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INTERNATIONAL JOURNAL OF ENGINEERING SCIENCES & RESEARCH TECHNOLOGY

EXPERIMENTAL, ANALYTICAL AND THEORETICAL STUDY ON TWO - BOLTED, THREE- BOLTED AND WELDED COLD-FORMED ANGLES UNDER ECCENTRIC COMPRESSION

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DOI: 10.5281/zenodo.1434713

ABSTRACT

Cold-formed steel structural elements and its applications have extensively increased. Angle sections always design to carry axial loads. The main objective of this study is to understand the existing literature review of behaviour and load carrying capacity of equal and unequal angles under compression and the effect of eccentricity on load carrying capacity were described. Experimental, Analytical and theoretical investigations on cold-formed steel angle sections and the comparison of strengths from the experimental results with finite element analysis and design strengths compared with different National and International codes. Design rules and recommendations were briefly discussed.

KEYWORDS: cold-formed steel, column, Bolted & welded angles, compression, Experimental Testing, Finite element Analysis.

1. INTRODUCTION

Now a day's cold-formed steel structures are very high demand because of its light weight, various types of cross sections, economy, and easy to fabricate and erect. Angles are used as single angles or double angles and the connections are bolted or welded. Angle members are commonly attached to other members by one leg only, so the load is applied eccentrically. Single- angle structural compression members are very difficult to analyze and design. Single–angles are commonly used in light roof trusses, decks, transmission line towers, bridges, multistoried buildings, industrial structures, latticed electrical transmission line towers, and antenna-supporting towers. The design is further complex due to eccentric axial loads.

2. RESEARCH REVIEW OF ANGLE SECTIONS

Review of existing research on compression members a number of studies had been done on the cold formed steel even though the research is very limited on angle sections because of its design complex due to eccentricity. The results from the significant research on cold-formed steel angle columns are given below.

Madugula M.K.S., Prabhu T.S. and Temple M.C., (1983) investigated the ultimate load carrying capacity of concentrically loaded cold-formed single angles with hinged end conditions. The research provided the out-of-straightness of the test specimens was measured. Load-deflection curves were obtained experimentally, theoretically. The magnitude and distribution of residual strains were also determined. Experimental failure loads was carried out and it was validated by four codes (ASCE, AISI, CSA, ECCS) ECCS code predicts most cases conservative.

Madugula M.K.S. and Ray S.K (1984) investigated the Ultimate strength of eccentrically loaded cold -Formed steel angles with pin ended conditions. Experimental failure loads was carried out and it was validated by ECCS recommendations are generally conservative and ASCE manual no 52 failure loads for single- bolt end connection higher than experimental. For all slenderness ratios, the strength of the member increases when the number of bolts in the end connection is increased from one to three. Location of shear center and magnitude of

ISSN: 2277-9655
Impact Factor: 5.164
CODEN: IJESS7

warping constant have an insignificant effect on the predicted failure loads according to the general theory of torsional- flexural buckling.

Dan Popovic, Kim J. R. Rasmussen, Gregory J. Hancock (1999) investigated fixed-ended and pin-ended compression tests and residual strain as well as initial geometric imperfections on cold-formed, in-line galvanized equal angles. It is concluded that there is no need to include the additional eccentricity specified in the Australian and American cold-formed steel structures standards accounting for the shift of the effective centroid, and that the eccentricity of L/1,000, specified for all section classes, should be applied to slender sections only.

Dhanalakshmi and Shanmugam (2000) investigated the ultimate load capacity of non-perforated and perforated equal angle cold-formed steel stub columns. Compression tests were carried out under axial or eccentric loading. This test shows reduction in the ultimate strength of the columns loaded at an eccentricity away from the corner. As slenderness ratio increases, the effect of eccentricity has relatively less influence on the ultimate load capacity. Tests on perforated cold-formed angles subjected to axial compressive loading show that the presence of perforations results in reduction of the ultimate capacity of the specimens. Finite element model is capable of predicting the ultimate load carrying capacity and the failure modes with reasonable accuracy.

D. Popovic; G. J. Hancock and K. J. R. Rasmussen (2001) conducted a series of compression tests on cold-formed equal angles with slender cross-section. The angles were tested between pinned ends and loaded axially with eccentric load which caused bending parallel with a leg. The test strengths were compared with the design strengths calculated using Australian and American specifications for cold-formed and hot-rolled steel structures, as well as the ASCE Standard for the design of Latticed Steel Transmission Structures. The design rules of the specifications for cold-formed steel structures (AS/NZS4600 and AlSI) are shown to be very conservative.
The cause of the conservatism is explained and improved design rules are proposed.

D. Dubina and V. Ungureanu (2002) the influence of imperfections on the behaviour of cold-formed steel members are analyzed. Special attention was paid on the characterization and codification of imperfections for non-linear FEM 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.

S. Narayanan and M. Mahendran (2003) the distortional buckling behavior of a series of innovative cold-formed steel columns of different configurations are studied. More than fifteen laboratory experiments were undertaken on these innovative steel columns of intermediate length under axial compression. The finite element analysis using ABAQUS was carried out incorporating the relevant geometric imperfections and residual stresses. The deflection and strain results from the experiments compared well with those from the analysis. 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 analysis.

Ben Young (2004) Conducted an experimental investigation of cold-formed steel plain (un stiffened) angles. The columns were tested under fixed end conditions at various lengths from short to long columns. The test strengths were compared with the design strengths calculated using the American Specification and Australian/New Zealand standard for cold-formed steel structures. It is shown that the design strengths predicted by the Specification and Standard are generally very conservative A reliability analysis was performed to assess the current and proposed design rules for cold-formed steel plain angle columns.

Ehab Ellobody and Ben Young (2005) An accurate finite element model was developed to understand the behaviour of cold formed steel plain angle columns. The initial local, overall geometric imperfections and residual stresses were taken in to finite element analysis. The non-linear finite element model was verified with the experimental results. The finite element analysis was performed on plain angles compressed between fixed ends over different column lengths, and column curves were obtained. A large parametric study was carried out using the finite element model to study the effects of cross-section geometries on the strength and behaviour of angle columns The column strengths predicted from the finite element model were compared with the design strengths calculated using the American specification and Australian/New Zealand standard for cold-formed steel structures. The results obtained from the finite element model were also compared with the design strengths obtained from the design rules proposed by researchers.

Y. Shifferaw, Maximiliano Malite, BenjaminW. Schafer andGustavo M. B.Chodraui (2006) investigated the stability and strength of concentrically loaded cold-formed steel angles as determined by numerical methods, experimental and effective width and Direct Strength design methods. The imperfections were incorporated in the finite element model The elastic stability of cold-formed steel angle columns is examined primarily with the finite strip method to show that the coincident local-plate/global-torsional mode has some important behavior when multiple buckling half-wavelengths are considered along the length. Conducted a series of tests on single and double angles and the results used to examine existing design methods. The results indicate that the design practice of ignoring local/torsional buckling as a global mode and only considering it as a local mode may not be conservative in some circumstances. This conclusion is further supported and discussed in an extended set of nonlinear finite element analysis.

Ben Young and Ehab Ellobody (2007) analyzed the Numerical investigation and design of cold-formed steel unequal angle compression members. The initial local, overall geometric imperfections and residual stresses were incorporated in the finite element analysis. The finite element analysis was carried out on fixed-ended condition. Experimental results were compared with design strengths. The current design rules are generally un-conservative for short and intermediate column lengths for the unequal angles. It is shown that the strength and behaviour of unequal angle columns predicted using the finite element analysis are generally in good agreement with the experimental results. The proposed design strengths accurately predicted the column strengths for angle sections. The design rules were proposed for cold – formed steel unequal angle columns.

Ben Young, Ju Chen (2008) Conducted column tests of cold-formed steel non-symmetric lipped angle sections. It was shown that the design strengths are generally quite conservative for the cold-formed steel non-symmetric lipped angle columns. Reliability analysis has been performed to assess the current design rules in the North American Specification for the cold-formed steel non-symmetric lipped angle columns. It was shown that the current design rules are reliable for the sections having plate thickness of 1.9 mm, but this is not the case for the more slender sections having plate thicknesses of 1.0 and 1.5 mm. The tests were performed at different column lengths ranged from stub column to long column with column slenderness of approximately 100.In the design calculation, elastic buckling stress was obtained by solving a cubic equation due to the non-symmetric sections.

Vishnuvardhan and Samuel Knight (2008) Conducted Column axial Compression tests on cold-formed steel single- angles, double angles welded back-to-back and starred angles under three different end connections are studied. Eight plain sections of different sizes of two different thicknesses of different strengths were tested as stub and as short columns. The ultimate loads predicted by IS 801-1975, BS: 5950(Part-5)-1987, AISI manual-1996 and AS/NZS: 4600-1996 codes of practices were compared with the experimental values. The load versus strain behaviour, load versus lateral deflection behaviour and the load versus strain behaviour was studied for the specimens. Analytical investigations were also carried out using finite element software ANSYS and the results were compared with the experimental results.

W. F. Maia, J. Munaiar Neto and M. Malite (2010) studied theoretical and Numerical analysis of cold-formed steel battened double angle members under compression. Battened double angle system is one of the systems most used in light truss. Two critical modes are observed in the elastic stability analysis are global flexural mode in the case of longer members and a coincident local-plate/global flexural-torsional mode. Presented the non-linear numerical analysis on the behavior of double angle in battened system and changing the no of batten plates and their effectiveness in the nominal axial strength was studied. Analytical investigations were also carried out using finite element software ANSYS and the results were compared with the North American Specifications. Initial geometric imperfections were also incorporated in finite element analysis. Except for the thin angle specimen (t = 1.5 mm) the results obtained from the nonlinear analysis showed that the presence of the batten plates significantly increased the nominal axial strength of the members.

YiLiu (2011) Conducted experimental study of 26 steel single unequal-leg angles under eccentric compression with respect to either major or minor principal axis of the cross section to study the steel single angle beam-column behaviour. The experimental results were compared with the values obtained from AISC Specification 2005 and the Direct Strength Method. Good correlation with test results when the concentric loading and eccentric loading causing minor axis bending are concerned. The major principal axis bending causing the angle short leg in compression, the presence of moment, in some cases, resulted in the angle ultimate load higher than its concentric compressive capacity. Over all the effect of eccentricity on the ultimate load decreased as the slenderness increased. Studied the design of angle beam–columns as proposed in AISC Specification 2005 and the Direct Strength Method was evaluated using the test results.

Zhou et al. (2012) Describes a non-linear elasto-plastic finite element model of angle sections connected to a gusset plate through a single bolt at each end subjected to axial compressive load. In the finite element model incorporated the initial imperfections and was validated against published test results for angle sections having different values of slenderness increased. For specimens subjected to major axis bending causing the angle long leg in compression, an increase in eccentricity results in a reduction in ultimate load. In the case of major axis bending causing the short leg in compression. When compared with experimental values, both AISC Specification2005 and the Direct Strength Method provide reasonably good correlation with test results. A parametric study covering a range of equal and unequal angles was described; in the case of the unequal angle sections, bolts through both the long-leg and short-leg were considered separately

Maia and Vieira (2012) Numerical and experimental investigation of cold formed steel double angle members concentric and eccentric axial under compression.. The number of batten plates was varied to study the influence on the nominal axial strength. Numerical analyses are able to accurately predict the behavior and strength found in the experiments, except for long columns under eccentric axial compression where the composite section failed in major-axis flexural buckling the use of batten plates significantly increases the strength of the system, especially for members under eccentric compression. An interesting observation is that the pairs of angles perform better when there is a batten plate at mid-length. In many cases, members with one batten plate performed better than members with two batten plates.

Silvestre et al. (2013) Investigation on developments on the design of cold-formed steel angles The procedures for the design of fixed- and pin-ended equal-leg angle columns with short-to-intermediate lengths were presented. It was also shown that the LRFD resistance factor of 0.85, used in the current DSM, can also be safely adopted when applying the proposed DSM approach. Finally, the paper closes with the proposal of new design procedures for fixed- and pin-ended angle columns based on the direct strength method (DSM).The DSM-based approach proposed for the design of fixed- and pin-ended equal-leg angle columns. Adopts the local/global interactive failure concept. Uses distinct procedures (local strength curves) for fixed-ended (DSM-F) and pin-ended (DSM-P) columns, thus reflecting more closely the actual angle column behavior.

G.Vani, P.Jayabalan, Jikhil Joseph (2013) Numerical and experimental and theoretical investigation of cold formed steel pin-ended cold formed steel equal angles under compression. Experiments conducted for four specimens with different lengths for non-slender to slender sections. From the finite element analysis it is observed that the load carrying capacity of the section decreases as the b/t ratio increases. For the same b/t ratio as the length increases the load carrying capacity of the section decreases due to the slenderness effect. The non-linear analysis results are compared with the recent Direct Strength Method (DSM) and the traditional Effective Width Method (EWM) as well. The DSM method is found to predict the ultimate load capacities in a better way.

Kulatunga (2013) Finite element analysis of cold–formed steel structural members with perforations subjected to compression loading. The primary interest of this paper is to study the possible buckling occurrence on cold formed steel structural sections used as columns with perforations. Results showed that the displacement of the structure under compression varied significantly with the cut–out position the tests carried out in the experimental investigations were capable of validating the buckling behaviour of channel sections as exhibited in the FE models.

Shifferaw and Schafer (2014) Explored the significant post-buckling reserve in global buckling that has been observed in tests on cold-formed steel angle columns, and to provide design guidance for locally slender cold-formed steel lipped and plain angle columns with fixed end boundary conditions. Global buckling modes are generally regarded to have no post-buckling reserve, and indeed all column design curves, including those used in North America for cold-formed steel columns limit the strength to 0.877Pcre (where Pcre is the global buckling load) or lower. The tests conducted on cold-formed steel angles by Young (2004,2005) 1 and 2 demonstrate capacities significantly in excess of Pcre – an observation usually reserved for local-plate buckling modes, which due to transverse membrane resistance are known to have significant post-buckling reserve. In

ISSN: 2277-9655
Impact Factor: 5.164
CODEN: IJESS7

this work, specific attention is paid to the impact of end boundary conditions, with emphasis on warping (longitudinal) deformations. Utilizing nonlinear collapse analysis with shell finite element models, and existing testing, alternatives to current design methods are explored. New design procedures are recommended for strength prediction of cold-formed steel angle columns with fixed end boundary conditions.

G. Beulah Gnana Ananthi (2015) conducted experimental and numerical investigation on thin-walled single and starred angle sections under compression. A non-linear finite element model was developed and verified against the ball-and bolted-end conditions. Material non-linearities and geometric imperfections are included in the finite element model. The column strengths by the numerical analysis are compared with the design column strengths calculated by using the North American Standards for cold-formed steel structures. The starred angles under when tested under ball-end condition failed by torsional buckling irrespective of the slenderness ratio. The failure occurred in the flanges of the section at one-fourth height. North American Specifications are generally conservative for cold-formed steel angle sections.

Chayanon (2015) Conducted experimental study on four different sections of columns was tested to investigate effect of stiffening and width- to thickness ratio on buckling behaviour. For each of the section studied short, intermediate and long columns. This study was mainly focused on buckling performance of irregular section cold-formed steel columns under axially concentric loading. The comparisons in the terms of load-deformation response and buckling mode show good agreement and hence the Finite element analysis models were validated. For short columns centroid and shear center coinciding, local buckling dominated with ultimate compressive stress is higher than yielding strength. For intermediate and long column combination between local buckling and distortional buckling can be seen. Over all buckling governs the failure mode and thicker wall plays a little role to increase the load carrying capacity.

G. Beulah Gnana Ananthi (2017) Investigated cold-formed steel compound angle section subjected to axial compression with pinned-end condition. Studied the compressive strength on pin-ended thin-walled steel built-up double angles placed as a box section. A numerical finite element analysis ABAQUS was used to validate initially by verifying the experimental data on the behaviour of built-up box angles. Based on the parametric results, an analytical model was proposed to calculate the ultimate load carrying capacity on the built-up box angle column based on DSM. Parametric analysis has been carried out for 88 number of columns to examine the behaviour of 8 types of box angle columns by varying the slenderness ratio between 20 to 120.The increase in the leg dimension played a major role in initiation of the local buckling in the lips for both the thickness taken up for this study.

AlexandreLandesmann,DinarCamotim, **Pedro B.Dinis andRenatoCruz (2017)**Experimental investigation, numerical simulations and DSM design for Short-to-intermediate slender pin-ended cold-formed steel equal-leg angle columns. Incorporated initialimperfections in the numerical analysis. Experimental failure loads of slender pin-ended columns with intermediate-to-high slenderness values, which implied that the design procedure was validated for such columns exclusively on the basis of numerical failure loads. b/t ratios are considered between 32 and 58. The failure loads from the experimental and numerical results are also compared with the direct strength method design approach.

3. CONCLUSION

From the available literature, it is observed that behaviour of cold- formed steel angle sections under compression and eccentric compression equal and unequal plain and lipped angles various authors have been carried out the research work. The experimental, numerical and theoretical investigations of plain and lipped angle sections have been investigated. Design strengths are calculated various national and international codes. Euro code specifications are generally conservative. Single-bolt end connection, ASCE Manual No. 52 predicts failure loads that are higher than the experimental failure loads and for multiple-bolt connection, the predicted failure loads are either less or very close to the experimental failure loads. Tests on perforated cold-formed angles subjected to axial compressive loading show that the presence of perforations results in reduction of the ultimate capacity of the specimens. A reliability analysis was performed to assess the current and proposed design rules for cold-formed steel plain angle columns. The proposed design rules are simple compare to present design rules to calculate the load carrying capacity of the sections.

The strength obtained from finite element analysis showed good agreement with design strengths obtained using the equation proposed by Ben Young 2004. The design rules specified in AISI (American Iron and Steel Institute Specifications) and the Australian/New Zealand specifications were conservative for plain angle

ISSN: 2277-9655
Impact Factor: 5.164
CODEN: IJESS7

columns. North American Specifications are unconservative for cold-formed steel unequal angle columns, except some of the angle column sections with longer lengths. Reliability analysis has been performed to assess the current design rules in the North American Specification the current design rules are reliable for the sections having plate thickness of 1.9 mm, but this is not the case for the more slender sections having plate thicknesses of 1.0 and 1.5 mm. The finite element model required contact to be modelled between the angle sections and the gusset plates; a model without contact which assumed that full torsional restraint was provided was demonstrated to produce unconservative results. The design recommendation produce reliable limit state designs when calibrated with the resistance factor (φ) of 0.9 for both equal and unequal angle sections. It is also recommended LRFD resistance factor of ϕ =0:85, used in the current DSM, can also be safely adopted when applying the proposed DSM approach.

It is recommended that the pin-ended specimens were tested with a minimal eccentricity of *L*/1,000 applied about the minor axis to cause compression at the tips of the legs. The proposed design rules are simple compare to present design rules to calculate the load carrying capacity of the sections. Direct strength method was proposed for the design of fixed and pinned-leg angle columns. Unequal single angles under eccentric loading AISC and Direct Strength Method underestimate the axial load carrying capacity of the specimens when the short leg is in compression. Direct Strength Method performed better than the AISC equations providing predicted values closer to experimental results. All the theoretical ultimate load showed conservative results as the analysis was done using unfactored design column strength equations provided in DSM.

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CITE AN ARTICLE

Saleema Begum, R., & Jane Helena, H., Dr. (2018). EXPERIMENTAL, ANALYTICAL AND THEORETICAL STUDY ON TWO -BOLTED, THREE- BOLTED AND WELDED COLD-FORMED ANGLES UNDER ECCENTRIC COMPRESSION. *INTERNATIONAL JOURNAL OF ENGINEERING SCIENCES & RESEARCH TECHNOLOGY*, *7*(9), 259-265.