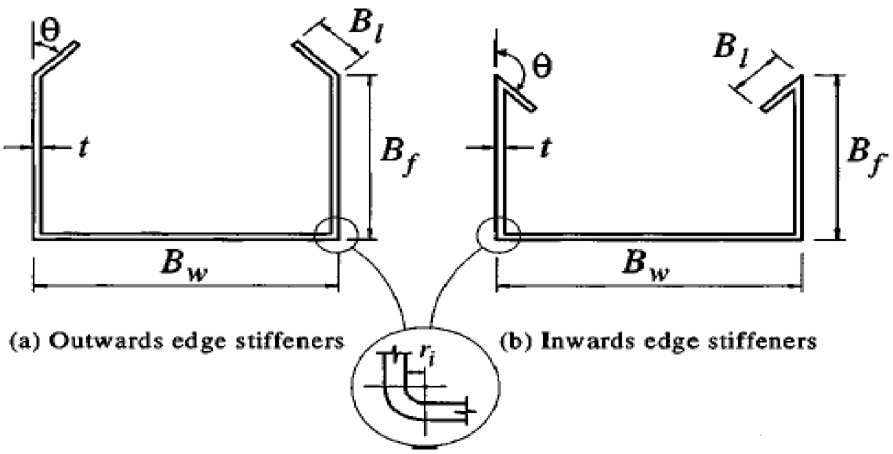


**Fig.11. Channel sections with inclined edge stiffeners**

## 3. EXPERIMENTAL INVESTIGATIONS

Mohan SJ et al [4] were carried out a series of compression tests on lipped angle sections and their behaviour was studied in the elastic and in the inelastic ranges of loading. Experimental investigations on full scale tower panels with conventional patterns of leg and diagonals were also carried out. The results of the experiments were compared with analytical predictions using torsional flexural buckling equations, finite element analysis and the equivalent radius of gyration approach. Young and Rasmussen [21] presented an experimental study of the behaviour of cold-formed plain and lipped channel columns as shown in Fig.12, compressed between fixed ends and pinned ends. It is demonstrated experimentally that the shift in the line of action of the internal force caused by local buckling deformations does not induce overall bending in fixed ended singly symmetric columns as it does in pin-ended singly symmetric columns.

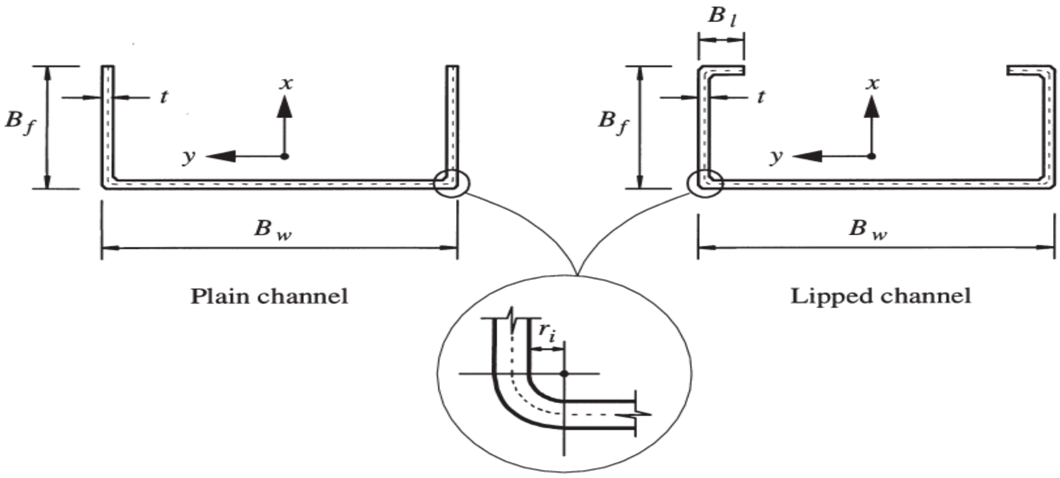


**Fig.12. Plain and lipped channel sections**

Ngoc TB Nguyen et al [22] presented experimental and numerical investigations on the strength and behavior of Z-sections with complex stiffeners as shown in Fig.13 subjected to major axis bending.

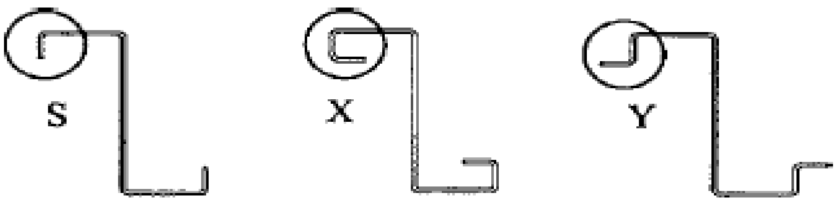


**Fig.13. Z-sections with simple, inside angled, and outside angled return lips**

In the numerical investigation, a finite-element model for the Z-section with complex stiffeners subjected to major axis bending was developed to simulate the experimental results. Young and Ellobody [23] were performed the finite element analysis on equally lipped angles compressed between fixed ends for different column lengths, and column curves were obtained. The nonlinear finite element model was verified against recent experimental results. Yu Cheng [24] shown the developed testing plan and details through computational and experimental means, to adequately restrict distortional buckling and provide a simple repeatable test that generates the local buckling flexural capacity for C and Z sections. Paczos and Wasilewicz [25] presented the results of experimental investigations of lipped I-section beams as shown in Fig.14.

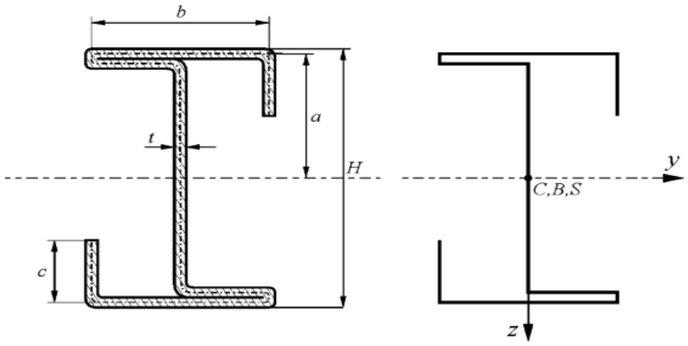


**Fig.14. Anti-symmetric lipped I-section.**

The experimental values of critical load are compared with those obtained with the help of FEM and theoretical analyses. Yap and Hancock [26] described the design and testing of web-stiffened high strength steel cold-formed lipped channel columns as shown in Fig. 15.

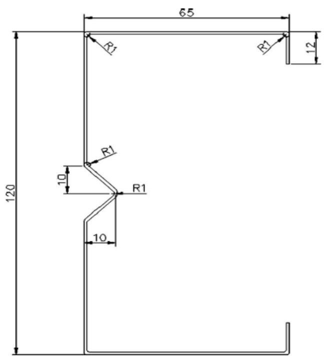


**Fig.15. Design and dimensions of stiffened-web open-shape section**

The effect of the different types of failure modes were also discussed in this paper. Yap [27] described the design and experimental investigation of a series of compressive tests on a stiffened cross-shaped section. The complex shape had been chosen as shown in Fig.16 so that it has a local buckling mode, two distinct distortional buckling modes, and a flexural-torsional mode.

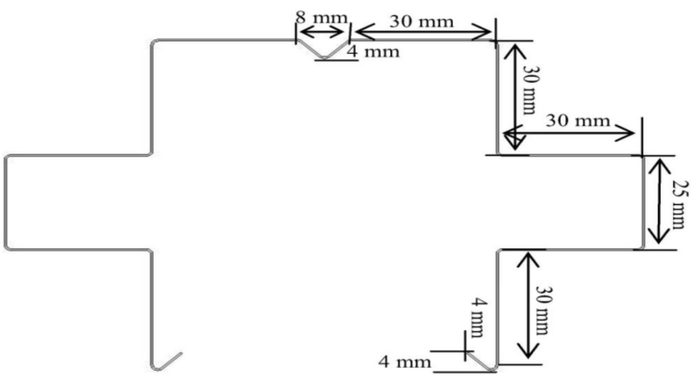


**Fig.16. Dimensions of stiffened cross-shaped section**

The experimental results were then compared with design methods in the existing design standards. This paper presents the procedures taken to design the complex shape and the experiments carried out to obtain the geometric imperfections and material properties of the specimens and the test results. New design methods are proposed for the local buckling DSM curve as well as for the distortional buckling strength curves so as to account for the effects of interaction of local and distortional buckling modes. Barbara Rossi et al [28] presented a series of 48 full-scale tests on press-braked stainless steel lipped channel section columns subjected to concentric compression. Kwon Y B et al [29] described a series of compression tests conducted on cold-formed simple lipped channels and lipped channels with intermediate stiffeners in the flanges and web as shown in Fig.17.

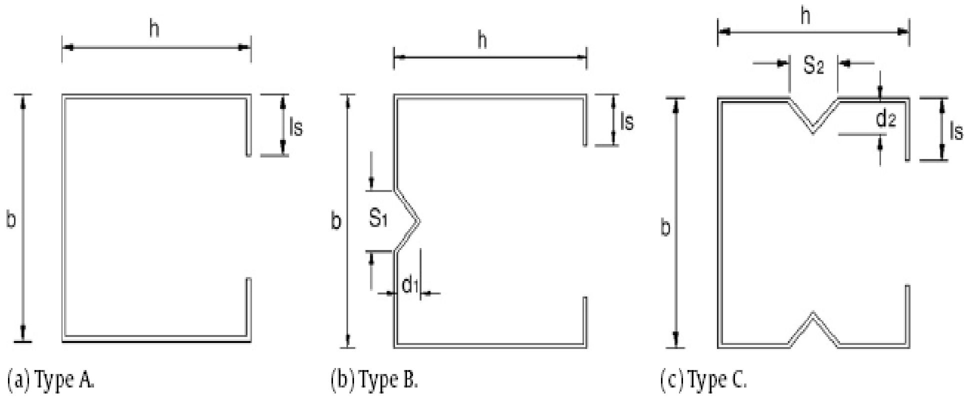


**Fig.17. Cross-sectional geometries**

Simple design strength formulas in the Direct Strength Method for the thin-walled cold-formed steel sections failing in the mixed mode of local and distortional buckling had been studied. The strengths predicted by the strength formulas proposed were compared with the test results for verification.

## 4. COMPARATIVE STUDY OF TEST STRENGTHS WITH THE DESIGN STRENGTHS

Young Ben et al [30] compared the test strengths and the design strengths as shown in Fig.18 of channel sections with inclined edge stiffeners as shown in Fig.11 obtained using the North American Specification(NAS 2001), the American Iron and Steel Institute Specification (AISI 1996), and the Australian/New Zealand Standard (AS/NZS 1996) for cold formed steel structures.

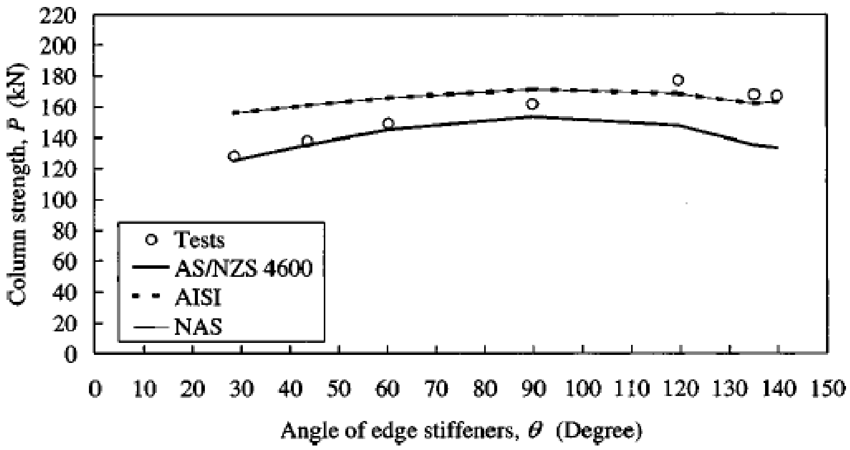


**Fig.18. Comparison of test strengths and design strengths of channel sections with inclined edge stiffeners**

Yap and Hancock [26] compared the experimental results with design methods in the existing design standards of web-stiffened high strength steel cold-formed lipped channel columns as shown in Fig. 15. The methods include the effective width method and the DSM as described in the Australian Cold-Formed Steel Structures Standard and the North American Specification. It was shown that the existing standards are unconservative and new proposals for dealing with this were made. Yu and Schafer [24] shown that overall the test results indicate that AISI (1996), S136 (1994), and the new NAS (2001) design methods provide adequate strength predictions in the local buckling flexural capacity for C and Z sections. Among the considered methods, the direct strength method provides the best test-to-predicted ratio for both slender and unslender specimens. Ngoc Nguyen et al [22] presented experimental and numerical investigations on the strength and behavior of Z-sections with complex stiffeners of web-stiffened high strength steel cold-formed lipped channel columns as shown in Fig. 13 subjected to major axis bending. The combined design strengths predicted by the NAS Specification AISI Specification, AS/NZS Standard, and direct strength method were generally conservative for the tested specimens. Young and Yan [9] compared the column test results of cold-formed steel channels with complex edge stiffeners of web-stiffened high strength steel cold-formed lipped channel columns as shown in Fig. 5 with the design strengths predicted using the direct strength method. It was shown that the direct strength method is capable of producing reliable design when calibrated with the existing resistance factor of 0.85. The failure modes predicted by the direct strength method are generally in agreement with the failure modes observed in the tests for long columns, but not for short and intermediate columns.

Young and Chen [31] presented a test program on the behaviour and strengths of cold-formed steel non-symmetric lipped angle columns of web-stiffened high strength steel cold-formed lipped channel columns as shown in Fig. 19

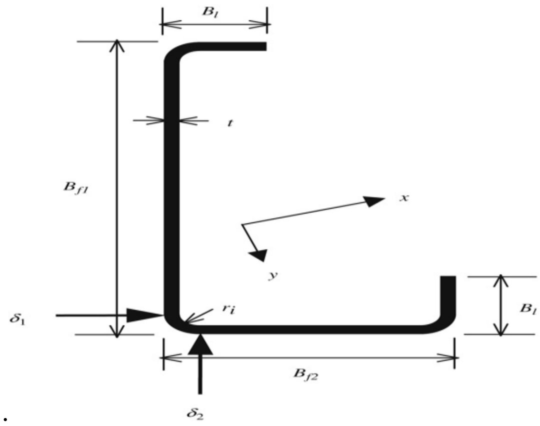


**Fig.19. Definition of symbols**

The test strengths were compared with the design strengths calculated using the North American Specification for the design of cold-formed steel structural members. In addition, the current design rules in the North American Specification for cold-formed steel non-symmetric lipped angle columns were assessed using reliability analysis.

## 5. LOCAL BUCKLING

Schafer B W et al [20] shown that in the elastic buckling regime, complex stiffeners hold a distinct advantage in local buckling over simple stiffeners in the design of open cross-section thin-walled cold-formed steel members that employ complex stiffeners as shown in Fig.10. Xiao-ting Chu et al [32] investigated the local and distortional buckling behavior of the cold-formed steel zed-section beams with simply supported conditions, subjected to a uniformly distributed load, using a semi-analytical finite strip method. Dinis and Camotim [33] addressed the elastic post-buckling behaviours of cold-formed steel lipped channel the design of open cross-section thin-walled cold-formed steel members that employ complex stiffeners as shown in Fig.20, simply supported columns affected by mode interaction phenomena involving distortional buckling, namely local/distortional, distortional/global (flexural-torsional) and local/distortional/global mode interaction.

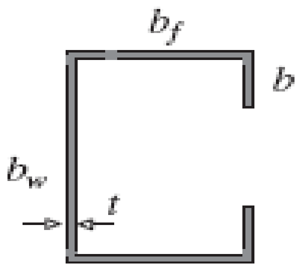


**Fig.20. Lipped-channel column**

The results presented were obtained by means of ABAQUS shell finite element analyses.

Wang and Zhang [34] presented an experimental and numerical investigation on the bending strength and behavior of cold-formed steel C-section flexural members with upright, inclined and complex edge stiffeners as shown in Fig.21.

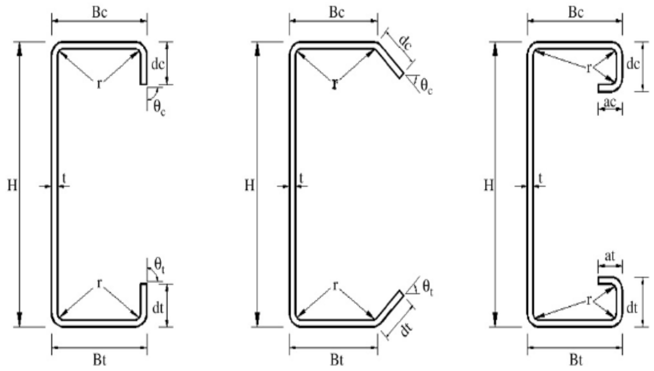


**Fig.21. Definitions for sectional dimensions**

Local buckling, distortional buckling and interaction between local and distortional buckling were observed in the tests. The experimental results shown that, the edge stiffener and buckling mode have great influence on member's bending strength. The tests were simulated by finite element program of ANSYS and the simulated results shown good agreement with the experimental results in terms of bending strength and buckling mode.

## 6. DISTORTIONAL BUCKLING RESISTANCE

Kesti and Davies [35] assessed the applicability of Eurocode 3 (EC3) to the prediction of the compression capacity of short fixed-ended columns with different cross-sections as shown in Fig.22.

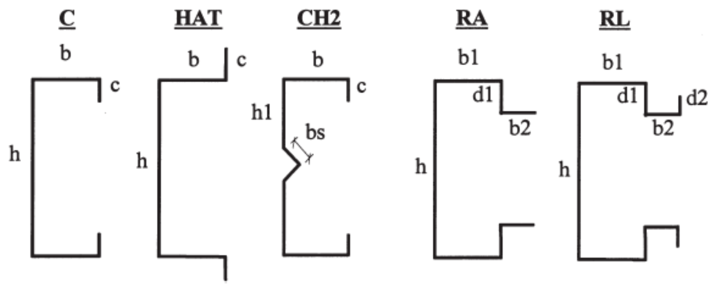


**Fig.22. Notations for Cross-Sections**

That compression capacity was determined by combining the effective width of plane elements due to local buckling and the effective stiffener thickness due to distortional buckling. Numerical calculations had been carried out in order to compare alternative methods, for determining the minimum elastic distortional buckling stress in compression. Schafer and Pekoz [7] developed new hand methods to predict the critical buckling stress in both the local and the distortional mode of laterally braced cold-formed steel flexural members with edge stiffened flanges as shown in Fig.23. A design method for strength prediction, based on the unified effective width approach, was developed.

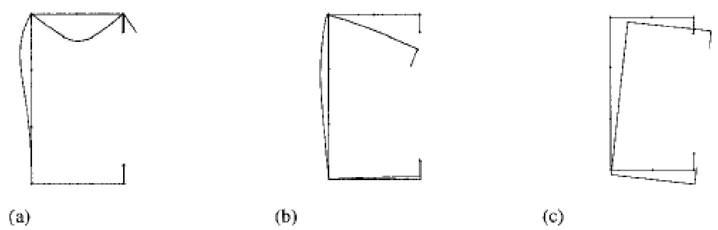


**Fig.23. Finite Strip Analysis of flexural member with edge stiffened flange: (a) Local Buckling; (b) Distortional Buckling ;( c) Lateral-Torsional Buckling**

The design method used the new expressions for prediction of the local and distortional buckling stress and also introduced a new approach for determining the effective width of the web. The resulting design method was compared with a large body of experimental results. Maura Lecce and Kim Rasmussen [36] described the experimental investigation of cold-formed, thin-walled stainless steel sections as shown in Fig.24, subjected to distortional buckling under compression. Teng et al. [37] extended the Lau and Hancock method (J. Struct. Eng. ASCE 113 (1987) 1063), which was developed for axially loaded columns as shown in Fig.25 to beam-columns subjected to combined axial compression and biaxial bending.

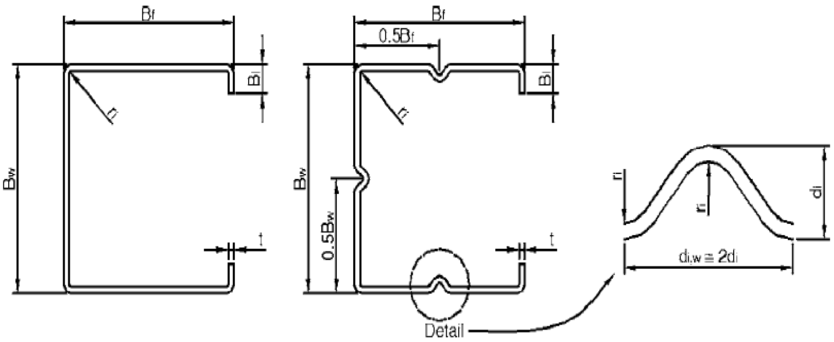


**Fig.24. Schematic of sections tested**

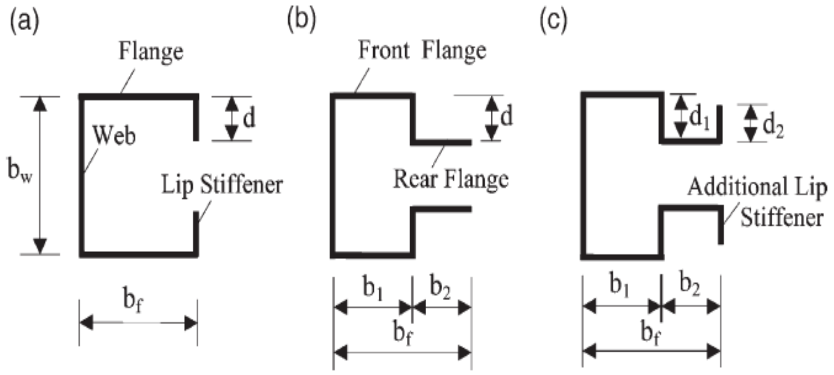


**Fig.25. Cold-formed channel sections. (a) Simple lipped channel; (b) lipped channel with rear flanges;**

(c) Lipped channel with rear flanges and additional lip stiffeners

Numerical results from the present closed-form solution were compared with those from the finite strip method, showing a close agreement between the two. Li and Chen [38] addressed the distortional buckling problem of cold-formed steel sections, with the particular focus on developing the simple model to predict the critical stress of distortional buckling and investigating the influence of added folds in the web as shown in Fig.26 on the critical stress of distortional buckling of cold-formed steel sections.

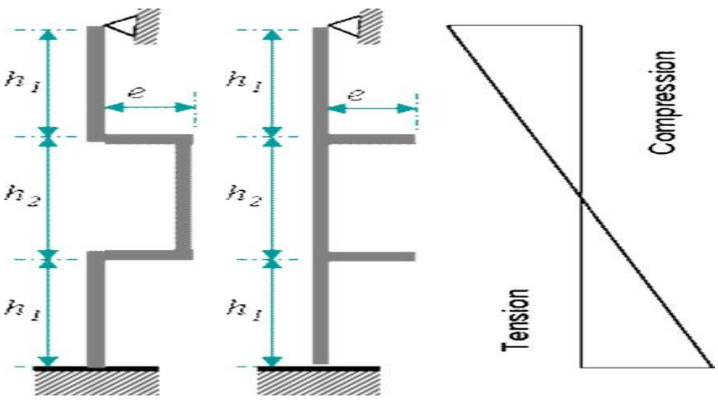


**Fig.26. (a) The web with folds in the sigma section. (b) The model used to determine buckling stress. (c) The distribution of bending stresses.**

Closed-form expressions are derived and validated by using the finite-strip method. Long-yuan Li [19] presented a study on the calculation of the critical stress of distortional buckling of cold-formed sigma purlins using EN1993-1-3[14]. The discussion was focused on the determination of the spring stiffness of the stiffened element. Comparison with finite strip analysis indicates that the model as shown in Fig.27, having a fixed support for the tension end and a roller support for the compression end of the web provides the best fit to the finite strip analysis.

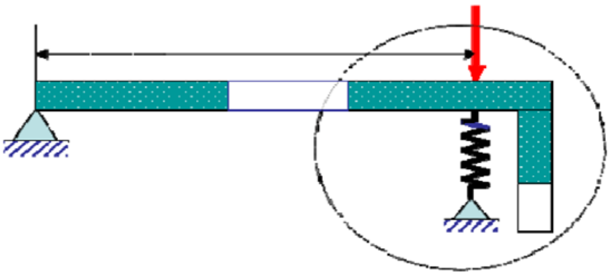

**Fig.27. The analytical model used to analyse distortional buckling in EN1993-1-3.**

Yu and Yan [39] proposed a design method, based on the Effective Width Method, for determining the nominal distortional buckling strength of typical cold-formed steel C and Z sections as shown in Fig.28, subjected to bending.

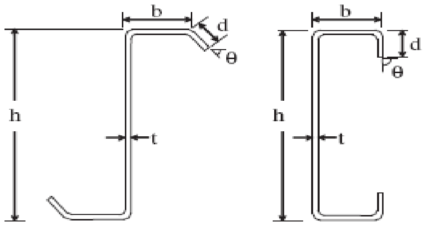


**Fig.28. Definitions for dimensions of Z and C sections**

The proposed method was calibrated by the flexural distortional buckling strength predicted by the Direct Strength Method. Comparison with experimental results indicates that the proposed method yields reasonable predictions for the flexural distortional buckling strength of industrial standard C and Z sections.

## 7. POST BUCKLING BEHAVIOR

Schafer BW et al [20] used nonlinear finite element analysis to examine the post-buckling and ultimate strength regime. Complex stiffeners as shown in Fig.10 were shown to provide improved ultimate strength performance over simple stiffeners, but with a slight increase in imperfection sensitivity. Schafer B W [40] provided closed-form prediction of the buckling stress in the local mode, including interaction of the connected elements, and the distortional mode, including consideration of the elastic and geometric stiffness at the web/flange juncture, and shown to agree well with numerical methods. Numerical analyses and experiments indicate postbuckling capacity in the distortional mode was lower than in the local mode. Young and Hancock [41] presented a series of compression tests on lipped channel sections, with and without intermediate stiffeners in the web as shown in Fig.29. The tests were carried out between fixed ends and investigated postbuckling in the distortional and mixed local-distortional modes.

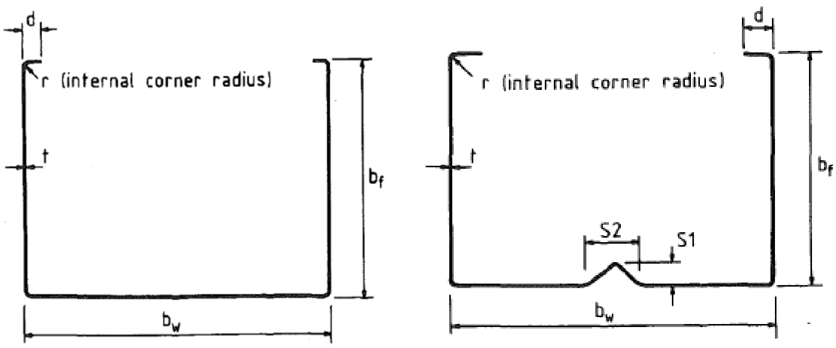


**Fig.29. Test Sections: (a) Simple Lipped Channel (CH1); *(b)* Stiffened Lipped Channel (CH2)**

Dinis and Camotim [42] reported the results of a numerical investigation concerning the elastic and elastic–plastic postbuckling behaviour of cold-formed steel lipped channel columns affected by distortional/global (flexural– torsional) buckling mode interaction. The results presented and discussed were obtained by means of analyses performed using the finite element code ABAQUS. Silvestre and Camotim [43] were presented and discussed the results of a GBT-based investigation concerning the local-plate and distortional postbuckling behaviors of cold-formed steel lipped channel columns with web and flange V-shaped intermediate stiffeners as shown in Fig.30.

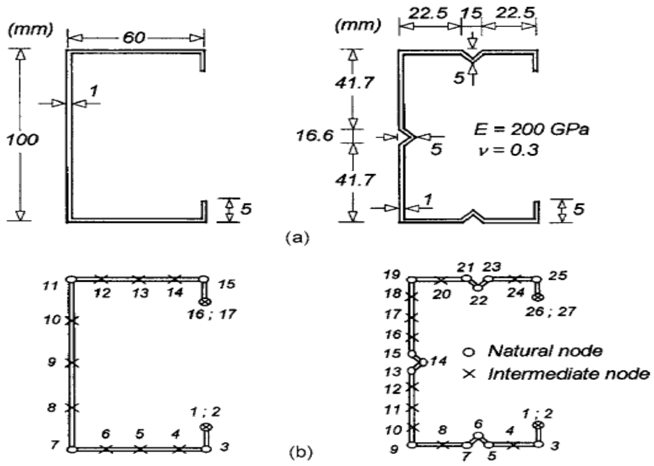


**Fig.30. Plain and stiffened lipped channel cross sections :(a) dimensions and (b) GBT discretization**

In order to assess the effect of these stiffeners, the postbuckling behaviors of similar plain lipped channel columns were almost always used as a reference. Columns with pinned/free-to-warp and fixed/ warping-prevented end sections were analyzed and some of the results obtained were validated through a comparison with values yielded by FEM analyses performed in the code ABAQUS. Dinis et al [33] reported the results of a numerical investigation concerning the elastic and elastic–plastic post-buckling behaviour of cold formed steel lipped channel columns affected by local-plate/distortional buckling mode interaction as shown in Fig. 31.

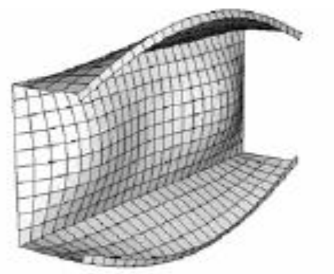

**Fig.31. Combined LP/D Mode**

The results presented and discussed were obtained through analyses performed using the finite element code ABAQUS and discretising the columns by means of fine 4-node shell element meshes.

## 8. FLEXURAL BUCKLING RESISTANCE

Schafer and Pekoz [6] determined the method to find the critical stress for distortional buckling of the entire stiffened element as a unit, and local buckling of the subelement plates between stiffeners. Approximate expressions for calculating distortional buckling are verified via comparison to numerical methods. Comparison to experimental data and numerical analysis shows the resulting method was a reliable predictor of the flexural capacity of cold-formed steel members with multiple longitudinal intermediate stiffeners in the compression flange. El-Sheikh et al [1] shown that flexural buckling strength, Pc, was large with the smallest size web stiffener; 463% and 38% on average for plain and lipped channels, respectively as shown in Fig.32. Further increases in the web stiffener size was also beneficial, but to a much lesser extent; 26% on average. On the other hand, using flange stiffeners also led to considerable increases in Pc, especially in sections without web stiffeners and with small aspect ratios.

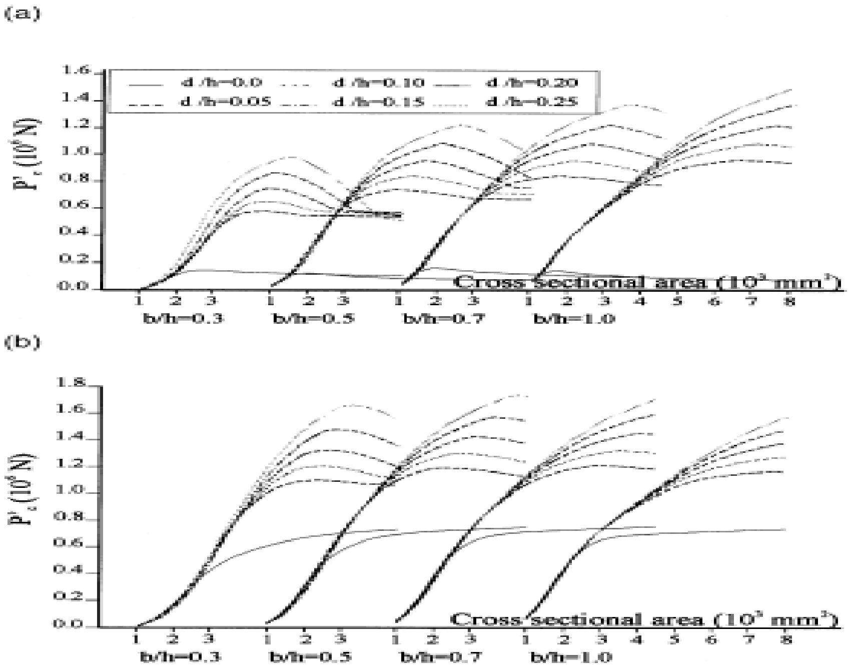


**Fig.32. Effect of stiffeners on the flexural buckling resistance of channel members.(a) Plain channels; (b) Lipped channels.**

## 9. FLEXURAL TORSIONAL BUCKLING RESISTANCE

Determining the value of the warping coefficient, $C_w$, is an essential step in calculating the channel members' resistance to torsional buckling. El-Sheikh et al. [1] developed and presented a coefficient ($C_w$) as BS5950: Part 5 [44] does not provide a warping coefficient for sections with web stiffeners. This value of $C_w$ is identical to that presented by BS5950 [8] for lipped channels. From the calculated value of $C_w$, it was shown that adding a web stiffener did not result in a consistent effect on the torsional flexural buckling strength of sections, $P_{TF}$, as can be seen in Fig. 33. For the same reasons explained above, adding a web stiffener resulted in increases in $P_{TF}$ values in sections with low aspect ratios and without flange stiffeners. The effect of using flange stiffeners was more consistent.

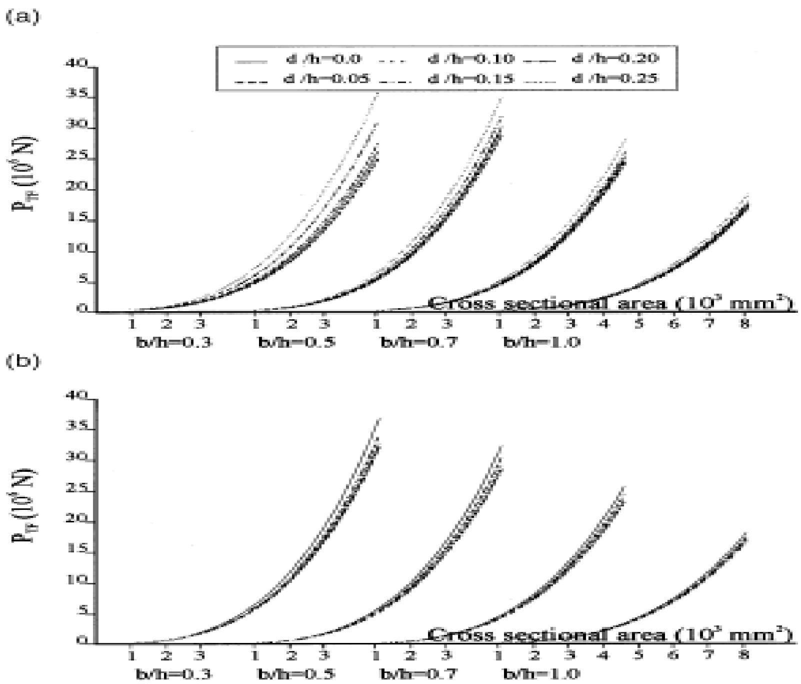


**Fig.33. Effect of stiffeners on the torsional flexural buckling resistance of channel members. (a) Plain channels; (b) Lipped channels.**

## 10. DESIGN RECOMMENDATIONS

Several design recommendations had been proposed in the aforementioned research projects. Some of these recommendations are listed in this paper. Bambach [45] developed a modified effective width method and validated against a database of 913 compression and flexure members as shown in Fig.34.

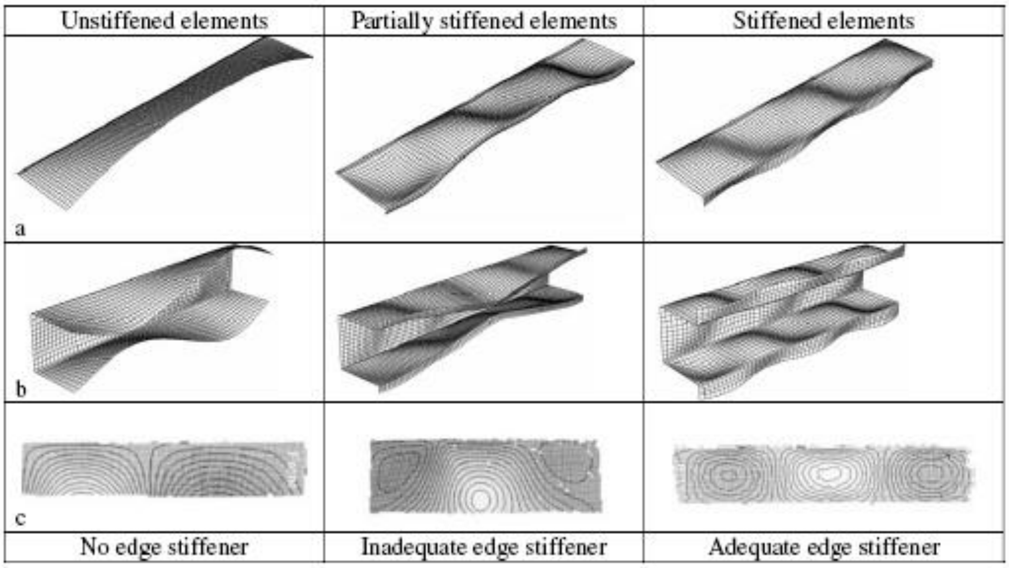


**Fig.34. Fundamental behavior of elements in compression at ultimate condition; (a) plate elements simply supported with longitudinal edge stiffened with edge stiffener of increasing size from nonlinear FEM (Bambach 2009a);(b) flange element section with increasing edge stiffener size from nonlinear FEM of tests in Bambach (2009b); and (c) isoplots of transverse flange displacement from photogrammetry of flange with increasing edge stiffener size in tests in Bambach (2009b)**

Schafer B W [40] shown that current North American design specifications for cold-formed steel columns ignore local buckling interaction and do not provide an explicit check for distortional buckling. Existing experiments on cold-formed channel, zed, and rack columns indicate inconsistency and systematic error in current design methods and provide validation for alternative methods. A new method was proposed for design that explicitly incorporates local, distortional and Euler buckling, does not require calculations of effective width and/or effective properties, gives reliable predictions devoid of systematic error, and provides a means to introduce rational analysis for elastic buckling prediction into the design of thin-walled columns. Yong Ben [8] were compared the column strengths obtained from the finite element analysis with the design strengths obtained using the American Specification and the Australian/ New Zealand Standard for cold-formed steel structures. It was shown that the design strengths predicted by the American Specification and the Australian/ New Zealand Standard are generally conservative for the cold-formed steel channel columns with inclined edge stiffeners, even though the design rules for inclined edge stiffeners are purely intuitive. The design strengths predicted by the Australian/ New Zealand Standard are more conservative than the design strengths predicted by the American Specification. Young and Ellobody [5] described the buckling behavior of cold-formed steel equally lipped angle columns. The column strengths predicted by the finite element model were compared with the design strengths calculated using the North American Specification and Australian/New Zealand Standard for cold-formed steel structures. In addition, the results obtained from the finite element model were also compared with the design strengths obtained from proposed design rules. It was shown that the proposed design rules accurately predicted the column strengths for non-slender lipped angles and were quite conservative for slender lipped angles. Schafer BW et al [20] investigated the behavior, and provide recommendations on, the design of open cross-section thin-walled cold-formed steel members that employ complex stiffeners as shown in Fig.10. The cold-formed steel design specification in current use was shown to be a poor predictor for the ultimate strength of bending members with complex stiffeners. However, the direct strength method, recently adopted as an alternative design method in the North American Specification for cold-formed steel members is shown to be a reliable predictor of ultimate strength. The direct strength method is recommended for design and optimization of members with complex stiffeners.

## 11. CONCLUSION

The development and complexity and of design of cold-formed sections has been increased as their use has been increased and this is likely to continue for the foreseeable future. This development has been a combination of improvements in technology and developments in applications. It has placed researchers under some demands to find adequate practical design procedures for increasingly complicated section shapes. Practical design models have been developed for the local and distortional buckling, and the interaction between them, for most of the sections of interest to the designers of building structures. For cold-formed steel columns and beams with the proportions typically used in practice, distortional buckling is often critical. Some design codes actually specify the need to use second order analysis under certain conditions. The direct strength method makes a more formal allowance for post-buckling and is evidently more appropriate when local buckling is significant. It would seems that perhaps this would be an opportune time to create a link between specifications and computer packages, with rigorous analysis using approved packages specified as complying with the design code.

## REFERENCES

[1] El-Sheikh A I, El-Kassas E M A, Mackie R I, "Performance of stiffened and unstiffened cold-formed channel members in axial compression," Engineering Structures, vol. 23, pp.1221–1231, 2001.

[2] Moldovan A, "Compression tests on cold-formed steel columns with monosymmetrical section," Journal of Thin-Walled Structures, vol. 20, pp.241–52, 1994.

[3] Weng C, Pekoz T, "Compression tests of cold-formed steel columns," In: 9th International Specialty Conference on Cold-Formed Steel Structures, Missouri, USA, pp. 1–23, 1988.

[4] Mohan S J, Rahima S S, Samuel Knight G, "Behavior of cold formed lipped angles in transmission line towers," Thin-Walled Structures; vol. 44, pp. 1017–1030, 2006.

[5] Young B, Ellobody E, "Buckling analysis of cold-formed steel lipped angle columns," Journal of Structural Engineering, vol. 131, pp. 1570–1579, 2005.

[6] Schafer B W and Pekoz T, "Cold-formed steel members with multiple longitudinal intermediate stiffeners," Journal of Structural Engineering, vol. 124, pp. 1175- 1181, 1998.

[7] Schafer B W, Pekoz T, "Laterally braced cold-formed steel flexural members with edge stiffened flanges," Journal of Structural Engineering, vol. 125, pp.118-127, 1999.

[8] Young B, "Design of channel columns with inclined edge Stiffeners," Journal of Constructional Steel Research, vol. 60, pp.183–197, 2004.

[9] Young B, Yan J, "Numerical investigation of channel columns with complex stiffeners—part II: parametric study and design," Thin-Walled Structures, vol. 42, pp.95–909, 2004.

[10] American Iron and Steel Institute, "Specification for the design of cold-formed steel structural members," Washington DC, AISI, 1996.

[11] Australian/New Zealand Standard, "Cold-formed steel structures", AS/NZS 4600, Australia, 1996.

[12] American Iron and Steel Institute, "Commentary on the 1996 edition of the specification for the design of cold-formed steel structural members," Washington, DC, AISI, 1996.

[13] Dabaon M A, El-Boghdadi M H, Hassanein M F, "A comparative experimental study between stiffened and unstiffened stainless steel hollow tubular stub columns," Thin-Walled Structures, vol. 47, pp.73– 81, 2009.

[14] EN 1993- 1-5. Eurocode 3, "Design of steel structures — Part 1–5: Plated structural elements," CEN, 2007.

[15] ASCE, "Specification for the design of cold-formed stainless steel structural members (SEI/ASCE8-02)," American Society of Civil Engineers, 2002.

[16] Osama B, "A cost-effective design procedure for cold-formed lipped channels under uniform compression," Thin-Walled Structures, vol. 47, pp.1281–1294, 2009.

[17] American Iron Steel Institute (AISI), "North American Specification for the Design of Cold-Formed Steel Structural Members," Washington DC, USA, 2007.

[18] Canadian Standard Association (CSA-S136-07), "North American Specification for the Design of Cold-Formed Steel Structural Members," Canadian Standard Steel Association, Mississauga, Ontario, 2007.

[19] Long-yuan L, "Analyses of distortional buckling of cold-formed sigma purlins using EN1993-1-3," Journal of Constructional Steel Research, vol. 65, pp. 2099-2102, 2009.

[20] Schafer B W, Sarawit A, Peköz T, "Complex edge stiffeners for thin-walled members," Journal of Structural Engineering, vol. 132, pp. 212–226, 2006.

[21] Young B, Rasmussen K J R, "Behavior of cold-formed singly symmetric Columns," Thin-Walled Structures, vol. 33, pp. 83–102, 1999.

[22] Ngoc T B N, Tat C F, Ben Y, "Strength and Behavior of Cold-Formed Steel Z-Sections Subjected to Major Axis Bending," Journal of Structural Engineering, vol. 132, pp. 1632–1640, 2006.

[23] Young B, Ellobody E, "Buckling analysis of cold-formed steel lipped angle columns," Journal of Structural Engineering, vol. 131, pp. 1570–1579, 2005.

[24] Yu C, Schafer B W, "Local buckling tests on cold-formed steel beams," Journal of Structural Engineering, vol.129, pp. 1596–1606, 2003.

[25] Paczos P, Wasilewicz P, "Experimental investigations of buckling of lipped, cold-formed thin-walled beams with I-section," Thin-Walled Structures, vol. 47, pp.1354–1362, 2009.

[26] Yap D C Y, Hancock G J, "Experimental study of high-strength cold-formed stiffened-web C-sections in compression," Journal of Structural Engineering, vol. 137, pp. 162–172, 2011.

[27] Yap Derrick C Y, "Experimental study of complex high-strength cold-formed cross-shaped steel section," Journal of Structural Engineering, vol. 134, pp. 1322–1333, 2008.

[28] Barbara R, Jean-Pierre J, Kim J R R, "Combined distortional and overall flexural-torsional buckling of cold-formed stainless steel sections: experimental investigations", Journal of Structural Engineering, vol.136, pp. 354–360, 2001.

[29] Kwona Y B, Kima B S, Hancock G J, " Compression tests of high strength cold-formed steel channels with buckling interaction," Journal of Constructional Steel Research, vol. 65, pp.278 – 289, 2009.

[30] Young B, Hancock G J, "Compression tests of channels with inclined simple edge stiffeners," Journal of Structural Engineering, vol.129, pp. 1403–1411, 2003.

[31] Young B, Chen B. J, "Column tests of cold-formed steel non-symmetric lipped angle sections," Journal of Constructional Steel Research, vol. 64, pp. 808–815, 2008.

[32] Xiao-ting C, Zhi-ming Y, Long-yuan L, Roger K, "Local and distortional buckling of cold-formed zed-section beams under uniformly distributed transverse loads," International Journal of Mechanical Sciences, vol. 48, pp. 378–388, 2006.

[33] Dinis P B, Camotim D, "Post-buckling behavior and strength of cold-formed steel lipped channel columns experiencing distortional/global interaction," Computers and Structures, vol. 89, pp.422–434, 2011.

[34] Wang H, Zhang Y, "Experimental and numerical investigation on cold-formed steel C-section flexural members," Journal of Constructional Steel Research, vol. 65, pp. 1225-1235, 2009.

[35] Kestia J, Davies J. M, "Local and distortional buckling of thin-walled short columns", Thin-Walled Structures, vol. 34, pp. 115–134, 1999.

[36] Maura L, Kim J R R, "Distortional Buckling of Cold-Formed Stainless Steel Sections: Experimental Investigation," Journal of Structural Engineering, vol. 132, pp. 497–504, 2006.

[37] Teng J G, Yao J, Zhao Y, "Distortional buckling of channel beam-columns," Thin-Walled Structures, vol. 41, pp. 595–617, 2003.

[38] Long-yuan L, Jian-kang C, "An analytical model for analyzing distortional buckling of cold-formed steel sections," Thin-Walled Structures, vol. 46, pp.1430-1436, 2008.

[39] Yu C, Yan W, "Effective width method for determining distortional buckling strength of cold-formed steel flexural C and Z sections," Thin-Walled Structures, vol. 49, pp. 233–238, 2011.

[40] Schafer B W, "Local, Distortional, and Euler Buckling of Thin-Walled Columns," Journal of Structural Engineering, vol. 128, pp. 289–299, 2002.

[41] Kwon Y B, Hancock G J, "Tests of cold-formed channels with local and distortional buckling," Journal of Structural Engineering, vol.117, pp.1786-1803, 1992.

[42] Dinis P B, Camotim D, Silvestre N, "FEM-based analysis of the local-plate/distortional mode interaction in cold-formed steel lipped channel columns," Computers and Structures, vol. 85, pp.1461–1474, 2007.

[43] Nuno S, Dinar C, "Local-Plate and Distortional Postbuckling Behavior of Cold-Formed Steel Lipped Channel Columns with Intermediate Stiffeners," Journal of Structural Engineering, vol. 132, pp. 529–540, 2006.

[44] BS5950, "Structural use of steelwork in building, Part 5: Code of practice for design of cold formed sections," British Standards Institution, London, UK: BSI, 1999.

[45] Bambach M R, "Unified element and section approach to design of cold-formed steel structures," Journal of Structural Engineering, vol. 136, pp. 343–353, 2010.