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Design of Cold-form Beams Using Effective Width Method and Direct Strength Method: A Comparative Study

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Abstract. In cold-form steel structures, distortional buckling of beams is a predominant phenomenon, unfortunately, largely unaddressed yet Yu and Lokie (2006). This study focuses on evaluating the distortional buckling in comparative manners for effectiveness of cold-form C section beams designed using Effective Width Method (EWM) and a computer based program known as the Direct Strength Method (DSM). In this study, five (05) sample specimens from 20 gauge C section having a web of 100 mm and a flange of 60 mm were designed. The cross sectional properties of the C section were verified using American Iron and Steel Institute (AISI) specifications reported in AISI (2007). The safe loads for EWM and DSM were found to be 6.74 KN and 6.13 KN, respectively. In comparison to experiments, EWM over estimates by 12.9%, while DSM is over conservative by only 6.42%. Thus, the DSM is more accurate and efficient for the design of cold-form steel structures. It is preferable to utilize DSM in future designing of cold-form steel structures for the accurate determination of local and global buckling.

Keywords: cold-formed beams, effective width method, direct strength method, channel section

Introduction

In recent years, among the members of steel structures, cold-form steel members have gained popularity and are being highly used because of their high strength to weight ratio, high resistance towards corrosion as compared to regular high carbon steel and ease of handling in construction. In Pakistan, the utilization of cold-form by the construction industry is still in its infancy. Therefore, it is of vital importance to evaluate the practiced designed methods of cold-form steel structures, which would be helpful in policy making regarding the utilization of cold-form steel structures. The general thickness range of steel strips in cold-formed steel structures lies between 0.0149 inches (0.378 mm) and 0.25 inches (6.35 mm). One inch thick steel plates and bars can be cold-formed into structural member shapes. However, always main consideration aim in the design of cold-form steel structures is that structure or member should resist distortional buckling, local buckling and lateral-torsional buckling.

In the past, steel structures designed using Effective Width Method (EWM) and allowable strength design, both are equations based and labour intensive. In this modern era of digital advancements, computer software based designs for steel structures have become more attractive compared to conventional design methods because of their accuracy and time effectiveness.

Nowadays, computer aided programs are mostly based on the Finite Element Method (FEM) such as ABAQUS, CFS10 and CUFSM5. The accuracy and reliability of these programs have their own importance in steel structures design is still a question mark. However, extensive and supportive experimentation is of prime importance for the validation of computer aided programs.

In ensuring the safety of steel structures, validation of cold-form steel structures designs is compulsory. To the best of our knowledge, literature still lacks a study comprehensively comparing EWM (conventional) and Direct Strength Method (DSM) (based on numerical simulation) for the design of cold-form steel structures available locally in Pakistan. This will ultimately help in determining the safe loads and deflection of cold-form steel structures. It is important to validate the results of computer aided programs for the design of steel structures with those of laboratory experimentation. Therefore, this study establishes a comparison for a cold-form C section designed using FEM based DSM with laboratory experimentation results designed using EWM. This study utilizes computer programs CFS10

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and CUFSM5 for the design of a cold-form beam. The main objectives of this study are:

- FEM based modelling of a C-section cold-form beam using DSM in CFS10 and CUFSM5.
- Design of cold-form-beams by EWM to perform laboratory experiments.
- Comparison of both methods to determine more reliable design method for the design of cold-form steel structures.

The use of cold-form steel in construction as a structural member dates to 1850 in the United States of America (USA) and the United Kingdom (UK). But due to the lack of specifications, several challenges were confronted by industry. Initially, in 1939 specification codes were established by the American Iron and Steel Institute (AISI). Later, the Canadian Standards Association (CSA) in 1963 published its specification code for cold-form steel.

$$F_y = [F_y + \{5D/W(F_u - F_y)\}] \quad (1)$$

where;
F_y is the yield stress used for design; F_u is the ultimate yield stress; F_y is the effective yield stress. Lind also formulated the equation to evaluate the effective width (Schuster, 2006). Where; F_y the yield stress used for design; F_u is the ultimate yield stress; F_y is the effective yield stress. Lind also formulated the equation to evaluate the effective width (Schuster, 2006).

$$b/t = 1.64\sqrt{(E/f)} \quad (2)$$

where;
b is the width of the section; t is the thickness of the section; E represents the Young's modulus of steel; f_{max} is the maximum shear strength.

Generally, in cold-form steel, three types of buckling (local, distortional and lateral distortional) are common. Among these, distortional buckling is the more susceptible failure mode. Therefore, evaluation of distortional buckling strength in cold-formed steel structures, series of tests were conducted on the C and Z sections. The results were compared with the AISI specification. The results concluded that the Australian and New Zealand specification codes provide a more accurately predict the distortional buckling strength than the AISI (2007), Yu and Schafer (2006). As the research progressed, Schuster (2006), simplified the equation of ultimate strength and formulated the equation to evaluate the effective width.

In 2006, research was made using the EWM. The design was carried out against the distortional buckling. In this research Z section and C section beams were designed. These results helped in establishing a comparison between Australian code and direct strength approach. The research concluded that the direct strength approach is much accurate and useful than the effective width approach Yu and Lokie (2006). DSM being a latest method is modern practice along with the EWM which is an old method. DSM is more reliable and accurate as it based on FEM. However, experimental verification is always required to make sure the reliability therefore, high strength tubular cold-form beams have always been designed and tested both experimentally and numerically. Usually, the design of cold-form beams, AISI S100, ANSI/AISC, EN 1993 and AS 4100 are commonly in practice. Detailed testing showed high accuracy and reliability level of DSM in predicting the ultimate bearing capacity of cold-form high strength steel beams Ma *et al*. (2017). Similarly, with the increased demand of cold-form steel structures, researcher started to find out more reliable design method for the design of cold-form beams. Particularly, for the design of C and Z sections, EWM is less reliable, compare to DSM approach which is more accurate (de Miranda Batista, 2009). DSM being a new approach deploys member elastic buckling and helps in directly calculating local, global and distortional buckling. It utilizes gross properties and does not depend on alterations for the determination of strength of steel members.

Design guide for DSM was prepared by AISI, it mainly focused on; member elastic buckling based on finite strip method, beam development, column charts and beam column design along with some design examples Schager (2002). Official acceptance of DSM started after 2004 when it was added in Appendix 1 of north American specifications for the design of cold-form steel structures.

Recently, a detailed study was carried out, in this study two beams having of length 1.25 m were designed, one beam section was with lips, while other one was prepared without lips sections in ABAQUS. The experiments concluded higher flexural strength of beam with lips in comparison to without lips section beam Gowri and Manu (2018).

A study by Wang and Young (2014) conducted on the channel section with stiffeners on web of plain channel sections and on the lipped channel sections to enhance flexural strength, indicated that when edges of sections are stiffened and intermediate stiffeners are used EWM becomes complex thus tedious. However, in such sections, with few modifications DSM performed well. It was also concluded that simple DSM is more conservative. The effect of thickness on the back-to-back buildup channel section was carried out through numerical and experimental investigation. These build up channel sections were examined under the axial compression test. After the experimentation, it was observed that these specifications were un-conservative in the case of short and stub columns. On the other hand, these specifications were over conservative in the case of intermediate and slender columns Roy *et al*. (2018).

Face-to-face buildup channel sections were experimentally examined to evaluate the effect of screw spacing. Three different steel grades were used for the channel section and were examined under axial compressive load. After testing it was observed that DSM was 15% conservative in case of buckling of columns and 5% un-conservative in case of local buckling Roy and Lim (2019). A study Roy *et al*. (2020) compared experimental and numerical simulations conducted on the back-to-back channel sections of cold-form steel. Detailed testing indicated that the flexural capacity of conventional design method can be conservative up to 27%. Moreover, they concluded that slight modifications enhance effectiveness of direct strength method (DSM) compared to EWM.

Usually, cold-form steel channels beam has web holes for installation. A detailed study was conducted in which cold-form steel channel beams having both edge stiffened and unstiffened web holes were experimentally investigated. These beams were designed using DSM and EWM. After detailed testing, it was concluded that DSM predicts the flexural strength more accurately than the effective width method. It was observed that DSM predicts the flexural capacity of the beam without web holes with much accuracy. On the other hand, DSM becomes over conservative, in the case of channel beams with un-stiffened and edge stiffened web holes by 11% and 28%, respectively Chen *et al.* (2020a). A total of 27 experiments (tensile coupon tests) were executed to evaluate the compressive strength of back-to-back channel sections having edge stiffened holes. It was revealed that axial strength was increased by 6.6% due to the presence of edge stiffeners. The results obtained from both DSM and EWM were compared with Finite Element Method (FEM) clearly indicated that DSM was conservation on by 3%, while EWM showed deviation upto 21% Chen *et al.* (2020b).

Material and Methods

This study compares EWM and DSM for the design of C section cold-form steel structures. Each has been explained separately as follow:

Effective width method (EWM). EWM relies on concept of "effective width" originally proposed by Von Karman for the design of cold-form steel structures, later, it was calibrated by Yu and Yan (2011). This approach determines local and distortional buckling of thin walled members in compression as well as in bending using effective width of stiffened and unstiffened elements. This method functions by reducing total flat width (w) of an element and reduced design width is called as effective design width (b). Therefore, before the utilization of element as structural member it is of prime most importance to predict buckling and post-buckling strengths of element.

This study follows the basic condition of EWM that is uniform distribution of edge stress (f_{max}) generated because of the action of total load (P) on the fictitious width (b) known as effective width of the element. Thus, post-bucking strength helped in calculating the effective width (b) of the stiffened element. For the design of cold-form beams, Winter's equation (Yu *et al.*, 2019) from the cold-formed specifications is used in below.

$$b = 1.9t \sqrt{(E/f_{max})}\, [1-0.415(t/w) \sqrt{(E/f_{max})}] \quad ....(3)$$

C and I complex sections design concept rely on the assumption that applied load is being only resisted by the effective width (b). Thus the effective width should be known for each compression region to determine the section strength. Contrarily, EWM was introduced for the local buckling, later was extended to distortional buckling of stiffened elements. Contrarily, EWM considers individual elements, as initially and it was proposed for local buckling but with the later advancements and extended to distortional buckling stiffened elements. At design stress, EWM utilizes reduced plate width (effective width and intermediate stiffeners), thus adopts complex calculations to determine post buckling Yu and Lokie (2006).

Design guide of direct strength method (DSM). DSM instead of focusing individual elements, uses elastic buckling for complete member, thus, determines strength curve for entire member. DSM is accurate in predicting distortional buckling strength of flexural as well as compression members. Therefore, is effectively applicable to compute elastic buckling stresses. On the larger extend, simple calculations for complex sections and accurately predicting the local buckling make DSM more advantageous to provide elastic buckling solutions.

A practical and detailed Design Guide of this method is available in AISI (2007) specifications in which various solutions of elastic buckling based on finite strip method, finite element method, general beam theory and in manual solution.

This study utilizes finite strip method based computer program CUFSM and CFS, both these are in build equipped with detail specifications and member checking options. Moreover, these programs can easily handle interaction of various elements for general cross-sectional area. Additionally, these programs are capable to investigate various buckling modes such as local, distortional, global in the design of cold-form steel structural members.

Basic beam design equations. The nominal flexural strength (M_n) should remain low compared to M_{ne}, M_{nl}, and M_{nd} according to AISC (2007) specifications. For beams, Ω_b and φ_b can be calculated using following relations

M_{ne} = Nominal flexural strength for overall buckling; M_{nl} = Nominal flexural strength for local buckling; M_{nd}=Nominal flexural strength for distortional buckling; Ω_b=Resistance factor for bending strength; φ_b=safety factor;

$\Omega_b = 1.67$ (ASD);

$\varphi_b = 0.90$ (LRFD);

0.85 (LSD)..(4)

Lateral–torsional buckling. Following conditions must be fulfil for the calculation of nominal flexural strength M_{ne} from lateral torsional buckling.

$M_{cre} < 0.56M_y$

$2.78M_y \geq M_{cre} \geq 0.56M_y$

$M_{cre} > 2.78M_y$

$M_{ne} = M_y$

where,

M_{cre} is the critical elastic lateral torsional buckling moment determined by analysis in accordance with AISC (2007) specification stated as,

$M_y = S_f * F_y$ ....(5)

where,

S_f is the gross section modulus referenced to the extreme fiber in first yield.

Local buckling. The nominal flexural strength M_{nl}, for local buckling was calculated as follow:

$\lambda_l \leq 0.776$

$M_{nl} = M_{ne}$

$\lambda_l > 0.776$

$M_{nl} = [1-0.15(Mcrl/Mne)^{0.4}]\ (Mcrl/Mne)^{0.4} \times M_{ne}$ ... .(6)

$\lambda_l = \sqrt{(Mne/Mcrl)}$...(7)

Distortional buckling. The nominal flexural strength, M_{nd} for distortional buckling was calculated using:

$\lambda_d \leq 0.673$

$M_{nd} = -M_y$

$\lambda_d > 0.673$

$M_{nd} = (1-0.22(Mcrd/My)^{0.5})\ (Mcrd/My)^{0.5}\ My$.(8)

$\lambda_d = \sqrt{(My/Mcrd)}$...(9)

Nominal flexural strength of cold-form beam is minimum of M_{nd}, M_{nl} and M_{ne}.

Design and experimentations on cold-form beam. cold-formed steel sections were prepared from locally available steel sheets. These sheets were then molded into desired shape using a bending machine. This C section cold-form beam has section depth of 100 mm and flange width of 60 mm. A cold-form beam without lips having length of 1.25 m was designed by EWM and DSM and numerous experiments were conducted on it. Figure 1 shows the cross sectional dimensions of cold-form designed C section beam.

Figure 2 depicts the screen shot dialog box of CFS10 computer program representing the modeling setting of cold-form C section beam designed in this study. Figure 3 illustrate the dialog box showing the full sectional properties of the cold-form beam in CFS 10.

Prequalification of beam. The pre-qualification of beam was done by exactly following the AISI specifications. In this regard, Fig. 4 shows the symbols nomenclature (h_o, D, b_n and θ*)* used in this study for the design of cold-form beam. Table 1 shows the prequalification of cold-form beam according to the AISI (2007) specifications.

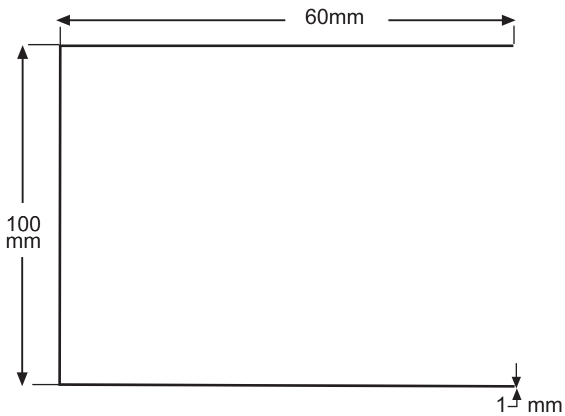

Fig. 1. Cross section showing the dimensions of designed cold-form C section beam.

Fig. 2. Cold-form beam data input dialog box in CFS10.

Determination of safe load. The cold-form C section beam was designed in CUFSM5. Figure 5 shows the dialog box of modeling designed beam in CUFSM5. After the application of EWM, the safe load of this specific designed beam was found to 6.74 KN. On the other hand, with the application of DSM, safe load was (φP_n) 6.138 KN. Both safe loads calculated by EWM and DSM are comparable.

Figure 6 shows the analysis result of beam in CUFSM 5. The x-axis shows the length in (mm), while y-axis

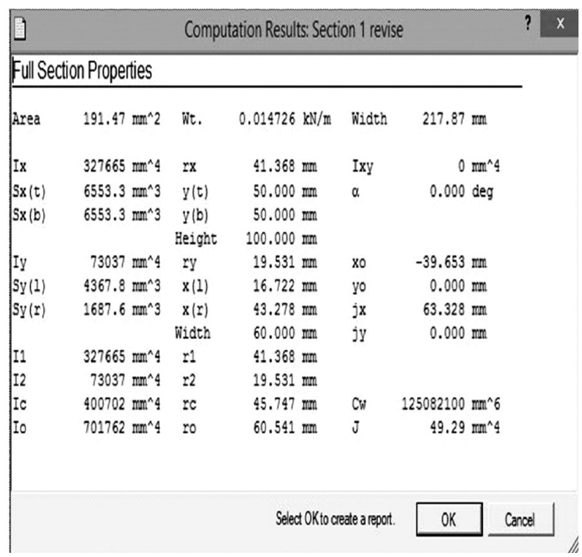

Fig. 3. Calculated sectional properties in CFS 10.

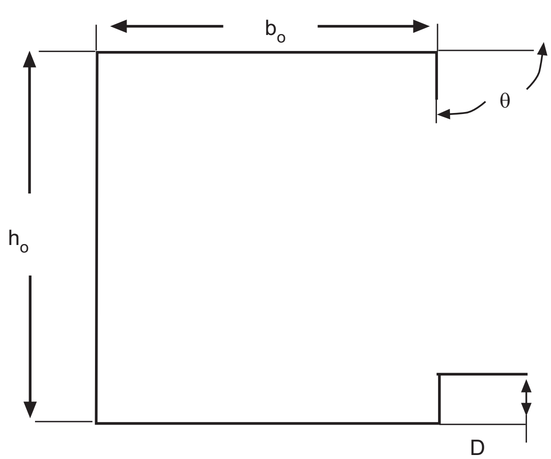

Fig. 4. Symbols used in prequalification of cold-form beam.

represents the load factor on the beam. This curve below is the design curve for the beam. The value of the graph can be read easily with respect to vertical axis. These values have been used for further design.

Experiment 1: One-point load test on the flange. After properly marking the specimen, it was placed in a universal testing machine (UTM) having a capacity of 500 KN. This UTM is capable to apply loads both in effective span and point load mode. This UTM is placed in Mechanics of Solids (MoS) laboratory, Department of Civil Engineering, The University of Lahore along with the placement of the specimen in UTM, three dial gauges having the least counts of 0.01 mm were setup on Sample no. 1. These dials were arranged in such a way that one was placed vertically on the upper flange of the beam to measure the vertical deflection. The second dial gauge was placed on the front edge of the upper flange to measure the lateral deflection of the flange, while the third dial gauge was placed in the middle of the web to measure the lateral deflection of the web. An assembly of installed dial gauges is shown in Fig. 7 and Fig. 8.

Dimensions and cross-sectional properties of the beam were inserted in the UTM software. The test was conducted with a loading rate of 2 mm/min. The specimen started to take the load and UTM software plot a graph between load and displacement. The load gradually increased and dial gauges readings were noted at the intervals of 0.5 KN load increment. At the maximum value of 2.34 KN load, the specimen started to twist and load carrying on the specimen was reduced. Further, increase of load, the specimen continued to

Table 1. Prequalification of cold-form beam according to the AISI specifications.

Condition	Calculation	Comment
$H_o/T < 321$	100/1 = 100	OK
$B_o/T < 75$	60/1 = 60	OK
$0 < D/T < 34$	NIL	OK
$1.5 < H_o/B_o < 17$	100/60 = 1.667	OK
$0 < D/B_o < 0.7$	NIL	OK
$44° < \Theta < 90°$	NIL	OK

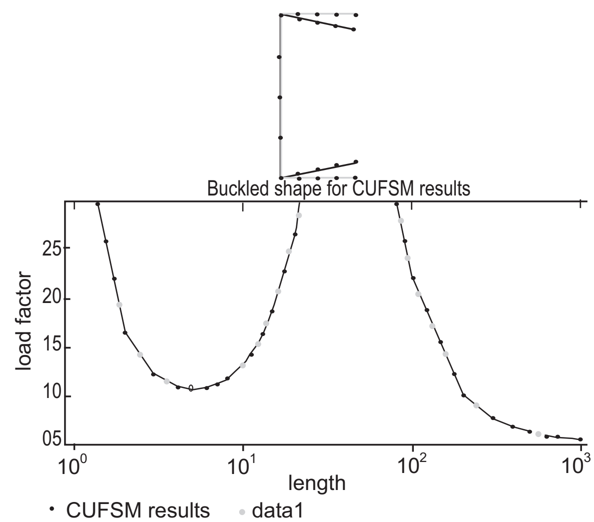

Fig. 6. Analysis results of beam in CUFSM 5.

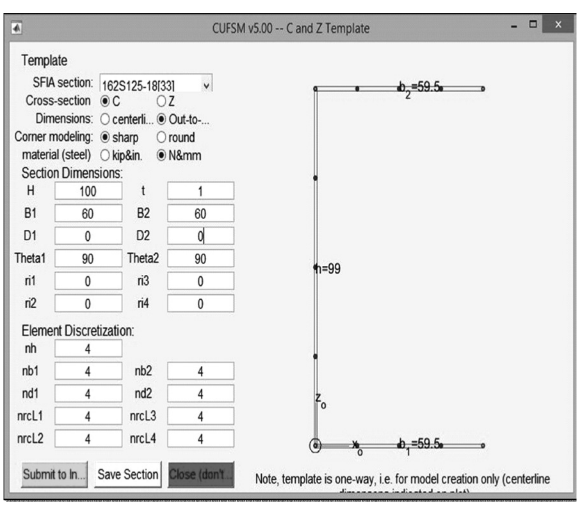

Fig. 5. Modeling of the designed beam in CUFSM 5.

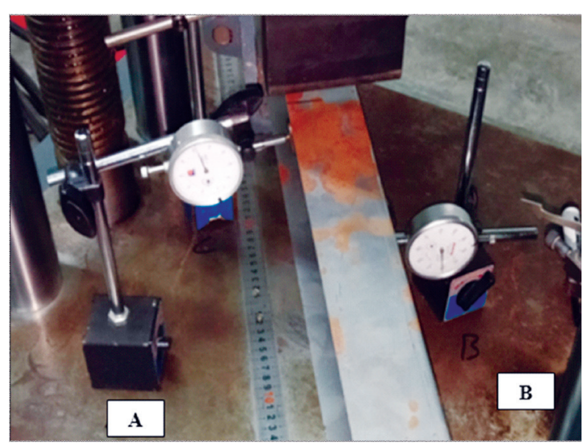

Fig. 7. Installation of dial gauges '**A**' and '**B**' on the designed beam.

twist until a moment came when all the load was being only carried by the web still there was no deflection failure on the specimen. Figure 9 shows the deflection of the beam under the applied load.

The maximum load for this beam was found to be 2.34 KN. At complete twisting of the specimen and at the start of deflection failure of web all the dial gauges were detached from the specimen. With the continued application of load, the specimen was completely deflected at this moment test was stopped. Figure 10 shows the deflected shape of the specimen with the action of the applied load.

Experiment 2: One-point load test on flange on its shear center. In this experiment, first the shear center of the channel section was determined. The shear center of the channel was found to be 3 cm outside the web of channel section. After the placement of the specimen in UTM, the dial gauges were set up in the same way as they were adjusted in experiment 1. In this test run, the little deflection was visible on the flange of the specimen but the stiffener was failed and deflected due to the load applied. Moreover, the triangular plates are not much strong enough to support the rectangular rods on which load is being applied. Figure 11 shows the deflected shape of the flange and stiffener. Test no. 2 was not successful due to low weld strength. After properly wielding the stiffener with specimen, it was tested using UTM in one-point load test on flange of C section with applied on shear center of beam using heavy stiffeners. Figure 12 shows the setup assembly of test. One dial gauge was attached vertically to the

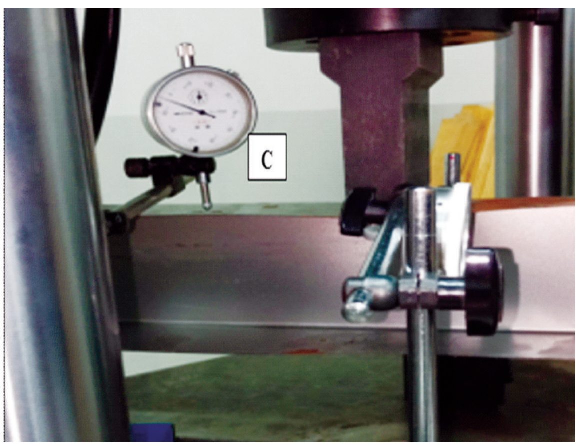

Fig. 8. Assembly of dial gauge 'C' on the designed beam.

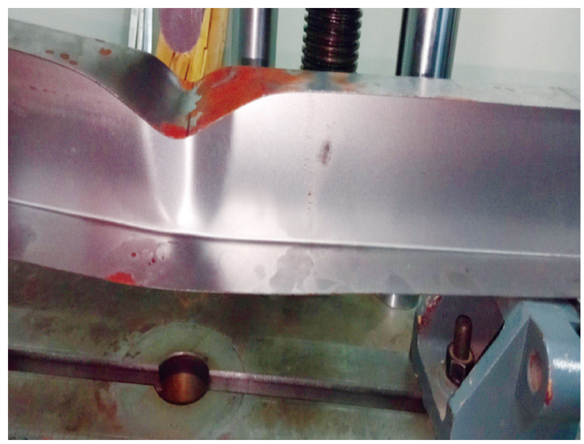

Fig. 10. Deflected shape of specimen with the application of load.

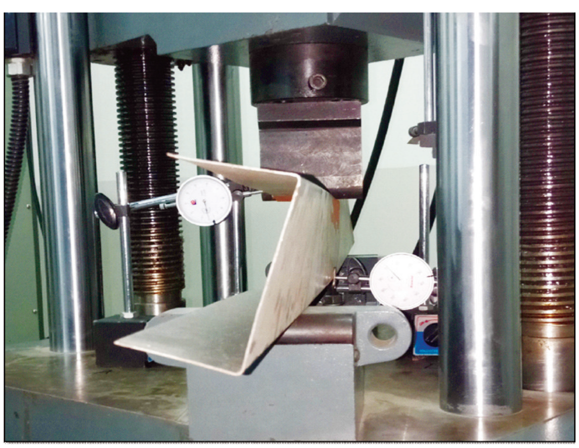

Fig. 9. Deflection of beam under applied load.

Fig. 11. Deflection in stiffener.

flange to note the vertical deflection of beam. Other two dial gauges were attached to note the lateral deflections. One of these two lateral dial gauges was attached to upper flange and other one was attached with web to note the lateral deflection of web of beam.

After completion of all experimental setup, dial gauge readings were noted. Then the test was started at the rate of 2 mm/min. The load was gradually applied on the specimen and due to applied loading dial gauges starts to give readings. The dial gauge readings were noted at the interval of 0.5 KN Load. Maximum load taken by the specimen was found to be 5.84 KN at the deflection of 4 mm. After that load specimen was suddenly deflected and it reduces to take load uptill deflection was 5.7 mm. Later, specimen showed irregular behaviour, it suddenly reduces to take load and suddenly starts to take load but overall trend of load was decreasing. The test was stopped at 2.2 KN because of 18 mm vertical deflection and deflected shape of flange was clearly visible also a little bit deflection was noted in web of beam as shown in (Fig. 13).

Experiment 3: Two-point load on the web of channel section. This test was performed as two point load on the web of channel section with the help of UTM. After properly marking the specimen was placed in UTM. The specimen was placed according to marked line of effective span and points of application of two point load. When the complete assembly of two point load test was set up in UTM (Fig. 14), then the cross sectional dimensions and cross sectional properties and effective length was inputted to the UTM operating software. The test was started at the loading rate of 2 mm/min. Then specimen started to take load it was gradually increased on specimen with the loading rate of 2 mm/min. In this case, only vertical deflection was noted. By applying load with the loading rate of 2 mm/min. specimen takes load up to a certain limit of maximum load of 6.38 KN then specimen was deflected at the points of application of load and load as suddenly decreased to 4.1 KN after this no load was further increased or decreased but deflection was still increasing. The test was stopped at this point. The deflected shape of specimen shown in (Fig. 15).

Results and Discussion

Comparison of results of all experiments performed on the C section cold-form beam is shown in (Fig. 16). The safe load calculated by EWM was found to be 6.74 KN, on the other hand, safe load determined from DSM

Fig. 12. One point load test on flange of C section with applied on shear center of beam using heavy stiffeners.

Fig. 13. Deflection of flange and web.

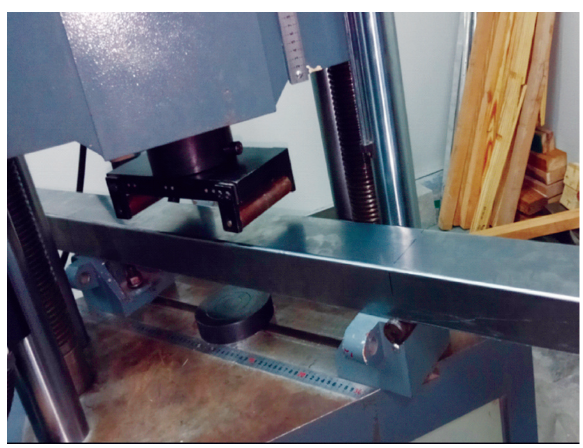

Fig. 14. Placement of specimen in UTM in two-point load on web settings.

was 6.13 KN. The results of DSM are more accurate as in actual loading safe load of same beam was 5.92 KN on average. The percentage difference between experimental work and DSM design work is 3.5% whereas, the percentage difference between EWM and DSM is 11.2%. Results of experiments showed DSM is more accurate and effective because all results of experiments are closer to DSM results. The EWM is old method in the presence of DSM it is concluded that EWM is an approximate method for the design of cold-form beam. DSM is new and more accurate method and it is developing further for the better and accurate results.

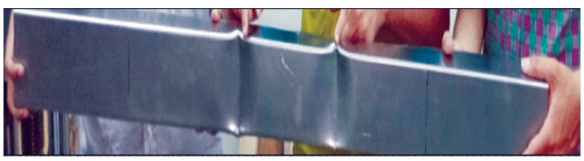

Fig. 15. Deflected beam under two-point load test.

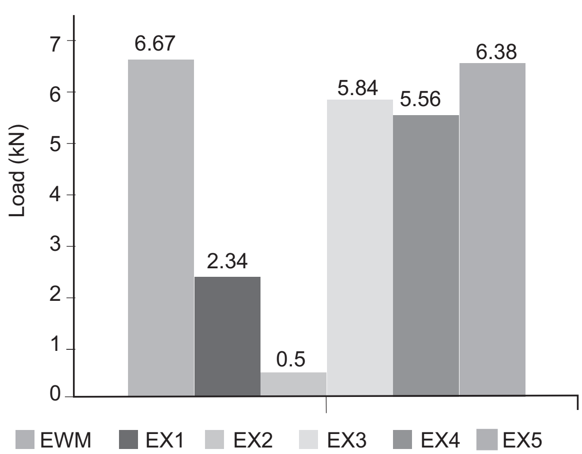

Fig. 16. Comparison of results for C-Section beam designed using EWM and DSM.

Conclusions

This study experimentally compares the effective width method (EWM) and direct strength method (DSM) for the design of steel structures especially beams build from cold-form channel sections after designing the cold-formed beam by EWM and DSM and the entire experimentation many points are concluded which are as follows:

- The EWM being an older method and thus is not an FEM based method whereas DSM is more accurate.
- Detailed experimentation revealed that EWM over estimates by 12.9% on average while on the other hand, the DSM is over conservative only 6.42% within an acceptable limit. In the case of local buckling, EWM does not give accurate results of local buckling modes on the other hand DSM gives comparatively accurate results of all modes of local and global buckling.
- DSM reliably and accurately performs for local as well as for global modes of deformation of cold-form channel section beams. Moreover, DSM is advantageous in terms of considering different end conditions. Conclusively, it is preferable to utilize DSM for the design of steel structures.
- EWM is very much limited and does not involve different end conditions whereas direct strength method involves different end conditions which are included in software.

For the further research channel section with lips can be made and tested for the comparison with beam having no lip. As computer software helps to analyze different sections many different sections can be designed and tested such as I section, z sections and built up sections with two channel sections (with both cases channel faces outside or inside). If the proper assembly is available sections can be tested with variety of end conditions and all modes of local and global buckling can be tested which will enhance the quality of research and the design work. If the channel section or z section is designed load should be properly applied to its shear center which lie outside the section for the accurate results of local and global buckling.

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Conflict of Interest. The authors declare that they have no conflict of interest.

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