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Structural performance of cold-formed Steel channel joist with web openings subjected to bending

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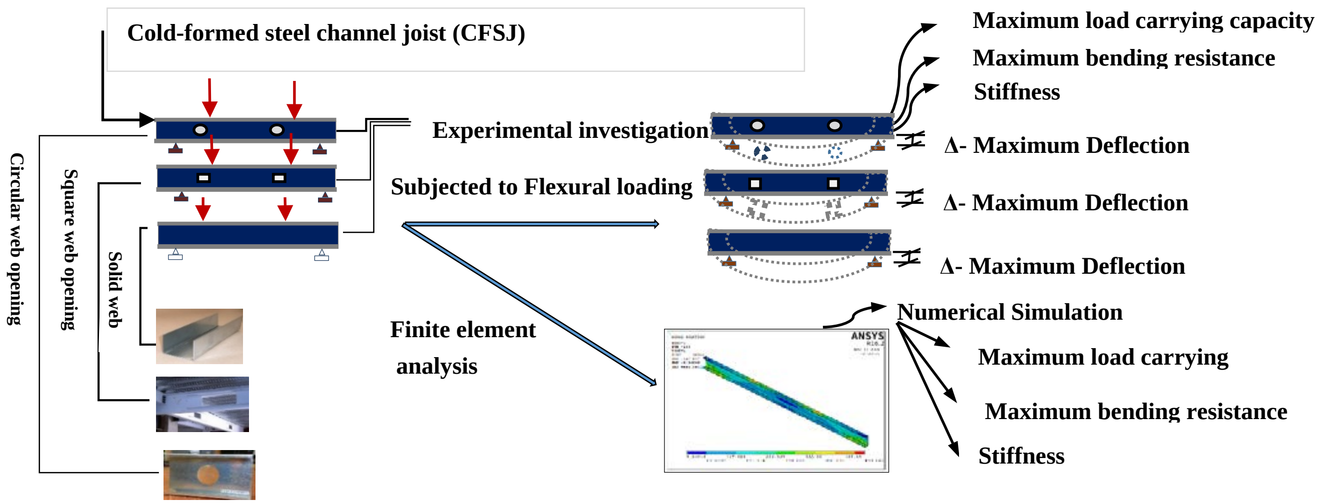
ABSTRACT



This study investigates the structural behaviour of a cold-formed steel channel joist subjected to bending. Channel joists with or without web opening were considered. Web-opening types, such as circular and square were considered. Channel joist selection for this investigation was performed on the basis of a section frequently used in construction practice. Two different heights of the joists were considered. The significant factors that influence the performance of joists subjected to bending were examined. An analytical investigation was conducted on the experimental models considered. Analytical investigation was performed using ANSYS16.2 APDL software. Thus, significant factors that influence the performance of joists subjected to bending were identified. Specifically, the maximum load-carrying capacity, load –deflection relationship and stiffness these were taken as influence factors and discussed. As a continuation of this study, a comparison of the experimental and analytical results was performed. The analysis results revealed that when joists with different web openings were observed. The circular type exhibited better performance than the other web-opening types. The circular shape generally falls under the economic cross-section category and has a good shape factor. Thus, joists with this type of web opening exhibited high stiffness and low deflection value.

Keywords: Cold-formed steel (CFS), Channel joist, Web-opening types, Finite Element Analysis (FEA), Steel structures, Static flexural loading

INTRODUCTION

Cold-formed steel is increasingly used in building construction, from residential to industrial buildings. Cold-formed steel is formed by press braking or cold rolled-forming, and there is a change in the mechanical properties of the material due to the cold working of the metal.[1]

Steel section is cold-formed from a flat sheet or strip, and the yield strength, and to a lesser extent the ultimate strength, is increased because of this cold working, particularly in the bends of the section.[2] Cold-formed steel (CFS) sections with thicknesses ranging from 0.5 mm to 6 mm have traditionally been used as secondary steelwork in buildings. Common examples include roof purlins and wall girts consisting of lipped channels, sigma or zed

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sections, as well as wall and roof cladding made of profiled sheets with thicknesses of up to 1.5 mm.Cold-formed steel joists play a significant role in load transfer components in structural frames made in light gauge construction. But this type of beam/joist subjected to bending results in buckling.[3] Web openings present in the joists can enhance the aesthetic appearance and improve the construction efficiency of cold-formed steel structural systems.[4] The finite element method is by far the most popular and general method, and it can handle practically any cross-sectional geometry and arbitrary loading and support conditions. In the finite element method, the member is discretized both within the cross-section and along its length, requiring a large number of degrees of freedom to accurately predict the stresses and deformation of the elements. Accordingly, this study investigates channel joists with varying web openings subjected to bending and attempts to identify factors that enhance the strength and stiffness of cold-formed steel joists with or without web openings.[5]

LITERATURE REVIEW

Several research studies have investigated the varying load-bearing capacities of cold-formed beams or joists without web openings under shear, bending, combined bending and shear and web crippling actions. From this, Imanfaridmehr et.al.[6] investigated the behaviour and design of cold formed steel C-sections with cover plates under bending. Cover plates with three different thickness were used to evaluate the slenderness effects on the performance of the sections installed at top flanges only where it would be predicted to fail by local and distortional buckling. The result explicitly showed that the cover plate reduced the slenderness which resulted in improving buckling capacity.In current scenario, only little work has been carried out on the structural behaviour of built up sections as flexural members. So the proposed work aims to study the structural behaviour and moment capacity of the cold formed steel built up I beams A. M. Anbarasu[7] 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. 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 Wang and Young[8] experimentally investigated the flexural behaviour of built-up CFS members with open and closed cross-sectional geometries and with circular web holes, with the aim of extending the direct strength method (DSM) to cover these types of members. The open geometry consisted of two lipped channels screw connected in a back-to-back configuration, while the closed cross section was assembled from two plain channels screwed together through their flanges. The authors explored different ways of calculating the elastic buckling stresses required as input to the DSM, in order to account for the effects of the connectors and the web openings.

MATERIAL AND METHODS

Methods included in this study involve experimental investigation of cold-formed steel channel joist, with/without web opening including material testing. In addition, for scrutiny, analytical investigations involve a finite element analysis procedure using ANSYS version 16.2 APDL finite element modelling software. The finite element models were developed on the basis of the experimental prototype model.[9]

The channel joist comprises cold-formed steel. The properties of steel also influence the assessment of the load-carrying capacity of the member and the deformation characteristics of the structural member. In this study, to identify the material properties, mechanical property tests were conducted on sample specimens prepared according to the ASTM standards. Prior to the main flexural 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 1 presents the mechanical properties of the steel materials.

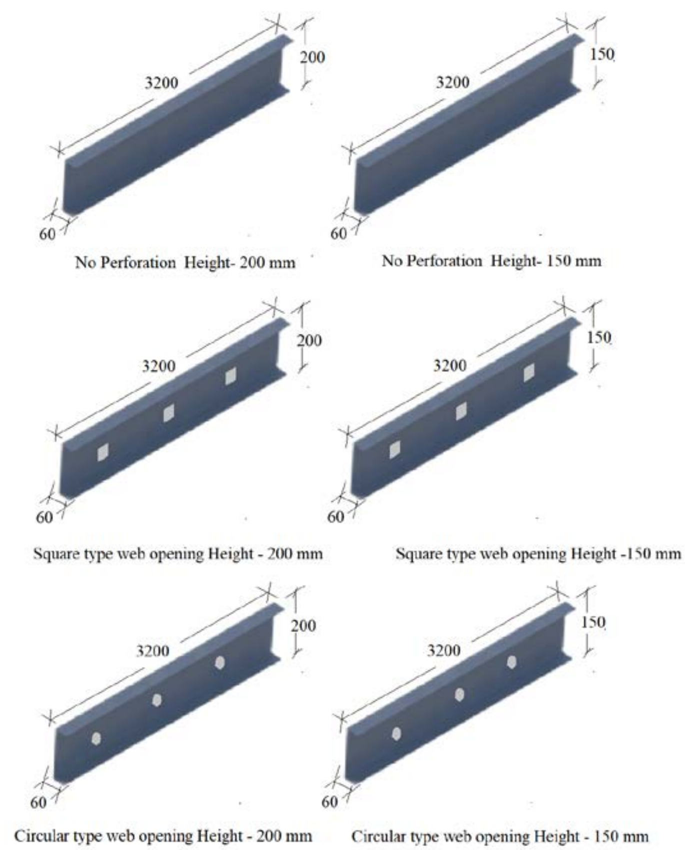

Figure 1. Geometry details of Channel joist with and without web opening

Table 1 Mechanical Properties of Cold-formed steel

Material	Yield strength (N/mm^2)	Ultimate rength (N/mm^2)	Elastic modulus (N/mm^2)	Elongation (mm)
Grade 2 (YS2)	345	460	$2.02x10^5$	16

The sectional properties of the selected sections for joists were obtained from the IS811 specification for cold-formed light gauge structural steel sections. The cross dimensions for the joist were decided on the basis of the AISI specification for cold-formed steel constructions and factory practise specifications. Figure 1 depicts the geometry details of the channel joist specimen. Table 2 depicts geometric details of testing specimens 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.[10,11]

Table 2 Geometry details of Cold-formed steel frame models.

S. No	Beam designation	Joists section (mm)	Joists Depth (mm)	Web opening type	Size of web opening Radius/side (mm)
1	CFSJNP20YS2	200 X 60 X 2.5	200	No perforation	-
2	CFSJNP15YS2	150 X 60 X 2.5	150	No perforation	-
3	CFSJSQ20YS2	200 X 60 X 2.5	200	Square	44.3
4	CFSJSQ15YS2	150 X 60 X 2.5	150	Square	44.3
5	CFSJCIR20YS2	200 X 60 X 2.5	200	Circle	25
6	CFSJCIR15YS2	150 X 60 X 2.5	150	Circle	25

EXPERIMENT PROGRAM

Experiment investigations were conducted on cold–formed steel channel joist specimen in a structural testing laboratory. Figure 2 depicts the processed joist specimen prepared for the experimental work. Fig. 3 presents a schematic of the loading arrangements and instrumentation for measuring deflection. 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.[3,12] 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 centre 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.[13]

a) Cold-formed steel channel joist specimens 200 mm height.

b) Cold-formed steel channel joist specimens 150 mm height.

Figure 2 Test Specimen completed for testing

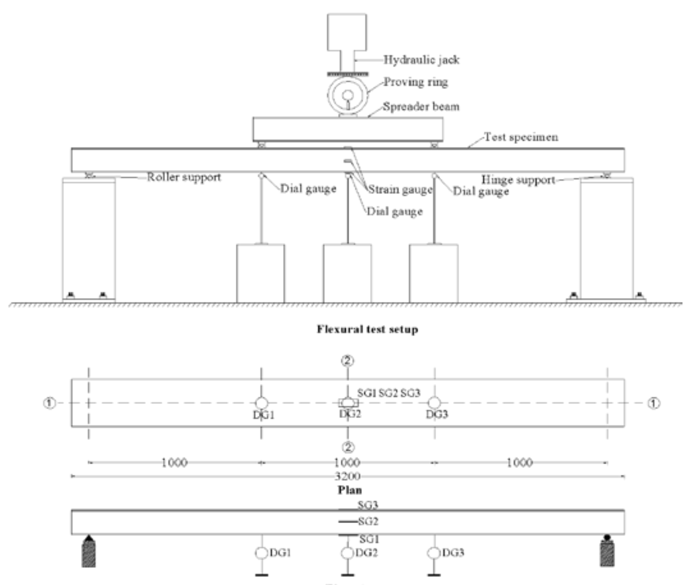

Figure 3 schematic diagram of test setup

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. Figure 4 presents captured picture of experiment done on channel joist specimen.

Figure 4 Experiment setup (Ex.CFSJSQ20YS2)

Analysis 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.[13] 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 6.75 kN. Similarly, the down step channel joist with rectangular web-opening joists had a maximum load of 6.00 kN. Similarly, channel joists with circular web-opening joists had a maximum load of 6.5 kN. Likewise, in the case without web opening joists, the maximum deflection measured was 117.89 mm. similarly, the deflections recorded for rectangular web opening joists and circular web opening joists were 98.42 mm and 99.56 mm, respectively. Table 3 result summary of laboratorial tested CFS joist specimens.

Table 3 Geometry details of Cold-formed steel frame models.

S. No	Joist designation	Maximum load (kN)	Maximum Central Deflection (mm)	Maximum Strain (mm/mm)	Stiffness (N/mm)
1	CFSJNP20YS2	6.75	117.89	0.0024	100.65
2	CFSJNP15YS2	5.75	96.12	0.0022	71.74
3	CFSJSQ20YS2	6.00	98.42	0.0027	115.41
4	CFSJSQ15YS2	5.50	84.77	0.0025	84.77
5	CFSJCIR20YS2	6.50	99.56	0.0028	131.32
6	CFSJCIR15YS2	5.75	86.42	0.0029	130.72

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 element analysis software Ansys 16.2 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. SOLID185 is used for the 3D modeling of solid structures. It is defined by eight nodes with three degrees of freedom at each node: translations in the nodal x, y, and z directions. The element exhibits plasticity, hyper elasticity, stress stiffening, creep, large deflection, and large strain capabilities. It also has a mixed formulation capability for simulating the deformations of nearly incompressible elastoplastic materials and fully incompressible hyperelastic materials. To obtain accurate results, mapped mesh types were employed.

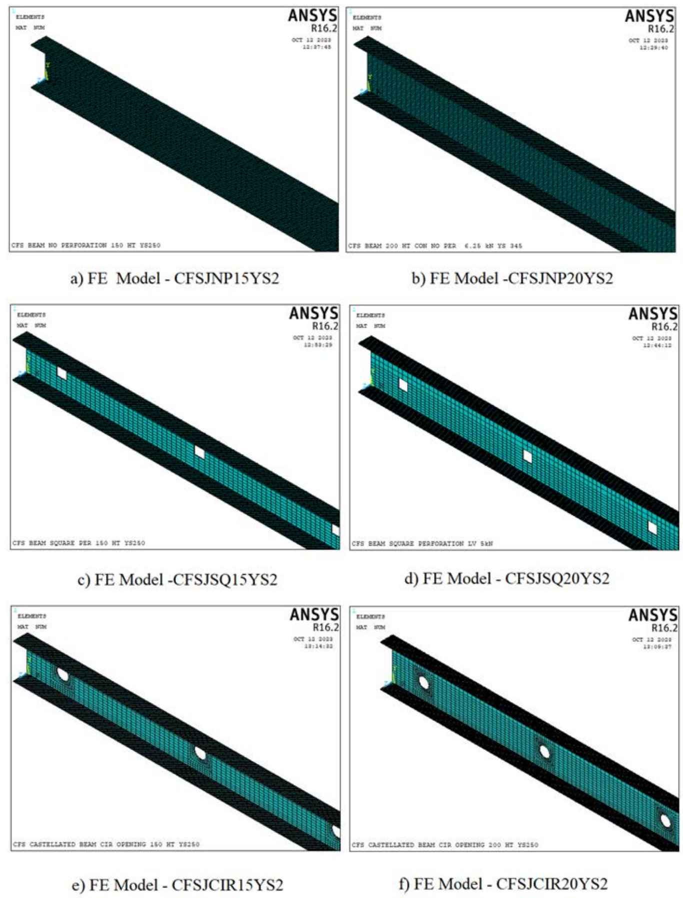

Figure 5 Finite element discretized models

Keeping a regular element size of 25 X 25 mm and changing suitable open web shapes was done. A full FE model was developed. Figure 5 presents the FE models developed for the finite element analysis. Likewise figure 6 presents force and support condition assigned according to 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.

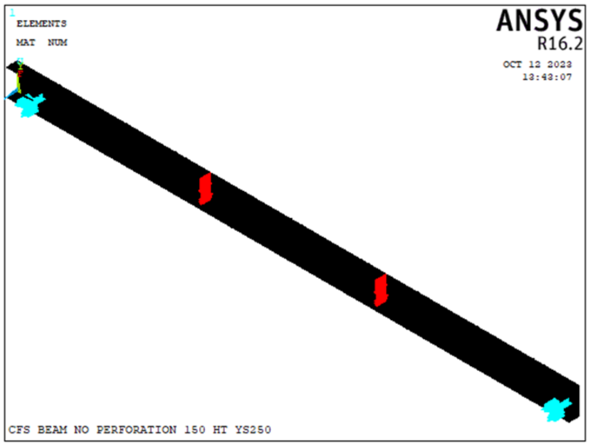

Figure 6. Force applied and support condition assigned in FE model

Table 4. Material properties input into FE model

S.No	Element type	Material properties input
1.	Solid185	Young's Modulus EX: 2.02X 10^5 MPa Poisson's ratio PRXY: 0.2 Yield Stress: 345 MPa Tangent modulus 8000 MPa

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.

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 5.75 kN. Likewise, the channel joist without opening model with a height of 200 mm had a maximum force resisting capacity of 6.50 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 5.25 kN, respectively.[14] Likewise, the circular web-opened channel joist model with heights of 150 and 200 mm acquired maximum force resisting capacities of 5.50 and 6.0 kN, respectively. Table 5 summarises the results of the maximum force resisting capacity. Figure 7 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 carrying capacity (kN)	Maximum Stress (N/mm^2)
1.	CFSJNP20YS2	200	6.50	493.64
2.	CFSJNP15YS2	150	5.75	542.59
3.	CFSJSQ20YS2	200	5.75	564.76
4.	CFSJSQ15YS2	150	5.25	619.69
5.	CFSJCIR20YS2	200	6.00	524.69
6.	CFSJCIR15YS2	150	5.50	645.33

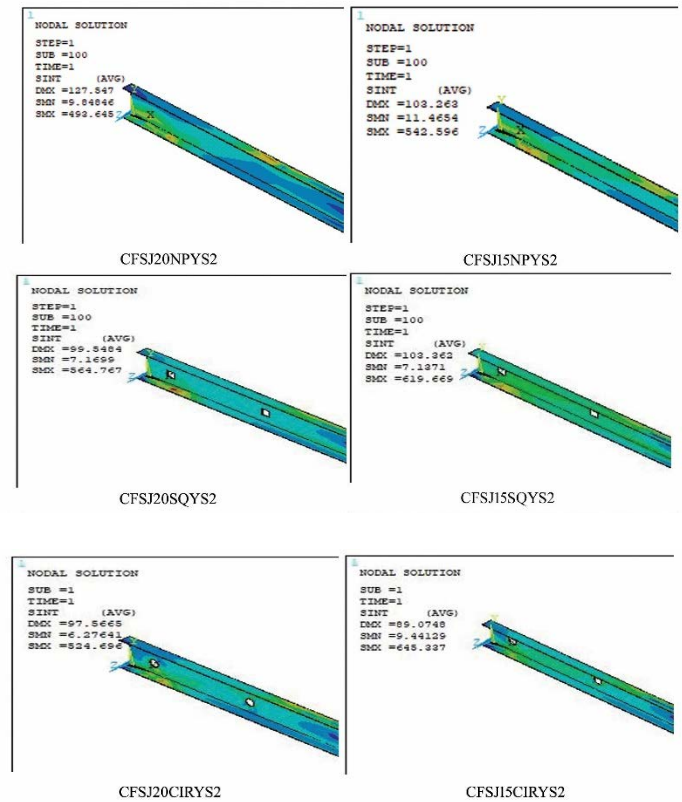

Figure 7. Stress contour diagram

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 100.65 N/mm. The channel joist without a web opening of 150 mm height acquired a low stiffness value of 70.54 N/mm. Similarly, the channel joist with the web opening square type 200 height model had a high stiffness value of 96.25 N/mm. The channel joist without a web opening of 150 mm height acquired a low stiffness value of 89.37 N/mm. Likewise, the channel joist with the web-opening circle type 200 height model had a high stiffness value of 121.36 N/mm. A channel joist with a web-opening-type circle 150 mm in height acquired a low stiffness value of 121.65 N/mm table 6 presents the results obtained through finite element analysis.

Table 6 FEA result stiffness

S.No	Joist designation	Maximum load Load carrying capacity (kN)	Maximum Central Deflection (mm)	stiffness N/mm
1.	CFSJNP20YS2	6.75	127.54	76.22
2.	CFSJNP15YS2	5.75	103.36	70.54
3.	CFSJSQ20YS2	6.00	101.12	96.25
4.	CFSJSQ15YS2	5.50	89.37	89.37
5.	CFSJCIR20YS2	6.50	97.56	121.36
6.	CFSJCIR15YS2	5.75	89.07	121.65

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 a web opening with a height of 200 mm had a maximum displacement of 127.54 mm. The maximum deflection found for a height of 150 mm was 96.12 mm. In the case of the channel joist with a web opening of 200-mm height square type, the maximum displacement value was found 101.12 mm. Similarly, for a height of 150 mm, the maximum deflection was found 85.86 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 97.56 mm. Similarly, for a height of 150 mm, the maximum deflection was 89.07 mm. Table 7 presents the results of the maximum deflection corresponding to the maximum failure loads.

Table 7 FEA results Load - deflection

S. No	Joist designation	Maximum load load carrying capacity (kN)	Maximum Central Deflection (mm)
1.	CFSJNP20YS2	6.50	127.54
2.	CFSJNP15YS2	5.75	103.36
3.	CFSJSQ20YS2	5.75	101.12
4.	CFSJSQ15YS2	5.25	85.86
5.	CFSJCIR20YS2	6.00	97.56
6.	CFSJCIR15YS2	5.50	89.07

RESULT AND DISCUSSION

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 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 6.75 kN in the case of channel joist without web opening having a height of 200 mm.The maximum load carrying capacity was found 6.00 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 6.50 KN in the case of channel joist with circle web opening having a height of 200 mm. In the case of cold-formed steel structural elements residual stress is the significant factor. It seems amount of residual stress leads the cold formed steel made member when subjected to loading that fluctuates strength of the member. In the case of channel joist with circular web opening delay and restrict residual stress releases for some extents. Therefore channel joist with web opening experiences maximum load carrying capacity compared to channel joist with solid web. Table 8 maximum load carrying capacity results comparison.

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.	CFSJNP20YS2	6.75	6.50	3.70
2.	CFSJNP15YS2	5.75	5.75	-
3.	CFSJSQ20YS2	6.00	5.75	4.17
4.	CFSJSQ15YS2	5.50	5.25	4.55
5.	CFSJCIR20YS2	6.50	6.00	7.69
6.	CFSJCIR15YS2	5.75	5.50	4.35

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 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 100.65 N/mm and 76.22 N/mm experimentally and analytically, respectively. In the case of channel joists with a web opening 200 mm in height, the circular open type has a high stiffness value of 131.32 N/mm and 121.36 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.

Table 9 Result analysis stiffness

S. No	Joist designation	Stiffness (mm) (EXP)	Stiffness (N/mm) (FEA)	variation in load stiffness (%)
1.	CFSJNP20YS2	100.65	76.22	24.27
2.	CFSJNP15YS2	71.74	70.54	1.67
3.	CFSJSQ20YS2	115.41	96.25	16.60
4.	CFSJSQ15YS2	105.4	89.37	15.21
5.	CFSJCIR20YS2	131.32	121.36	7.58
6.	CFSJCIR15YS2	130.72	121.65	6.94

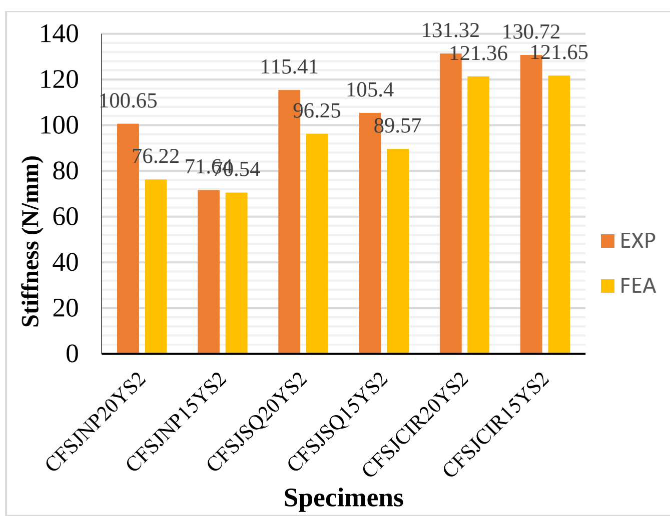

Figure 8 Comparison graph Stiffness results

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 displacement 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, displacement was observed via physical experiments and analytical investigations. 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 8 %. It was observed in all specimens. Figure 9 presents the load–deflection curve comparison resulting from analytical investigation as well as experimental investigation.[8,10,15,16]

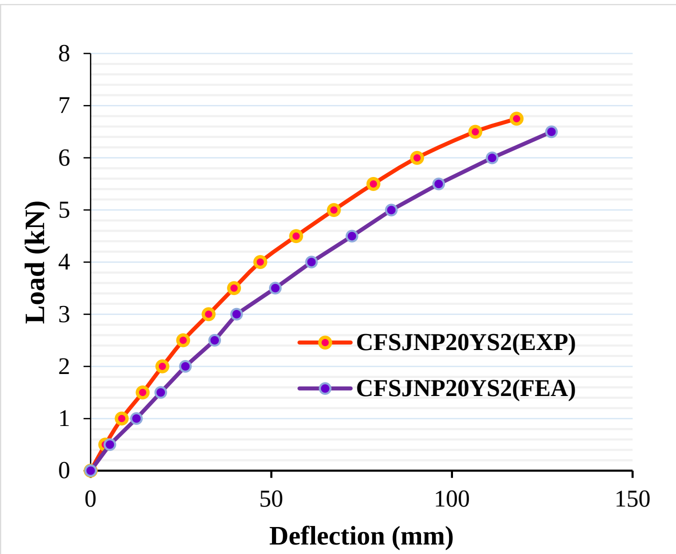

Figure 9 a. Load -Deflection – CFSJNP20YS2

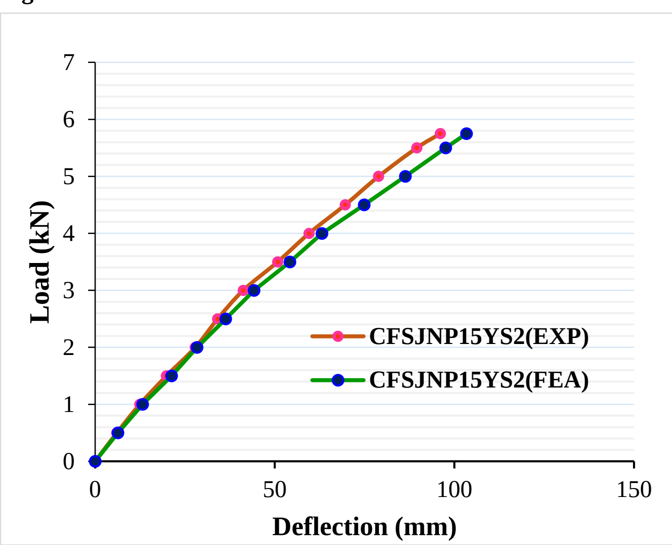

Figure 9 b. Load -Deflection – CFSJNP15YS2

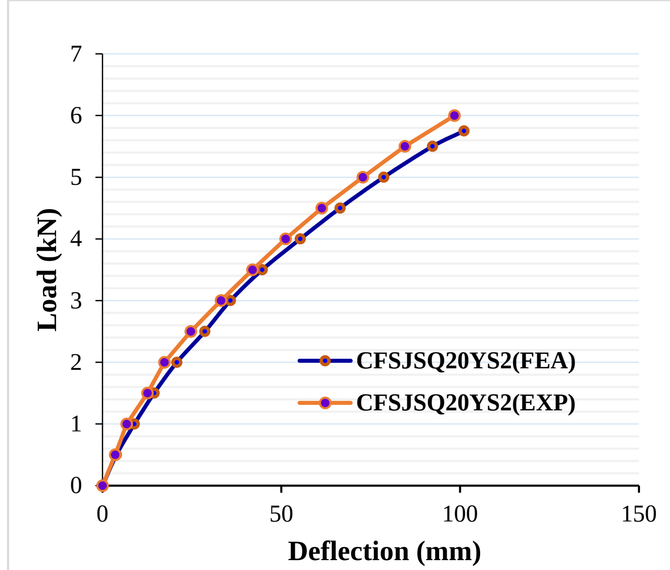

Figure 9 c. Load -Deflection – CFSJSQ20YS2

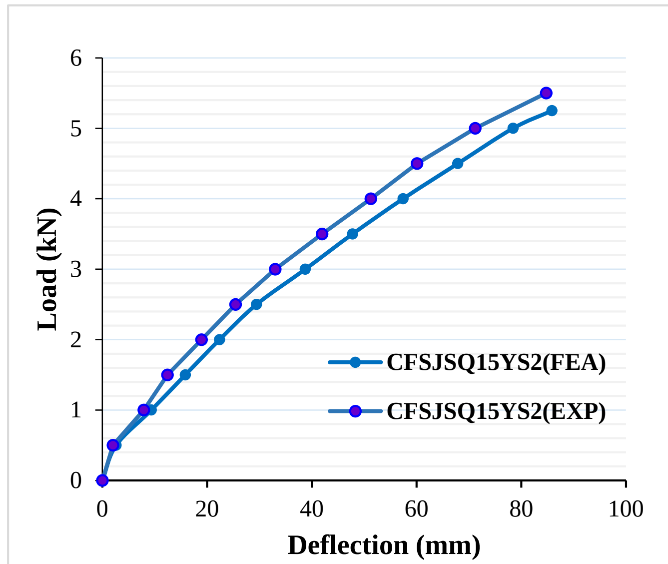

Figure 9 d. Load -Deflection – CFSJSQ15YS2

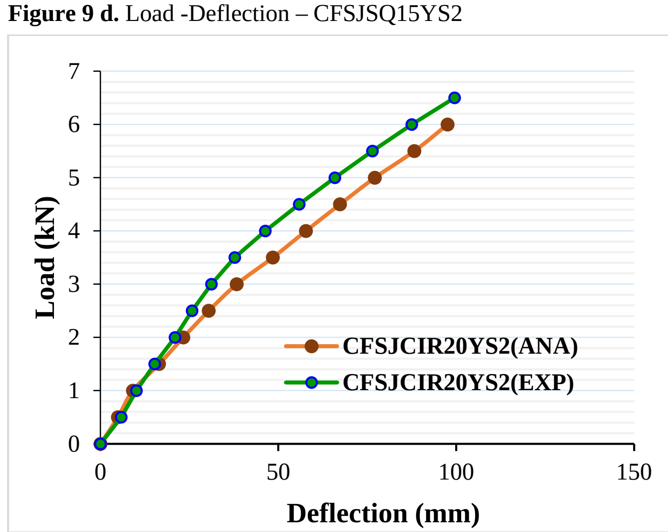

Figure 9 e. Load -Deflection – CFSJCIR20YS2

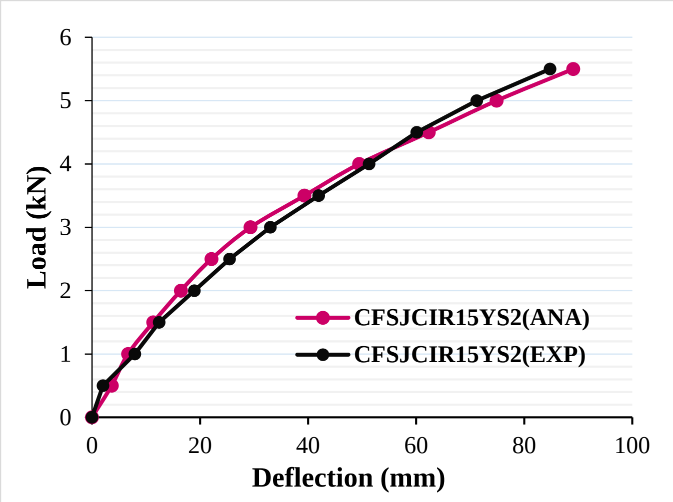

Figure 9 f. Load -Deflection – CFSJCIR15YS2

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 6.75 kN. Likewise, in the case of with a web opening circular type has acquired a maximum load carrying capacity 6.5 kN. Stiffness of channel joist height 200 mm in the case without web opening, with a maximum value of 100.65 N/mm. Likewise, in the case of with a web opening circular type has acquired a maximum value of 130.72 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.

CONFLICT OF INTEREST STATEMENT

Authors declare that there is no conflict of interest for this work.

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