Behavior of Compression Members under Effect of Initial Imperfections: A Literature Review

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***Abstract*--Behavior of compression members becomes complex when buckling gets combined with yielding. This is usually the case when the columns are not too slender. The strength of such compression members cannot be accurately predicted and more sophisticated approaches need to be followed. A comprehensive review of available literature on behavior of thin-walled cold-formed steel structural members has been carried out with an emphasis on the buckling and crushing. Further, literature on effects of compression behavior under existing imperfections has also been reviewed. Experimental investigations focused on the strength calculation and web crippling of cold-formed tubular steel structures have also been included in the review. While a number of publications are available in the literature, the most significant publications have been selected and reported here.**

***Index Terms:* buckling, compression members, initial imperfection, literature review, web crippling**

I. INTRODUCTION

The tubular structures consist of circular, square and rectangular hollow sections. Tubular structures offer better performance under compressive loads due to their higher moment of inertia and radius of gyration. Due to the obvious benefits of using cold formed steel over other structural material such as timber and concrete, it is considered as a material of choice for structural engineering applications. The most prominent properties include high stiffness and strength, ease of fabrication and speedy installation.

Web crippling [1] is a common mode of failure experienced by web elements of thin-walled beams under concentrated loads or reactions. Most of the studies done on web crippling are experimental and based on compression testing of beams under various loads in order to determine the ultimate web crippling strength by Santaputra [16,17]. Various theoretical studies have been reported in literature, especially on elastic and plastic behavior of plate elements with the intention of developing analytical models to describe web crippling behavior. It is evident that most of the design codes around the world make design recommendation to predict the load at which web crippling would occur, based on equations obtained from such web crippling tests conducted by various researchers.

The study of web crippling behavior of cold-formed steel flexural members has been going on since early 1940s [11]. Most of the research work that has been done on this area is based on experimental studies and the results have been used to develop the design formulae for calculation of web crippling strength. The theoretical analysis of web crippling behavior despite the fact that it is extremely complicated it involves the following factors:

- Non-uniform stress distribution under applied loads.
- Elastic and inelastic behavior of web.
- Local yielding in the immediate region of load application.
- Bending produced by eccentric load when applied on the bearing flanges at a distance beyond the curved transition of the web.
- Initial out-of-plane imperfection of plate element.
- Various edge restraints provided by beam flanges and interaction between flanges and web element.

II. EXPERIMENTAL INVESTIGATIONS

Young, 2003 [34,36,40] carried out experimental investigation of cold-formed stainless steel tubular columns structures. A series of fixed-ended columns tests on square, rectangular and circular hollow sections were conducted. Experimental investigations were focused on the strength behavior of stainless steel columns [35]. The reported test strengths compared well with the design strengths predicted using the American, Australian/New Zealand and European specifications for cold-formed stainless steel structures. The test results strengths were also compared with the design strengths calculated from the design rules proposed by other researchers. It is shown that the design strengths predicted by the standards are generally conservatory for the tested fixed ended cold-formed stainless steel SHS (Square Hollow Section) by Liu, Y and Young [10] and RHS (Rectangular Hollow Section) columns.

Popov and Stephen [13] carried out experimental investigations of the capacity of column with splice imperfections. The results of these experiments indicate that the lack of perfection contact at compression splices of columns may not be important provided that the gaps are shimmed and welding is used to maintain the section in alignment. However, that the kl/r ratio of the columns tested was low, being on the order of 30. A slenderness ratio in the range 25-30, is not at all uncommon in actual buildings. It may be desirable to extend the research to include columns with higher slenderness ratios, to determine the effect of the splicing on a wider range of columns. Columns and braces in buildings as well as in off shores structures may buckle in compression under extreme excitation and then become subjected to tensile forces. This investigation provides data on the behavior of full-size members.

During the 1940s, the behavior of the web crippling was studied experimentally by Winter and Plain [29] at Cornell University in the United States. Since then a number of experimental investigations on web crippling behavior have been reported. Experiments on single web sections, multi-web decks by Studnicka [26] and Wing [28], and cassette sections to improve design codes have also been reported. Further, experiments have been reported in literature to validate various theoretical and numerical models developed by researchers around the world. Experimental investigations provide the observations necessary to understand the failure behavior. The present AISI design provisions for web crippling are based on the extensive experimental investigations conducted at Cornell University by Winter and Pian [29], and by Zetlin [44] in the 1940s and 1950s, and at the University of Missouri-Rolla by Hetrakul and Yu [43] in 1970s.

Young and Hancock [31,33] carried out experimental investigations on web crippling behavior of cold-formed un-lipped channels. Experiments were carried out under four loading conditions to the AISI specification. The concentrated load or reaction forces were applied by means of bearing plates which acted across the full flange width of the Australian/new Zealand standard for cold-formed steel structures. The design web crippling strength predictions given by the specification have been found to be unconservative for the un-lipped channel sections tested.

An experimental investigations of cold-formed steel stiffened C-and Z-sections subjected to web crippling were carried out by Beshara and Schuster [2]. Two loading conditions were considered namely, ETF (End-Two-Flange loading) and ITF (Interior-Two-Flange loading), with particular emphasis on large inside bend radius to thickness ratio R/t, (up to 12) and the specimens being fastened to the support during testing. They observed that there was no experimental data available in the literature regarding the web crippling resistance of such members that are fastened to the support and having inside bent radius to the thickness ratio greater than 2.7. The test results were compared with the calculated values of AISI web crippling design equations.

In 2003, an experimental investigation was carried out by Holesapple and LaBoube [8] to find out the effects of overhang length on the web crippling capacity of cold-formed steel members. It was found that the current AISI design specifications for EOF web crippling capacity were conservative for overhang length ranging from 0.5h to 1.5h, where h is the web depth. A total of 27 specimens of channel and Z-sections were tested. All of the test specimens had an overhang or cantilevered extensions. A modified equation was obtained by analyzing the test results for EOF loading condition (Gerges [6]).

III. THEORETICAL INVESTIGATIONS

In designing cold-formed steel compression members, it is important to recognize the different buckling modes. Four buckling modes are usually encountered during the failure of compression members:

- Local buckling
- Distortional buckling
- Overall flexural buckling
- Overall flexural & Torsional buckling

Young [41] developed an analytical model to describe local buckling and shift of slender sections. The main effect of local buckling is to cause a redistribution of the longitudinal stress in which the greatest portion of the load is carried near the plate junctions. The redistribution produces increase stresses near the plate junctions and high bending stresses as a result of plate flexure, leading to ultimate loads below the squash load of the section. In singly symmetric cross-sections, the redistribution of longitudinal stress caused by local buckling also produces a shift of the line of action of the internal forces. The fundamentally different effects of local buckling on the behavior of pin-ended and fixed-ended singly symmetric columns lead to consistencies in traditional design approaches. The experimental local buckling of cold-formed steel channel columns were compared with the theoretical local buckling loads obtained using an elastic finite strip buckling analysis [20]. The local, distortional and overall buckling stresses and the channel columns have been presented. The shift of the effective centroid of the cold-formed steel channel columns was compared with the shift predicted using the Australian/New Zealand and American specifications for cold-formed steel structures.

In 1998s experimental investigations were carried out by B. W. Schafer [15] on open thin-walled cold-formed steel columns. The columns were observed to have three types of buckling modes viz. local buckling, distortion buckling, and Euler (i.e. flexural or flexural-torsional) buckling. In the local mode, buckling stress occurs due to closed-form and it includes interaction of the connected elements and the distortional mode. It was further deduced that numerical analysis and experimental evidences indicate that the post buckling capacity in the distortional mode is lower than the local mode. Cold-formed channel, Zed and Rack columns indicate inconsistency and systematic error in design methods & it requires validation with Euler buckling. The local and distortional buckling modes are not significant but are inconclusive regarding distortional and Euler interaction. This method does not require effective width calculations and shows that numerical elastic buckling solutions is the key to determining the strength of large variety of thin walled compression members.

The Direct Strength Method (Schafer and Pekoz 1998[21,22,23]) is rapidly gaining acceptance in the Australian and American research communities as a reliable and efficient method for taking advantage of advanced software in the design of cold-formed steel structures. The method combines the elastic local and/or distortional buckling stresses of the entire cross-section, as determined from a rational buckling analysis, with the yield stress to define slenderness, and uses direct strength equations to determine the ultimate limit state buckling capacity. It presents a competitive alternative to existing effective section methods as it obviates lengthy effective width calculations. The method has been formulated for the design for local and distortional buckling as well as overall flexural and flexural-torsional buckling. A draft specification (AISI 2002) now exists for the design of compression and flexural members by the Direct Strength Method (DSM). Hancock et al. 1994 [3] used the a fore mentioned approach informulating direct strength equations for distortional buckling.

Schafer 2003 [19] recently presented a paper outlining how the DSM may also be used for the design of beam-columns. The underlying idea being that the local and distortional modes of buckling can be accurately predicted using software for any combination of compression and bending, and hence, the method has the potential of leading to more accurate solutions for combined compression and bending than current strength predictions, which disassociate the calculations for pure compression and pure bending and combine these through an interaction equation. He considered short lengths of lipped channel section beam-columns and accounted for local and distortional bucking. Duong and Hancock [3] extended the approach to long lipped channel beam-columns, thus considering the influence of 2nd order bending (moment amplification) in determining the overall capacity.

Because the DSM (Direct Strength Method) dispenses with effective width calculations, it does not produce an effective cross-section representing the stiffness of the section in the presence of local buckling. In current specifications, the eccentricity of loading is measured from the centroid of the effective cross-sections in recognition of the fact a concentrically loaded member may undergo bending as the stiffness of the section changes with the development of local buckling. Not withstanding the facts that a] local buckling does not induce overall bending of columns fixed against rotations at the ends (Rasmussen and Hancock 1993[14]; Young and Rasmussen 1998[38,39]) and [b] the shift of the effective centroid may be in accurately predicted when based on the effective cross-section (Young and Rasmussen 1999[40]), the DSM has been criticized because it cannot account for the shift of the effective centroid. For the same reason, the effect of the shift of the effective centroid was not considered in Duong and Hancock's[3] application of the DSM to long lipped channel sections.

In the report of the DSM is applied to plain equal angle section beam-columns with locally unstable legs. This type of member does not have a distortional buckling mode but the overall buckling behavior requires particular attention because the local buckling mode is identical to the torsional mode at short column lengths, as discussed in detail in a previous report (Rasmussen 2003 [40]) on the design of slender equal angle columns. Furthermore, this type of member is particularly sensitive to the effect of the shift of the effective centroid when free torotateflexurally at the ends. Consequently, the formulation reported herein incorporates anexpression for the shift of the effective centroid. The results are compared with tests on equal angle columns with slender legs subjected to varying eccentricity.

The prime objective of performing theoretical investigations on web crippling behavior is to developanalytical models which can be used to determine ultimate web crippling strength and to study the post-failure behavior of a cold-formed steel sections under different loading conditions. Although webs and flanges of the sections are interactive, it is also useful to study the behavior of idealized separate rectangular flat plates loaded by localized in-plane edge forces. Elastic stability [27] and plastic behavior theories of plates are of tenused in analysis of thin-walled structures [12]. Zetlin [44] studied the behavior of the rectangular plate which was simply supported on its four edges and loaded on one edge of the plate. The energy method was used to analyze the plate and the formulated buckling load was given by:

$$P_{cr} = K \cdot 2 \cdot \frac{D}{L^2}$$

Where,
Pcr = critical elastic buckling load,
K = buckling coefficient depending on the ratio of L/B and C/B,
B = half-depth of the plate,
C = half width of loading,
D = flexural rigidity,
L = width of the plate.

Khan and Walker [9] investigated problems of plate buckling similar to those studied by Zetlin [44]. They approximated the deflected shape of the plate by using a finite element solution and used them to solve the potential energy of the plate. The buckling load reported by Khan and Walker was of the form:

$$Pcr = K.2.D/2B$$

Where,
B = half-depth of the plate,
K = buckling coefficient depending on the ratio of L/B and C/B where L and C are length of the plate and the half-width of the plate respectively.

The behavior of plates under compression load was studied by Korol and Sherbouneusing a plastic mechanism approach. According to their studies, the collapse loads of the plate can be obtained from the interaction of post-buckling loading paths and the rigid-plastic unloading lines. The elastic post-buckling path can be obtained by using the energy method while the rigid-plastic unloading or plastic mechanism can beobtained by considering the change in the plastic collapse load with geometric changesin the bent plate.

In 1994, Setiyono [24] developed a model to investigate the web crippling behavior of plain channel sections under combined bending and concentrated loading. Ultimate web crippling strength was determined using an elastic loading curve based on the effective width approach and rigid-plastic unloading curve based on plastic mechanism approach [25].

A new analytical model to predict the ultimate load of first-generation sheeting was developed by Hofmeyer [6, 7] in 2000. The model was based on two existing models, one was developed by Vaessenin 1995on the elastic web crippling stiffness of thin-walled cold-formed steel sections and the other was based on the solution of simultaneous differential plate equations offered by Marguerre. Hat sections were considered for the analysis and testing instead of sheeting because they were easier to manufacture with varying dimensions. Three failure mechanisms were observed: rolling, yield arc, and yield mechanisms.

Conclusion

A comprehensive review on literature available on experimental and theoretical investigations of compression behavior of columns and beam webs has been presented here. Failure of compression members depends significantly on initial imperfections and the way loads are applied. Various experimental data and theoretical formulations are available for prediction of the behavior of compression members, but there is a significant lack of literature reporting finite element simulations. Extensive crack propagation studies on compression members under combined effect of buckling and crushing may be conducted. The literature review highlights the fact that significant research needs to be conducted to thoroughly understand the behavior of compression members under effect of buckling and crushing.

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