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Tailoring Compression Performance of Cold-Formed Steel Columns

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Abstract

Since thin-walled structural analysis and design procedures are utilized for cold-formed steel columns, it is first necessary to understand thin plate behavior to employ proper cross sections which will serve under compression actions. As is well known, thin plates without any longitudinally and/or laterally stiffening elements usually are not present in structural applications. These stiffening elements significantly improve local buckling and collapse characteristics of plates, providing optimized solutions in terms of strength and cost. In cold-formed steel industry there exist some tailoring methods for columns to use the cross-section material more effectively. Designing lipped channels instead of plain ones or deploying rack sections can be shown as examples of stiffening and enhancing flange compression performance. Present study offers a novel tailoring technique which has the potential to improve collapse performance of cold-formed steel columns. Considering the manner of stiffening for thin plates, present work assesses cold-formed steel columns which are manufactured using stiffened sheets. Used stiffened sheets are called as checkered sheets which contain small stiffeners on thin plates in a shape of diamond pattern and are generally used to cover stairs and decks in outdoor environments to prevent slip. Aiming at investigating contributions of small stiffeners on compression performance of cold-formed steel columns, an experimental study was undertaken and column specimens were tested to failure. Plain channel test specimens were manufactured using press braking method and boundary conditions of specimens were designed in such a way that would represent fixed ends. Accompanying the experimental program, non-linear finite element

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simulation works and AISI-2007 method were employed for manufactured columns using equivalent thickness approach. Results imply that with the proper geometrical configurations, reserve of cold-formed steel columns manufactured using checkered sheets offer structural efficiency in satisfying greater compression loadings compared to that of columns manufactured using plain sheets of equivalent thickness. This stiffened sheets concept has the potential to be facilitated in cold-formed steel commercial and residential structures. More efficient sections also can be acquired for design purposes by optimizing those stiffener configurations under compression loadings.

Keywords: Cold-Formed Steel Column, Checkered Sheet, Experiments, Finite Element Simulations

Introduction

Light gauge cold-formed steel (CFS) structures have received significant interest across the world due to advantageous characteristics in manufacturing and construction stages. Such cold-formed steel members are utilized in construction of wall studs, chord members of roof trusses in steel frame housing and industrial buildings (Young and J.R. Rasmussen 1999). Thin-walled nature of these structural members leads to complications in design stages. Under action of compression loadings generally buckling governs the design. However, CFS sections experience distinct buckling behaviors which are not observed in hot-rolled sections. Local, distortional and flexural/flexural-torsional modes are expected under compression actions (Narayanan and Mahendran 2003). These complicated behaviors also their interactions compelled researchers to conduct numerous investigations. Advances in CFS design and developments can be followed from the reviews (Hancock 2003; Young 2008)

There exist several approaches to predict strengths of employed cross sections. For CFS columns design specifications are very active across the world. In particular, North American Specification (AISI 2007) and European standard (EN 1993-1-1 Eurocode 3 2005) play important role in strength assessments. AISI specification and the mechanics behind the formulations are detailed in reference books (Hancock, Murray et al. 2001; Yu and LaBoube 2010). Both American and European specifications rely on effective width formulations. However, they imply some different approaches in application of effective width equations. Today, computational simulation methods like Finite Element (FE) and Finite Strip (FS) methods find great use in analysis and design of CFS columns. Use of FS method in CFS design was originally encouraged by Schafer and Peköz (Schafer and Peköz 1998). They based capacity prediction on FS elastic buckling solutions to propose “Direct Strength Method”. FE method also received great attention from research communities for the purpose. The guidelines for the use of FE method to predict strength of CFS members were presented in literature (Schafer, Li et al. 2010).

New, safe and high performance residential and industrial buildings require adoption of novel structural configurations with high strength weight ratio. In this sense, some optimization studies were conducted by researchers to propose more efficient cross sectional geometries (Kolcu, Ekmekyapar et al. 2010; Leng, Guest et al. 2011). A further choice to improve compression performance of CFS columns is to focus on plate behavior under compression loadings. As is well known, compression performance of thin plate members in ships, bridges and aircrafts are strengthened by some stiffener elements. These stiffener elements significantly improve local buckling and post-buckling behavior of plates, providing more efficient sub segments. In this paper referring such an approach, it is intended to assess performance of CFS columns manufactured using stiffened sheets. Towards this aim, employing checkered sheets laboratory specimens were produced. Produced column specimens were tested to failure under concentric compression loading. Having obtained the experimental results, FE models of test specimens were built using equivalent thickness approach. In addition to FE models, AISI-2007 specification was also adopted to predict performance of columns with equivalent thickness. Comparisons of the experimental results with FE simulations and AISI-2007 solutions imply that with the proper configurations checkered sheets have the potential to improve compression performance of CFS columns.

Experimental Study

Checkered sheets which have diamond pattern stiffeners were used to produce six laboratory test specimens. Those sheets in practice are used to cover stairs and decks in outdoor environments to prevent slip. Small stiffeners cover the one face of the sheet whereas the other face is flat. Figure 1 provides dimensional details of used sheet and stiffener pattern.

The sheet itself has thickness of 1.9 mm. However, stiffeners on the sheet have varying thickness from junction points to midpoint of stiffener. That is to say, at the junction points the thickness is 2.4 mm whereas it is 2.7 mm at the midpoint of stiffeners, Figure 1. In order to specify the mechanical properties of steel checkered sheet, nine coupon specimens were cut from the sheet in three different angles. Three coupons perpendicular to 54 mm dimension, three coupons perpendicular to 18.5 mm dimension and three coupons parallel to stiffeners are cut from the sheet. Tension tests of coupons were conducted in accordance with ASTM E8/E8M-11 standard. Dimensional details of coupon specimens also conform to same standard. Consequently, mechanical properties of S235 European steel were verified. Figure 2 shows a coupon specimen. Also yield strength and ultimate strength of coupon specimens are given in Table 1.

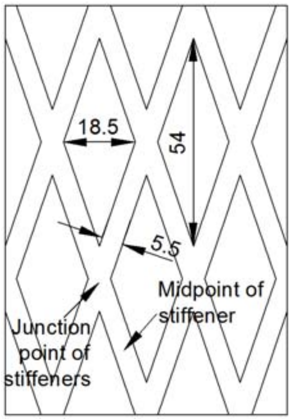


Figure 1. Checkered sheet pattern used to produce specimens (dim. in mm)

Figure 2. A coupon specimen

There are three methods in the field to manufacture CFS members; 1) Cold roll forming, 2) Press brake operation and 3) Bend brake operation, (Yu and LaBoube 2010). In present study, press brake method was used to manufacture six plain channel test specimens, Figure 3. Stiffened face of the sheet was kept to form outer side of the columns. Table 2 shows dimensional details of manufactured column specimens. The dimensions given in Table 2 represent the measurements between thinner portions of the columns. Figure 4 illustrates the configuration of test specimens.

Table 1. Yield strength and ultimate strengths of coupon specimens

Coupon spec.	Yield strength (MPa)	Ultimate strength (MPa)
C1	238.1	356.0
C2	238.9	348.7
C3	236.8	354.2
C4	229.4	348.6
C5	226.2	346.2
C6	227.1	352.8
C7	237.2	355.3
C8	243.6	361.4
C9	236.8	354.9

Figure 3. Press brake used to manufacture column specimens

Table 2 Dimensional detail of CFS column specimens

Column specimen	b_0 (mm)	h_0 (mm)	L (mm)	R (mm)
UCC-80-30-600	31.52	84.92	600	1.7
UCC-90-40-600	41.45	95.59	600	1.7
UCC-100-50-600	51.52	105.17	600	1.7
UCC-80-30-1000	31.58	84.51	1000	1.7
UCC-90-40-1000	41.89	94.94	1000	1.7
UCC-100-50-1000	51.82	103.53	1000	1.7

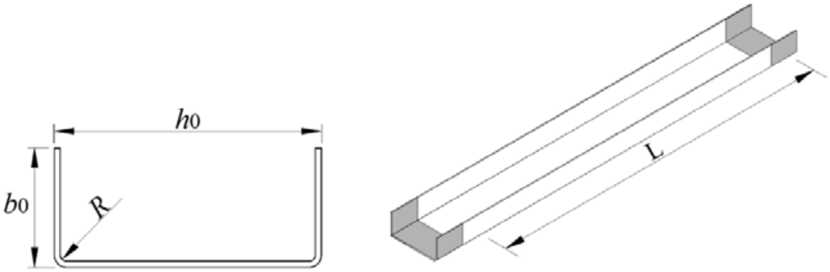


Figure 4. Column configuration

Specimen ends were designed to represent fixed end boundary conditions. To provide such boundary conditions 15 mm thick epoxy resin bases were cast on to top and bottom ends of the specimens (shaded areas in Figure 4). Epoxy resin connects specimen ends to flat end plates as shown in Figure 5. Prior to connecting two separate parts, each specimen was centered on the flat plates with careful measurements to provide concentric loading condition. Those end plates were then fastened to 16 mm thick loading plates which are stiff enough to distribute uniform loading on the cross section.

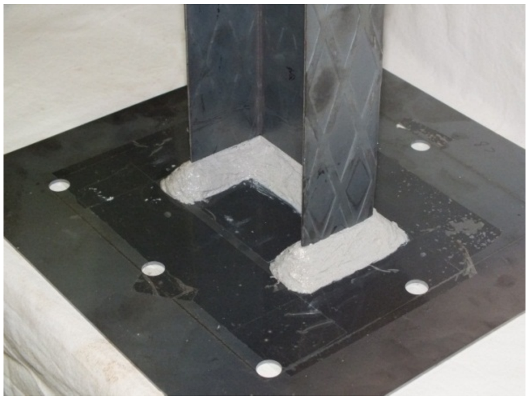


Figure 5. Fixed end boundary condition

Column tests were performed using a 300 kN universal testing machine. A displacement controlled loading was applied to each column specimen with a slow rate. Behaviors of columns under compression loading were pictured at constant loading intervals.

Finite Element Models

In order to assess performance of considered stiffened sheet it is necessary to compare compression performance of stiffened test columns with equivalent thickness counterparts. To specify dimensions of equivalent thickness columns weight of each specimen was used. In calculation of equivalent thickness, 7850 kg/m^3 mass density of steel was taken into account. Following such an approach, 2.095 mm equivalent thickness was found. Commercial software ANSYS was used to simulate equivalent thickness column performances. Shell181 shell element available within software was employed to build column models. It is a four node element with six degrees of freedom at each node (ANSYS). As a result of cold-forming column specimens consist radii with the magnitude shown in Table 1. Those radii were also incorporated into models to obtain more accurate representations. Figure 6 illustrates FE model of UCC-80-30-600.

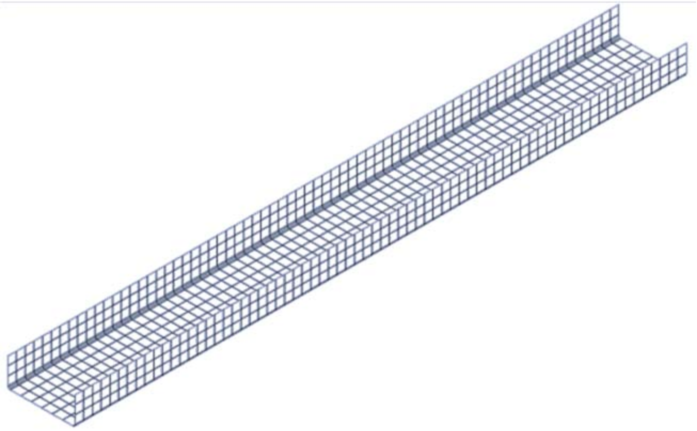


Figure 6. FE model of UCC-80-30-600

Initial geometrical imperfections as a consequence of manufacturing process have the potential to compromise column strength in thin-walled structures (Godoy 1996). Therefore, it is necessary to consider shapes and magnitudes of initial geometrical imperfections. In this manner, the best simulation can be performed by incorporating measured magnitude and shapes of geometrical imperfections into FE models. Unfortunately, there was no such an opportunity to measure real initial imperfections on the column specimens. If there is no information available on the magnitude and shape of real imperfections in the structure, imposing the eigenmode shape with scaled magnitude may be the only satisfactory method. So, in present study the column specimen have been given an initial imperfection with a magnitude of 10% of column equivalent thickness in its first buckling mode.

Geometric and material non-linear properties were activated during the simulation series. An elastic-perfectly plastic material stress strain diagram was adopted for steel with 235 MPa yield strength and 205 GPa elastic modulus. Boundary conditions of FE models were created in such a way that would represent specimens' fixed end boundary conditions. Displacement controlled Newton-Raphson method was preferred to load the specimen models.

Experimental and Computational Results

Experimental and computational results are presented in Table 3 in a comparative form. Second and third columns in the table show the results of FE simulations and AISI-2007 calculations obtained using equivalent thickness.

Table 3. Experimental and computational results

Column specimen	Experimental (kN)	FE (kN) Eq. thick.	AISI-2007 (kN) Eq. thick.
UCC-80-30-600	69.73	65.55	65.73
UCC-90-40-600	74.07	76.33	76.38
UCC-100-50-600	80.40	80.90	81.06
UCC-80-30-1000	61.32	65.18	60.16
UCC-90-40-1000	76.19	75.38	73.07
UCC-100-50-1000	84.27	79.93	78.43

Except specimen UCC-80-30-1000 which was failed in a combined local and global mode, all specimens exhibited local failure modes in experiments. Examining the failure shapes of the specimens, it was observed that junction points of stiffeners promote failure locations, Figure 7. Stiffeners have thinnest dimension at those junction locations. So, such a behavior can be expected from column configurations.

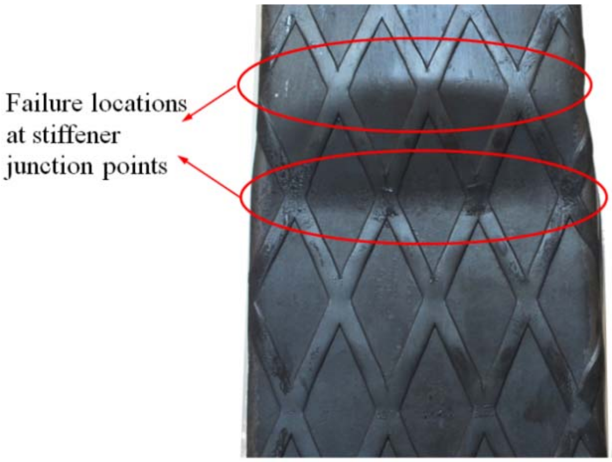
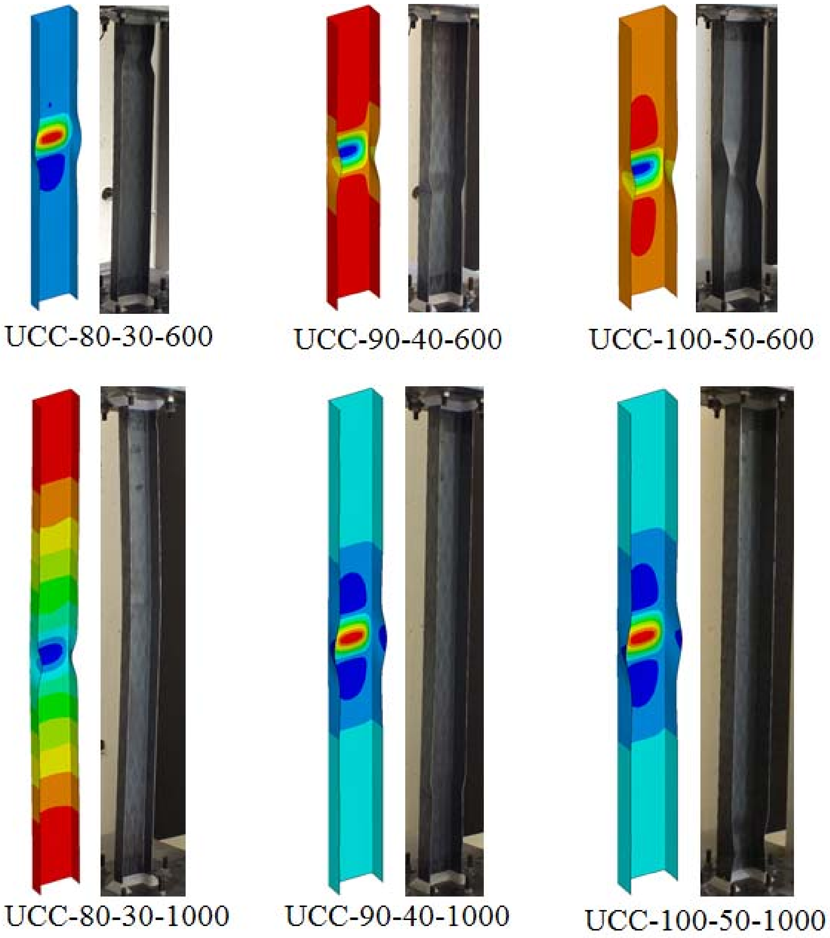


Figure 7. Failure locations are promoted by stiffener junctions

Figure 8 provides the failure modes of test specimens in conjunction with obtained failure modes from FE simulations. It can be seen from this figure that failure mode obtained from simulation of UCC-80-30-1000 is consistent with failure mode of test specimen which is a global mode combined with local mode. But, in simulation model flanges of the column are in compression whereas in test specimen flanges are in tension.

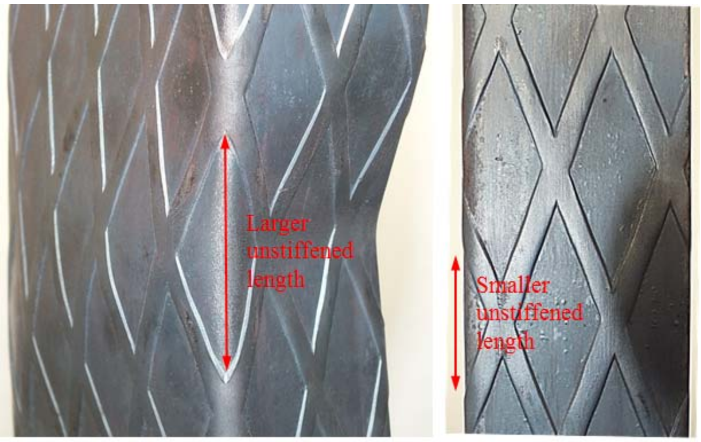
In Table 3 it can be seen that performance of stiffened test specimens of UCC-80-30-600, UCC-90-40-1000 and UCC-100-50-1000 are greater than the performances of equivalent thickness FE models and AISI-2007 predictions. For specimen UCC-80-30-600 test result is 6.38% greater than FE model prediction. Also it is 6.08% greater than AISI-2007 solution for equivalent thickness. Examining performance of specimen UCC-90-40-1000 it can be concluded that experimental performance is 1.07% and 4.27% greater than FE prediction and AISI-2007 solution respectively. For the specimen UCC-100-50-1000 experimental performance of stiffened column is 5.43% greater than FE prediction. It is also 7.45% greater than AISI-2007 solution.

On the other hand, experimental results of other specimens are very close to simulation results and AISI-2007 solutions which mean that there is no performance increase for these specimen configurations. Such an observation required further investigation of column specimens. As a result of such an investigation it was seen that high performance columns have different stiffener configurations at the corners of specimen. That is to say, when midpoint of the stiffeners coincides with corner of the specimen it leads higher ultimate loads. Therefore, such a configuration reduces unstiffened length of corners and so improves compression performances of columns, Figure 9. Checkered stiffeners on the flat portions of columns seem to have no more contribution to column performance compared to equivalent thickness counterparts. One reason for such a behavior can be the thicknesses of stiffeners which are very small compared to sheet thickness.


UCC-80-30-600 UCC-90-40-600 UCC-100-50-600

UCC-80-30-1000 UCC-90-40-1000 UCC-100-50-1000

Figure 8. Failure modes of test specimens and FE models



UCC-100-50-600 UCC-100-50-1000

Figure 9. Different stiffener configurations at the corners

Having identified the behavior of CFS columns with small stiffeners, it can be deduced that those stiffeners are required to be located in such a way that would increase performances of corners. For a checkered stiffener configuration with used thicknesses, stiffening of the flat portions of the column seems to be not more efficient.

Conclusions

Underlined mechanics of CFS columns is based on thin plate theory, since such columns are thin-walled members. It is well known that compression performances of plates can be enhanced by attaching stiffener elements. In present study it is intended to investigate the applicability of stiffening concept on plain channel columns. To this end an in-depth experimental and computational study of CFS stiffened columns subjected to compression loading has been undertaken. Toward this aim, checkered sheets which have diamond pattern stiffeners were employed. Six column specimens were manufactured using press brake method. Three different cross sections and two different column lengths were chosen. To capture the contributions of stiffeners to column compression performances FE models of columns were developed using equivalent thickness approach. Same approach was also used to evaluate performances of columns according to AISI-2007.

Comparison of experimental and computational results shows that such a stiffening approach has the potential to tailor column performance, provided that stiffeners are appropriately located. For this purpose, corner locations of plain channels were specified to be more sensitive. Reducing the unstiffened length at those locations improves the compression performance. Herein, it is worth noting that no effort was made to produce used checkered sheet. A checkered sheet configuration available on sale was preferred. So, it is clear that this configuration is not the optimum one for compression loaded CFS columns. But it offers a new concept for CFS structural members. Of course further studies on this concept are required to characterize more efficient stiffener configurations. That is to say, performance of used checkered sheet with lipped column sections, different stiffener thicknesses, and different orientation of stiffeners like longitudinal stiffeners in ship and aircraft panels must be investigated. Possibly, some structural optimization studies would be required to introduce benign effect of stiffeners of CFS columns. Properly optimized stiffened section would also permit to acquire higher performance from flat portions of CFS columns.

Limited number of test results are presented in this paper. Web depth to thickness ratios of specimens range from 40.32 to 50.20 and flange width to thickness ratios are in between 15.04 and 24.73. The proposed concept is a novel approach for CFS column members. In this manner, it was intended to examine the concept with the dimensions which find great use in industry. Off course, it is necessary to extend web depth to thickness ratios and flange width to thickness ratios to possess a comprehensive view of the concept. With proper configurations, promising results have been obtained. Performance increments led authors to extend the study by manufacturing specimens with different dimensions and different cross sectional configurations. When the experimental program is completed there will be significant number of test results for the concept. These results will be presented in an accompanying paper in near future.

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