CHAPTER 2

REVIEW OF LITERATURE

2.1 GENERAL

A brief review of the research related to the behaviour of cold-formed steel single and compound open sections subjected to compression carried out during the last 15 years is presented in this chapter. Literature pertaining to experimental investigations is presented in the first part, literature pertaining to analytical and numerical investigations is presented in the second part and studies on theoretical investigation are presented in the third part.

2.2 STUDIES ON EXPERIMENTAL INVESTIGATIONS

Seah (1996) investigated the collapse behaviour of uniformly compressed edge-stiffened thin-walled sections. Fifty specimens were tested under uniform compression, of which twenty six were outwardly-turned lipped top-hat sections and the rest were inwardly-turned lipped channel sections. Design procedures were proposed based on the modifications of the draft Eurocode to predict the ultimate strength of such edge-stiffened thin-walled sections. The ultimate load of a compound edge-stiffened element is higher than for a simple edge stiffened element of the same area, when the width of the simple edge stiffener becomes excessively large. The investigation reported here shows that the shifting of the stiffener effective
neutral axis, due to the different rate of reduction in the effectiveness of plate and stiffeners, causes a significant reduction in the load carrying capacity. The predicted results compared well with the experimental results. A further comparison with an independent source of experimental results confirms the rationality of the approach.

Nabil Abdel-Rahman and Sivakumaran (1997) reported the results of experimental investigations carried out to evaluate the mechanical properties and the built-in residual stresses of cold-formed steel sections. The investigations were performed on channel shaped cold-formed steel sections manufactured using cold-roll forming technique. Tensile coupon tests were conducted to evaluate the mechanical properties of sections. Electrical strain gauges, were used to establish the magnitudes and the distributions of residual stresses. Based on the experimental results, analysis models for the stress-strain relationship, the variation of the yield strength and the residual stresses in cold-formed steel channel sections have been established. The proposed analysis models for material properties have been incorporated within a large deformation shell finite element to form an analysis model for cold-formed steel sections. The efficiency and accuracy of the proposed models and their material properties have been evaluated by comparing the finite element analysis results with the corresponding experimental results of cold-formed steel sections subjected to axial compressive loads.

Ben Young and Rasmussen (1999) carried out an experimental investigation on the behaviour of cold-formed plain and lipped channel columns compressed between fixed and pinned ends. Four different cross-section geometries were tested over a wide range of lengths which involved pure local buckling, distortional buckling as well as overall flexural buckling and torsional-flexural buckling. The different effects of local buckling on the behaviour of fixed-ended and pin-ended channels were investigated by
comparing strengths, load-shortening and load-deflection curves, as well as longitudinal profiles of buckling deformations. It was concluded that for singly symmetric columns of the same effective length, the fixed-ended column strength is higher than the pin-ended column strength when the ultimate load exceeds the local buckling load. For plain channel columns, the difference in strength is greatest at short and intermediate lengths where the strength is influenced by local buckling. However, the tests of lipped channel columns showed that the fixed-ended column strength at short and intermediate lengths is likely to be influenced by distortional buckling. As a result, the difference in strength caused by the different effects of local buckling of pin-ended and fixed-ended lipped channels diminishes at short lengths.

An experimental investigation on cold-formed steel channel columns with complex stiffeners consisting of simple lips and return lips subjected to pure axial compression with both ends fixed was studied by Jintang Yan and Ben Young (2002). Thirty column specimens with four different cross sections and different flange slenderness were tested over a range of column lengths. Detailed studies were conducted to obtain the material properties, geometric imperfections, and local buckling loads of the specimens. Failure modes encountered included local buckling, distortional buckling, and flexural–torsional buckling. The test strengths of the columns were compared with the design strengths predicted by the American Specification and the Australian/New Zealand Standards for cold-formed steel structures. It was shown that the design strengths predicted by the American Specification were generally unconservative for short and intermediate columns, whereas the design strengths predicted by the Australian/ New Zealand Standards were generally conservative for all column lengths. The failure modes predicted by the AISI specification were generally in agreement with the failure modes observed in the tests for long columns, but not for
short and intermediate columns. It was recommended that the AS/NZS Standards be used in the design of concentrically loaded channel columns with complex stiffeners. It was also shown that the theoretical local buckling loads obtained using an elastic finite strip buckling analysis were in good agreement with the experimental local buckling loads.

Shosuke Morino et al (2003) investigated the distortional buckling of light-gauge lipped channel short columns. Compression tests were carried out with plate thickness of 1 mm and the fundamental behaviour of thin walled compression members failing in the local and distortional buckling modes were classified. Eighteen specimens with three different web depths and three different web-flange width ratios were tested. The test results were compared with the numerical analysis based on the yield line theory. Stiffness, strength and failure modes were also discussed. Two types of failure modes were observed in the tests, that is, the local and distortional buckling types. The failure mode determined from the analysis coincided very well with those observed in the tests. It was concluded that the yield patterns assumed in the analysis, were suitable to estimate the ultimate strength and the failure mode accurately.

Narayanan and Mahendran (2003) studied the distortional buckling behaviour of a series of innovative cold-formed steel columns. More than fifteen laboratory experiments were conducted on these innovative steel columns of intermediate length under axial compression. All these columns failed by distortional buckling with very little post-buckling strength. The section and the buckling properties of the columns were determined using the finite strip analysis program THINWALL. The distortional buckling and the nonlinear ultimate strength behaviour of the columns were investigated in detail using finite element analysis program ABAQUS. The finite element analyses included relevant geometric imperfections and residual stresses. The
ultimate design load capacities were evaluated using the provisions of Australian Cold-formed Steel Structures Standard AS/NZS 4600-1996, and were compared with those from experiments and finite element analyses. A series of parametric studies were also carried out by varying the yield strength, thickness and column length. It was found that residual stresses had insignificant effect on the ultimate load. The ultimate strength results from experiments, finite element analyses and the Design Standards were compared, and appropriate recommendations were made. This investigation has shown that further research was needed to improve the accuracy of design code predictions for distortional buckling strengths of innovative cold-formed steel columns made of thin, high strength steels.

Demao Yang and Gregory (2004) conducted a series of tests on lipped channel section columns fabricated from cold-reduced high strength steel of thickness 0.42 mm with nominal yield stress 550 MPa. It was shown from the tests that distortional buckling and the interaction of local and distortional buckling had a significant effect on the strength of the sections formed from such thin high strength steel. Two simple design methods were proposed for intermediate length lipped channel sections which gave a lower bound of the test results. It was found that prediction by the NAS (AISI 2001) gave an unconservative result since it ignored distortional buckling. The AS/NZS 4600 predicts an unconservative result for intermediate lengths as it ignores interaction of local and distortional buckling.

Lam et al (2006) discussed the load carrying capacities of cold formed steel cut stub columns with lipped C- sections. The cutting of roll-formed steel C-sections may introduce different extent of cross section distortion along the lengths and cause additional initial geometric imperfections. In order to determine the effect of the geometric imperfections on the ultimate strength and modes of failure of the cut stub columns, ten stub
columns cut from two different sections were tested under axial compression. Flanges of the stub columns experienced distortional mode of failure, whereas the webs showed signs of local buckling. Ultimate compressive strengths obtained from the test results were 75 to 77% of the strengths estimated based on BS 5950: Part 5. This indicates that geometric imperfections caused by cutting may significantly reduce the ultimate strength of stub columns.

Wang et al (2006) reviewed the cross section distortion due to cutting of cold-formed steel lipped C-section. The process of cutting a roll-formed steel section to specified length may lead to cross section distortion and may cause initial geometric imperfection. Initial geometric imperfections of the cut stub columns along the longitudinal direction were estimated using a laser transducer. For a cut stub column, variation of imperfection along the longitudinal direction at the flanges can be represented by a half-sine wave. The initial geometric imperfection of a cut stub column attains maximum values at the flanges, and is insignificant at the corners where the web and the flanges intersect.

Young Bong et al (2007) described a series of compression tests performed on channel section columns fabricated from a mild steel plate of thickness 6 mm with nominal yield stress of 240 MPa. The compression tests indicated that the interaction between local and overall buckling had a significant negative effect on the ultimate strength of the thin-walled welded steel section columns. The Direct Strength Method (DSM), which was newly developed and adopted as an alternative to the effective width method for the design of cold-formed steel sections recently by NAS AISI-2004, was calibrated by using the test results for application to welded steel sections. The ultimate strengths predicted by the Direct Strength Method were also compared with those estimated by the effective width method adopted in the NAS, AISC and EC3. The comparisons of the ultimate strengths predicted by
the design specifications and the test results have proved the reliability of the Direct Strength Method.

Yaochun Zhang et al (2007) presented an experimental investigation and a finite element analysis study on cold-formed channels with inclined simple edge stiffeners compressed between pinned ends. Thirty six channel specimens including three different cross sections with different angles of inclination edge stiffener and column lengths were tested. The results indicated that the angle of inclination and loading position significantly affected the ultimate load-carrying capacity and failure mode of specimens. Results from the finite element analysis agreed well with the experimental ultimate loads and failure modes. All the stub columns failed in combined local and distortional buckling modes. The buckling and ultimate loads for the section with 45° sloping lip stiffener were lower when compared to stiffeners with 90° and 135° slope. The eccentrically loaded columns with positive eccentricity and the concentrically loaded columns with 45° sloping lip stiffener failed in combined distortional and flexural buckling modes. Axial loaded columns and columns loaded through negative eccentricity with 90° and 135° sloping lip stiffener failed in combined local and flexural buckling modes. The FEA predictions were in good agreement with the experimental ultimate loads and failure modes of columns with inclined edge stiffeners.

Ben Young (2008) conducted both experimental and numerical investigations on the strength and behaviour of cold-formed steel channel columns. The column strengths obtained from the investigations were compared with the design strengths obtained using the various standards - the North American, the Australian/New Zealand and the European for cold-formed steel structures. It was shown experimentally that the shift in the line of action of the internal force caused by local buckling does not induce
overall bending in fixed-ended channel columns as it does in pin-ended channel columns. It was recommended that a fixed-ended singly symmetric column failing by local and overall buckling be designed as a concentrically loaded member.

2.3 STUDIES ON ANALYTICAL AND NUMERICAL INVESTIGATIONS

Sivakumaran and Nabil Abdel-Rahman (1998) developed a Finite Element Analysis (FEA) model for the post-local buckling behaviour of cold-formed steel members subjected to axial compression. The FEA model consisted of a Total Lagrangian non-linear 9-node “assumed strain” shell finite element. Experimentally derived residual stress variations and initial geometric imperfections were incorporated. A special loading technique and a displacement solution algorithm were employed to obtain a uniform displacement condition at the loading edges. Experiments were conducted on twenty non-perforated and perforated cold-formed steel stub column sections. The test results were compared with finite element results. The axial and lateral displacement behaviour, buckling loads, ultimate loads and axial stress distributions agreed well.

Ben Young and Jintang Yan (2004) did numerical investigations on cold-formed channel columns with complex stiffeners. A parametric study was performed using finite element analysis. An accurate and reliable model was used for the parametric study in which different sizes of complex stiffeners were investigated. Column strengths predicted by the finite element analysis were compared with the unfactored design column strengths calculated using the American Specification and the Australian/New Zealand Standards for cold-formed steel structures. It was shown that the design strengths obtained from the specification and standard were generally conservative for fixed-ended cold-formed steel channel columns with
complex stiffeners for more slender sections having a plate thickness of 1 mm with the flat flange width to thickness ratio of 57, but unconservative for sections having a plate thickness of 2 mm with the flat flange width to thickness ratio of 27.

Studies on channel columns with inclined edge stiffeners were conducted by Ben Young (2004). The edge stiffeners consisted of simple lips that were inclined at different angles both outwards and inwards. A non-linear finite element model was developed and verified with fixed-ended column tests. Geometric and material non-linearity were included in the finite element model. It was shown that the finite element model closely predicted the experimental ultimate loads of the cold-formed steel channel columns with inclined edge stiffeners. The column strengths predicted by the finite element analysis were compared with the design column strengths calculated using the American and Australian/New Zealand specifications for cold-formed steel structures. These design rules for designing an edge-stiffened element were mainly based on tests on channels with simple edge stiffeners perpendicular to the flanges. However, these specifications allowed the design of inclined edge stiffeners that were purely intuitive. It was also shown that the design column strengths calculated based on the specifications were generally conservative for cold-formed steel channel columns with inclined edge stiffeners.

Macdonald and Rhodes (2005) discussed the results obtained from the finite element investigation and studied the load carrying capacity of column members of lipped cold-formed channel cross-section, made up of 304 stainless steel, subjected to concentric and eccentric compression loading. The main aim of this investigation was to determine the effect of non-linearity of the stress-strain behaviour of the material on the column behaviour under concentric or eccentric loading. Stress-strain behaviour derived from tests and
design codes were incorporated into non-linear finite element analyses of eccentrically loaded columns and the results obtained were compared with those obtained on the basis of experiments with the same properties and dimensions. Comparisons of the finite element analysis results and the test results were also made with the existing design specifications. A non-linear finite element analysis using virgin material stress-strain properties provided accurate load predictions. However, for eccentrically loaded columns with shorter lengths, the design codes predicted very conservative load capacities. Improvements were gained by employing enhanced stress-strain properties and by incorporating the full section moment capacity within the code interaction formulae. Finally, it has been shown that finite element analysis can be used with a high level of confidence in predicting the load capacity of eccentrically loaded cold formed stainless steel, short-to-medium length columns of lipped channel section. This has been shown to be true for various stress-strain curves including that obtained from virgin material tensile tests.

Bambach (2009) studied the Photogrammetry measurements of buckling modes and interactions in channels with edge-stiffened flanges. With the advent of flange edge stiffeners and higher-strength steels, and consequent use of thinner structural sections, additional complexities in buckling modes and their interactions have arisen. A detailed buckling analysis was carried out to explain the fundamental behaviour of flanges and webs, particularly with respect to interactions of buckling modes. The full-surface transverse buckling deformation photogrammetry results showed that the flanges and webs of sections behaved independently of each other, and may buckle at different loads and with different half-wavelengths. Webs always behaved as stiffened elements, whereas flanges could behave as unstiffened, partially stiffened or stiffened elements depending on the ratio of the edge stiffener to flange dimension. A modified effective width approach was presented, whereby a reduced Winter strength equation (1970) for partially stiffened
elements was employed to provide accurate and reliable predictions. Implementation of the procedure into current specifications requires only the addition of a single strength equation. Comparisons of the test results with the recently modified effective width method and the Direct Strength Method were also discussed.

2.4 STUDIES ON THEORETICAL AND NUMERICAL INVESTIGATIONS

Al-bermani and Kitipornchai (1994) presented a Finite Element Method capable of predicting the buckling capacity of arbitrarily shaped thin-walled structural members under any general load and boundary conditions. A rectangular thin plate element with 30 degrees of freedom was chosen. The linear and geometric stiffness matrices for this element were derived explicitly using symbolic manipulation. For sections composed of rigid flanges and flexible web, a lower-order plate element was used in combination with a general beam-column element to form a super element for predicting distortional buckling modes. Numerical examples of thin-walled structural members involving local, distortional and flexural-torsional buckling modes were presented to demonstrate the accuracy, efficiency and versatility of the method.

Chou et al (1996) examined the accuracy of existing codes of practice for the design of cold-formed steel sections. American Iron and Steel Institute (AISI - 1986), British Standards Institution (BS : 5950 Part 5 - 1987) and European code of practice (ECCS - 1987) were reviewed. Selected experimental results of ultimate load capacity on columns were compared with the predictions by the codes of practice. Plain sections, lipped sections, hat sections and compound lipped hat sections were considered for study. It was found that the accuracy of the codes of practice varied with different types of cross-sectional shapes. It was also observed that all the codes of
practice were not comprehensive enough. From the results, it was observed that each code of practice predicted the behaviour differently, although they produced similar results at times.

Leach and Davies (1996) compared the critical buckling predictions of Generalised Beam Theory with the results obtained in two series of tests carried out on plain and lipped channels subjected to a major axis bending moment. It was concluded that GBT gave a good estimate of the elastic critical loads of a beam, particularly when local buckling and distortional effects were dominant. In all the analysis, local buckling effects were calculated by GBT without recourse to effective width formulae or other empirical methods. These predictions were then combined with the yield criteria of Eurocode to allow a comparison with the analysis of these tests carried out by Lindner and Aschinger (1994). It was concluded that the Generalised Beam Theory was a powerful and effective analysis tool for the solution of interactive buckling problems where both local and overall buckling could occur.

Guo and Fukumoto (1996) studied the post buckling behaviour and ultimate load carrying capacity of thin-walled cold-formed and welded stub columns subjected to a constant eccentric load. Based on a geometric and material nonlinear finite strip analysis, a theoretical investigation was done to find the ultimate load-carrying capacity and post buckling behaviour of cold-formed welded stub sections in the large deflection elastic-plastic range. The effect of the geometry of the section on the ultimate load was investigated based on the numerical results obtained by Finite Strip Method. There was an optimal load eccentricity in cold-formed channel stub columns where the stub column could gain the maximum ultimate load percentage in the full section yield load, and there also existed optimal aspect ratio of sections where the stub column displayed the most optimal design profit.
Pantelides (1996) examined the buckling and post-buckling behaviour of thin-walled stiffened elements under uniform compression with geometric and material uncertainties which were modeled by a convex model. The results showed that in the case of elastic buckling, the reduction in the buckling load due to geometric uncertainties could be significant. In the case of post-buckling, the effective width uncertainty was found to vary within the range of experimental results.

The behaviour and design of cold-formed steel sections with single and multiple intermediate stiffeners in compression were investigated by Schafer and Pekoz (1997). Existing experimental data were used to evaluate critically the AISI specification and Eurocode. AISI specification was observed to be unconservative for bending strength prediction of sections with multiple intermediate stiffeners and Eurocode yielded conservative results. A finite element model was developed and calibrated using existing experimental data. An extensive parametric study was conducted using the finite element model. The results of the study were used to gain a better understanding of the behaviour of the elements and to help evaluate alternatives to the existing design procedures. Based on the experimental data and the finite element study, recommendations were made for improved strength prediction procedures.

Dubina et al (1998) developed a new analytical technique called Erosion Critical Bifurcation Load (ECBL) approach for the stability problem of thin-walled cold-formed members. A more appropriate theoretical understanding of the interactive buckling phenomenon and an accurate design procedure were also presented. The diversity of the cross-section shapes as well as the reduced number of experimental results in the coupling range, have led to the idea of substituting the experimental results found to be included by numerical results. For this purpose, a large-deformation elastic-
plastic FE model was created based on test results. This model took into account geometrical imperfections and inelastic behaviour of members. Only a very small number of tests were necessary to calibrate the FE model. This model could be further used to obtain numerical results for the specimens within the coupling range and allowed for the evaluation of the erosion level of critical bifurcation load. Relevant numerical results and comparison with tests were presented. The ECBL approach offered a more appropriate theoretical understanding of the interactive buckling phenomenon and made it possible to build, starting from a rigorous scientific basis, an accurate design procedure, which could pave the way to unify the design methods used in stability analysis.

Torsional-flexural buckling of singly symmetric cold-formed steel beam columns was studied by Kalyanaraman and Srinivasa Rao (1998). A review was made for the various methods presented in the International Standards and other literature was made for the evaluation of the strength of singly symmetric members subjected to eccentric compression in the plane of symmetry. It was observed that the procedure recommended by the AISI and the Eurocode 3 for evaluating torsional-flexural buckling stress, disregarded the effect of local buckling and the strength was evaluated by multiplying the stress by effective area. Further, while evaluating the effective section properties, the effective width of the elements should be taken into account for the membrane stress gradient on the element. The effect of rotational restraint provided by the adjacent elements on the buckling element should also be properly accounted for.

Ben Young and Rasmussen (1999) studied experimentally the effects of shift of effective centroid of channel columns experimentally based on the fixed-ended test results. It was shown that the effective width rules of the American and Australian specifications accurately predicted the direction
and magnitude of the shift of effective centroid for plain channels but not for lipped channels with slender flanges. The study proposed simple modifications to the current effective width rules to provide agreement between the measured and predicted shifts of the effective centroid for lipped channels. The modifications were shown to produce more accurate design strengths for lipped channel columns.

Kesti Jyrki and Davis (1999) assessed the applicability of the Eurocode 3 to the prediction of the compression capacity of short fixed-ended columns with different cross-sections. The 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 were carried out in order to compare alternative methods for determining the minimum elastic distortional buckling stress in compression. It was concluded that the end boundary conditions had a significant influence on the distortional buckling strength, and thus also on the compression capacity of short columns. The applicability of Eurocode 3 to the prediction of the compression capacity of short fixed-ended columns with different cross-sections was presented. Selected experiments from compression tests on C, hat and rack upright-sections were compared with the predictions prescribed by Eurocode 3. The procedure was modified by determining the distortional buckling stress using Generalised Beam Theory, taking into account the actual column length and the end conditions. This led to better agreement between the experimental results and the theoretical predictions.

Chou et al (2000) presented a Finite Element Analysis on the post-buckling behaviour of thin-walled cold-formed lipped channel and hat-section stub columns under axial compression. The specifications were modelled exactly as that used in the carefully controlled stub column tests conducted by
Zaras and Rhodes. Numerical predictions on the load versus end-shortening characteristics and ultimate load capacity of the sections were obtained using a non-linear Finite Element Analysis. The effect of the input parameters such as the degree of prescribed initial imperfection and the size of the element mesh, on the convergence of the solution was examined. The initial imperfection for post-buckling analysis was achieved by making use of the exact linear buckling wave form. Standard design procedures were developed for post-buckling analysis of thin-walled stub columns using Finite Element Method. Results from the design procedure correlated well with the experimental results and BS: 5950 (1998) predictions.

El-Sheikh et al (2001) studied the performance of stiffened and unstiffened cold-formed channel members in axial compression. A parametric study was done on channel members with various aspect ratios, stiffener sizes and slenderness ratios. It was observed that increasing the web stiffener beyond certain limits was counter-productive. Load eccentricity in the weak direction led to significant loss in the buckling strength. The effect of web stiffeners in reducing the torsional buckling strength lower than the flexural buckling strength gave overall strength losses. On the other hand, it was found that providing flange stiffeners in channel section resulted in consistent increase in the member’s buckling strength.

Schafer (2002) studied the local, distortional and Euler buckling behavior of thin-walled columns. A closed-form prediction of the buckling stress in the local mode and distortional mode agreed well with numerical results. The formulation included the interaction of the connected elements and the elastic and geometric stiffness at the web and flange juncture. Numerical analyses and experiments indicated that post-buckling capacity in the distortional mode was lower as compared to the local mode. A new design method was proposed that explicitly incorporates local, distortional
and Euler buckling. A rational analysis for the prediction of elastic buckling stress was presented for thin-walled columns.

Ben Young and Jintang Yan (2002) presented a design and numerical investigations into the strengths and behavior of cold-formed lipped channel columns under fixed end condition using finite element analysis. A nonlinear finite element model was developed and verified against fixed-ended channel column tests. Geometric and material nonlinearities were included in the finite element model. It was demonstrated that the finite element model closely predicted the experimental ultimate loads and the behavior of the cold-formed channel columns. The column strengths obtained from the finite element analysis were compared with the design column strengths calculated using the American, the Australian/New Zealand, and the European specifications for cold-formed steel structures. It was shown that the design column strengths calculated from the three specifications were generally conservative for lipped channels having a maximum plate thickness of 6 mm.

Dubina and Ungureanu (2002) analysed the influence of imperfections on the behaviour of cold-formed steel members. Special attention was paid to the characterisation and codification of imperfections for non-linear finite element simulation. Based on the Erosion Critical Bifurcation Load (ECBL) approach and using an advanced non-linear inelastic analysis, the erosion of theoretical buckling strength, due to geometrical imperfections, in single and coupled instability modes was evaluated. It was observed that the different shapes of local sectional imperfections have a different effect on the member buckling strength. It was emphasized that the sine shape of the imperfections not always represented the appropriate mode to be introduced into the non-linear analysis. It was
reported that the distortional overall interactive buckling was highly sensitive to sectional imperfections.

Pandian et al (2003) compared the strengths of channel, hat, box and I sections subjected to compression using LRFD by the American (AISI) and the British Standards (BS) by varying the yield strength and slenderness ratio. In each shape one section was considered having an average area of the sections listed in IS: 811 - 1987. The slenderness ratios were chosen from 25 to 175. BS and AISI codal provisions were reviewed with reference to the compression load capacity of the sections. For most of the shapes irrespective of the yield strength and slenderness ratio, prediction by BS gave higher compressive strength as compared to AISI provisions. It was observed that there was a marginal difference between the predictions by BS and AISI for smaller slenderness ratios of I section without lips.

Bakker and Pekoz (2003) presented the basic principles of Finite Element Method for thin-walled members. The study focused on the possible sources of error in linear and non-linear finite element solutions and suggestions were given to check and prevent these errors. Errors in idealisation, in discretisation, in geometry, in element formulation and solution and in convergence were discussed.

Szymczak (2003) reviewed the problems related to sensitivity analysis of thin-walled members with open monosymmetric and bisymmetric cross-sections. The restraints imposed on cross-section rotation, transverse displacement and cross-section warping were taken into account. The first variations of state variables due to a change in the design variable were investigated. Arbitrary displacement, internal force or reaction of the member subjected to static load, critical buckling load, frequency and mode of torsional vibration were assumed to be the state variables. Dimensions of cross-section, material constants, restraints stiffness, and their locations,
position of the member ends were taken as the design variables. Accuracy of
the approximate changes of the state variables achieved by sensitivity analysis
was also discussed.

Teng (2003) extended the Lau and Hancock method, which was
developed for axially loaded columns to beam-columns subjected to combined
axial compression and biaxial bending. Particular attention was paid to the case of
axial compression in combination with uniaxial bending in the plane of symmetry.
Numerical results from the present closed-form solution were compared with those
from the finite strip method, showing a close agreement between the two. It was
stated that the accuracy of the closed-form solution could be improved by
including the effects of shear and flange distortion, through a simple
modification of the expression for the rotational stiffness offered by the web.
The interaction relationship between the axial load and the bending moment was
shown close to being linear. It was also proved that the load eccentricity had little
effect on the buckling half-wavelength.

Tian and Lu (2004) presented a theoretical and experimental study
on the minimum weight and the associated optimal geometric dimensions of
an open-channel steel section subjected to axial compressive load. Sections
both with and without lips were analysed. The results obtained using a non-
linearly constrained optimisation method was compared with those estimated
from a simple-minded optimisation procedure that assumed the simultaneous
occurrence of all failure modes in a minimum weight structure. The type of
failure mode considered included yielding, flexural buckling, torsional-
flexural buckling and local buckling. The failure criterion was based purely
on compressive strength; with possible design constraints. The effect of end
conditions and restraint on torsional buckling was examined. The load
capacity of a C-section calculated according to the 1998 BS specification was
used to check the validity of theoretical predictions. Two new C-sections with
lips were designed based on the optimal results and the test results confirmed the analytical predictions. The test results confirmed the analytical predictions, with the optimal C-sections performing much better than the existing sections.

Bambach and Rasmussen (2004) presented a general design procedure for calculating the moment capacity of sections with unstiffened elements with stress gradient. The method used the design equations for effective widths of unstiffened elements with stress gradients based on plate test results. The investigation presented methods for the calculation of the capacity where inelastic reserve capacity may be taken into account for sections containing fully effective unstiffened elements with stress gradient. The methods were also shown to be in good agreement with the experimental data of I-sections and plain channels in minor axis bending. Particular attention was given to the effect of both the elastic buckling coefficient used in the effective width method and the use of inelastic considerations on the bending capacity. Specific design proposals were also presented in the form of amendments to the current American and Australian standards for cold-formed steel structures for elements and sections in bending.

Ungureanu and Dubina (2004) presented recent developments and applications of Erosion Critical Bifurcation Load (ECBL) approach for the interactive buckling. Two different types of problems were analysed. The occurrence of local plastic mechanisms in cold-formed steel sections in compression and implementation in the ultimate limit state analysis of the members were analysed. The study suggested the use of interactive local-overall buckling analysis instead of traditional effective section. The ECBL approach was used to implement the proposed interactive buckling model. Results were compared with those of Direct Strength Method and Plastic Effective Width approach. Comparison with European and American design codes were also presented. It was concluded that the ECBL elastic-plastic
interactive approach, based on the erosion theory of coupled bifurcation was much more rigorous and understandable than the semi-empirical methods used for the buckling curves in existing design codes.

Lin et al (2005) presented a new formulation to simplify the determination of flexural buckling stress without iterative process. Taylor series expansion theory was used to study the numerical approximations. The proposed design formulae presented could be alternatively used to calculate the flexural buckling stress for austenitic type of cold-formed stainless steel columns. It was shown that the column strengths determined by using the proposed design formulae had good agreement with those calculated by using the ASCE standard specification. A design example was also included for cold-formed stainless steel column using the ASCE standard equations and the proposed design formulae.

Dinis et al (2006) presented, validated and illustrated the application of Generalised Beam Theory (GBT) developed to analyse the buckling behaviour of thin-walled members with arbitrarily branched open cross-sections. The derived formulation was employed to investigate the local-plate, distortional and global buckling behaviour of simply supported and fixed asymmetric E-section columns. They dealt with the issues related to the choice of the appropriate elementary warping functions and to determine the initial flexural shape functions. The derive formulae was then employed to investigate the local-plate, distortional and global buckling behaviour of simply supported and fixed asymmetric columns and beams with unequal stiffened flanges. For validation purposes, several GBT-based results were compared with exact values obtained by the Finite Strip Analysis and a perfect coincidence was found in all cases.

Wang et al (2007) investigated the behaviour of pin-ended cold-formed channel columns with inclined simple edge stiffeners. Thirty
pin-ended cold-formed channel columns with three different lengths were studied. All three sections had certain post-buckling strength, and the failure modes of most of the specimens contained distortional buckling. It was observed that the capacity of the specimens with 45° inclined angle for bearing compression was appreciably higher than the other two types of specimens with 90° or 135° inclination at the same negative eccentricity, but obviously lower than the other two at the same positive eccentricity. Furthermore, tests were simulated by finite element analysis. Results from the analysis were in good agreement with the experiment. Three types of failure modes were observed in medium and long column tests. All the columns loaded with positive eccentricity failed in combined distortional and flexural buckling modes. The concentrically loaded columns with 45° sloping lip stiffeners also failed in combined distortional and flexural buckling modes, but other concentrically loaded columns failed in combined local and flexural buckling modes.

Schafer (2008) reviewed the development and current progress in the Direct Strength Method (DSM) which had been formally adopted as an alternative design procedure in the North American Specifications for the Design of Cold-Formed Steel Structural Members, as well as in the Australian/New Zealand Standard for cold-formed steel design. The advantage of methods that integrated computational stability analysis into the design process, such as the Direct Strength Method, was highlighted. The Direct Strength Method employed gross cross-section properties, but required an accurate calculation of member elastic buckling behaviour. Numerical methods, such as the finite strip method or generalized beam theory, were the best choice for the required stability calculations. It was concluded that the reliability of the Direct Strength Method equaled or bettered the traditional Effective Width Method for a large database of tested beams and columns. The development of the Direct Strength Method for beams and columns, including the reliability of the method was provided.
An analytical model for calculating the critical stress of distortional buckling of compression flange and lip in channel sections under compression and bending about an axis perpendicular to the web was studied by Long-yuan Li and Jian - Kang Chen (2008). Closed-form expressions were derived and validated by using the finite-strip method. Comprehensive comparisons had been made between several alternative methods for determining the minimum elastic distortional buckling stress and demonstrate that the present model provided a good prediction of the distortional buckling stress of channel sections.

Anil Kumar and Kalyanaraman (2010) studied the suitability of Direct Strength Method (DSM) to evaluate the compressive strength of plain channel sections, I and rectangular tubular members. Extensive experimental data in literature and additional data generated using currently accepted effective width method based on better estimate of local buckling stress evaluated considering element interaction were used in this study. The applicability of DSM for the strength of plain channel sections which did not have stiffener and hence did not suffer distortional buckling, was evaluated. It was observed that the DSM could also be applied to calculate the strength of such compression members without either lip or intermediate stiffeners. The comparative study with test results and Effective Width Method results had shown that DSM estimated the strength of these compression members within acceptable accuracy, for practical purposes.

Based on literature reviewed on the theoretical, numerical and experimental studies it is concluded that limited research work is available on the behaviour of cold-formed plain channels loaded through positive and negative eccentricities. The present study is conducted to analyse the behaviour of plain channels with different loading patterns along the plane of symmetry. The slenderness ratios of the sections chosen are from 40 to 120.