

Experimental and Numerical Investigation of Flexural Behavior of Cold-Formed Steel Beams with Optimized Intermediate Flange Stiffeners

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ABSTRACT

Cold-formed (light gauge) steel beams are extensively used in modern construction owing to their high strength- to-weight ratio, ease of fabrication, and economic efficiency. However, due to their thin-walled nature, such members are highly susceptible to instability phenomena, particularly distortional buckling of the compression flange and lateral-torsional buckling under flexural loading. To improve the flexural performance and buckling resistance of cold-formed steel beams, the use of intermediate flange stiffeners has proven to be an effective solution. In the present study, an experimental and numerical investigation is carried out to evaluate the influence of different shapes of intermediate flange stiffeners on the flexural behaviours of cold-formed steel I-sections. Four-point bending tests were conducted on beams without stiffeners and beams strengthened with V-shaped, rectangular, and trapezoidal intermediate flange stiffeners using a 1000 kN universal testing machine. Load– deflection behaviours, ultimate moment carrying capacity, and failure modes were critically examined.

The experimental results reveal that the provision of intermediate flange stiffeners effectively eliminates distortional buckling of the compression flange and significantly enhances the flexural strength of the beams. Among the stiffener configurations studied, the rectangular stiffener exhibited the highest improvement in ultimate moment capacity. Finite element analysis conducted with ANSYS demonstrated strong concordance with experimental findings, thereby confirming the precision of the numerical model. The study concludes that the shape of intermediate flange stiffeners plays a crucial role in improving the flexural performance and structural stability of cold-formed steel beams.

Keywords:-Cold-formed steel beams, Flexural performance, Intermediate flange stiffeners, Distortional buckling control, Lateral-torsional buckling, Stiffener shape optimization, Load-deflection behaviour, Thin-walled steel sections, Experimental investigation, Finite element modelling.

1. INTRODUCTION:

Cold-formed steel (CFS), commonly referred to as light gauge steel, has gained significant acceptance in modern structural engineering due to its high strength-to-weight ratio, dimensional accuracy, ease of fabrication, and rapid construction capability. These members are manufactured by cold bending thin steel sheets at ambient temperature using roll-forming or press-braking processes, resulting in lightweight structural elements with thicknesses typically ranging from 1 to 3 mm. Cold-formed steel sections are widely used in industrial buildings, roof purlins, wall framing systems, floor decks, and prefabricated structural components.

Despite their numerous advantages, the thin-walled nature of cold-formed steel members makes them highly vulnerable to various forms of structural instability when subjected to flexural loading. Unlike hot-rolled sections, cold-formed steel beams often experience local buckling of plate elements, distortional buckling involving flange- stiffener interaction, and lateral-torsional buckling of the member as a whole. Among these, distortional buckling of the compression flange is a critical failure mode that can significantly reduce the load-carrying capacity and serviceability of beams.

To enhance the flexural performance and delay premature buckling, different stiffening techniques have been adopted in cold-formed steel sections. The inclusion of intermediate stiffeners in the flanges has been found to be an effective method for improving stability by increasing the stiffness of slender plate elements and restraining distortional deformation. However, the efficiency of these stiffeners is strongly influenced by their geometric configuration, particularly their shape and location within the flange.

Previous research has primarily focused on the effects of edge stiffeners or the presence of intermediate

stiffeners without detailed comparison of different stiffener shapes. Limited experimental data are available on the influence of varying shapes of intermediate flange stiffeners on the flexural behaviour and failure mechanisms of cold-formed steel I-sections. Therefore, a systematic investigation is required to identify the most efficient stiffener configuration for improving flexural strength and buckling resistance.

The present study aims to experimentally and numerically investigate the flexural behaviour of cold-formed steel I- beams strengthened with intermediate flange stiffeners of different shapes, namely V-shaped, rectangular, and trapezoidal configurations. Four-point bending tests are conducted to evaluate load–deflection response, ultimate moment capacity, and failure modes. Finite element analysis using ANSYS is performed to validate the experimental findings. The outcomes of this study contribute to a better understanding of stiffener shape efficiency and provide useful insights for the design and optimization of cold-formed steel beam sections.

2. TEST SPECIMENS

Description of Specimens

The experimental program comprised four cold-formed (light gauge) steel I-beam specimens designed to study the effect of intermediate flange stiffener shape on flexural behavior. All specimens were fabricated from cold-formed steel sheets having identical material properties and cross-sectional dimensions. The only parameter that varied among the specimens was the *shape of the intermediate flange stiffener* provided in the compression flange.

One specimen without any intermediate flange stiffener was considered as the control beam. The remaining three specimens were provided with V-shaped, rectangular, and trapezoidal intermediate flange stiffeners, respectively. In all stiffened beams, the stiffener was placed centrally along the width of the compression flange to effectively restrain flange deformation and suppress distortional buckling.

The overall length of each beam specimen was 1000 mm, with an effective simply supported span of 900 mm. The stiffeners were formed integrally with the flange to ensure proper stiffness and continuity. All specimens were carefully fabricated to minimize geometric imperfections.

Specimen Geometry and Dimensions

Table 1.2 presents the geometric details of the cold-formed steel I-beam specimens used in the experimental investigation.

Table 1.2 Geometric Details of Test Specimens

Parameter	Value
Overall length of beam	1000 mm
Effective span	900 mm
Flange width	As per design
Web depth	As per design
Thickness of steel sheet	1–3 mm
Type of support	Simply supported
Stiffener location	Centre of compression flange

Material Properties

All test specimens were fabricated using cold-formed structural steel. The material properties were obtained based on standard values recommended for cold-formed steel sections. The material was assumed to be homogeneous and isotropic.

Table 1.3 Material Properties of Cold-Formed Steel

Property	Value
Yield strength, f_y	250–350 MPa
Ultimate tensile strength	As per steel grade
Modulus of elasticity, E	2×10^5 MPa
Poisson's ratio, ν	0.3
Density	7850 kg/m ³

Specimen Identification and Coding

For clarity and ease of reference, each specimen was assigned a unique identification code as listed in

Table 1.4 Specimen Coding.

Specimen Code	Description
CF-I-NS	Cold-formed I-beam without intermediate stiffener
CF-I-VS	Cold-formed I-beam with V-shaped intermediate flange stiffener

CF-I-RS	Cold-formed I-beam with rectangular intermediate flange stiffener
CF-I-TS	Cold-formed I-beam with trapezoidal intermediate flange stiffener

Description of Stiffener Configurations

The intermediate flange stiffeners were designed in three different geometric shapes to study their effectiveness in controlling distortional buckling:

V-shaped stiffener: Provides inclined stiffening action and gradual stress redistribution. **Rectangular**

stiffener: Offers higher stiffness and effective restraint against flange deformation. **Trapezoidal stiffener:**

Combines inclined and flat surfaces to improve stability.

These configurations were selected to compare their relative performance in terms of load-carrying capacity, stiffness, and failure behavior.

Figure Captions

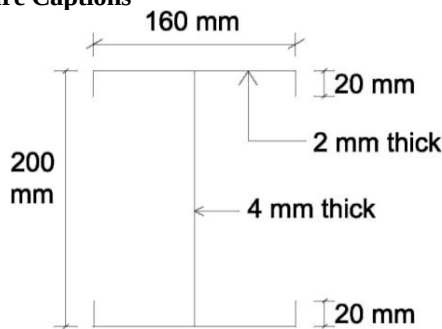


Fig 1a Cold formed I section without Intermediate stiffener

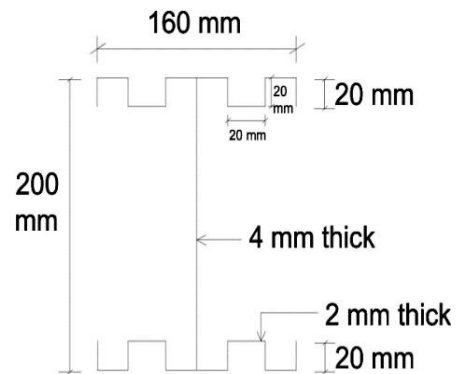


Fig 1c Cold formed I section with rectangular shape Intermediate flange stiffener.

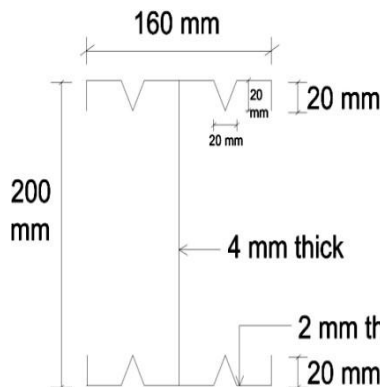


Fig 1b Cold formed I section with Vee shape intermediate flange stiffener.

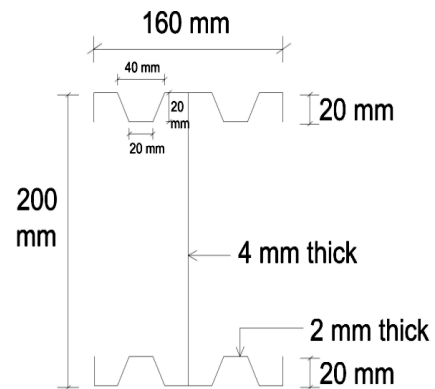


Fig 1d Cold formed I section with trapezoidal shape intermediate flange stiffener

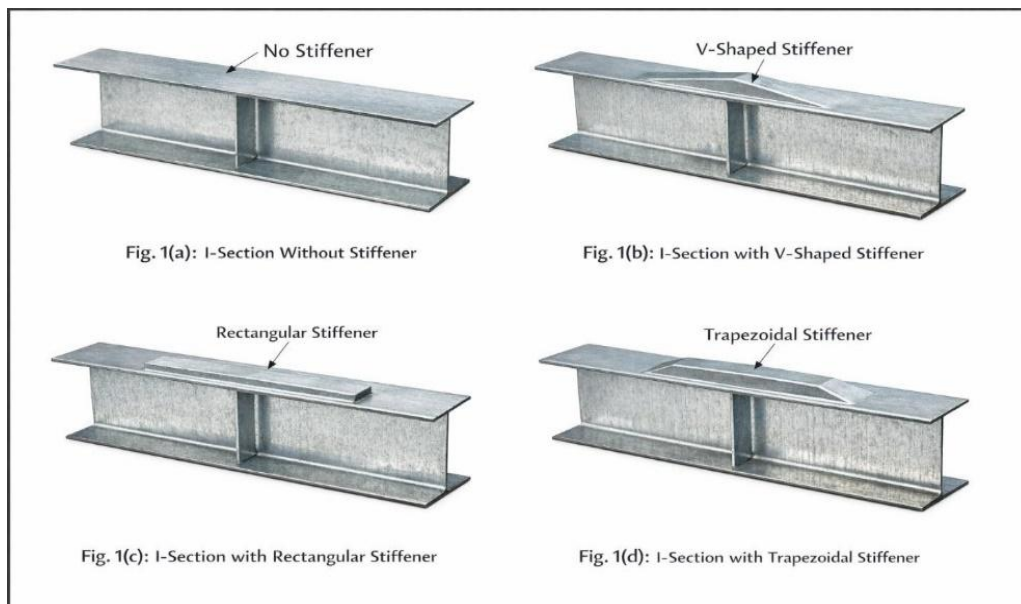


Fig. 1 shows the complete experimental test setup used for flexural testing of cold-formed steel beams.

3. EXPERIMENTAL INVESTIGATION

Test Setup

The experimental investigation was carried out to study the flexural behavior of cold-formed steel I-beams with different intermediate flange stiffener configurations under pure bending. All beam specimens were tested under a four-point bending arrangement to ensure the development of a constant moment region between the loading points. The tests were conducted using a **1000 kN Universal Testing Machine (UTM)**. The beam specimens were simply supported at both ends with a clear effective span of 900 mm. Steel rollers were used at the supports to allow rotation and prevent restraint-induced moments. Two equal point loads were applied symmetrically at one-third span locations from each support to generate uniform bending in the central region.

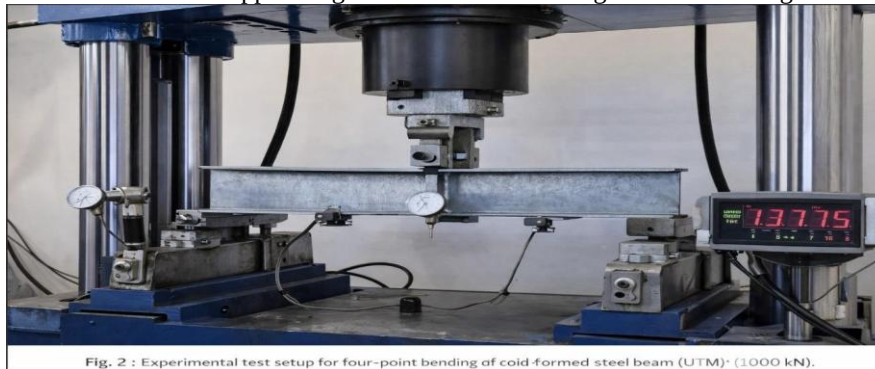


Fig. 2 : Experimental test setup for four-point bending of cold-formed steel beam (UTM): (1000 kN).

Instrumentation and Loading Procedure

Load was applied gradually through a hydraulic jack attached to the UTM in a displacement-controlled manner. The applied load was measured using the calibrated load cell of the testing machine. Vertical deflections at mid-span were recorded using a dial gauge with least count of 0.01 mm placed at the bottom flange. The load was increased incrementally, and at each load step, corresponding deflection values were recorded. The loading process was continued until the beam specimen exhibited significant loss of load-carrying capacity or visible buckling failure. Care was taken to ensure uniform loading and proper alignment of specimens throughout the test.

Experimental Procedure

The experimental procedure adopted for all specimens can be summarized as follows:

1. The beam specimen was placed on simply supported rollers ensuring correct alignment.
2. Dial gauges were positioned at mid-span to measure vertical deflection.
3. Load was applied incrementally under four-point bending conditions.
4. Load and deflection readings were recorded at each increment.

5. The test was continued until failure occurred.
6. Failure mode and buckling pattern were visually observed and documented using photographs.

Observed Behavior During Testing

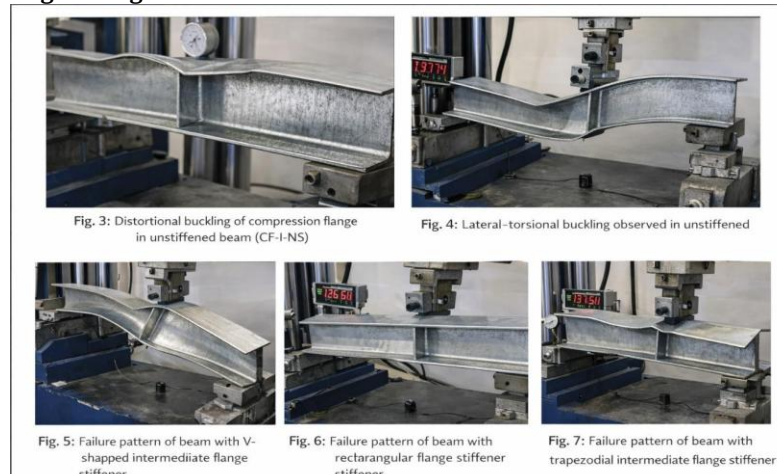


Fig. Experimental test setup for four-point bending of cold-formed steel beam **Fig.** Distortional buckling of compression flange in unstiffened beam (CF-I-NS) **Fig.** Lateral–torsional buckling observed in unstiffened beam

For the **unstiffened cold-formed I-beam (CF-I-NS)**, early onset of distortional buckling was observed in the compression flange at relatively low load levels. As the load increased, the buckling propagated along the flange– web junction, followed by lateral–torsional buckling of the beam. In contrast, beams provided with **intermediate flange stiffeners** exhibited improved stiffness and delayed buckling behaviour. The stiffeners effectively restrained the compression flange, thereby suppressing distortional buckling. Among the stiffened specimens, the beam with **rectangular stiffener (CF-I-RS)** showed the highest resistance to flange deformation and maintained stability up to higher load levels.

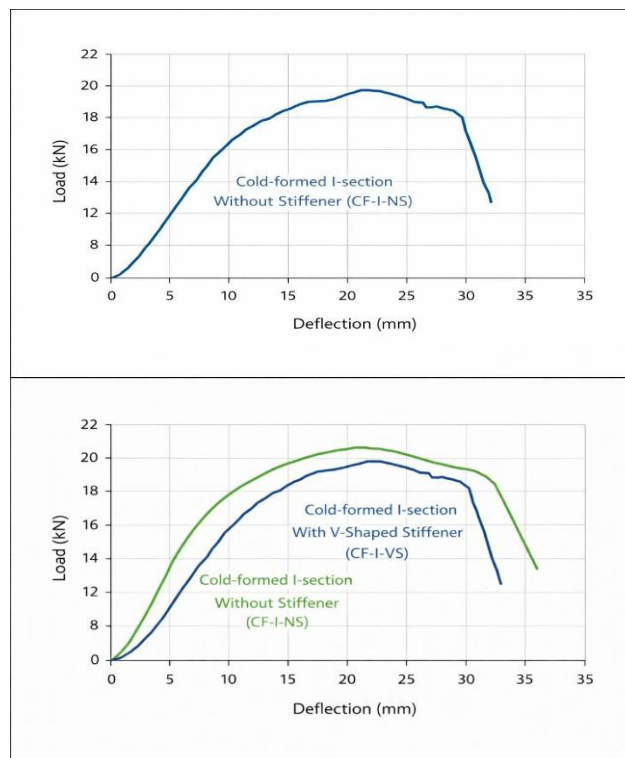


Fig. Failure pattern of beam with V-shaped intermediate flange stiffener **Fig.** Failure pattern of beam with rectangular intermediate flange stiffener **Fig.** Failure pattern of beam with trapezoidal intermediate flange stiffener

4. EXPERIMENTAL RESULTS OF COLD-FORMED STEEL BEAM SPECIMENS

Sr. No.	Specimen Code	Description of Section	Displacement at Ultimate Load (mm)	Ultimate Moment Carrying Capacity (k Nm)	Observed Failure Mode
1	CF-I-NS	Cold-formed I-beam without intermediate stiffener	5.10	6.795	Distortional buckling of compression flange followed by lateral–torsional buckling
2	CF-I-VS	Cold-formed I-beam with V- shaped intermediate flange stiffener	8.40	8.385	Lateral–torsional buckling; distortional buckling eliminated
3	CF-I-RS	Cold-formed I-beam with rectangular intermediate flange stiffener	6.00	9.255	Lateral–torsional buckling; stable flange behaviour
4	CF-I-TS	Cold-formed I-beam with trapezoidal intermediate flange stiffener	6.50	8.940	Lateral–torsional buckling; improved flange stability

5. FEM ANALYSIS USING ANSYS

To validate the experimental findings and to gain deeper insight into the flexural behaviour of cold-formed steel beams, a finite element modelling (FEM) study was carried out using **ANSYS APDL**. The numerical analysis aimed to simulate the four-point bending test conditions and to compare displacement response, ultimate moment carrying capacity, and buckling behaviour with experimental results

Finite Element Modelling

Three-dimensional finite element models of cold-formed steel I-beam specimens were developed using the exact geometric dimensions adopted in the experimental programme. The beam geometry, including intermediate flange stiffeners of V-shaped, rectangular, and trapezoidal configurations, was first modelled using **CATIA V5**, and subsequently imported into ANSYS APDL for analysis. The material properties assigned to the model correspond to cold-formed structural steel, assuming linear elastic and isotropic behaviour. The modulus of elasticity, Poisson’s ratio, and yield strength were defined in accordance with experimental material properties.

Element Type and Meshing

The beams were discretized using suitable shell elements capable of accurately capturing thin-walled behaviour and buckling effects. A refined mesh was adopted in regions near the compression flange and stiffeners to ensure precise stress and deformation prediction. Mesh convergence was checked to ensure that results were independent of element size.

Boundary Conditions and Loading

The boundary conditions in the numerical model were defined to replicate the experimental setup. Simply supported conditions were applied at both beam ends by restraining vertical displacement while allowing rotational freedom. Four-point bending was simulated by applying two equal concentrated loads at the same locations used in the experimental tests, thereby creating a constant bending moment region at mid-span.

Analysis Procedure

Eigenvalue buckling analysis was initially performed to identify critical buckling modes and corresponding load factors. Subsequently, nonlinear static analysis was carried out to obtain load–deflection response and ultimate moment carrying capacity of the beams. Large deformation effects were included to capture post-buckling behaviour accurately.

Numerical Results

The finite element results provided displacement contours, stress distribution, and buckling mode shapes for all beam configurations. The numerical analysis successfully predicted distortional buckling in the unstiffened beam and lateral–torsional buckling in stiffened beams, which closely matched experimental observations.

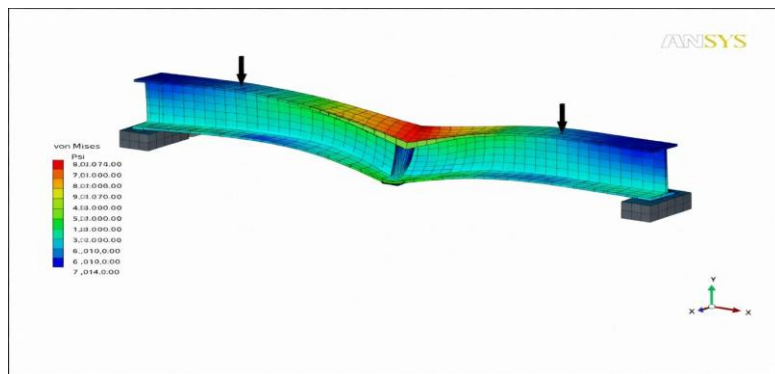


Fig. a shows the deformation pattern of the beam obtained from ANSYS analysis

Comparison with Experimental Results

The comparison between experimental and numerical results shows good agreement, with percentage variation in displacement and ultimate moment capacity generally within acceptable limits. This confirms the reliability of the finite element model in predicting the flexural behaviour of cold-formed steel beams with intermediate flange stiffeners.

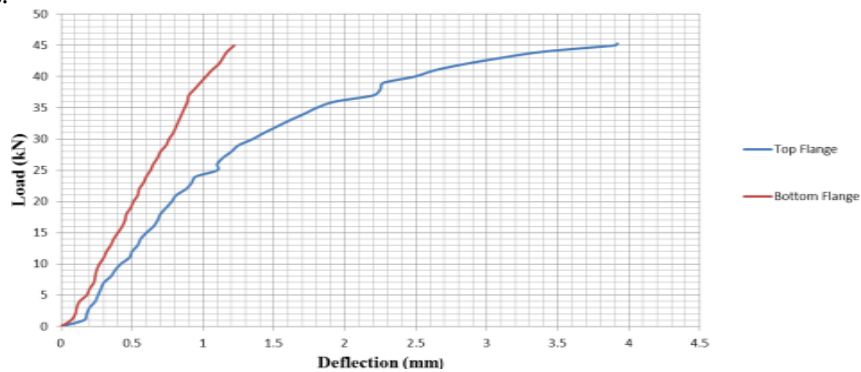


Fig a Load vs deflection graph for cold formed I section without intermediate stiffener.

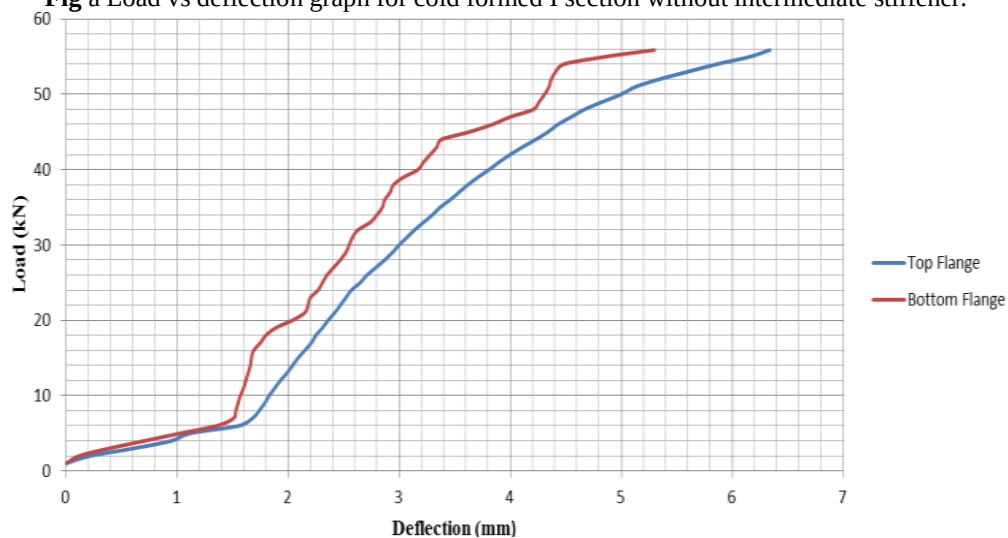


Fig b Load vs deflection graph for cold formed I section with vee shape intermediate flange stiffener

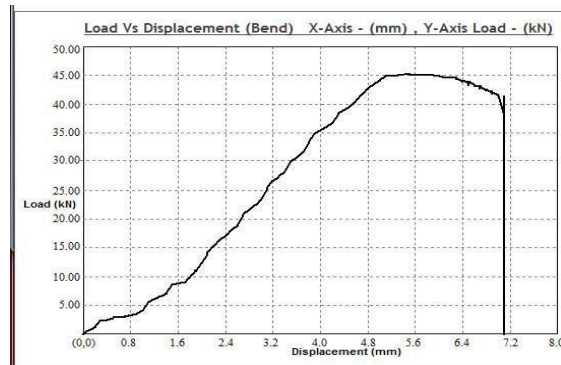


Fig c Load vs displacement graph for cold formed I section without intermediate stiffener.

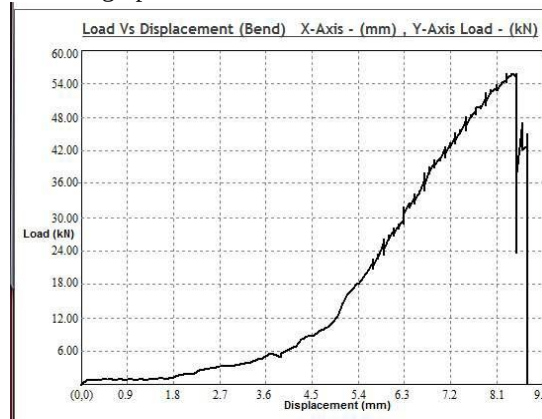


Fig d Load vs displacement graph for cold formed I section with vee shape of intermediate flange stiffener

6. EXPERIMENTAL RESULTS

FEM Analysis Using ANSYS

To study flexural behaviour of section under 4-point bending test the finite element analysis based software, ANSYS is used. The modeling of beam is done in CATIA V5R20 software and then it is imported to ANSYS APDL. Precise model is developed by actual boundary condition and load application on 3-D model. Results are obtained for displacement at ultimate load of beam and for ultimate load carrying capacity of beam. To calculate ultimate load carrying capacity of beam Eigen buckling analysis is done in ANSYS APDL.

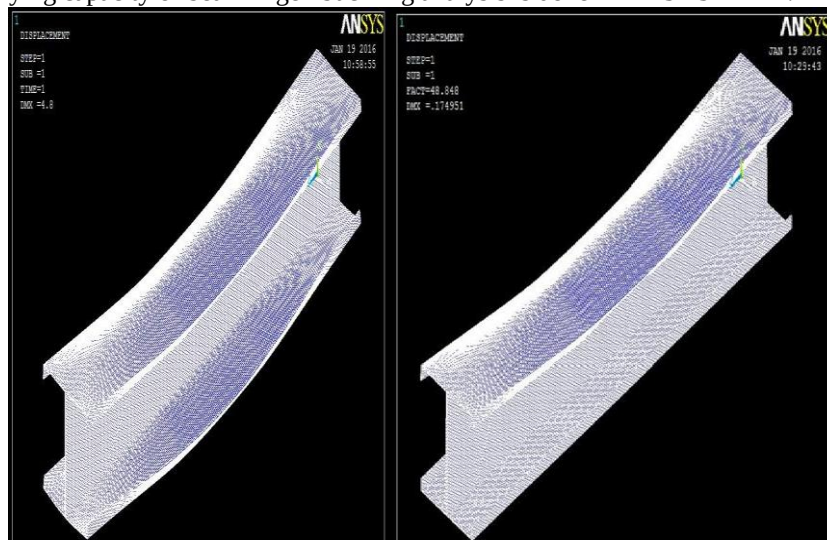


Fig a Displacement of finite element model in ANSYS APDL. Fig b Ultimate LCC of finite element model in ANSYS APDL.

Table 5.1 Comparison of Experimental and ANSYS Results

Sr. No.	Specimen Code	Displacement at Ultimate Load (mm)	Percentage Error (%)	Ultimate Moment Carrying Capacity (kNm)	Percentage Error (%)
		Experimental	ANSYS		Experimental
1	CF-I-NS	5.10	4.80	6.25	6.795
2	CF-I-VS	8.40	8.90	6.32	8.385
3	CF-I-RS	6.00	6.39	6.50	9.255
4	CF-I-TS	6.50	7.19	9.67	8.940

Key Observations from Comparison

Observation	Description
Agreement level	Experimental and ANSYS results show close agreement
Displacement variation	Within 10% for all specimens
Moment capacity variation	Less than 9% across all configurations
Model accuracy	FEM model accurately predicts flexural behaviour and failure trends

7. RESULTS AND DISCUSSION

The results obtained for displacement at ultimate load and ultimate moment carrying capacity of cold-formed light gauge steel I-sections, with and without intermediate flange stiffeners, from experimental testing and ANSYS finite element analysis show a close agreement. This strong correlation between experimental and numerical results confirms the accuracy and reliability of the finite element modelling approach adopted in the present study. The comparison of test results indicates that the unstiffened cold-formed I-section (CF-I-NS) exhibits the lowest ultimate moment carrying capacity of 6.795 kNm, whereas beams provided with intermediate flange stiffeners show a significant improvement in flexural performance. The beams strengthened with V-shaped, rectangular, and trapezoidal stiffeners achieve ultimate moment capacities of 8.385 kNm, 9.255 kNm, and 8.940 kNm, respectively, demonstrating the beneficial role of intermediate flange stiffeners in enhancing load-carrying capacity. From the load-deflection response of the unstiffened cold-formed I-section, it is observed that the deflection of the top compression flange is considerably higher than that of the bottom tension flange. This behaviour clearly indicates the initiation of distortional buckling in the compression flange, which is a critical and commonly observed failure mode in thin-walled cold-formed steel beams subjected to flexural loading. Due to the slender nature of the compression flange, distortional instability occurs at relatively lower load levels, leading to a reduction in stiffness and ultimate strength. In contrast, the load-deflection behaviour of cold-formed I-beams provided with intermediate flange stiffeners shows nearly equal deflections of the top compression flange and the bottom tension flange. This response confirms that the intermediate flange stiffeners effectively restrain the compression flange and successfully eliminate distortional buckling. As a result, the beams exhibit improved stiffness, enhanced stability, and higher ultimate load-carrying capacity. The experimental results further reveal that the inclusion of intermediate flange stiffeners leads to a substantial increase in ultimate moment carrying capacity. Compared to the unstiffened beam, beams with V-shaped, rectangular, and trapezoidal intermediate flange stiffeners show an increase of 23.39%, 36.20%, and 31.56%, respectively. This significant enhancement in flexural strength highlights the effectiveness of intermediate flange stiffeners in improving the structural performance of cold-formed steel beams.

Among the stiffener configurations investigated, the rectangular-shaped intermediate flange stiffener exhibits the maximum improvement in ultimate moment carrying capacity, achieving a value of 9.255 kNm. Hence, based on both experimental and numerical findings, the rectangular intermediate flange stiffener is identified as the most efficient configuration for enhancing flexural strength and effectively controlling buckling behaviour in cold-formed light gauge steel beams.

8. CONCLUSION

Based on the experimental and numerical investigation carried out on cold-formed steel I-beams with optimized intermediate flange stiffeners, the following conclusions are drawn:

- Cold-formed steel I-beams without intermediate flange stiffeners are highly susceptible to distortional buckling of the compression flange, which initiates at relatively low load levels and significantly reduces flexural strength and stiffness.
- The provision of intermediate flange stiffeners is highly effective in restraining compression flange deformation and eliminating distortional buckling, thereby enhancing overall flexural performance and structural stability.

- Experimental four-point bending tests demonstrate a substantial increase in ultimate moment carrying capacity for stiffened beams compared to the unstiffened control specimen:
- V-shaped stiffener: 23.39% increase
- Trapezoidal stiffener: 31.56% increase
- Rectangular stiffener: 36.20% increase
- Among the three stiffener configurations studied, the rectangular intermediate flange stiffener exhibits the highest improvement in flexural strength, stiffness, and buckling resistance, making it the most efficient configuration for cold-formed steel I-beams.
- Load–deflection responses of stiffened beams show nearly uniform deformation of compression and tension flanges, confirming the effectiveness of stiffeners in suppressing local and distortional instabilities.
- Finite element analysis performed using ANSYS APDL shows close agreement with experimental results, with displacement and moment capacity variations generally within 10%, validating the accuracy and reliability of the numerical modelling approach.
- The FEM results successfully predict observed failure modes, including distortional buckling in unstiffened beams and lateral–torsional buckling in stiffened beams, confirming the suitability of shell element modelling for thin-walled cold-formed steel sections.
- Overall, the study confirms that stiffener shape plays a critical role in improving the flexural behaviour of cold-formed steel beams, and optimized intermediate flange stiffeners can be effectively used to enhance strength, stiffness, and serviceability.
- The findings of this research provide useful design insights for engineers and can contribute to the optimization of cold-formed steel beam sections in practical structural applications.

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