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Experimental study on innovative sections for cold formed steel beams

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Abstract. Cold Formed Steel members are widely used in today's construction industry. However the structural behavior of light gauge high strength cold formed steel sections characterized by various buckling modes are not yet fully understood. Because of their simple forming and easy connections, the commonly used cold formed sections for beams are *C* and *Z*. However both these sections suffer from certain buckling modes. To achieve much improved structural performance of cold formed sections for beams both in terms of strength and stiffness, it is important to either delay or completely eliminate their various modes of buckling. This paper presents various innovative sectional profiles and stiffening arrangements for cold formed steel beams which would successfully contribute in delaying or eliminating various modes of premature buckling, thus considerably improving the load carrying capacity as well as stiffness characteristics of such innovative cold formed sections compared to conventional cold formed steel sections commonly used for beams.

Keywords: buckling modes; cold formed steel; failure modes; innovative sectional profiles; structural behavior; structural efficiency; ultimate load carrying capacity

1. Introduction

The use of cold formed steel is increasing rapidly around the world. The main use of cold formed steel is found in the construction of residential buildings and other low rise buildings such as commercial industrial and institutional buildings. Some of the commonly used cold formed section types (Hancock 2001) are shown if Fig. 1. These sections are more susceptible to structural instability due to their buckling prone geometrical shapes. Cross-section instabilities in *C* and *Z* section beams include: local buckling, distortional buckling and lateral torsional buckling (Yu and Schafar 2006). The cold-formed sections commonly have mono-symmetric or point symmetric shapes, and normally have stiffening lips on flanges and intermediate stiffeners in wide flanges and webs (Meiyalagan *et al.* 2010). The characteristics due to point symmetric nature of these sections are normally encountered in doubly symmetric sections such as *I*-sections or tubular sections. Therefore by combining the advantages of Hot-rolled *I*-sections i.e., better stability and conventional cold formed steel sections such as *C* and *Z* sections i.e., high strength to weight ratio

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Fig. 1 Conventional light gauge sectional profiles (Hancock 2001)

we can produce an improved cold formed steel section that can be made, using modern technologies available in the cold formed steel industries. Complex structural shapes may now be formed in two or more parts and then assembled to a single shape this may have the advantage of combing the different material qualities and thickness into single component, however the use of higher strength steel is inevitably accompanied by reduction in thickness of the section and may result in more slender section which could be structurally instable. Structural behavior of the commonly used cold-formed steel sections has been well researched in the past. However, only limited research has been carried out to investigate the structural performance of other cold formed steel member type, therefore there is an urgent need in the cold formed steel industries to look beyond the conventional cold formed steel sections and generate new or innovative cold formed steel beam sections which are structurally very efficient and economical.

2. Problem statement

The main problem encountered in the light gauge steel is its stability failure. This stability failure occurs at a load well before the material has reached its yield strength (which leaves the section un-utilized to its full capacity). Hence the need of the hour is to come up with new innovative sectional profiles and stiffening arrangements which would either delay or completely eliminate undesirable trend of early stability failure thereby allowing the section to reach to its full load carrying capacity (Dar *et al*. 2014). As we all know in the conventional hot-rolled steel sections, the section which is most efficient under flexure is *I*-section. Thus to propose a replacement for the conventional *I*-section, some similar section has to be proposed. But forming *I*-section in light gauge steel can only be done by connecting two channel sections back to back. But channel section without edge stiffener would again show local buckling; hence the section had to be stiffened using edge stiffeners/lip stiffeners. But this showed torsional failure (due to

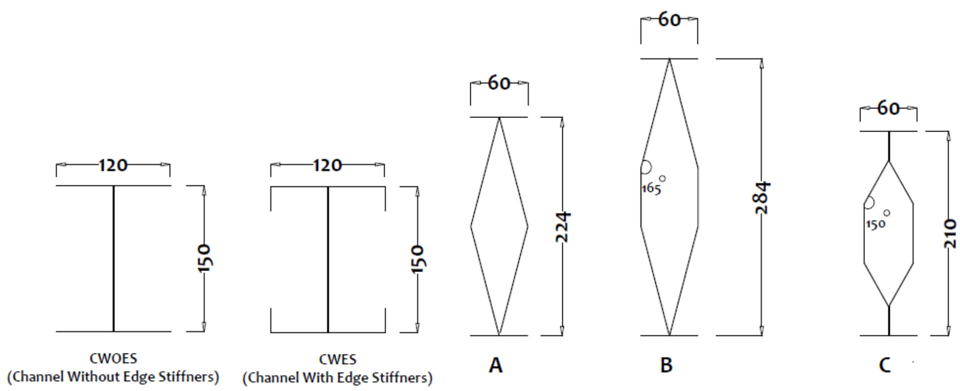

Fig. 2 Proposed sectional profiles

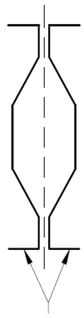

Fig. 3 Fabrication of innovative sections

in-evitable eccentricity in loading) hence sectional profile 'A' as shown in the Fig. 2 had to be proposed. But this showed only marginal improvement in the load carrying capacity. Thus stiffing arrangement had to be made in the section. To increase the load carrying capacity to some more extent the section modulus had to be increased which was done by proposing sectional profile 'B' as shown in the Fig. 2. But the problem with sectional profile 'A' and 'B' is that when provided with stiffening arrangement the acute angle corners were left un-attended, thus the sectional profile 'C' was proposed with 90° corner in which angle section can be used as stiffener which would more efficiently serve as a stiffening arrangement.

Making sections out of single strip will no doubt be structurally efficient but the fabrication process of cold forming and electric welding will make the manufacturing process complicated and expensive. Therefore the method of formation of the proposed sectional profiles should be simple. The innovative sections were formed by joining suitable channel sections (2 mm wall thickness) back to back as shown in Fig. 3 Bolt size of 5 mm was provided at a spacing of 170 mm spacing at top and bottom in most of the sections and additional bolt at mid-depth in deeper sections.

3. Literature review

Extensive literature review enabled the accumulation of the required knowledge in the following topics: types of cold formed steel sections used for flexural members, special design criteria for cold-formed steel design, and failure modes of cold-formed steel beams, current cold-formed steel design standards and procedures, and experimental investigations of cold-formed steel beams. The main focus of all the above topics was based on the flexural members. Typically used cold-formed steel sections for flexural members, such as *C*-*Z* and hat sections are found to be more susceptible to structural instabilities due to their inappropriate profile geometry. However, the characteristics due to mono symmetric nature of the *C*-sections and the point symmetry nature of *Z*-sections are not normally encountered in doubly symmetric sections such as *I*-sections and tubular sections (i.e., RHS, CHS, and SHS). Therefore, the recently proposed cold-formed steel section known as innovative beams, are considered to be structurally more efficient than conventional sections such as *C* and *Z*-sections (McDonald *et al*. 2008).

Local buckling and post-buckling strength of cold-formed steel members subjected to compression or flexural actions play an important role in the design of cold-formed steel structures. The inclusion of these buckling effects in cold formed steel design is important to achieve more structurally efficient cold formed structures in an economical manner. The load-carrying capability and the buckling performance of compression components of beams and columns can be enhanced significantly by the use of edge stiffeners or intermediate stiffeners (Bayan *et al*. 2011).

Experimental researches have also been carried out by previous researchers to investigate the flexural behavior of conventional *C*-*Z* shapes and sometimes to validate finite element models. This literature review showed that the uniform bending moment distribution within a selected span is the common practice for buckling tests, since these conditions allow comparing experimental and theoretical results accurately. Two explicit methods have been used by previous researchers to generate uniform moment conditions over a span of the beam. In the first method, two equal overhang loads are applied at an equal distance outside the supports to generate a uniform bending moment between the supports. In the second method, two equal loads at an equal distance from the supports but within the span are applied to generate uniform bending moment between the loading positions.

4. Methodology

Independent reading and literature review was undertaken to gain background knowledge required in this research field. Following the literature review and using concepts of beam behavior, various innovative cross-sectional profiles for beam were worked out there shapes were analytically evaluated for their efficient use as a beam section so as to short list promising profile for experimental validation, laboratory experiments were carried out to understand the flexural behavior of innovative beams. The laboratory experiments included a series of tests on these new innovative section profiles and appropriate stiffening arrangements to determine their improved moment carrying capacity. The tests were conducted on innovative beams by keeping the member lengths and steel grades constant for the models. In addition to this the weight of the material used in each sectional profile is all most the same.

5. Material testing

Three tensile test specimens were tested. This allowed the determination of an accurate stress-strain relationship for each steel sheet and thickness used in the tests that can be used in the section and member capacity calculations of innovative beams. The material properties of cold reduced steels have been shown to be anisotropic (Wu *et al*. 1995, Dhalla and Winter 1971). Hence all the tensile test specimens were cut in the longitudinal direction with respect to the rolling direction of steel sheets, as it was the same longitudinal direction along which the test beams used for section and member capacities were made. Specimen size and shape are important variables which can affect its behavior. Accurate and consistent fabrication procedures were used for all specimens included in this test program to ensure that test specimens were of near identical size and shape. Various standards exist which specify the requirements for the testing of tensile specimens. Tensile specimens for this test program were prepared in accordance with IS 1608 (2005) (Part – I) as shown in Fig. 4.

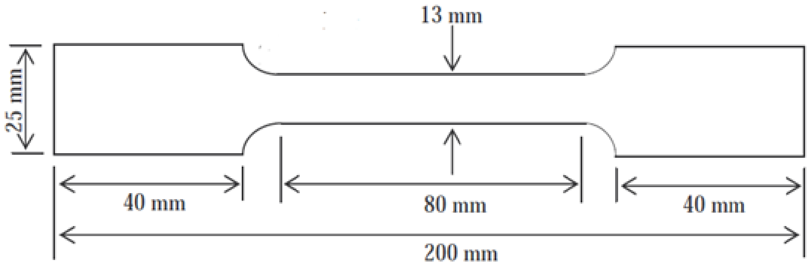

Fig. 4 Nominal size of the tensile test specimen

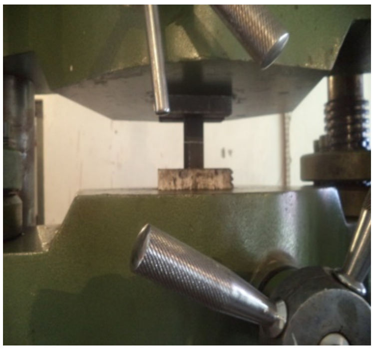

Fig. 5 Tensile test coupon in the U.T.M.

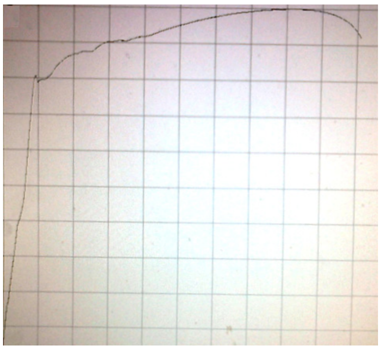

Fig. 6 Typical load Vs. displacement curve of tensile test

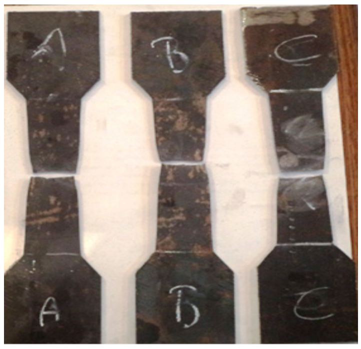

Fig. 7 Test specimens after tensile test

All the tensile tests were conducted on precision universal testing machine as shown in the Fig. 5. To record the deformation dial gauge was mounted and the deformation was noted as every 0.4 kN. The typical stress strain curve of tensile test is as shown in the Fig. 6 all three tensile test coupons showed an approximate yield stress of about 260.3 N/mm^2.The pattern of yielding of the test coupons can be seen in Fig. 7.

6. Analysis and design of innovative sections

All the five sections mentioned earlier were analyzed in accordance with I.S. 801 (1975), Satpute and Varghese (2012). The analytical load carrying capacities are given in Table 1.

Table 1 Improved strength characteristics of innovative sectional profiles

Section	Analytically obtained load carrying capacity (kN)
CWOES	7.76
CWES	15.37
A	15.24
B	23.77
C	16.32

Fig. 8 Two point load arrangement

Fig. 9 Single point load arrangement

7. Evaluation of experimental set-up

Before carrying out the serious experimental work for achieving well defined objectives form high precision experimental testing, it is essential to critically evaluate the performance of the experimental set up being used for the purpose. This is necessary to have confidence in the accuracy and reliability of experimentally measured data (Dar *et al*. 2013). For checking the performance of the experimental set up, the best course of action is to perform preliminary testing on a trial model. This would not only help in identifying the shortcoming (if any) in the experimental set-up but will also provide clues in making changes (if required) in the loading arrangement, to obtain better results from the experiments.

7.1 Loading Arrangement and Data Recording System

7.1.1 Two point load arrangement

Initially the beam was intended to be tested under two point load arrangement as shown in the Fig. 8. This two point loading was simulated by using a spreader beam, this spreader beam was made of *I*-section with attachments for rollers placed at 0.46 m apart thus the distance between the two point loads applied was 0.46 m as shown in Fig. 8. This whole two point load arrangement had a weight of 0.16 kN (approximately). But when the beam model was tested under this two point load arrangement the beam model underwent torsion at a very lower load this was because some inevitable eccentric loading incorporated by the two point load assembly. Hence this loading assembly had to be discarded.

7.1.2 Single point load arrangement

Since two point load arrangement had inevitable eccentricity in loading which made the beam model to fail in torsion. Thus beam models hereafter were tested under single point load as shown in the Fig. 9. By using single point load assemble it was ascertained that the load applied was concentric which would ensure the beam models failed under flexure. Some common features of the models are given below

- Uniform effective span of 1 m.
- Identical simple support conditions.

- Identical single point loading arrangement.
- Wall thickness of 2 mm.

7.2 Important lessons learnt from preliminary testing

The lessons learnt from preliminary testing are as follows:

- Two point load assemble had some evitable eccentricity which made the beam model to fail under torsion.
- Hence the loading arrangement had to be changed to single point loading which ensured that the loading was not eccentric and thus making sure that the beam model showed flexural behavior.
- To ascertain the beam was not undergoing torsion tow dial gauges one under each flange were mounted at mid span of the beam.

Since single point load arrangement exhibited flexure behavior now only one dial gauge at the mid span was enough to record the data.

8. Detailed testing of innovative models

8.1 Testing of unstiffened channel models

The fabricated models were mounted on the loading frame as shown in the Fig. 9. Necessary arrangements for ensuring simple supported end conditions were made and necessary checks for horizontal and vertical alignment were carried out. The selected loading arrangement (single point load) was assembled for application of the load at the mid span of the beam model. The dial gauge was mounted at the mid span of the beam model.

A proving ring of 20 T capacity was mounted between the loading jack and frame as shown in Fig. 10 to record the load applied. The model was loaded at constant rate of loading and the dial gauge readings were recorded at every 5 division increment in the proving ring up to failure. Local buckling of the top flange in CWOES is shown in the Fig.11. Test set-up of sectional profile ‘A’ without stiffening arrangements is shown in Fig. 12.

Fig. 10 CWOES test set-up

Fig. 11 Local buckling in the top flange

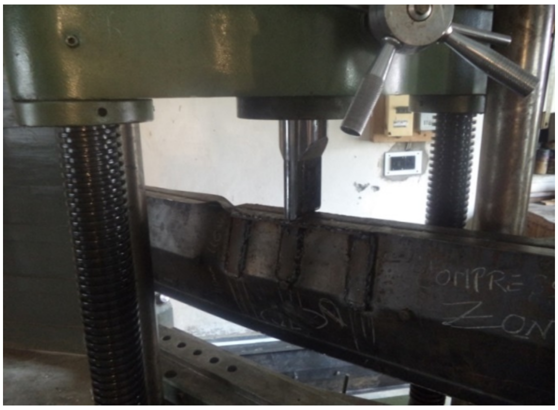

Fig. 12 Failure of sectional profile A

Fig. 13 Failure in the flange and web regiond

Fig. 14 Failure of sectional profile C by web buckling

Fig. 15 Failure of sectional profile B by web buckling

8.2 Testing of stiffened channel models

The beam models which were tested above showed pre –determined mode of failure which is nothing but pre-mature stability mode of failure by exhibiting local buckling in the flange portion under the point load.

As mentioned earlier, one of the objectives of this study program is to overcome this premature failure which in this study is done by providing judicious stiffening arrangement at required locations, this can be seen in the Fig. 12. Fig. 13 shows failure in the flange and web region. Fig. 14 and Fig. 15 show failure of sectional profile C and B by web buckling respectively.

9. Results and observation

The load Vs. deflection curves for various sectional profiles are given below

Without stiffeners

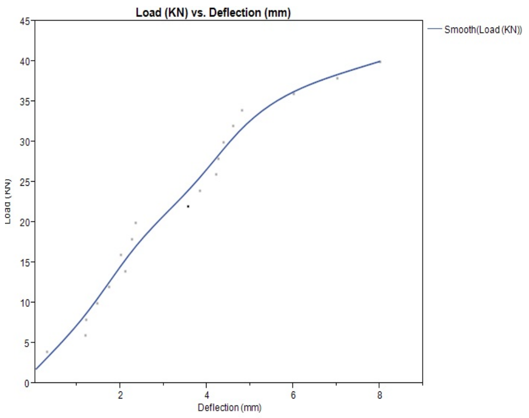

Fig. 16 Load Vs. deflection curve for CWOES

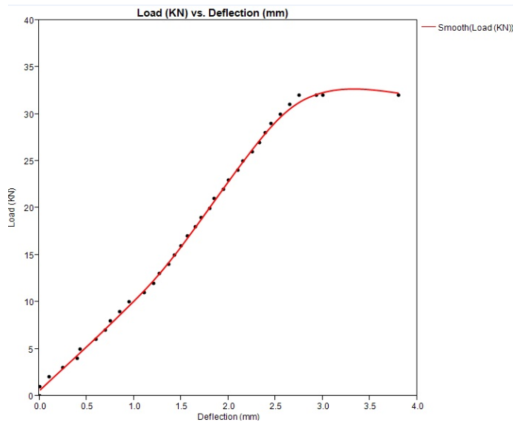

Fig. 17 Load Vs. deflection curve for A

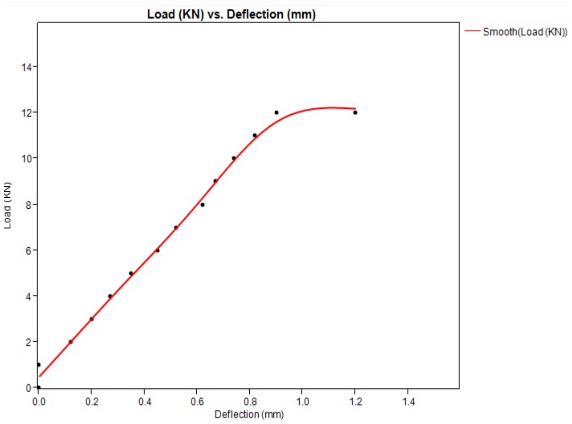

Fig. 18 Load Vs. deflection curve for B

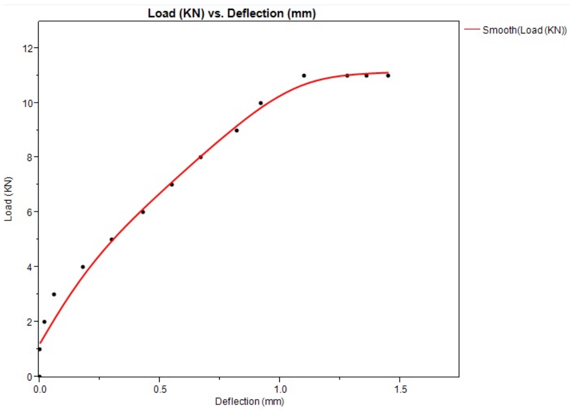

Fig. 19 Load Vs. deflection curve for C

With stiffeners

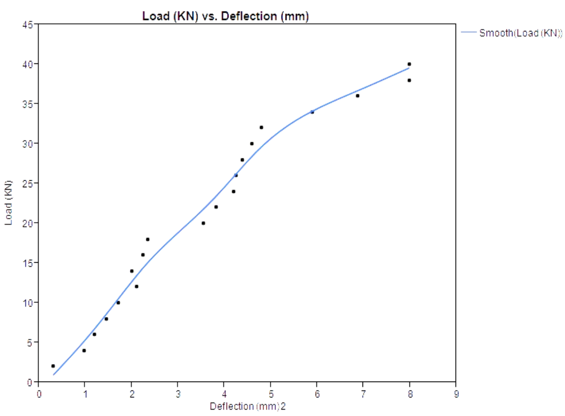

Fig. 20 Load Vs. Deflection Curve for CWES

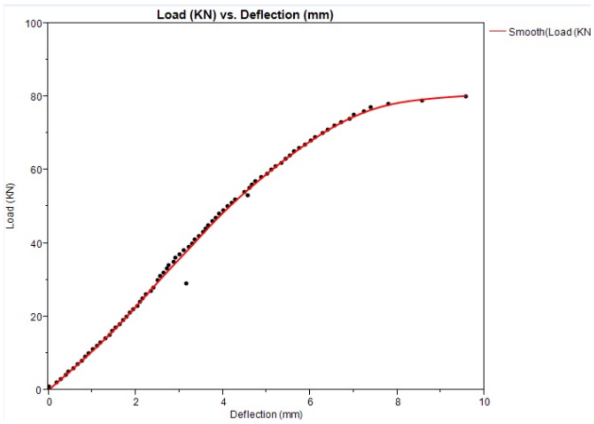

Fig. 21 Load deflection curve for A

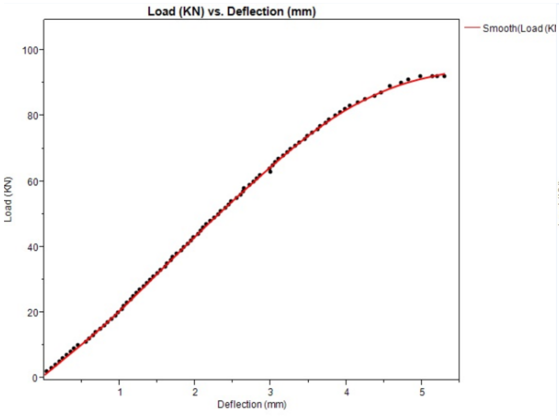

Fig. 22 Load deflection curve for B

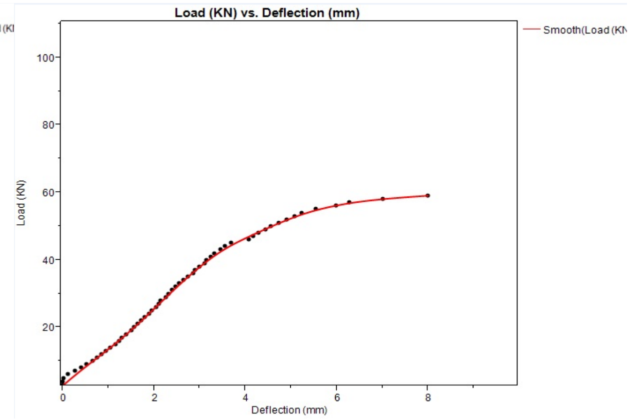

Fig. 23 Load deflection curve for C

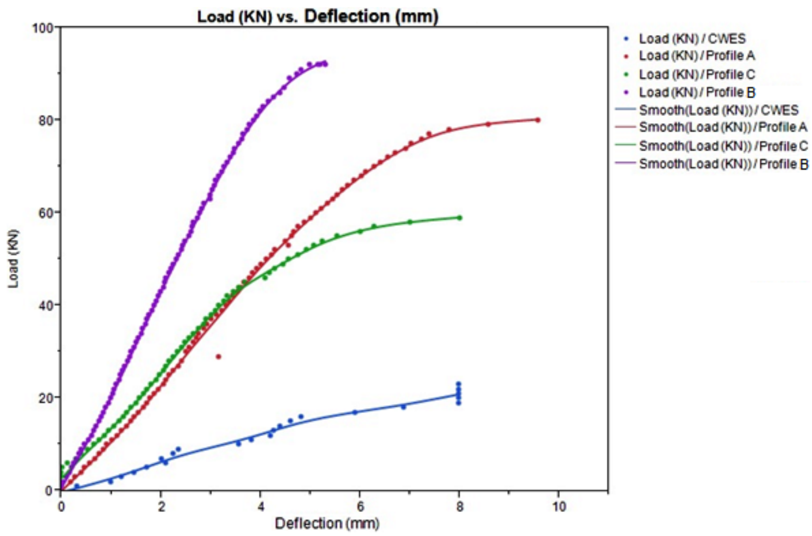

Fig. 24 Comparison of load Vs deflection curves of all stiffened beams (CWES, A, B & C)

CWOES: Channel without edge stiffeners
CWES: Channel with edge stiffeners
A: Sectional profile A
B: Sectional profile B
C: Sectional profile C

9.1 Important observations

It is clear from the plot that sectional profile 'B' has more load carrying capacity than sectional profile 'A', and sectional profile 'A' has more load carrying capacity than sectional profile 'C', and the channel with edge stiffeners has the least load carrying capacity.

(Sectional profile B) > (Sectional profile A) > (Sectional profile C) >>> (CWES) > (CWOES)

Table 2 Result interpretation

Sectional profiles	Weight in kg/m	Z (10^4 mm)	Maximum load expected (kN)	Maximum load carried (kN)	Moment carrying capacity (kN-m)	Increase in moment carrying capacity	Remarks (failure mode)
CWOES	9.45	2.55	7.76	32	8	----------	FB+WB
CWES	11.02	2.55	15.4	32	8	----------	FB+WB”
Sectional profile ‘A’	9.45	3.17	15.2	80	20	2.5	FB+WB”
Sectional profile ‘C’	10.23	3.112	16.3	59	14.75	1.84	BF
Sectional profile ‘B’	13.4	4.48	24	92	23	2.875	BF

FB : Local buckling in compression flange
WB : Web buckling under the application of concentrated load
WB” : Web buckling under the application of concentrated load and adjacent to stiffeners
BF : Bearing failure of web at the support location

10. Result interpretation

It is interesting to express the said qualitative results in quantitative form of meaning full interpretation. The expected and experimentally measured failure loads of the models in the consolidated form are given in Table 2 which clearly indicates that the load carrying capacity decreases in the following order.

11. Conclusions

The main objective of this study was to come up with an innovative sectional profile and appropriate stiffening arrangements for beam sections using cold-formed/light gauge steel, which would not only serve as a replacement for conventional hot-rolled steel sections, but would also be structurally very efficient and economical than the conventional cold-formed steel sections. When the innovative sectional profiles were tested after appropriate stiffening arrangements, the results so obtained through experimental investigations were promising. When a hot-rolled section was designed for the same load carrying capacity there was increase in the self-weight of section of about 3 to 5.5 kg/m length, thus confirming the accomplishment of objective of economical replacement of conventional hot-rolled sections with innovative cold-formed steel sections.

The judicious stiffening arrangement not only delayed the local buckling of the sectional elements but also was able to transform the local buckling of flange to regional buckling of flange and web portion. This in turn enhanced the load carrying capacity of the section by making the material reach close to its yield strength. This confirms the accomplishment of another objective of this study that is to delay the local buckling of the sectional elements so as to enhance the section’s load carrying capacity.

Having been able to achieve the above said objectives and from experimental validation of the same it can be concluded that these innovative sectional profiles along with appropriate stiffening arrangements proves to be an ideal replacement to conventional hot-rolled steel.

Acknowledgments

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