REVISTAMATÊRIA V.29 N.3
ISSN 1517-7076 articles e20240116, 2024

Performance study of cold-formed steel channel joist with web opening subjected to flexural loading

KSowrirajan Krishnamoorthy Duraimurugan[1], Rajaram Baskar[1]

[1]Faculty of Engineering & Technology, Department of Civil and Structural Engineering. Annamalainagar, Tamilnadu, India.
e-mail: kskduraimuruganphdau@gmail.com, rajaram_baskar@rediffmail.com

ABSTRACT

This study presents the structural behaviour of cold-formed steel joists with different web-opening shapes. The investigation incorporated both experimental and analytical approaches. The study involved the selection of square and circular web openings, and channel sections were chosen based on site-specific design considerations. In the experimental phase, channel joists were subjected to flexural loading and tested. An analytical investigation was conducted. Finite element (FE) models were developed using the FEM software ANSYS APDL version 16.2. FE models were used to simulate the structural response of the channel joist when subjected to flexural loading. A parametric study was conducted on the basis of simulation and experimental investigation. Factors that influence stiffness and load-carrying capacity considering variables in cold-formed steel channel joists were analyzed. Analytical investigations were conducted. Based on this result analysis, significant effects were observed, indicating a better agreement between the analytical and experimental results. In addition, it was shown that channel joists with circular web openings provide high efficiency in terms of load-carrying capacity and stiffness in web-opening shapes.

Keywords: Cold-formed steel; Channel joist; Finite element analysis; Web opening types; Static flexural loading.

1. INTRODUCTION

Cold-formed steel structural elements have gained widespread recognition and use in construction projects worldwide. These elements are fabricated from steel sheets that are cold-worked into desired shapes through bending, rolling, or pressing processes. Cold-formed steel channel joists are crucial in modern construction, offering lightweight, robust structural solutions for spanning distances and supporting loads. They are versatile and adaptable and are suitable for use in residential, commercial, and industrial buildings. In the case of cold formed steel, shape that is cold worked to a higher degree will have a higher yield strength, which may make it more appropriate for certain applications. Sometimes cold work is added by overbending and straightening.

Cold-formed steel is commonly used in structural framing systems such as stud walls, floor joists, roof trusses, and mezzanine platforms. Their inherent strength and design advancements ensure efficient load distribution and structural performance. Cold-formed steel is highly sustainable due to its recyclability and efficiency in material usage. Recycling steel reduces the energy and resources required for production, making it an environmentally friendly. Cold-formed steel channel joists with web openings represent a specialised and innovative aspect of structural engineering. These joists are designed with carefully positioned openings in their web, which serve various purposes such as accommodating services such as electrical and plumbing systems or reducing the overall weight of the joist. The openings are strategically located to maintain the load-bearing capacity of the joists while allowing for functional requirements. However, the behaviour of these beams is characterized by local buckling phenomena, where compressive flanges tend to buckle before the entire section undergoes yielding. In addition, the stiffness and flexural load capacity of cold-formed beams can be significantly affected by various parameters such as cross-sectional dimensions, material properties, and support conditions.

1.1. Literature review

Recently, cold-formed steel structural elements subjected to various loading conditions have been studied. Also, some research is in progress. Most studies have revealed ways to improve the flexural capacity and stiffness of cold-formed steel structural components and increase their applications. Some studies have attempted to explore

Corresponding Author: KSowrirajan Krishnamoorthy Duraimurugan Received on 18/03/2024 Accepted on 15/05/2024

DOI: https://doi.org/10.1590/1517-7076-RMAT-2024-0116

and characterize cold-formed steel beams with web openings using experimental and analytical methods. ZHAO *et al*. [1], GHANNAM [2], DOLAMUNE KANKANAMGE and MAHENDRAN [3] attempted investigation of behaviour of cold-formed channel section with incorporating strength improvement features. ANBARASU [4] experimented on the structural behaviour of cold-formed steel (CFS) closed Built-up beams composed of two sigma sections primarily fail due to local buckling under four-point bending about the major axis. It is aimed to establish accurate finite element models for CFS built-up I-beam subjected to a transverse load. The numerical model was developed by using Finite Element (FE) software ABAQUS 6.13. The numerical model is validated by means of comparison with the experimental results published in the literature in terms of moment capacities, moment versus deflection curve and failure mode of specimens. For different cross-section geometries and different thickness of the built-up closed beam, the numerical parametric study has been carried out by using the verified FE model, and the obtained flexural resistances were compared with those predicted by using current DSM and DSM proposed for built-up beams. Researcher concluded that the moment capacity decreases with increase in compression flange width to thickness ratio. In general, the moment of resistance of the section increases with decreasing the aspect ratio. There is no significant effect in flexural strength of the built-up closed beams due to the change in depth of web stiffener. FARIDMEHR *et al*. [5], LAÍM *et al*. [6], CHENG *et al*. [7], EL-SHEIKH *et al.* [8]. MADULIAT *et al.* [9], ALEX and IYAPPAN [10], AJEESH and ARUL JAYACHANDRAN [11], KEERTHAN and MAHENDRAN [12] tried investigation of lateral buckling behaviour of cold-formed channel section with involving resistance enhancement features by allowing alternation in beam section. MEZA *et al*. [13] experimented on the comprehensive experimental program on cold formed steel built-up beams with two different cross-sectional geometries. The work aimed to experimentally investigate the interaction between the individual components under increasing loading and to quantify the effect of the connector spacing on the cross-sectional moment capacity and the behaviour of the beams. In total, 12 specimens were tested in a four-point bending configuration, with lateral restraints provided at the loading points in order to avoid global instabilities. Researcher concluded that between the local buckling patterns of the components, with the interaction being affected by the connector spacing and the type of geometry. However, the connector spacing showed a less significant effect on the ultimate capacity when failure was governed by local instabilities of the components.YE *et al.* [14], LAÍM *et al.* [15], YE *et al.* [16] focused improvement in strength of cold-formed steel channel section with introducing strength enhancement techniques suit with appropriate base cold-formed channel section with the features of internal strength improvement techniques functioning in the modern scenario.

1.2. Methodology

The proposed methodology examines the structural behaviour of cold-formed steel channel joists by conducting analytical and experimental investigations. Analytical investigations comprised finite element models developed and analysed. An experimental investigation consisting of a flexural load testing programme was conducted. A comparison of the results of the analysis performed for both numerical and experimental investigations is made. According to this, performance parameters were derived and discussed.

2. MATERIALS AND METHODS

2.1. Analytical investigation

2.1.1. Selection of section

The sectional properties of the selected sections for joists were obtained from the Indian standard classification for cold-formed structural steel sections. The cross dimensions for the joist were decided on the basis of the American standard specification [17] for cold-formed steel constructions and factory practice specifications. Figure 1 depicts the geometry details of the channel joist specimen. Different web openings were made in the joist by marking and cutting the exact location of the web section using a precision laser cutting machine in the factory. Simultaneously, the web-opening area was set to be the same area as the web opening, even though different shaped web openings were applied.

2.1.2. Experiment program

For the experimental investigation, 12 trial joist specimens were tested. Joists were cold rolled and processed, and web opening in the joist was performed in the factory. The height of the joists was used at two different heights: 200 and 150 mm. The clear span of the joists was maintained at 3200 mm. Table 1 presents geometric details of specimens. Figure 2 depicts the processed joist specimen prepared for the experimental work. Mechanical property tests were conducted on sample specimens prepared according to the ASTM standards.

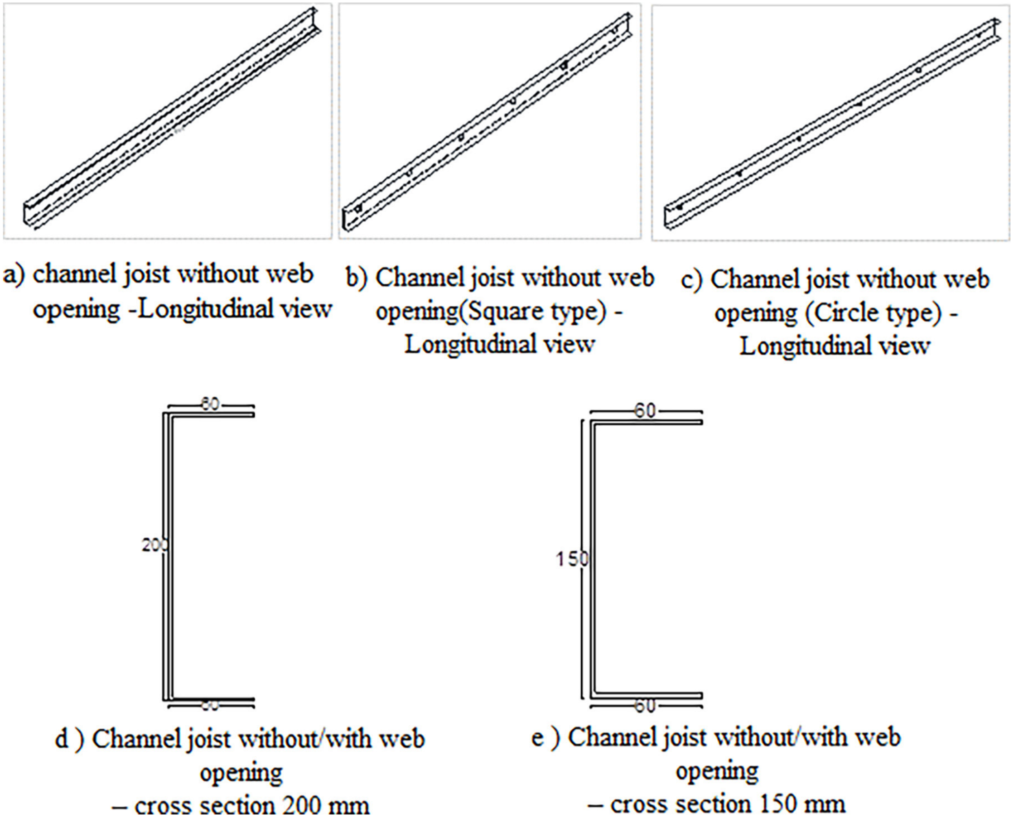


Figure 1: Geometry details of channel joist with and without web opening.

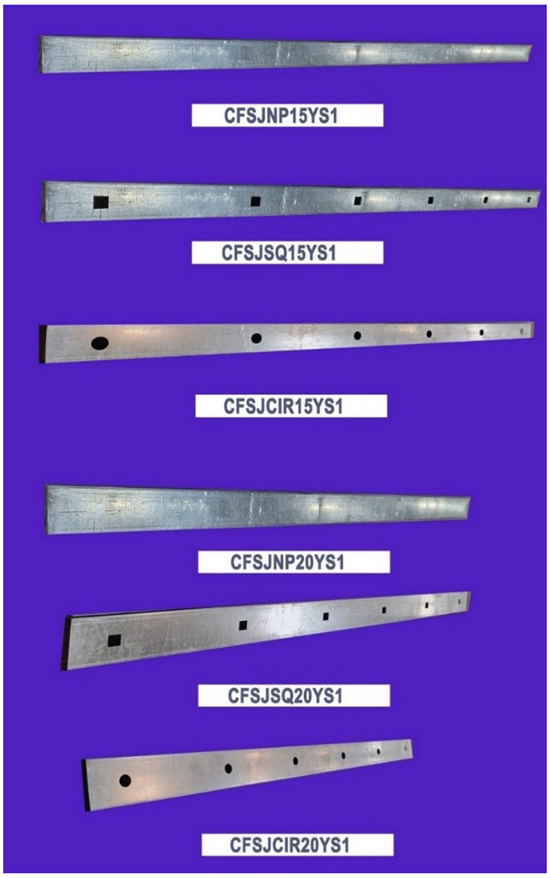


Figure 2: Display of cold-formed steel channel joist specimens used in this study.

Table 1: Geometry details of cold-formed steel frame models.

SL. NO.	BEAM DESIGNATION	JOISTS SECTION (mm)	JOISTS DEPTH (mm)	WEB OPENING TYPE
1.	CFSJNP20YS1	200 × 60 × 2.5	200	No perforation
2.	CFSJNP15YS1	150 × 60 × 2.5	150	No perforation
3.	CFSJSQ20YS1	200 × 60 × 2.5	200	Square
4.	CFSJSQ15YS1	150 × 60 × 2.5	150	Square
5.	CFSJCIR20YS1	200 × 60 × 2.5	200	Circle
6.	CFSJCIR15YS1	150 × 60 × 2.5	150	Circle

Table 2: Mechanical properties of cold-formed steel.

MATERIAL	YIELD STRENGTH (N/mm^2)	ULTIMATE STRENGTH (N/mm^2)	ELASTIC MODULUS (N/mm^2)	ELONGATION (mm)
Grade 2 (YS2)	345	460	2.02×10^5	18

Prior to the testing program, the mechanical properties of the cold-formed steel specimens used in this study were calculated by conducting laboratory tests. The mechanical properties analysed include parameters such as yield strength, ultimate tensile strength, modulus of elasticity, and elongation. Table 2 presents the mechanical properties of the steel materials.

Figure 3 Schematic of the test. The joist test setup follows a two-point loading flexural test. The test setup consisted of a beam testing frame with a 500-kN load-applying capacity, a hydraulic jack with a 100-kN load transfer capacity, and a Proving ring with a 100-kN load transfer capacity. In addition, the instrumentation consisted of dial gages with a precision of +0.001 mm. Strain gage with 320 ohms resistance capacity. To implement the test setup, the hydraulic jack was bolted to the loading frame with a proving ring. Specimen supporting arrangements in the test yard were made as per the two-point flexural loading setup prescribed by standard codes. For the two-point load distribution, a suitable runner beam was provided parallel to and over the specimen run. Dial gauges were positioned exactly in the load distribution and centre of the span to measure deflection. Likewise, strain gauges were mounted exactly in three positions exactly in the centre of the span near the bottom flange, in the center of the span near the web portion, and likewise in the centre of span near the bottom that connected to strain indicator in order to measure strain in the component of joist. Flexural loading was applied via an arranged setup with an equal increment of 0.5 kN. The loading progression was maintained with the help of a control unit in the testing yard. Beyond this deflection, the point of the joist was recorded. Likewise, strain at the point of the joist was recorded. Until recoverable bending occurred, the load application progression continued. A sign of large deflection occurred at the same time that the applied progress was controlled.

2.1.3. Interpretation of experimental program

Static two-point load flexural tests were conducted on all specimens. Loads with equal intervals of 0.5 kN step increment loads were applied. The response related to each increment of load was recorded. Based on the post result analysis. From this, the maximum load-carrying capacity, maximum deflection, and maximum strain were observed. In the case without web-opening joists, the maximum load is 6.25 kN. Similarly, the down step channel joist with rectangular web-opening joists had a maximum load of 6.0 kN. Similarly, channel joists with circular web-opening joists had a maximum load of 6.0 kN. Likewise, in the case without web opening joists, the maximum deflection measured was 168.52 mm. similarly, the deflections recorded for rectangular web opening joists and circular web opening joists were 111.72 mm and 103.32 mm, respectively. Table 3 result summary of laboratorial tested CFS joist specimens.

2.1.4. Finite element modelling, boundary and loading conditions

Analytical investigation: A finite element analysis tool was used in this study. Finite element analysis models were developed according to the experimental model. Likewise, material properties were assigned to the developed FEA models. Finite element analysis of the experimental models was performed using the finite

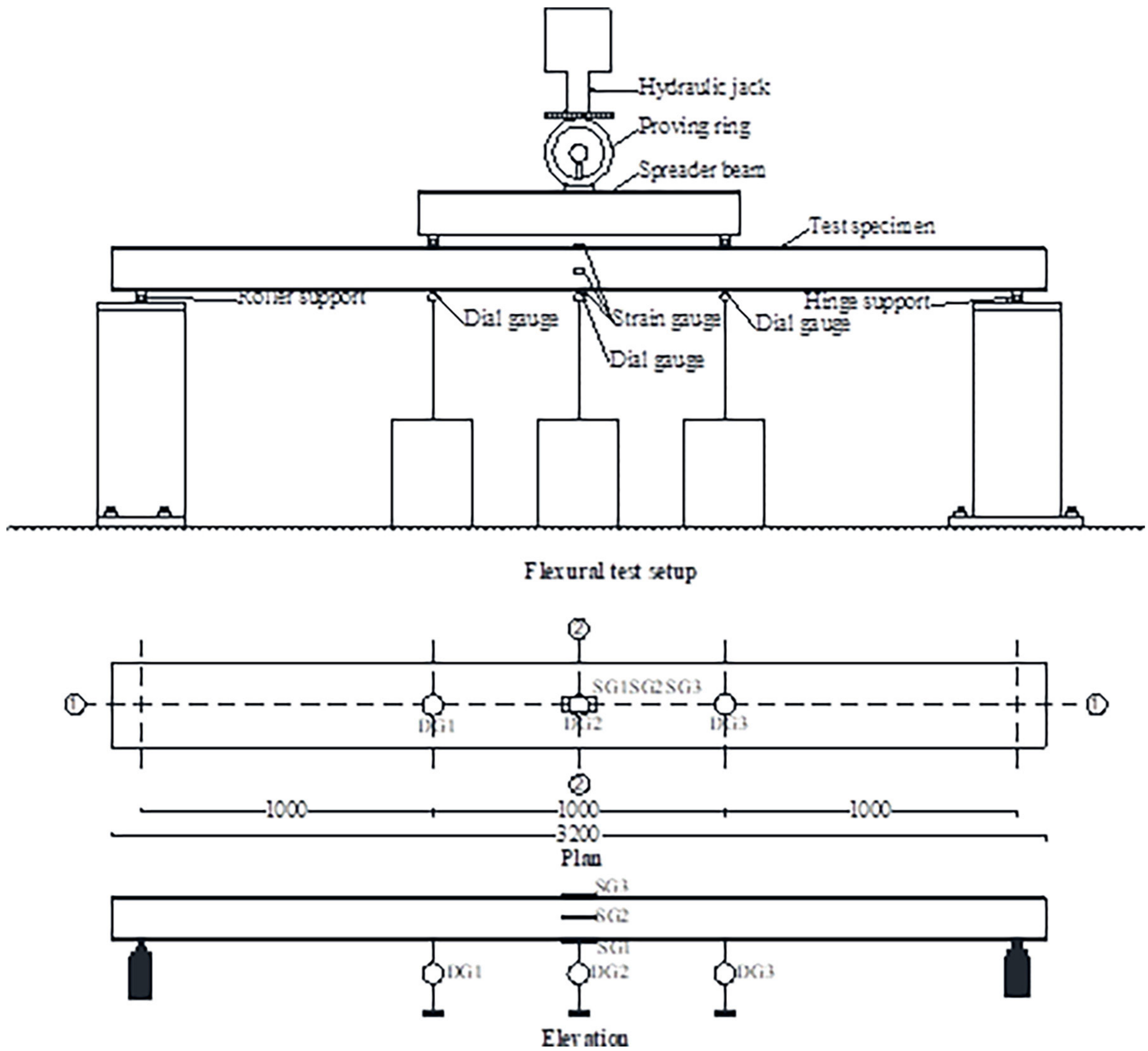


Figure 3: Test setup–block diagram.

Table 3: Experiment test results.

S.NO.	JOIST DESIGNATION	MAXIMUM LOAD (kN)	MAXIMUM CENTRAL DEFLECTION (mm)	MAXIMUM STRAIN (mm/mm)	STIFFNESS (N/mm)
1.	CFSJNP20YS1	6.25	168.52	0.0029	76.13
2.	CFSJNP15YS1	5.75	145.86	0.0026	60.31
3.	CFSJSQ20YS1	6.00	111.72	0.0030	82.57
4.	CFSJSQ15YS1	5.00	122.54	0.0032	60.56
5.	CFSJCIR20YS1	6.00	103.32	0.0028	89.52
6.	CFSJCIR15YS1	5.50	114.73	0.0029	71.53

element analysis software Ansys 16 APDL. The experimental model channel joist with/without web-opening geometry was considered on the basis on the developed discretized element model. To achieve the FE model, the solid 185 element type from the ANSYS APDL element directory was selected. The element type is utilized to model the steel members. The solid 185 element type consisted of eight nodes with three degrees of freedom

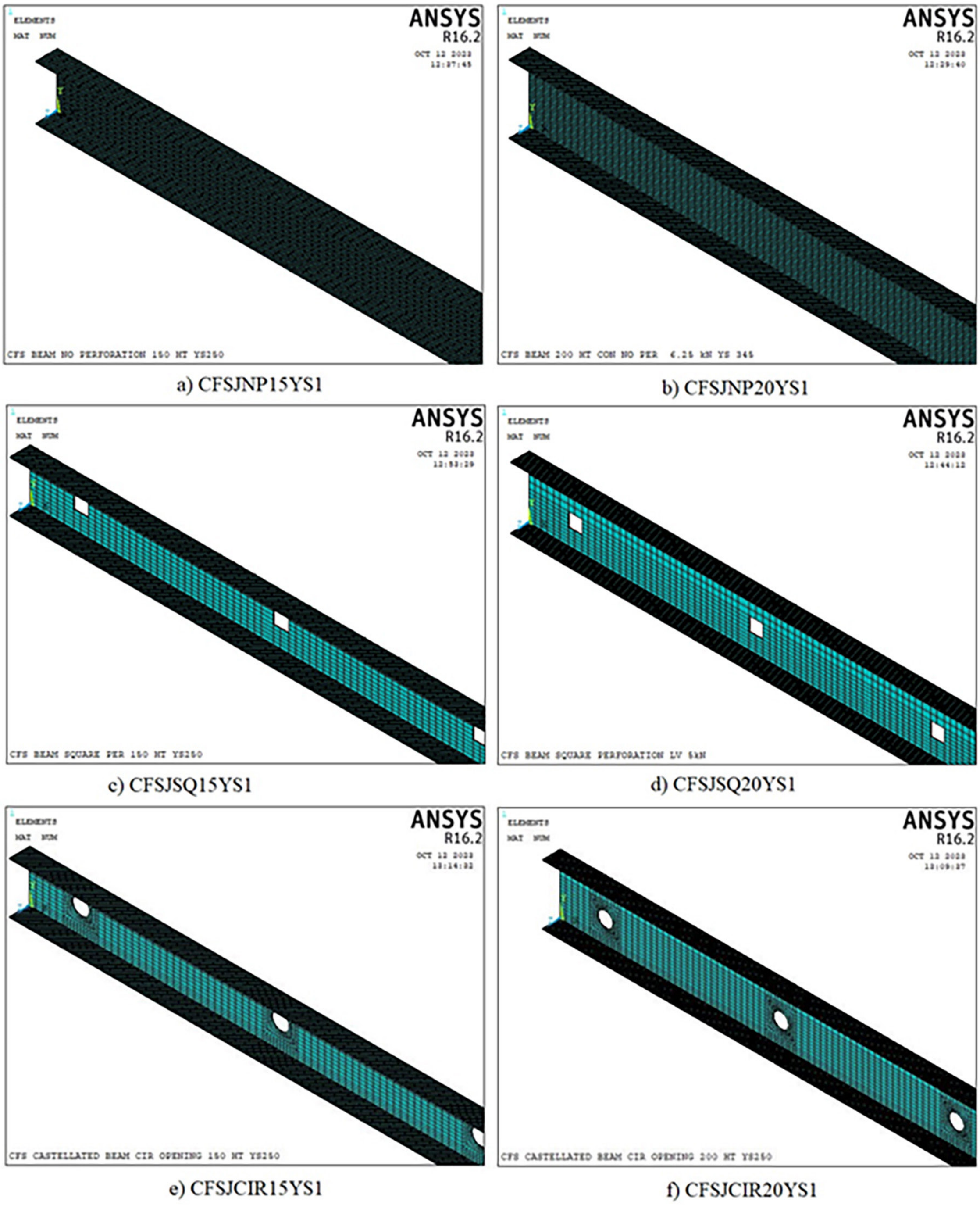


Figure 4: Finite element discretized models.

at each node: translations in the nodal x, y, and z directions. The element exhibits nonlinear phase properties. To obtain accurate results, mapped mesh types were employed. Keeping a regular element size of 25 × 25 mm and changing suitable open web shapes was done. A full FE model was developed. Figure 4 presents the FE models developed for the finite element analysis. To resemble support conditions provided in experiment model, same condition were assigned using boundary condition assigning features. For assigning hinged support one hand side turn condition Rotation in X direction (Rot x) released, Rotation in Y direction (Rot Y) released Rotation in Z direction (Rot Z) were allowed likewise translation in X direction were allowed (UX), translation in Y direction (UY) were restricted. For assigning roller support other hand side turn condition Rotation in X direction (Rot X) released, Rotation in Y direction (Rot Y) released Rotation in Z direction (Rot Z) were allowed likewise translation in X direction (UX) were allowed, translation in Z Direction (UZ) were allowed translation in Y direction (UY) were restricted. Likewise Figure 5 presents force and support condition assigned according to

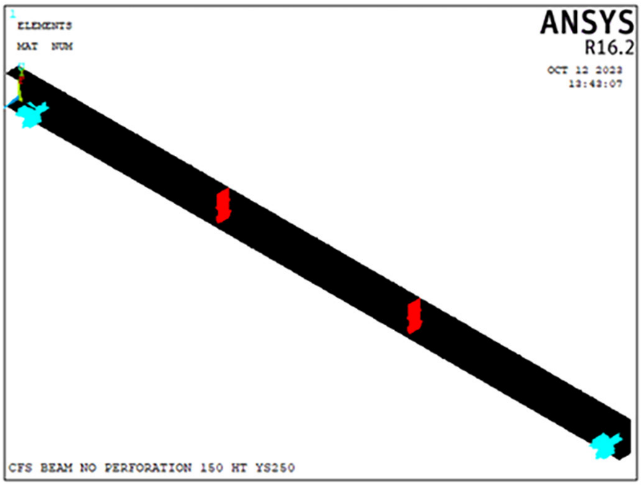


Figure 5: Force applied and support condition assigned in FE model.

Table 4: Material modeling input.

S.NO.	ELEMENT TYPE	MATERIAL PROPERTIES INPUT
1.	Solid185	Young's Modulus EX: 2.02×10^5 N/mm^2 Poisson's ratio PRXY: 0.2 Yield Stress: 250 N/mm^2 Tangent modulus:16000 N/mm^2

experiment condition. With the continuation of the developed FE model, the material properties were assigned to appropriate FE models. Material properties are one of the key factors in obtaining the exact result. Material properties were obtained by mechanical properties tests over the test sample machined from the original material considered for the experiment. Using the same material, cold-formed channel joints were produced. Table 4 presents the material modeling used for the analysis of channel joists subjected to flexural loading.

3. RESULTS

3.1. Analytical study results

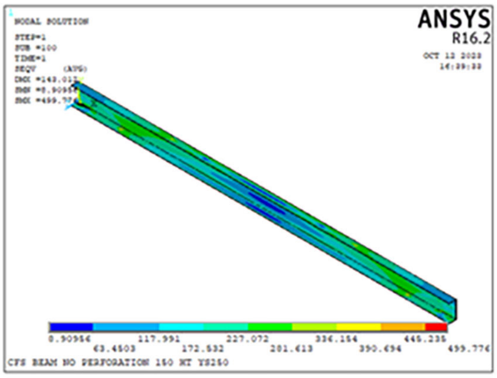
According to the experimental model, 12 FE models were developed and analysed. In this full model count, the following variants were included, such as variants in the height of channel joists of 150 mm and 200 mm. Likewise, variants in the web-opening shape of the channel joist were considered. The FE models were subjected to static flexural loading using the software features. Post processing results were observed. In this way, the results were accounted for and the parameters consisting of maximum load carrying capacity, stiffness, and load deflection behaviour were discussed.

3.2. FEA maximum load-carrying capacity

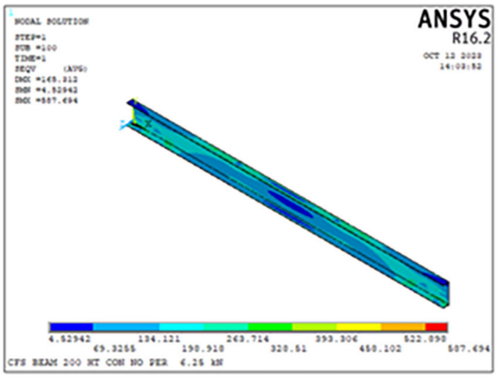
A finite element model of a channel joist with or without web opening was developed, and the post processing features were incorporated into an analysis result database. From this, each FE model response in terms of values and contour diagram was obtained. Accordingly, the maximum force resisting capacity for each FE model was observed. The maximum force resisting capacity is fixed on the basis of the maximum stress found in the models. The channel joist without opening model has a height of 150 mm and a maximum force resisting capacity of 5.25 kN. Likewise, the channel joist without opening model with a height of 200 mm had a maximum force resisting capacity of 6.25 kN. In the case of the channel joist with the web opening model notably square type web opened channel joist model consisting of heights of 150 mm and 200 mm, acquired the maximum force resisting capacities of 5.75 kN and 5 kN, respectively. Likewise, the circular web-opened channel joist model with heights of 150 and 200 mm acquired maximum force resisting capacities of 5.75 and 5.5 kN, respectively. Table 5 summaries the results of the maximum force resisting capacity. Figure 6 depicts the stress contour diagram simulated from FEA analysis.

Table 5: FEA result maximum load carrying capacity.

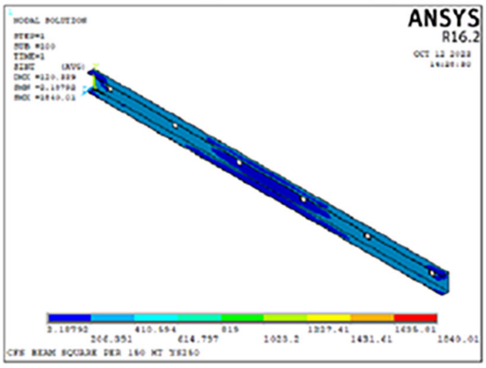
S.NO.	JOIST DESIGNATION	HEIGHT OF JOIST (mm)	MAXIMUM LOAD LOAD CARRYING CAPACITY (kN)	MAXIMUM STRESS (N/mm²)
1.	CFSJNP20YS1	200	6.25	587.69
2.	CFSJNP15YS1	150	5.25	499.77
3.	CFSJSQ20YS1	200	5.75	411.95
4.	CFSJSQ15YS1	150	5.00	601.5
5.	CFSJCIR20YS1	200	5.75	532.41
6.	CFSJCIR15YS1	150	5.50	464.61



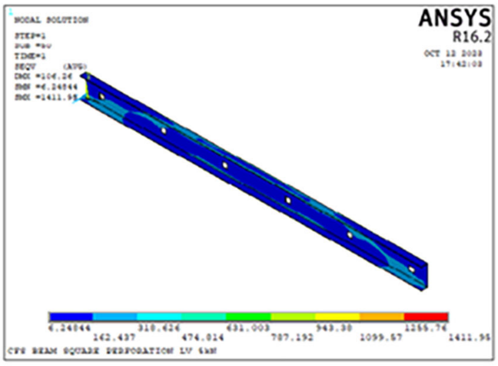
a) Stress contour CFSJNP15YS1



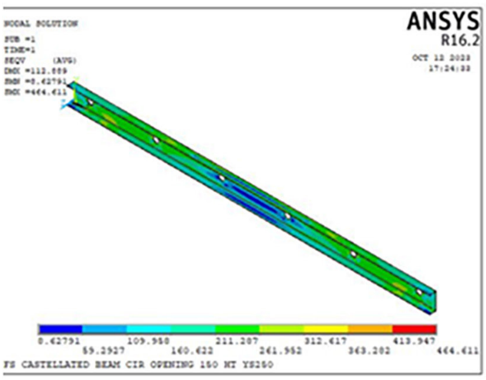
b) Stress contour CFSJNP20YS1



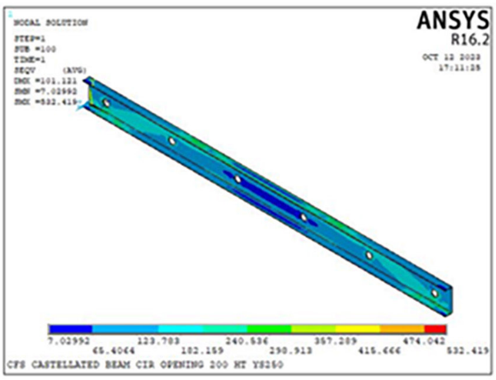
c) Stress contour CFSJSQ15YS1



d) Stress contour CFSJSQ20YS1



e) Stress contour CFSCIR15YS1



f) Stress contour CFSCIR20YS1

Figure 6: FEA results stress contour diagram for all specimens.

Table 6: FEA result stiffness.

S.NO.	JOIST DESIGNATION	MAXIMUM LOAD LOAD CARRYING CAPACITY (kN)	MAXIMUM CENTRAL DEFLECTION (mm)	STIFFNESS N/mm
1.	CFSJNP20YS1	6.25	165.31	69.66
2.	CFSJNP15YS1	5.25	143.012	56.73
3.	CFSJSQ20YS1	5.75	106.26	79.744
4.	CFSJSQ15YS1	5.00	120.33	58.63
5.	CFSJCIR20YS1	5.75	101.121	84.99
6.	CFSJCIR15YS1	5.50	112.88	65.23

Table 7: FEA results load–deflection.

S.NO.	JOIST DESIGNATION	MAXIMUM LOAD LOAD CARRYING CAPACITY (kN)	MAXIMUM CENTRAL DEFLECTION (mm)
1.	CFSJNP20YS1	6.25	165.31
2.	CFSJNP15YS1	5.25	143.012
3.	CFSJSQ20YS1	5.75	106.26
4.	CFSJSQ15YS1	5.00	120.33
5.	CFSJCIR20YS1	5.75	101.121
6.	CFSJCIR15YS1	5.50	112.88

3.3. FEA stiffness

The stiffness of the joist design was predicted by considering the elastic region of the load–displacement curve. The stiffness of the frame is equal to the initial slope of the load-deflection curve in the elastic phase. According to this, the channel joist without the web opening 200 height model had a high stiffness value of 69.66 N/mm. The channel joist without a web opening of 150 mm height acquired a low stiffness value of 56.73 N/mm. Similarly, the channel joist with the web opening square type 200 height model had a high stiffness value of 79.74 N/mm. The channel joist without a web opening of 150 mm height acquired a low stiffness value of 58.63 N/mm. Likewise, the channel joist with the web-opening circle type 200 height model had a high stiffness value of 84.99 N/mm. A channel joist with a web-opening-type circle 150 mm in height acquired a low stiffness value of 65.23 N/mm. Table 6 presents the results obtained through finite element analysis.

3.4. FEA load-deflection curve

From the post processing results, the corresponding displacement of the FE models was observed. Each load increment corresponding to the deflection response was obtained. The channel joist without web perforation hole with height of 200 mm had a maximum displacement of 165.31 mm. The maximum deflection found for a height of 150 mm was 143.01 mm. In the case of the channel joist with a web opening of 200-mm height square type, the maximum displacement value was found 106.26 mm. Similarly, for a height of 150 mm, the maximum deflection was found 120.33 mm. In the case of the channel joist with a web opening of the 200-mm height circle type, the maximum displacement value was found 101.121 mm. Similarly, for a height of 150 mm, the maximum deflection was 112.88 mm. Table 7 presents the results of the maximum deflection corresponding to the maximum failure loads. In the FEA simulation, the failure of the channel joist was detected through the stress contour map obtained in the post-processing section of the FEA analysis program. The stress contour diagram reveals the shear of the channel joist at any part of the channel joist at maximum loading.

4. RESULT AND DISCUSSION

4.1. Maximum load carrying capacity

The effect and response of cold-formed steel channel joists with or without web opening subjected to flexural loading was observed. On the basis of comparing experimental post result analysis and analytical post result

Table 8: Result analysis maximum load carrying capacity.

S.NO.	JOIST DESIGNATION	MAXIMUM LOAD LOAD CARRYING CAPACITY (kN) (EXP)	MAXIMUM LOAD LOAD CARRYING CAPACITY (kN) (FEA)	VARIATION IN LOAD CARRYING CAPACITY (%)
1.	CFSJNP20YS1	6.25	6.25	–
2.	CFSJNP15YS1	5.75	5.25	8.69
3.	CFSJSQ20YS1	6.00	5.75	4.16
4.	CFSJSQ15YS1	5.00	5.00	–
5.	CFSJCIR20YS1	6.00	5.75	8.69
6.	CFSJCIR15YS1	5.50	5.50	–

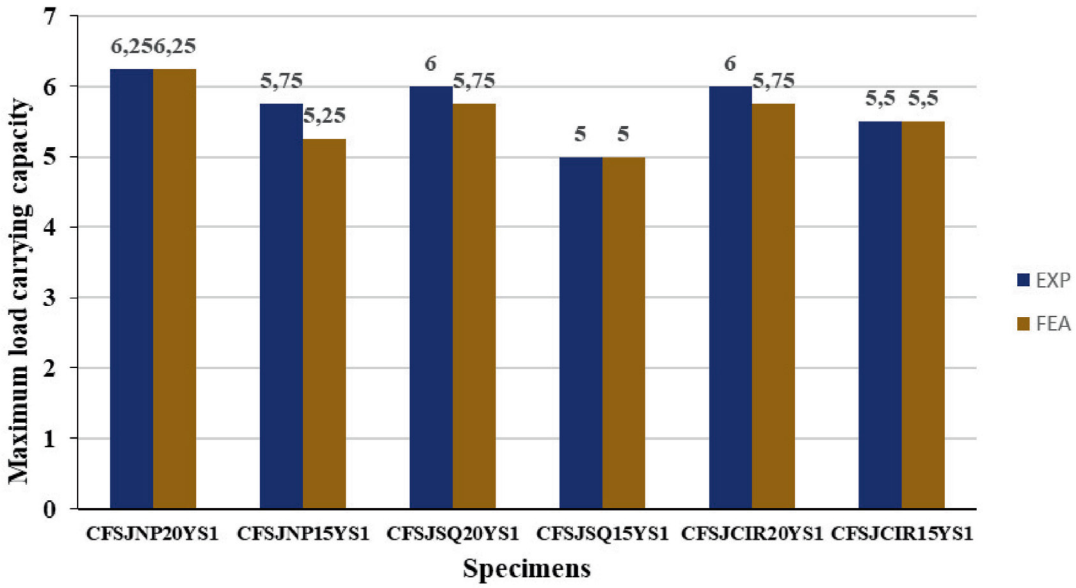


Figure 7: Comparison graph maximum load carrying capacity results.

analysis. In that way, the maximum load carrying capacity was determined based on the maximum load supported by the cold-formed steel channel joist specimens. according to this, the maximum load carrying capacity was found 6.25 kN in the case of channel joist without web opening having a height of 200 mm. The maximum load carrying capacity was found 5.75 kN in the case of channel joist with square web opening having a height of 200 mm. Similarly, the maximum load carrying capacity was found 6.00 kN in the case of channel joist with circle web opening having a height of 200 mm. Table 8 maximum load carrying capacity results comparison. Figure 7 presents a detailed graphical representation of the comparison of the maximum load carrying capacity results.

4.2. Stiffness

The stiffness of the channel joist was calculated using the load–deflection relationship. This relationship was obtained via experiments and analytical investigation. The stiffness is calculated through slope value of load-deflection curve with in the elastic phase. The stiffness parameter reflects the internal strength of the joist subjected to flexural loading. According to this, channel joists without a web opening 200 mm in height have a stiffness value of 76.13 N/mm and 69.66 N/mm experimentally and analytically, respectively. In the case

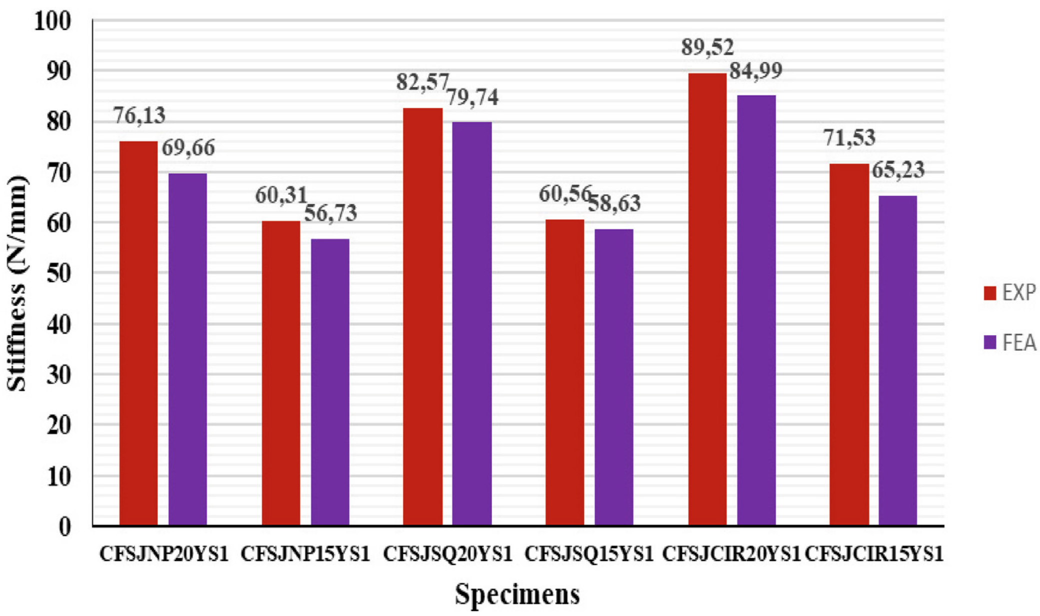


Figure 8: Comparison graph stiffness results.

Table 9: Result analysis stiffness.

S.NO.	JOIST DESIGNATION	STIFFNESS (N/mm) (EXP)	DEFLECTION (mm) (EXP)	STIFFNESS (N/mm) (FEA)	DEFLECTION (mm) (FEA)	VARIATION IN LOAD STIFFNESS (%)
1.	CFSJNP20YS1	76.13	168.52	69.66	165.31	8.49
2.	CFSJNP15YS1	60.31	145.86	56.73	143.012	5.93
3.	CFSJSQ20YS1	82.57	111.72	79.744	106.26	3.42
4.	CFSJSQ15YS1	60.56	122.54	58.63	120.33	3.18
5.	CFSJCIR20YS1	89.52	103.32	84.99	101.121	5.06
6.	CFSJCIR15YS1	71.53	114.73	65.23	112.88	8.80

of channel joists with a web opening 200 mm in height, the circular hole type has a high stiffness value of 89.52 N/mm and 84.99 N/mm experimentally and analytically, respectively. Figure 8 presents a detailed graphical representation of the comparison of stiffness result. Table 9 presents stiffness calculated comparison.

4.3. Load-deflection curve

The response of the channel joist subjected to flexural loading measured and described in one way is obtainable via the load–deflection curve. The deflection value is proportional to the measure of changes in the cross-section due to the application of an increment load. The displacement value highly depends on the resistance capacity of the structural element. Thus, deflection was observed via physical experiments and analytical investigations. Normally cold-formed steel solid web joist have more resistance against deflection compared to web opening joist because of lack area of web portion exist. From the result analysis, the load deflection curve was found to be consistent in both analytical and experimental investigations. From the result analysis, the load deflection curve was found to be consistent in both analytical and experimental investigations.

In the case where load values were obtained that exhibit less difference. Likewise, the deflection values showed less difference within 9%. It was observed in all specimens. Figure 9 presents the load–deflection curve comparison resulting from analytical investigation as well as experimental investigation.

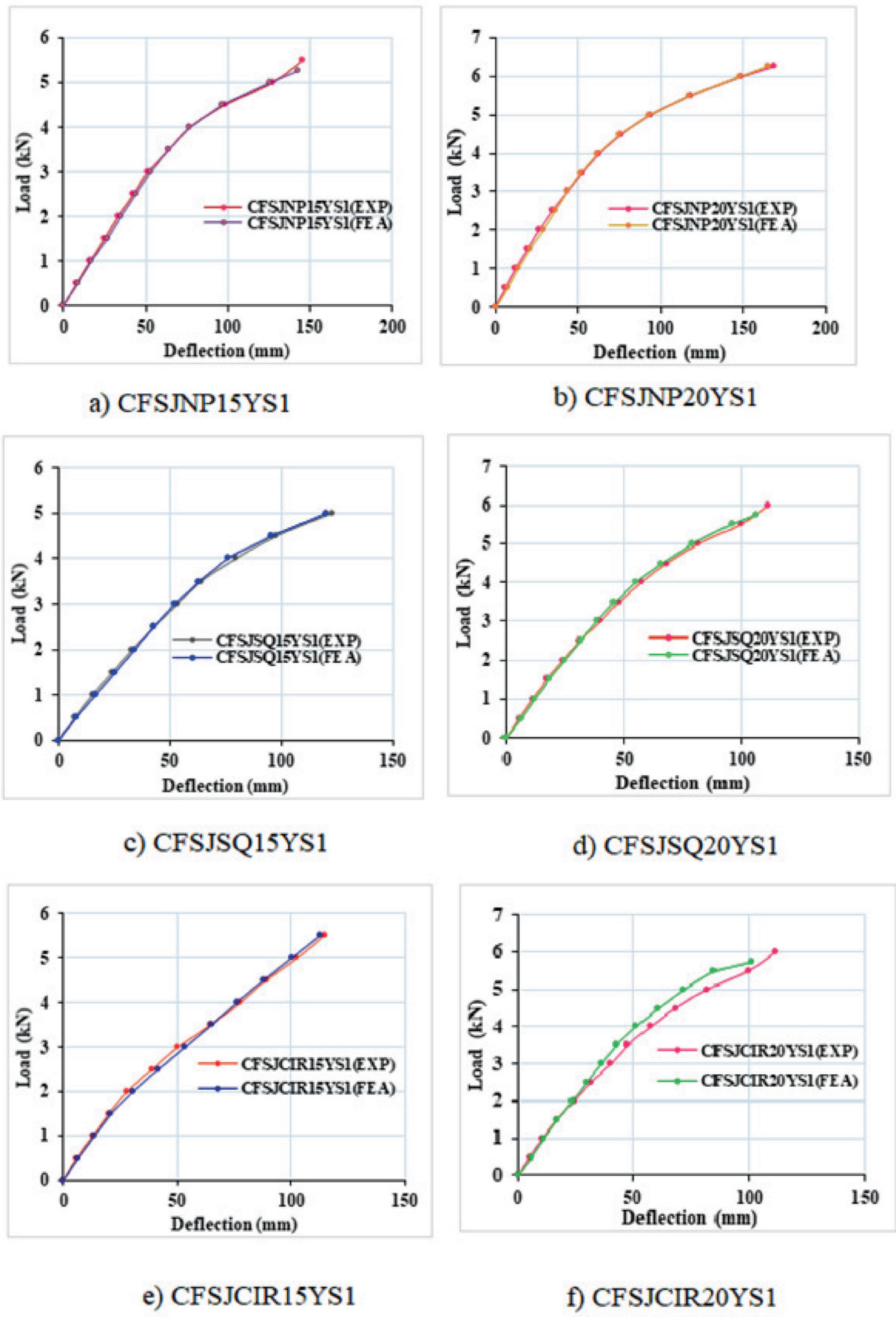


Figure 9: Load–deflection curve comparison.

5. CONCLUSION

The performance study of cold-formed steel joist channel joists with web openings subjected to flexural loading has provided valuable insights into the structural behaviour and practical applications of such members.

On the basis of the investigation outcome, valuable merit points were obtained. These are discussed as follows:

The maximum load capacity of the channel joist height 200 mm in the case without web opening was found to be 6.25 kN. Likewise, in the case of with a web opening circular type has acquired a maximum load carrying capacity 6.0 kN.

Stiffness of channel joist height 200 mm in the case without web opening, with a maximum value of 76.13 N/mm. Likewise, in the case of with a web opening circular type has acquired a maximum value of 89.52 N/mm.

It is concluded that, from the specimens used in this investigation, the channel joist with a circular web opening showed better performance than the other specimens.

In the case of channel joist with circular web opening delay and restrict residual stress releases for some extents The circular shape generally falls under the economic cross-section category and has a good shape factor. Therefore channel joist with circular web opening experiences maximum load carrying capacity compared to channel joist with solid web. Circular web opening also facilities hold and carrying electrical pipes and other steel sections.

6. ACKNOWLEDGMENTS

Thanks to Dr. Raguvaran Balasubramaniyan for providing useful comments for better drafting of this manuscript.

7. BIBLIOGRAPHY

[1] ZHAO, J., SUN, K., YU, C., *et al.*, "Tests and direct strength design on cold-formed steel channel beams with web holes", *Engineering Structures*, v. 184, pp. 434–446, 2019. doi: http://doi.org/10.1016/j.engstruct.2019.01.062.

[2] GHANNAM, M., "Bending moment capacity of cold formed steel built up beams", *International Journal of Steel Structures*, v. 19, n. 2, pp. 660–671, 2019. doi: http://doi.org/10.1007/s13296-018-0155-2.

[3] DOLAMUNE KANKANAMGE, N., MAHENDRAN, M., "Behaviour and design of cold-formed steel beams subject to lateral torsional buckling", *Thin-walled Structures*, v. 51, pp. 25–38, 2012. doi: http://doi.org/10.1016/j.tws.2011.10.012.

[4] ANBARASU, M., "Simulation of flexural behaviour and design of cold-formed steel closed built-upbeams composed of two sigma sections for local buckling", *Engineering Structures*, v. 191, pp. 549–562, 2019. doi: http://doi.org/10.1016/j.engstruct.2019.04.093.

[5] FARIDMEHR, I., OSMAN, M.H., TAHIR, M.M., *et al.*, " Behaviour and design of cold-formed steel C-sections with cover plates under bending", *International Journal of Steel Structures*, v. 16, n. 2, pp. 587–600, 2016. doi: http://doi.org/10.1007/s13296-016-6026-9.

[6] LAÍM, L., RODRIGUES, J.P.C., SILVA, L.S., "Experimental and numerical analysis on the structural behaviour of cold-formed steel beams", *Thin-walled Structures*, v. 72, pp. 1–13, 2013. doi: http://doi.org/10.1016/j.tws.2013.06.008.

[7] CHENG, S., KIM, B., LI, L., "Lateral-torsional buckling of cold-formed channel sections subject to combined compression and bending", *Journal of Constructional Steel Research*, v. 80, pp. 174–180, 2013. doi: http://doi.org/10.1016/j.jcsr.2012.07.026.

[8] EL-SHEIKH, I., EL-KASSAS, E.M.A., MACKIE, R.I., "Performance of stiffened and unstiffened cold-formed channel members in axial compression", *Engineering Structures*, v. 23, n. 10, pp. 1221–1231, 2001. doi: http://doi.org/10.1016/S0141-0296(01)00034-7.

[9] MADULIAT, S., BAMBACH, M.R., ZHAO, X.L., "Inelastic behaviour and design of cold-formed channel sections in bending", *Thin-walled Structures*, v. 51, pp. 158–166, 2012. doi: http://doi.org/10.1016/j.tws.2011.10.011.

[10] ALEX, J., IYAPPAN, G.R., "Experimental study on flexural behaviour of cold formed steel section", *Int J Res Sci Engg Tech*, v. 40, pp. 219–222, 2016.

[11] AJEESH, S.S., ARUL JAYACHANDRAN, S., "Simplified semi-analytical model for elastic distortional buckling prediction of cold-formed steel flexural members", *Thin-walled Structures*, v. 106, pp. 420–427, 2016. doi: http://doi.org/10.1016/j.tws.2016.05.015.

[12] KEERTHAN, P., MAHENDRAN, M., "Improved shear design rules of cold-formed steel beams", *Engineering Structures*, v. 99, pp. 603–615, 2015. doi: http://doi.org/10.1016/j.engstruct.2015.04.027.

[13] MEZA, F.J., BECQUE, J., HAJIRASOULIHA, I., "Experimental study of cold-formed steel built-up beams", *Journal of Structural Engineering*, v. 146, n. 7, pp. 04020126, 2020. doi: http://doi.org/10.1061/(ASCE)ST.1943-541X.0002677.

[14] YE, J., HAJIRASOULIHA, I., BECQUE, J., *et al.*, "Development of more efficient cold-formed steel channel sections in bending", *Thin-walled Structures*, v. 101, pp. 1–13, 2016. doi: http://doi.org/10.1016/j.tws.2015.12.021.

[15] LAÍM, L., RODRIGUES, J., CRAVEIRO, C., "Flexural behaviour of beams made of cold-formed steel sigma-shaped sections at ambient and fire conditions", *Thin-walled Structures*, v. 87, pp. 53–65, 2015. doi: http://doi.org/10.1016/j.tws.2014.11.004.

[16] YE, J., MEZA, F.J., HAJIRASOULIHA, I., *et al*., "Paul Shepherd and Kyron Pilakoutas experimental investigation of cross-sectional bending capacity of cold-formed steel channels subject to local distortional buckling interaction", *Journal of Structural Engineering*, v. 145, n. 7, pp. 04019064, 2019. doi: http://doi.org/10.1061/(ASCE)ST.1943-541X.0002344.

[17] AMERICAN NATIONAL STANDARDS INSTITUTE, *AISI S 100, North American Specification for the Design of Cold Formed Steel Structural Members Specifications*, Washington, D.C., ANSI, 2007.