Journal of Integrated
SCIENCE & TECHNOLOGY

Performance study on cold-formed steel structural frame made with lipped channel column and beam elements subjected to lateral loading

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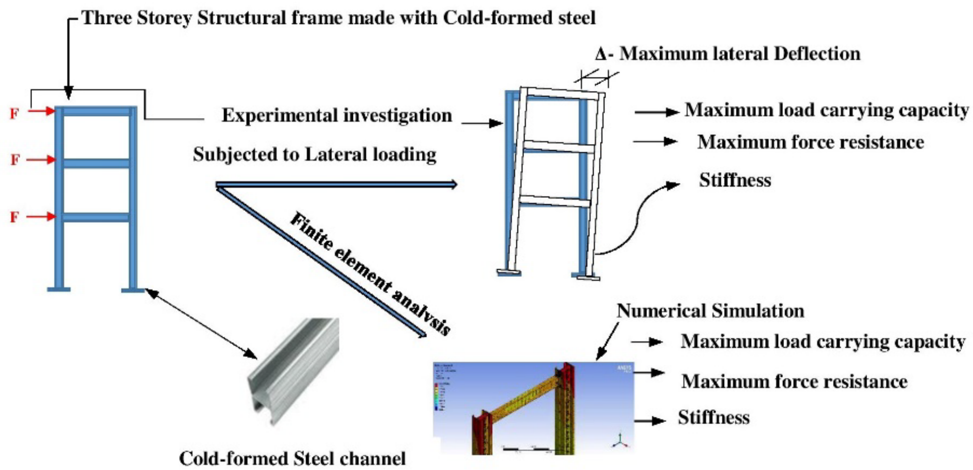
Received on: 05-Oct-2023, Accepted and Published on: 09-Jan-2024

Article

ABSTRACT



This paper presents a performance study of cold-formed steel (CFS) structural frames subjected to lateral loading. The study focuses performance based on the experimental and numerical study of cold formed steel made structural frame by investigating strength and stiffness. The cold-formed steel frame consist of three storey structural frame made with cold formed steel section columns and beams elements. Experiment investigation was conducted by varying the cross section of column made with back-to-back channel section. The study involves analytical investigation via ANSYS workbench software was used to perform FE analysis and examine the factors influencing failure of frame. Performance examined through comparing both analytical and experimental investigation. The result showed that the column made with lipped channel revealed stiffness higher than column made with normal cold formed steel. Moreover, increasing the thickness improved the lateral force resisting capacity of back-to-back channel made column in the frame.

Keywords: Cold-formed steel (CFS), Lateral loading, Finite element analysis (FEA), Structural Building Frame, Load-displacement relationship, Light-gauge construction.

INTRODUCTION

Cold-formed steel structures have gained significant popularity in the construction industry for low-rise buildings due to their numerous advantages, including a high strength-to-weight ratio, excellent durability, and flexibility in fabrication and construction.[1] CFS members, such as columns, beams, and roof truss members, are widely utilized as load-bearing components in lightweight and prefabricated constructions.[2] Various shapes of individual structural framing members, including angles, channels (C-sections), hat sections, I-sections, T-sections, Z-sections, and tubular members, are commonly employed in light gauge steel construction. The objective of this study is to examine the behavior of cold-formed steel frames subjected to lateral loading. Finite element (FE) analysis is conducted on four different specimens, considering variations in cross-section columns and member thickness used in the frame. The use of Lipped C and Sections, with column section thickness ranging from 1.2 mm to 3.2 mm, is prevalent in CFS beams and columns. The study focuses on evaluating the lateral load-resisting capacity, load-displacement curves, stiffness, and failure modes of cold-formed steel frames. Significant research has been conducted on CFS members with perforations, including an analysis of lipped channel sections.[3,4] Previous studies have employed finite element analysis to

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Cite as: *J. Integr. Sci. Technol., 2024, 12(4), 791*
URN:NBN:sciencein.jist.2024.v12.791

investigate the behavior of cold-formed steel frame models subjected to static lateral loadings.[5]

LITERATURE REVIEW

Some valuable studies have been conducted to investigate various aspects of cold-formed steel (CFS) structures, providing valuable insights into their behavior and performance. Belal et al.[6] focused on the seismic behaviour of light-gauge light gauge steel stud walls. They conducted numerical investigation to examine important factors such as failure modes, load capacities, initial stiffness, ductility ratios, and seismic response modification factors. The study accounted different structural components and revealed the positive effects of steel sheathing on loading capacity and initial stiffness, while cement board and ferrocement board sheathing had adverse effects. Hanisha et al.[7] addressed the analysis of connections in light gauge steel structures and emphasized the importance of designing innovative element profiles. They conducted experimental testing and compared the results with finite element analysis to assess the beam-column joint in light gauge steel structures. The study aimed to meet the specifications of the Indian standard and evaluate the structural strength. Kechidi et al.[8] investigated the performance of LGS framed shear walls with openings through experimental tests and numerical simulations. They designed three shear wall typologies and validated their findings through advanced finite element analysis. The study highlighted the conservative nature of existing design provisions for Type II shear walls and perforated design methods available in the literature. These studies collectively contribute to the understanding of cold-formed steel structures, including their seismic behaviour, connection analysis, lateral load capabilities, shear wall performance, and seismic performance evaluation.[9,10]

METHODOLOGY

The proposed methodology involves investigating sets of analytical models, which take into account significant variant such as column sections with and without lips. The ANSYS version 18.1 finite element modelling software is utilized for the analysis investigation. This was aimed to observe the structural behaviour of cold-formed steel frames comprising lipped channel section columns and beams subjected lateral loading.[11]

MATERIAL AND METHODS

SELECTION OF SECTION

The sectional properties of the selected sections for the frame were obtained from the IS811 specification for cold-formed light gauge structural steel sections. The cross dimensions were established based on the AISI specification for cold-formed steel constructions and covered the practical range of channel sections for beams and columns already utilized in the industry, this figure depicts the geometry details of the frame specimen. Figure 1 depicts the geometry details of the frame specimen.[12]

CONNECTION REQUIREMENTS

Cold cast steel frames are fabricated in the steel factory as per the design. The frame design was carried out based on AISI specification and industry practice specification. Angle cleats and mild steel bolts were used for beam-column joint connection, as well as base plate and column bottom connection. Details of bolts used and specifications are as follows: Diameter 6 mm, MS 4.6 grade, yield strength 250MPa, and tensile strength 410MPa.

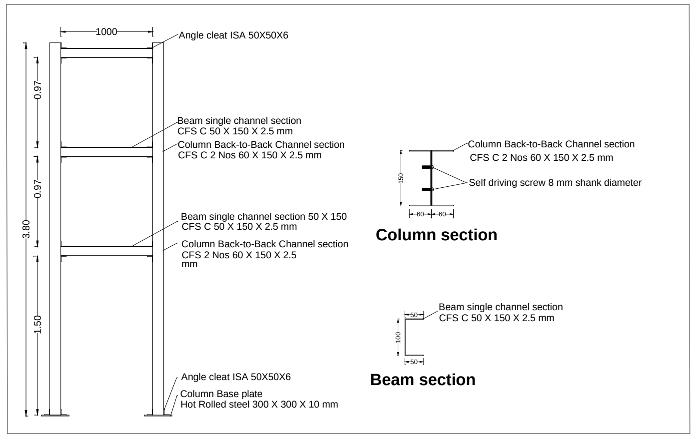

Figure 1 Geometry details of Cold-formed steel frame- 2D view

EXPERIMENTAL

For experimental investigation, totally 8 frames were tested. The frame comprised cold-formed steel channel section columns and cold-formed steel channel section beams. The connection between beams and columns likewise connection between column bottom base plate were executed through bolt connection using angle cleat bolt and nuts. Figure 2 depicts the processed frame specimen prepared for the experimental work. Likewise, no rotation, no translation allowing type such connection was provided between base plate and solid floor. Prior to the testing program, the mechanical properties of cold-formed steel specimens used in this study were calculated by conducting laboratory tests.[11]

The mechanical properties analysed include parameters such as yield strength, ultimate tensile strength, modulus of elasticity, and elongation. Table 2 presents mechanical properties of steel materials.

Figure 2 Built-up cold-formed steel frame -Experiment model

Table 1 Geometry details of Cold-formed steel frame models

Frame model designation	Thickness of Section (mm)	Column section (mm)	Beam section (mm)	Lipped /without lips length (mm)
LGSF2.5WOL	2.5	2 X 150 X 60 X 2.5	100 X 50 X 2.5	-
LGSF2.5WL	2.5	2 X 150 X 60 X 2.5	100 X 50 X 2.5	25

Table 2 Mechanical Properties of Cold-formed steel and Hot rolled steel

Material	Yield strength (N/mm^2)	Ultimate strength (N/mm^2)	Elastic modulus (N/mm^2)	Elongation (mm)
Cold-formed steel	385	429	2.02x10^5	17
Hot rolled steel	250	412	2.00x10^5	11

Figure 3 schematic diagram of test program. The lateral force is applied to the frame that implies to the tension in the face of loading. For implementing fixed boundary condition through bolt connection introduced between frames to base plate which connected to heavy joist positioned. The base plate and frame elements are supported by bolts over the test floor. The static lateral incremental loads are applied at the jack locations of the frame by hydraulic jacks of 250 kN capacity with a minimum measurable value of 1 kN. The jacks are placed horizontally in line with the centre of beams its horizontality is confirmed using spirit level. The hydraulic jacks were bolted to the loading frame. The load was transferred to the specimen by the jacks in the form of uniformly distributed load pattern; the jacks are controlled by an individual relief. Regular interval of Loads was applied by using a hand operated pump. A precise Linear Variable Displacement Transducer was used to measure displacement at beam-column joint positioned level. In addition to that dial gauge was provided at the bottom in order to measure column deflection at the bottom. Figure 4 test setup followed for testing of frame specimens. The deflections were measured accompanied with gradual increase of loads. The load increments are continued till the buckling of beam reached at maximum range.[12]

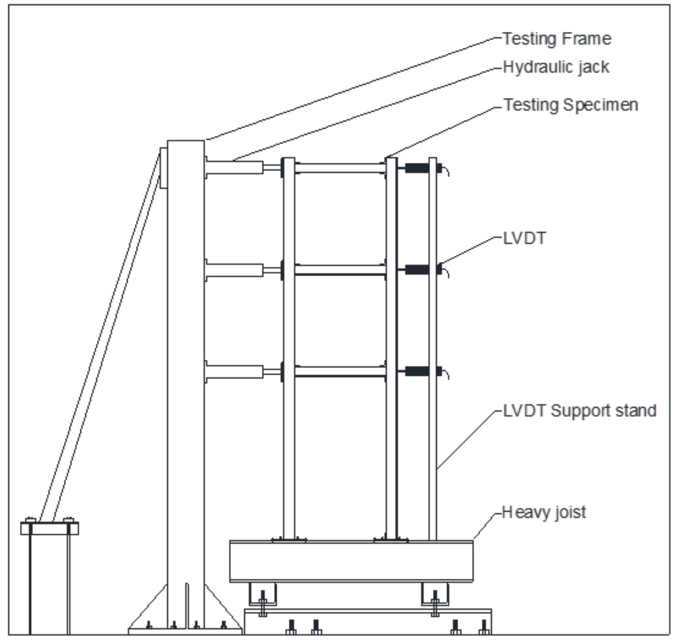

Figure 3 Schematic diagram of test program

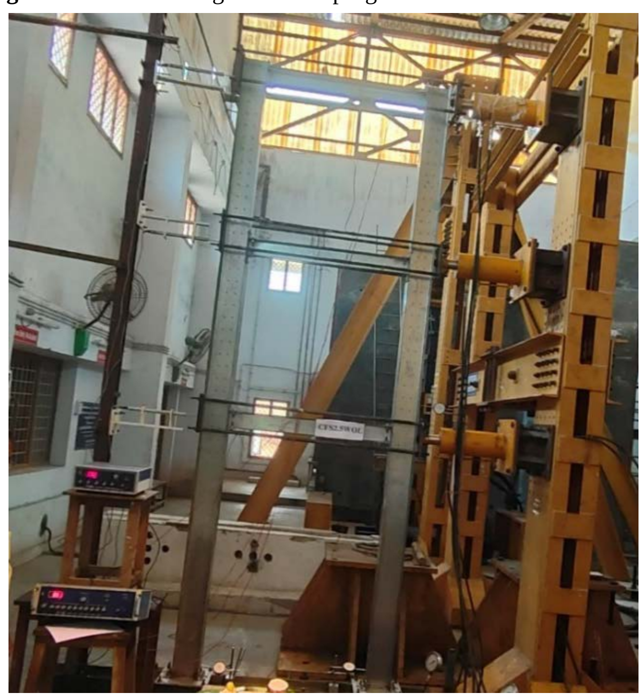

Figure 4 Full scale experiment setup

INTERPRETATION

The lateral load was applied at beam –column junction level through hydraulic jacks. The loads increased gradually at regular interval was set 1 kN. Initially the load transferred to the frame voyaged in load – deflection was in the linear progression. At one stage, buckling of element in the frame was observed. At the stage, it was recorded and it was informed such that the respective maximum load observed was the maximum load holdup by the corresponding frame type. The hydraulic jack was allowed transfer the load to the frame with the control rate of 1kN and pull back with the same procedure. At the same time the deflection was measured at every push and pull by using LVDT in the respective storey levels. As the result, on comparing response of all type of tested frames. It was found that the frame made of lipped channel column hold up maximum load of 16 kN. Corresponding maximum lateral deflection was found as 96.77 mm. Table 3 shows the loads and corresponding displacement, maximum strain were recorded. [13,14]

Table 3 Experiment results

Sl. No	Frame Model Designation	Maximum load (kN)		Maximum Deflection (mm)		Maximum Strain(mm/mm)	
		Push (kN)	Pull (kN)	Push (mm)	Pull (mm)	Push (mm/mm)	Pull (mm/mm)
1	LGSF2.5W	14	14	81.42	81.48	0.0052	0.0054
2	LGSF2.5WL	16	16	96.77	96.82	0.0054	0.0052

Finite Element Modelling, Boundary and Loading Conditions

The main elements of the frame consist of column channels, beam channels and the components of the frame consist of a base plate, angle cleats, and bolts, were modelled using the tools and features of ANSYS 18.1 workbench software.

Element type SOLSH190 was used to model channel beams, which is suitable for linear, large rotation, large strain nonlinear structural applications. This element type is accomplished of accounting for changes in thickness, making it suitable for nonlinear analysis. The base plate was modeled using the element type SOLID185. Bolted connections were modeled using the beam 188 link element, accurately capturing the behaviour of the connections between the column, beam, angle cleat, and base plate. The bolted connection model included separate meshing of the bolts into three parts, representing frictional contact between the bolt head and the top plate, frictional contact between the shank portion of the bolt and the plate, and frictional contact between the bottom plate and the nut. Figure 4 presents the finite element model of the cold-formed steel frame, illustrating the overall configuration and positioning of the structural elements. Additionally, Figure 5 presents an extended view of the finite element model depicting the beam-column connection in detail.Similarly, Figure 6 provides an enlarged view focusing on the column-base plate connection, capturing the intricacies of this critical junction. These finite

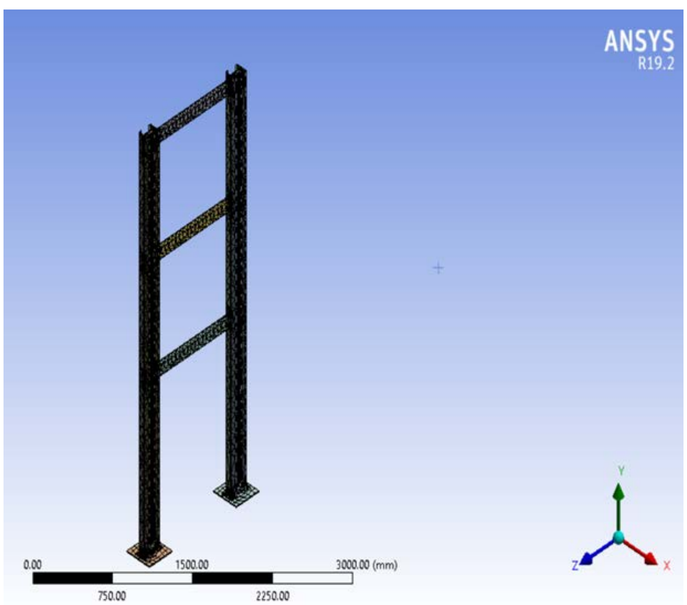

Figure. 5 Cold-formed steel frame full FE model-3D view.

element models, incorporating accurate material properties and connection details, allow for a detailed analysis of the performance of the cold-formed steel frame subjected to lateral loading. These material properties were then inputted into the finite element modeling software to accurately represent the behaviour of the steel within the models. The bilinear stress-strain curve enabled the simulation of nonlinear effects, such as plastic deformation and yielding, while the elastic modulus and Poisson's ratio ensured the appropriate representation of material stiffness and deformation characteristics.[15,16]

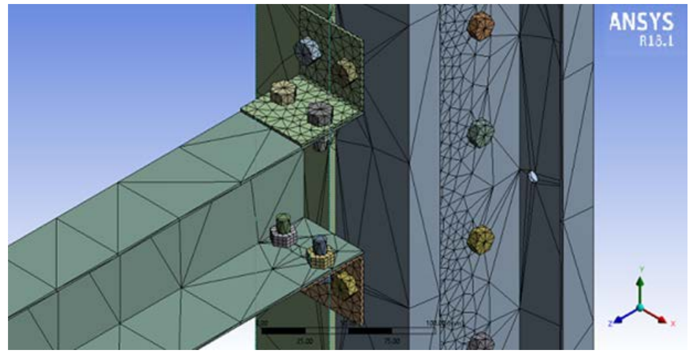

Figure 6. Cold-formed steel frame beam -column connection FE model- enlarged 3D view.

Table 4 presents the set of material properties utilized in the finite element modeling. It includes the relevant values for the bilinear stress-strain curve, elastic modulus, and Poisson's ratio.By incorporating these material properties into the models, the simulations were able to accurately capture the response of the steel structure under various loading conditions. In the experimental model, the application of loads and establishment of boundary conditions were crucial for studying the behaviour of the cold-formed steel frame. Lateral forces were applied to the beam-column junction using a hydraulic jack, with equal intensity of forces at three levels simultaneously.[17] An incremental load of 1kN was applied to a specific axial position on the face of the column. The resulting frame reactions, including displacements and stresses, were recorded for analysis. In the FEA, the same lateral force was applied through the nodes located on the face of the column. Regarding the boundary conditions, the experimental test specimen was securely bolted to a base plate, and the bottom of the frame's column was rested on a rigid platform. This arrangement provided a fixed support condition between the base plate and the rigid platform, ensuring stability during testing.[18]

The boundary conditions in the FEA aimed to accurately represent this support configuration. Displacement constraints and rotational constraints were implemented by setting the degrees of freedom (DOFs) as follows: UX=UY=UZ=URX=URY=URX=0. These constraints ensured that the base plate and the rigid platform remained fixed relative to each other, simulating the experimental fixed support condition. The boundary conditions in the FEA aimed to accurately represent this support configuration. Figure 7 illustrates the applied loading conditions, showcasing the hydraulic jack used to apply lateral forces to the beam-column junction. Figure 8 demonstrates the established boundary condition, highlighting the bolted connection between the test specimen and the base plate, as well as the contact with the rigid platform.[19]

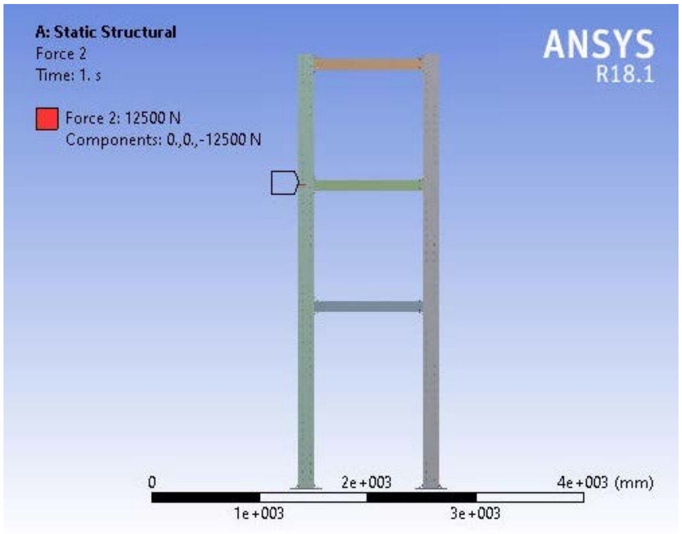

Figure 7 Lateral force applied in column — beam joint axially in the column face

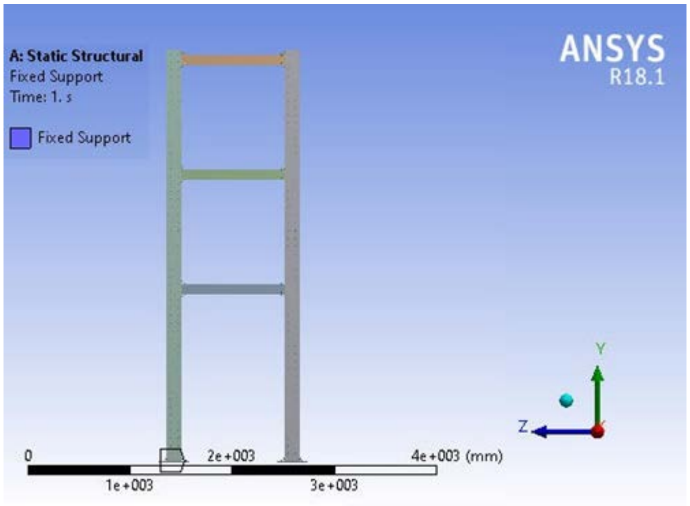

Figure 8. Fixed type support applied in the column-base plate interface and applied in the base plate bottom and rigid platform interface.

Table 4 Material properties input for cold -formed steel frame finite element models.

Structural Type	Element type	Material input
Cold-Formed Steel Plate	SOLSH190	Linear isotropic
		Young's Modulus Ex = 2.02x 10^5 MPa
		Poisson's ratio = 0.3
		Bilinear isotropic hardening properties
		Tangent modulus = 15000 MPa
		Yield strength fy = 385 MPa
Hot-Rolled Steel Plate	SOLID185	Linear isotropic
		Young's Modulus Ex = 2.00x 10^5 MPa
		Poisson's ratio = 0.3
		Bilinear isotropic hardening Properties
		Tangent modulus = 15000 MPa
		Yield strength fy = 250 MPa
Bolt, Self-Driving Screw	Beam188	Linear isotropic
		Young's Modulus Ex = 2.00x 10^5 MPa
		Tangent modulus = 15000 MPa
		Yield strength fy = 250 MPa

MAXIMUM LOAD-CARRYING CAPACITY

The two different types frame models were modelled and analyzed based on FEA principle using ANSYS 18.1 workbench software. From the analytical result, the maximum load-carrying capacity for each specimen was determined. Table 5 displays the maximum load carrying capacity of channel joists. From the table, on comparing four type frames it is found that the LGSF2.5WL frame has a cross sectional area of 1570 mm2 it hold up the maximum load of 15 kN which has higher than other frame types and correspondingly the maximum stress was found 2778.6 MPa which has higher stress value compared to other frame type.[20]

At other end LGSF2WOL frame has a cross sectional area of 1325 mm2 it hold up the maximum load of 13 kN which has acquired a lower load –carrying capacity compared to other frame type. Figure 9 presents a stress contour diagram for all type frames resulting from post processing results of FEA. The frames analytical models maximum load carrying capacity was found and compared shown in figure 10.Table 5 presents analytical result of maximum load-carrying capacity of frames.

Table 5 Analytical result Maximum load-carrying capacity

Sl. No	Frame Model Designation	Column cross section area (mm^2)	Maximum load carrying capacity (kN)	Maximum stress (N/mm^2)
1	LGSF2.5WOL	1325	13	2367
2	LGSF2.5WL	1570	15	2778.6

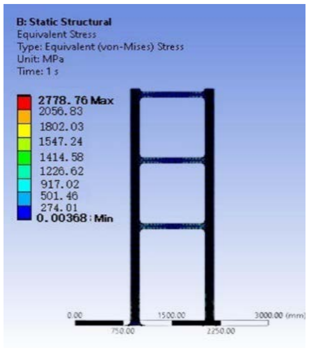

Fig 9(a) Stress contour LGSF2.5WOL

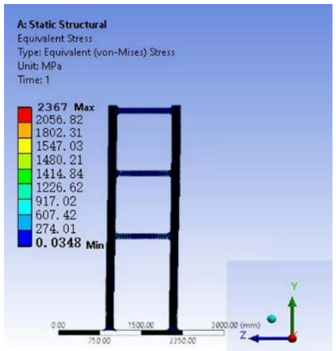

Fig 9 (b) Stress contour LGSF2.5WL

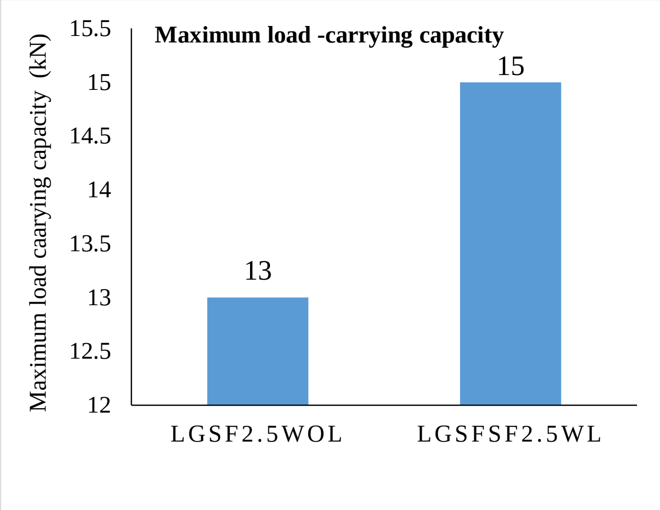

Figure 10 Maximum load carrying capacity analytical result

STIFFNESS

The stiffness of the frame design was calculated by taking into account the elastic region of the load-displacement curve. The stiffness of the frame equal to initial slope value of load-deflection curve with in elastic phase. Stiffness of the frame types were obtained based on analytical load-deflection curve. It is found that the LGSF2.5WL frame has acquired high stiffness value 243.57 N/mm compared to other frame type. In other end the frame LGSF2.5WOL frame has acquired low stiffness value 220.52 N/mm. The graphical representation of stiffness shown in the Figure.11. Table 6 presents calculated analytical results.

Table 6 Analytical result Stiffness

Sl. No	Frame Model Designation	Maximum load carrying capacity (kN)	Maximum Deflection (mm)	Stiffness
1	LGSF2.5WOL	13	74.82	220.52
2	LGSF2.5WL	15	89.77	243.57

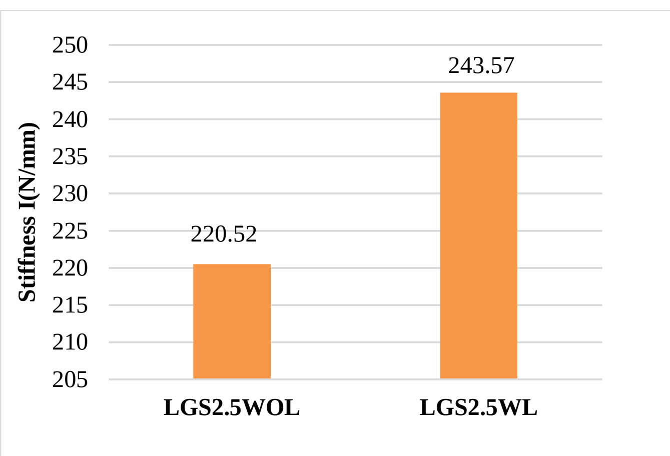

Figure 11 Stiffness analytical result

LOAD- DEFLECTION CURVE

The cold forming steel frames subjected to lateral force. Forces were subjected to frame using a feature in the software. Displacement simulation revealed. Thus, the maximum deflection corresponding to the maximum load for the frame types was obtained. Comparing the load-deflection values. The CSF2.5WL frame has a maximum load of 15 KN. Comparing the frame type values, these are larger relational and the corresponding displacement value is 81.52 mm. At the other end the CSF2.5WOL frame was found to have a maximum load value of 13 KN and 74.82 mm. These are the lesser relational compared to the values of the frame types. The frames load deflection curve is shown in the Figure.12.

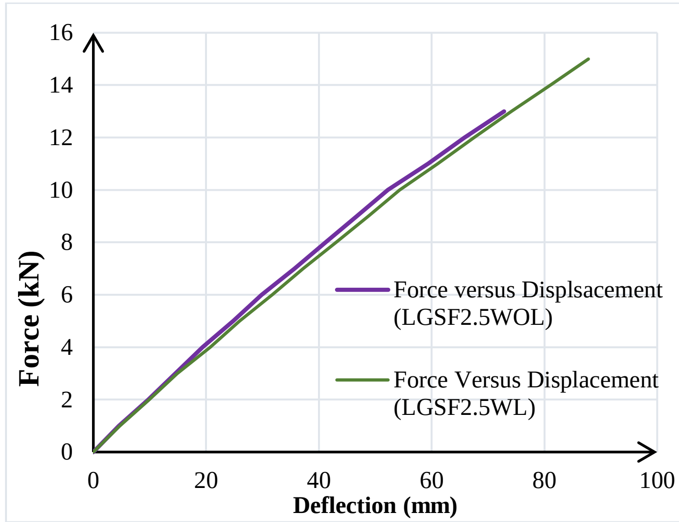

Figure 12 Load –Deflection curve analytical result

RESULT AND DISCUSSION

COMPARISON OF ANALYTICAL AND EXPERIMENTAL LOAD – DEFLECTION CURVE

On comparing experimental and analytical results analysis. The results revealed that as the applied force increased, the displacement of all frame models exhibited an ascending trend. However, the frame model with a lipped channel section column demonstrated a comparatively lower rate of displacement increase. Furthermore, the frame model with the lipped channel section column exhibited a higher load-carrying capacity compared to the other frame types. This indicates that the presence of the lipped channel section column contributed to enhanced structural performance and resistance against lateral loading. The load-lateral displacement curves of the cold-formed steel frames, depicting the relationship between applied loads and resulting deflection, are presented in Figure 13. Table 7 presents result comparison of maximum load –deflection of frame.[20]

COMPARISON OF ANALYTICAL AND EXPERIMENTAL RESULT STIFFNESS

The stiffness of the cold-formed steel frames was analyzed to assess their resistance to deformation under lateral loading. The inclination of the load-lateral displacement curve was determined

Table 7 shows comparison of analytical results and experimental results.

Frame Model Designation	Maximum load carrying capacity kN Exp	Maximum Deflection mm Ana	Maximum load carrying capacity kN Ana	Maximum Deflection mm Ana	Increase in maximum load carrying capacity %
LGSF2.5WOL	14	81.42	13	74.82	7.14
LGSF2.5WL	16	96.77	15	89.77	6.25

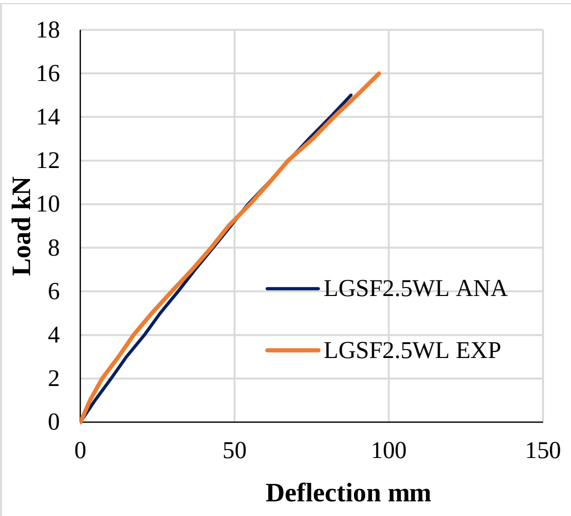

Figure 13 (a) Load versus Deflection LGSF2.5WL

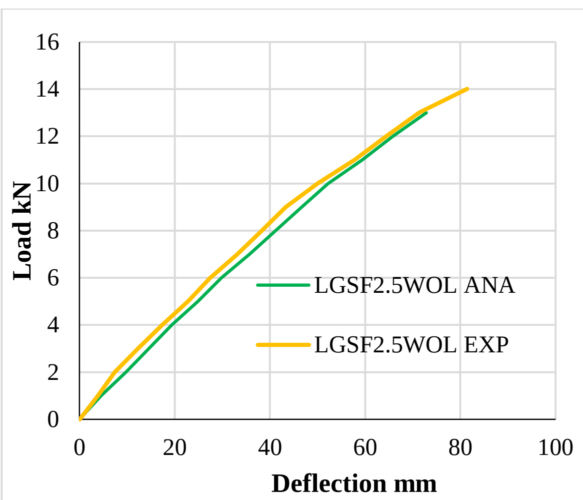

Figure 13 (b) Load versus Deflection LGSF2.5WOL

by fitting a linear elastic line that best represents the initial linear portion of the curve. From this analysis, the relevant stiffness values were calculated for each frame model. The results indicate that the frame model with a lipped channel column section LGSF2.5WL exhibited a higher stiffness compared to the other frame models. This implies that the frame with the lipped channel column section is more resistant to deformation and exhibits a greater ability to maintain its shape under lateral loading. Table 8 presents results stiffness parameter. Figure 14 presents a comparison of analytical results and experiment results of calculation based stiffness.

Table 8. comparison of analytical results and experimental results stiffness.

Sl. No	Frame Model Designation	Stiffness N/mm Exp	Stiffness N/mm Ana	Increase in stiffness %
1	LGSF2.5WOL	269.54	220.52	22.22
2	LGSF2.5WL	280.89	243.57	15.22

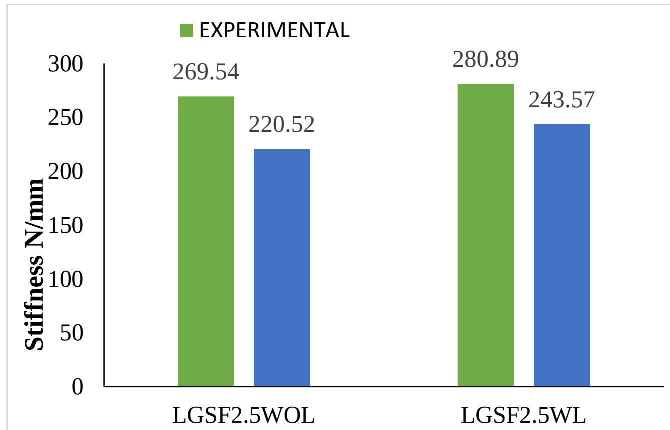

Figure 14 Comparison of Experimental result and Analytical result stiffness

Comparison of analytical and experimental result Maximum force resisting capacity

The many criteria discussed included maximum force resisting capacity, load–deflection behaviour failure mode, and. The loads corresponding to the maximum lateral displacement for LGSF2.5WOL, and LGSF2.5WL were aligned for both analytical and experimental investigations. It was revealed and showed Table 9 that the experimental result has got higher face value than the analytical result, specifically in LGS2.5WL, which has 7.14 % and 6.25% higher force resisting capacity than LGS2.5WOL in the analytical and experimental investigations, respectively, as shown in Figure 15. The results were compared to the experimental investigation outcome.

Table 9 comparison of analytical results and experimental results Maximum force resisting capacity**.**

Sl. No	Frame Model Designation	Maximum load carrying capacity kN Exp	Maximum load carrying capacity kN Ana	Increase in maximum load carrying capacity %
1	LGSF2.5WOL	14	13	7.14
2	LGSF2.5WL	16	15	6.25

Failure modes

On comparing experimental results and analytical results, the maximum load was reached for the respective frame models which will be decided at which load step frame model undergoes long deformation and exhibits high-concentration stress in the element.

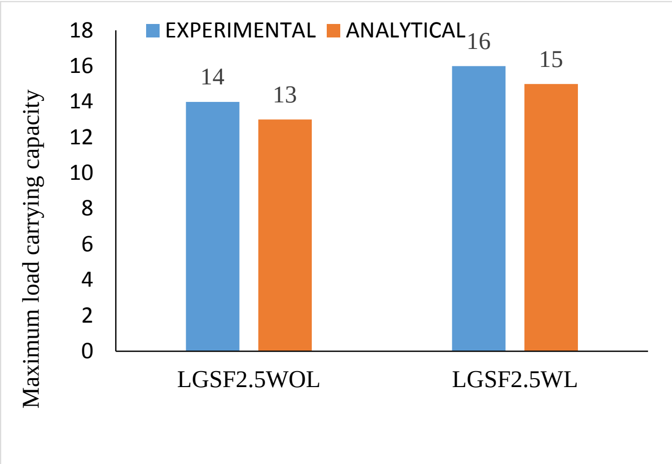

Figure 15 Comparison of Experimental result and Analytical result Maximum load carrying capacity.

In this analysis, high concentration of stress exhibited on the beam portion of the frame model in the maximum load step in analytical study also in experiment test and it was observed and recorded as local buckling failure. Figure 16 shows occasion of failure of frame recording at testing laboratory.

Figure 16 observation and Recording of local bucking failure at the end of test

Conclusion

Based on the comparison of post-processing results of the FEA and Experimental and, it was observed that the frame model incorporating lipped channel columns exhibited superior load-carrying capacity compared to other frame models. This suggests that the use of lipped channel columns enhances the frame's overall strength and ability to meet serviceability requirements. Additionally, the frame model utilizing 2.5 mm thick channel columns exhibited higher stiffness compared to other frame models. This indicates that increasing the thickness of the column sections positively influences the frame's rigidity, which can contribute to improved structural stability and reduced deformations under lateral loading conditions.

Conflict of Interest

No Conflict of interest.

Acknowledgements

We thank Dr.Raguvaran Balasubramaniyan who helped in solve technical issues while rising computer working.

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