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Flexural Behaviour of CFS Gapped Built-Up Channel Beam with Web and Flange Stiffeners

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CFS built-up beam, channel section, back-to-back, web stiffeners, flange stiffeners, ANSYS

Abstract

This study investigates the structural performance of cold-formed steel (CFS) gapped built-up beams with flange and web stiffeners, focusing on load-carrying capacity and deflection characteristics. Experimental tests and finite element (FE) analysis were conducted to evaluate the influence of varying stiffener configurations and gap sizes on beam behavior under four point bending. Results indicate that beams with flange stiffeners exhibit higher load-carrying capacity and greater resistance to deflection compared to those with web stiffeners, due to improved stability against bending stresses. Increasing gap between the back to back channel from 25 to 100 mm was found to affect load distribution and deflection, with moderate gaps (50 mm) yielding optimal performance. The FE model showed good correlation with experimental results, though deflection under ultimate loads was slightly underpredicted, highlighting the impact of real-world imperfections. These findings provide valuable insights for designing optimized CFS gapped beams with enhanced structural efficiency by providing flange and web stiffeners for practical applications.

1. Introduction

Cold-formed steel (CFS) members have become increasingly popular in modern structural applications due to their lightweight, high strength-to-weight ratio, and ease of fabrication. CFS members, particularly in built-up sections, offer enhanced performance for structural systems, as their customized geometry can address specific load and stiffness requirements. Built-up beams, created by connecting CFS channels back-to-back, have been widely explored for their advantages in load-carrying capacity and flexural performance. However, due to the thin-walled nature of CFS, these sections are vulnerable to various buckling modes, including local, distortional, and global buckling, which can limit their load-carrying capacity and overall structural integrity [1], [2]. The introduction of gaps between CFS channel sections in a built-up beam has shown potential to alter the load-distribution mechanism and increase stability. These gapped built-up beams are subjected to complex behaviors, including interaction between the webs and flanges, which influences both the bending and shear resistance of the beam. Recent studies have indicated that an appropriate gap between channels in back-to-back configurations can affect the load-carrying capacity, deformation patterns, and failure modes, by providing some flexibility to the system and redistributing stresses [3], [4]. Despite the promising benefits, the gapped configuration introduces further complexities in terms of stability and buckling behavior, necessitating detailed investigations through both experimental studies and finite element (FE) modeling.

In addition to the gap, the incorporation of flange and web stiffeners has been investigated as an effective measure to enhance the load-carrying capacity of CFS beams. Flange stiffeners are known to provide lateral support, reducing the likelihood of lateral-torsional and distortional buckling, particularly under bending stresses.

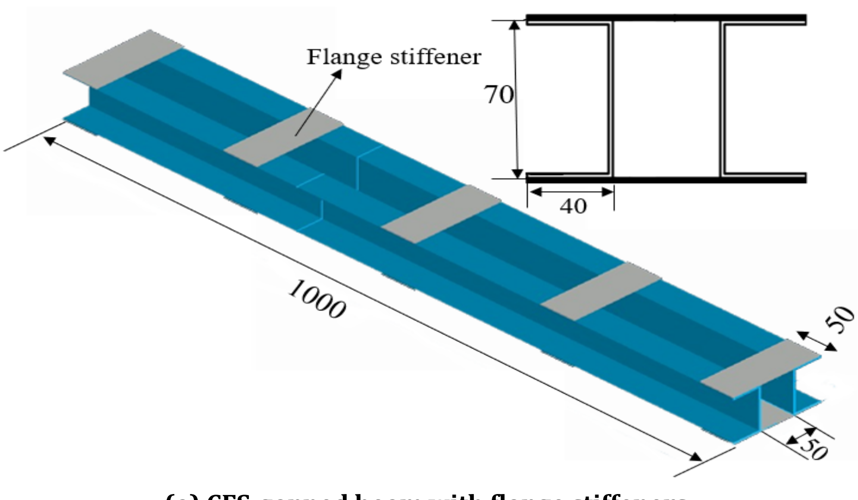
Web stiffeners, on the other hand, are more effective in preventing shear buckling in the web, though they may have limited impact on the bending strength [5], [6]. Studies by Wang *et al.* [7] and Deng *et al.* [8] highlighted that flange stiffeners contribute significantly to the moment capacity, while web stiffeners are crucial in resisting shear forces, but their relative impact varies depending on the gap size and the configuration of the CFS beam. Experimental and numerical studies have been essential in understanding the behavior of these gapped CFS built-up beams. Finite element modeling provides a powerful tool for predicting structural responses under various loading conditions and configurations. By incorporating factors like initial imperfections, material nonlinearity, and boundary conditions, FE models can closely approximate experimental outcomes and offer insights into optimal design parameters [9]. Validation of these FE models through experimental testing is critical for confirming the model's accuracy and applicability in real-world scenarios, especially since CFS members are highly sensitive to imperfections and localized buckling [10].

Despite these advances, there is still a gap in the literature regarding the load-strain behavior of CFS gapped beams with different stiffener configurations and varying gap sizes. The current study aims to address this gap by investigating the comparative effect of flange and web stiffeners on the load-carrying capacity, deformation characteristics, and failure modes of gapped CFS built-up beams. Experimental results and FE simulations will be used to analyze the effects of varying the gap size, providing a comprehensive understanding of how these design parameters influence the structural performance of CFS built-up beams. The outcomes of this study will contribute to optimized design practices, enhancing the structural reliability and load efficiency of CFS systems.

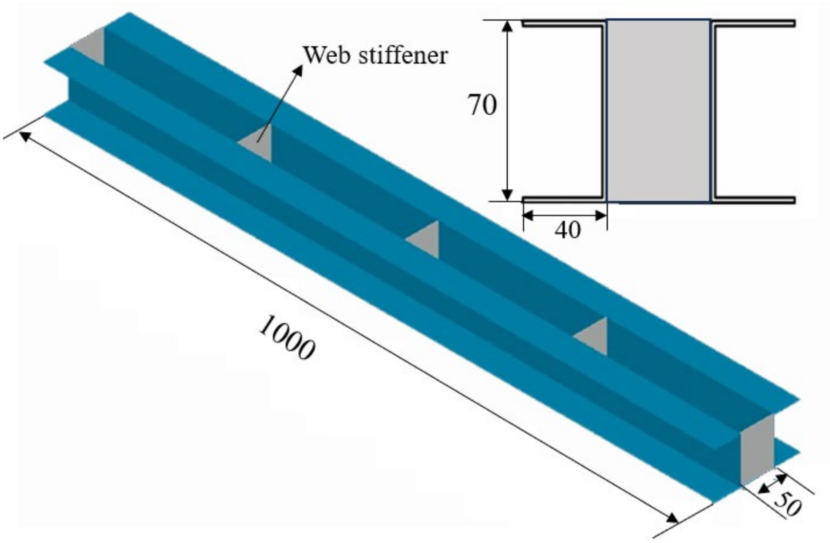
2. Materials and Methods

2.1 Experimental Study

In test program, back – to – back-channel arrangement [11] of CFS built-up Gapped Beam (GB) with Flange Stiffener (FS) and Web Stiffener (WS) were fabricated and tested to failure under four-point bending. The gap between the back – to – back-channel section varied in the beam are 25 mm, 50 mm, 75 mm and 100 mm. All eight specimens were fabricated from 2 mm thick CFS. The channel section of 70 x 40 x 2 mm was arranged back-to-back with the gap of 25 mm to 100 mm. The channel sections are held in position by welding five numbers of web and flange stiffeners at equal spacing in the beam of length 1000 mm. In this study, five stiffeners were used for both flange and web configurations based on a combination of practical fabrication feasibility, symmetry, and effective buckling control along the beam length. The beam specimens were designed with a total span of 1.0 m, and stiffeners were placed symmetrically, dividing the span into four equal segments of 250 mm. This spacing ensures that each segment remains below the critical buckling length for local and distortional buckling modes, which are common in cold-formed steel elements. The use of five stiffeners was based on design standards, literature, and FE analysis. Prior studies and AISI S100-16 recommend intermediate stiffeners to control local and distortional buckling when slenderness is high. The length of the flange stiffeners varied based on the gap between the channel section but width is uniform as 50 mm. Similarly, the width of the web stiffeners varied based on the gap between the channel section but the height is constant as 70 mm. The Fig. 1(a) and (b) show the specification of CFS gapped beam with web stiffener and flange stiffeners.



(a) CFS-gapped beam with flange stiffeners



(b) CFS-gapped beam with web stiffeners

Fig. 1 *Specification and details of stiffeners in the CFS gapped beam*

Fig. 2 describes the labelling of the specimens followed in the study. In which cold-formed steel (CFS), Gapped Beam (GS), Web Stiffener (WS), Flange Stiffener (FS), and the number (25, 50, 75, 100) is the spacing between the back-to-back channel section. The detailed dimensions of the specimens are tabulated in Table 1.

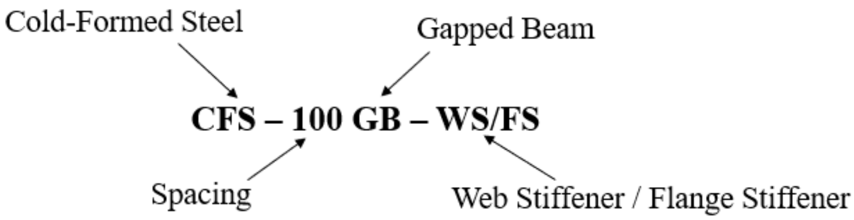
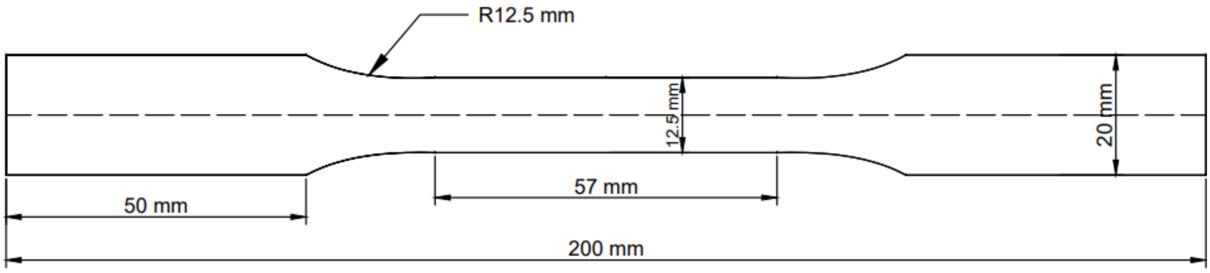


Fig. 2 *Specimen labelling*

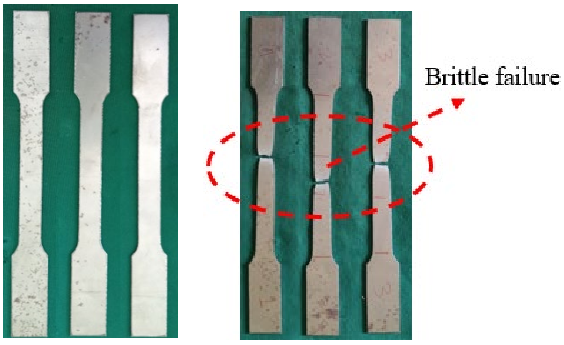
Table 1 *Dimensions of the CFS-gapped beam specimens*

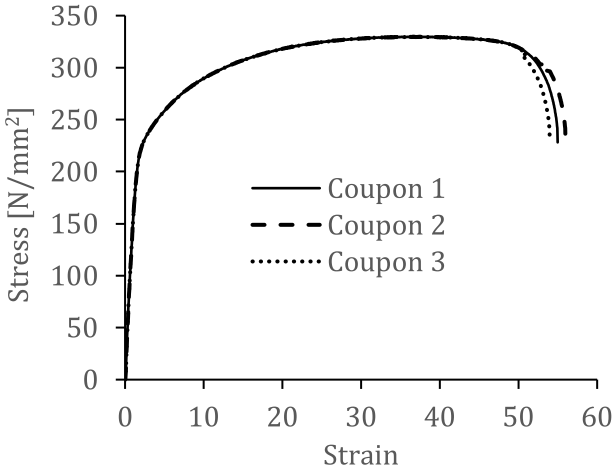
Specimen ID	Length L	Channel section d x b x t	Spacing -	Flange Stiffener L x b x t	Web Stiffener b x d x t
			mm		
CFS-25GB-FS	1001	70 x 40 x 2	25	105 x 50 x 2	-
CFS-50GB-FS	1002	70 x 40 x 2	50	130 x 50 x 2	-
CFS-75GB-FS	999	70 x 40 x 2	75	155 x 50 x 2	-
CFS-100GB-FS	1001	70 x 40 x 2	100	180 x 50 x 2	-
CFS-25GB-WS	1003	70 x 40 x 2	25	-	25 x 70 x 2
CFS-50GB-WS	998	70 x 40 x 2	50	-	50 x 70 x 2
CFS-75GB-WS	1005	70 x 40 x 2	75	-	75 x 70 x 2
CFS-100GB-WS	1004	70 x 40 x 2	100	-	100 x 70 x 2

The tension coupon test was conducted for three samples whose standard dimension are as per ASTM and it was shown in Fig. 3(a). All the coupon specimen fails in the neck and necking failure was observed. The specimen before and after failure was shown in Fig. 3(b). The stress and strain values were plotted and the yield strength, ultimate strength and modulus of elasticity obtained are 262 N/mm^2, 315N/mm^2, and 2.04 x 10^{5}N/mm^2, respectively.



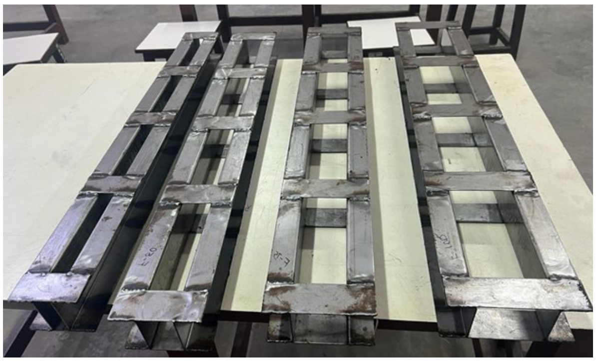
(a) Details of coupon specimen



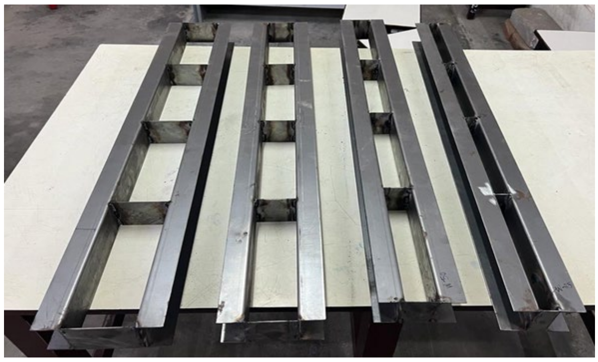


(b) Coupon specimen before and after test **(c) Stress – strain curve of coupon specimens**

Fig. 3 *Coupon test specimens and its stress-strain curves*



(a) CFS-gapped beam with flange stiffener



(b) CFS-gapped beam with flange stiffener

Fig. 4 *CFS gapped built-up beam specimens with stiffeners*

The CFS gapped built-up beams are supported at the ends and tested to failure under four-point bending. The loads are applied using a 600 kN capacity Universal Testing Machine, all eight CFS gapped beam with stiffeners were loaded until they fail by bending. Hydraulic stroke control was used to apply a displacement rate of 0.5 mm/min. Using a dial gauge with a count of 0.01 mm, the central vertical deflections were measured. Fig. 5 illustrates the schematic and experimental test setup. Using a 20 mm strain gauge pasted horizontally along the length of the beam to measure the strain in x- direction of the gapped built-up beams. The 5-channel strain indicator was deployed to measure the strain levels as shown in Fig. 5. All of the gapped beams were tested until the maximum load was reached, and the deflection and strain were measured for every 2 kN load interval.

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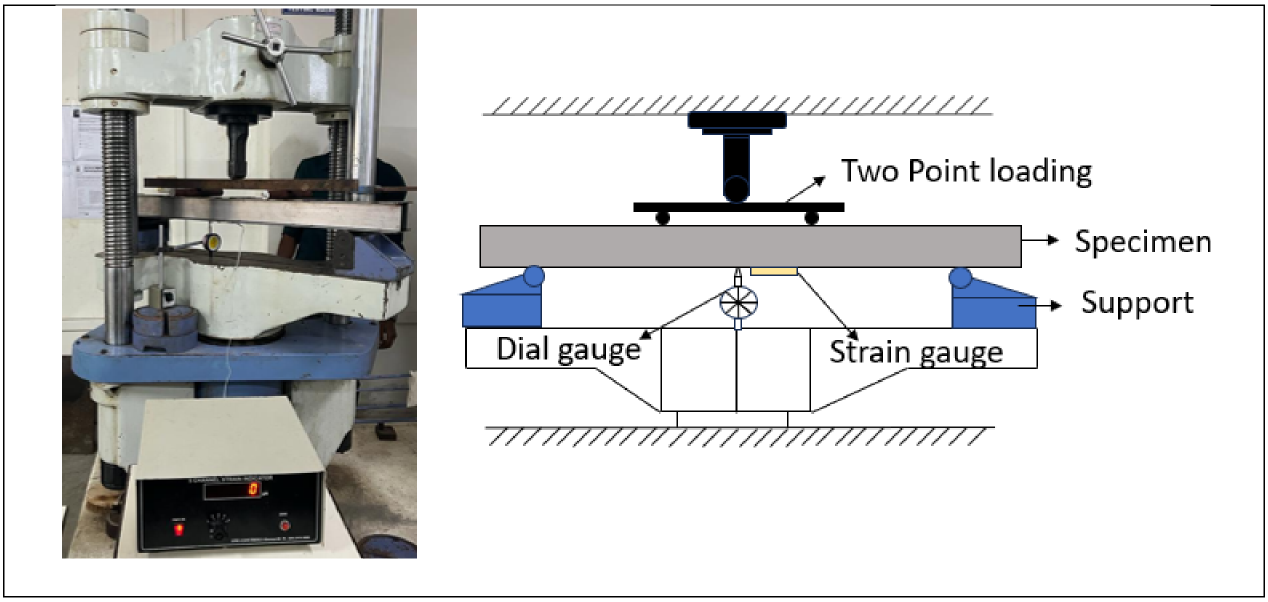


Fig. 5 *Test set-up and specimen under testing*

2.2 Numerical Study

All CFS built-up beams are modelled using AutoCAD and imported into the ANSYS programme. The CFS gapped beam with stiffeners was meshed using element SOLID 185 from the available element collection of ANSYS. Fig. 6 shows the mesh model of CFS gapped beam with flange stiffeners. In the FE model, a nominal yield strength of 250 MPa was adopted, consistent with standard design values specified in AISI S100-16. Although coupon tests indicated a slightly higher average yield strength of about 262 MPa, the nominal value was used to maintain a conservative approach. An elastic–perfectly plastic model without strain hardening was assumed to avoid overestimation of stiffness and capacity. The simple support conditions in terms of displacement and rotation are simulated in the FEA at the ends of the beam [12]. The translations along x, y and z were also constrained at the ends. The load was applied in increments as sub-steps using Newton-Raphson method from ANSYS library [13]. The overall imperfection was taken as 1/1000 of the overall length of the beam, including both the initial bending of the member and initial eccentricity of the loading. For each incremental step of central deflection, the total reaction at the end is obtained. Using, 'UPGEOM' command in ANSYS, local flange buckling and torsional buckling was obtained. To validate the results, the material properties acquired from the experimental study were allocated to the built-up-beam models. The load was applied at two points at the distance of L/3 from either of the support.

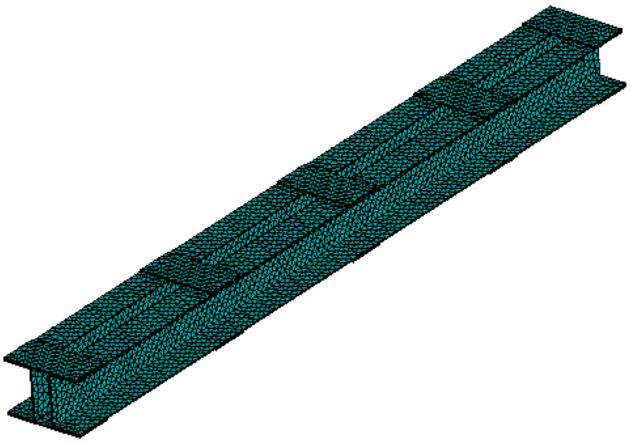


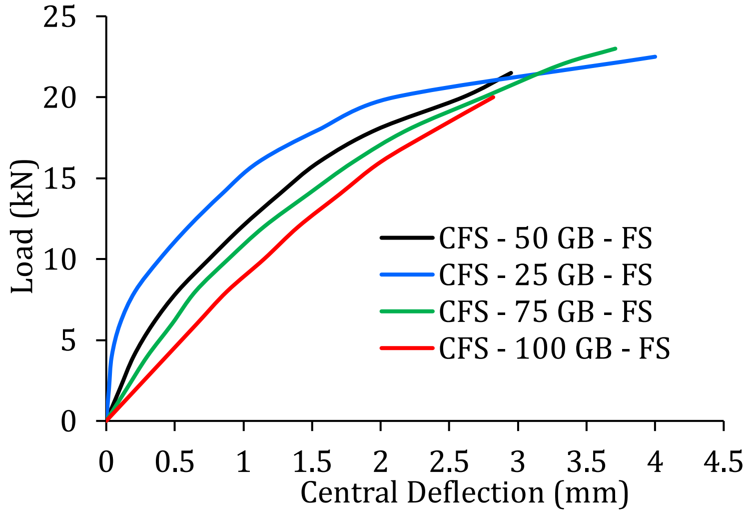
Fig. 6 *Finite element mesh model of the CFS – 50GB – FS*

3. Result and Discussion

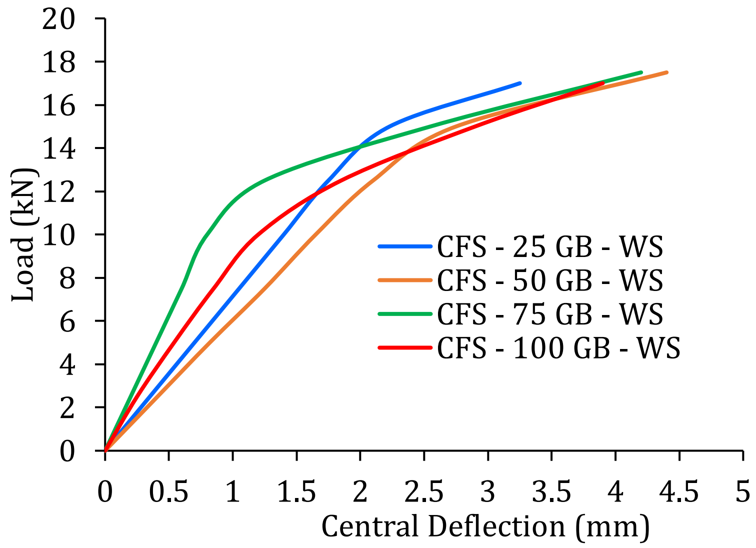
3.1 Load-Central Deflection Behaviour of Gapped CFS Built-Up Beam

The deflection measured at the mid span of the gapped beam specimen were plotted against the corresponding load applied. Fig. 7(a) and Fig.7(b) shows the load-deflection behaviour of the CFS-Built-up gapped beam with flange and web stiffeners respectively. Fig 7(a) describes that increase the gap between back-to-back channel section of the built-up beam with flange stiffeners, reduces the load carrying capacity and stiffness. The increase in gap reduces the bending strength by 7%, this may be because of as gap increases, the distance from the neutral axis to the outermost fibre decreases, which in turn reduces the section modulus and moment of inertia. The reduction in overall central deflection of gapped beam was observed due to lateral supports or partial loading by flange stiffeners. The presence of the flange stiffeners changes the distribution of stress along the flanges that potentially reduces the overall deflection.

From Fig. 7(b) it was observed that the built-up beam CFS - 25 GB – WS and CFS – 50GB – WS were found to be less stiff than the specimen CFS - 75 GB – WS and CFS - 100 GB – WS. The stiffness of a CFS gapped beam with web stiffeners increases with the gap between the back-to-back channels increases, thus web stiffeners become more effective at preventing local web buckling, improving shear resistance, and stabilizing the webs. This allows the beam to utilize the increased section width and moment of inertia, leading to a stiffer response.



(a) CFS-gapped beam with flange stiffeners



(b) CFS-gapped beam with web stiffeners

Fig. 7 *Load-central deflection curve of CFS gapped beam specimens*

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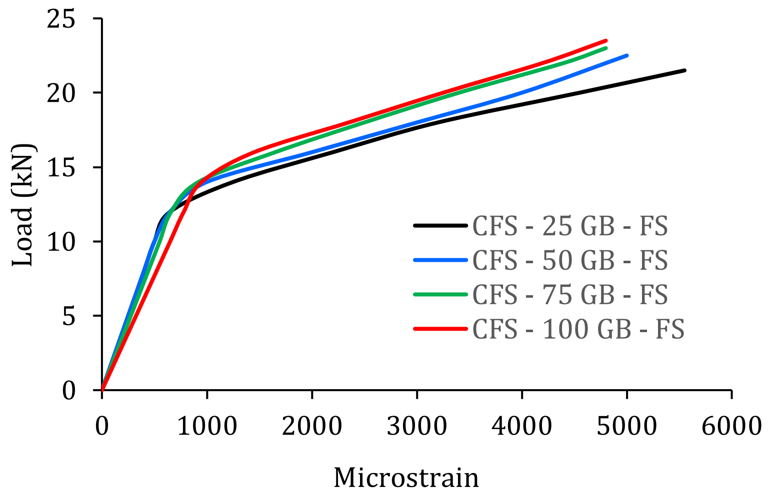
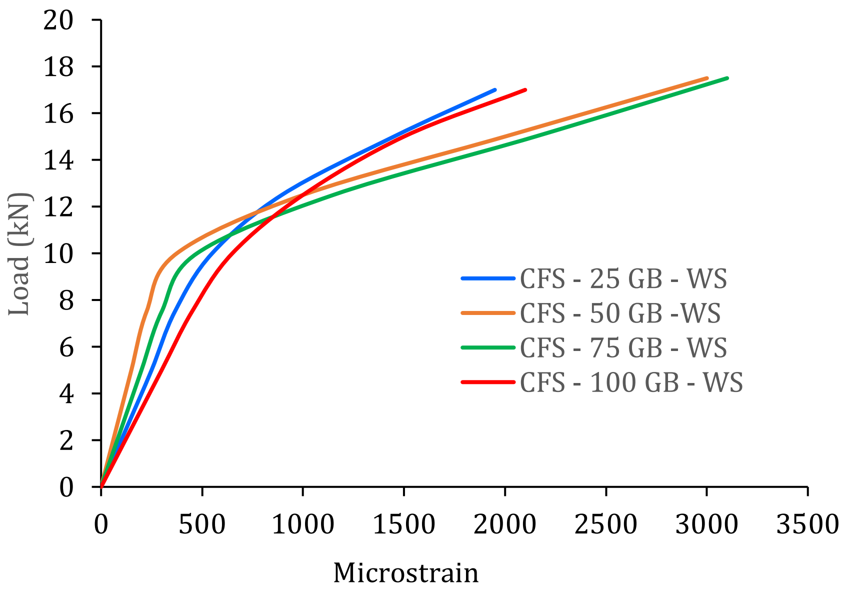
3.2 Load-Strain Behaviour of Gapped CFS Built-Up Beam

Fig. 8(a) shows the load–strain behavior of the CFS gapped built-up beam with flange stiffeners. From the curves, it was observed that as the load approaches the ultimate capacity, the strain levels increase significantly. The flange stiffeners enhance the stiffness of the beam by providing additional resistance to local bending and delaying flange buckling. This effect is reflected in the steeper slope of the load–strain curve within the elastic region, indicating higher stiffness compared to beams without stiffeners. With an increase in the gap between channel sections, the channels act more independently, making the contribution of flange stiffeners more prominent in resisting local and distortional buckling.

Fig. 8(b) shows the load–strain behavior of the CFS gapped built-up beam with web stiffeners. It was observed that the beams with 50 mm and 75 mm gaps (CFS–50GB–WS and CFS–75GB–WS) exhibited comparatively stiffer response in the elastic region and sustained higher strain levels at ultimate load. On the other hand, specimens with 25 mm and 100 mm gaps (CFS–25GB–WS and CFS–100GB–WS) carried slightly higher loads but at relatively lower strain levels. This indicates that intermediate gaps provide a balance between web stiffening effectiveness and composite action, allowing the webs to receive better restraint from each other and thus improving resistance to local buckling.



(a) CFS-gapped beam with flange stiffeners



(b) CFS-gapped beam with web stiffeners

Fig. 8 *Load-strain curve of CFS gapped beam specimens*

3.3 Effect of Stiffeners

The comparison between the load carrying capacity of CFS gapped beam with flange and web stiffeners are shown in Fig. 9. From the bar chart, it was observed that the average percentage increase in the load carrying capacity of gapped beam with flange stiffeners is 24% more than the beam with web stiffeners. This may be due to the location of flange stiffeners on the flanges where the maximum compressive and tensile stresses occur during bending. By stiffening in this region, flange stiffeners effectively increase the beam's ability to resist bending moments. On the other hand, web stiffeners are provided at the web between the back-to-back channel section, which primarily resists shear force rather than bending moments. These web stiffeners improve the shear capacity and local buckling resistance of the web and not significantly increase the bending stress of the CFS – gapped built-up beam.

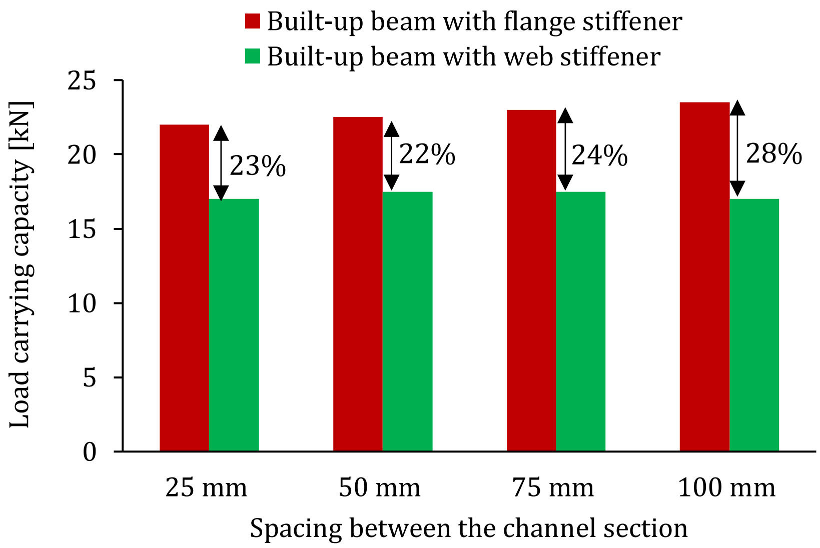
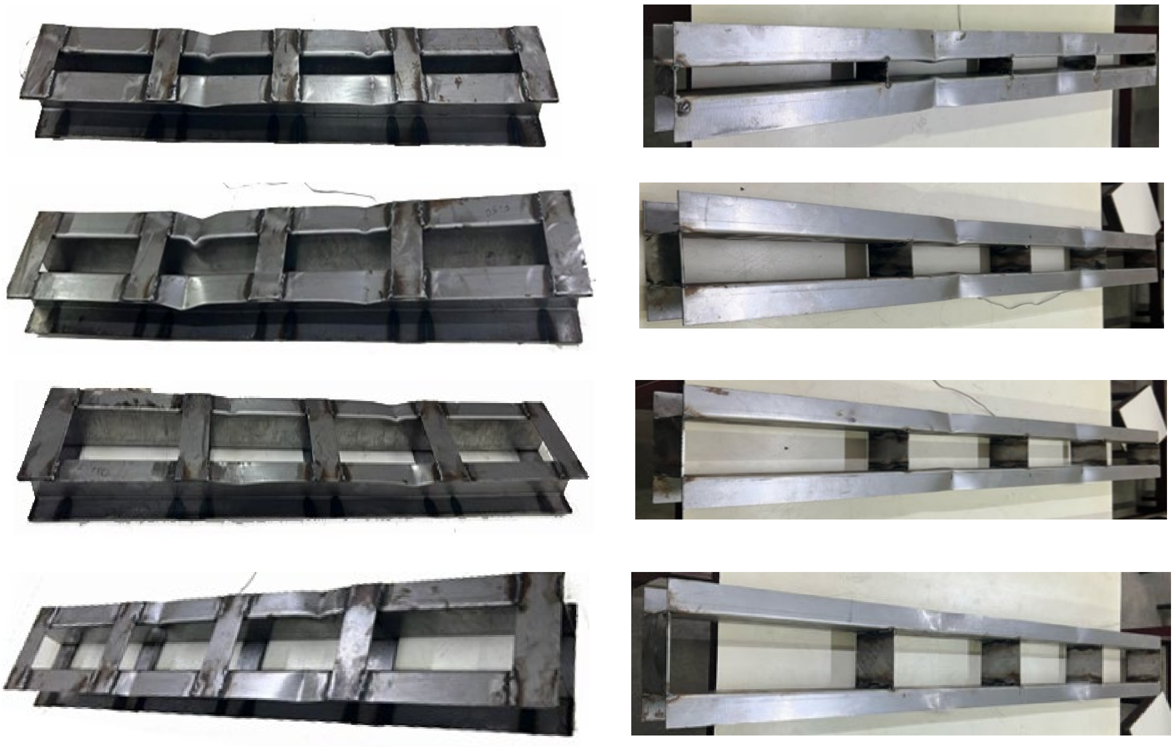


Fig. 9 *Comparison between load carrying capacity of the CFS built up gapped beam with stiffeners*

3.4 Failure Mode

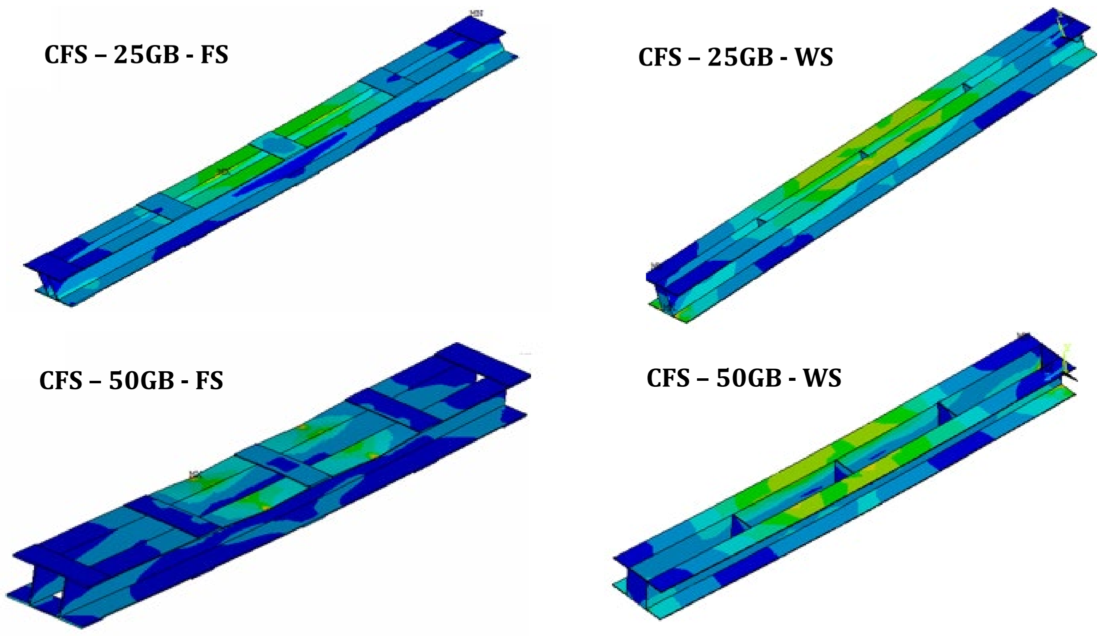
The tested specimens are shown in Fig. 10. It is observed that all the gapped beam specimen shows that local flange failure and overall torsional buckling of the CFS gapped beam. The specimen with flange stiffeners was able to resist deformation, thus local bucking of the flange can be minimised. In experimental tests, CFS gapped beams exhibit progressive failure, where localized buckling occurs first near load application points. The failure of the CFS gapped built-up beams was primarily governed by bending-induced mechanisms, characterized by significant central deflection and local buckling. As the applied load increased, yielding initiated near the mid-span corresponding to the region of maximum moment, and was followed by local or distortional buckling of the compression flange and web elements. The failure was defined based on the attainment of the ultimate load, marked by a peak in the load-deflection response, and the corresponding ultimate displacement measured at mid-span. Strain gauge readings at the central region indicated that the material strain approached or slightly exceeded the yield strain, confirming yielding before the onset of instability. No brittle fracture or crack propagation was observed; rather, the failure was gradual and ductile in nature. This confirms that the dominant failure mode was flexural, influenced by local buckling behavior typical of slender cold-formed sections.

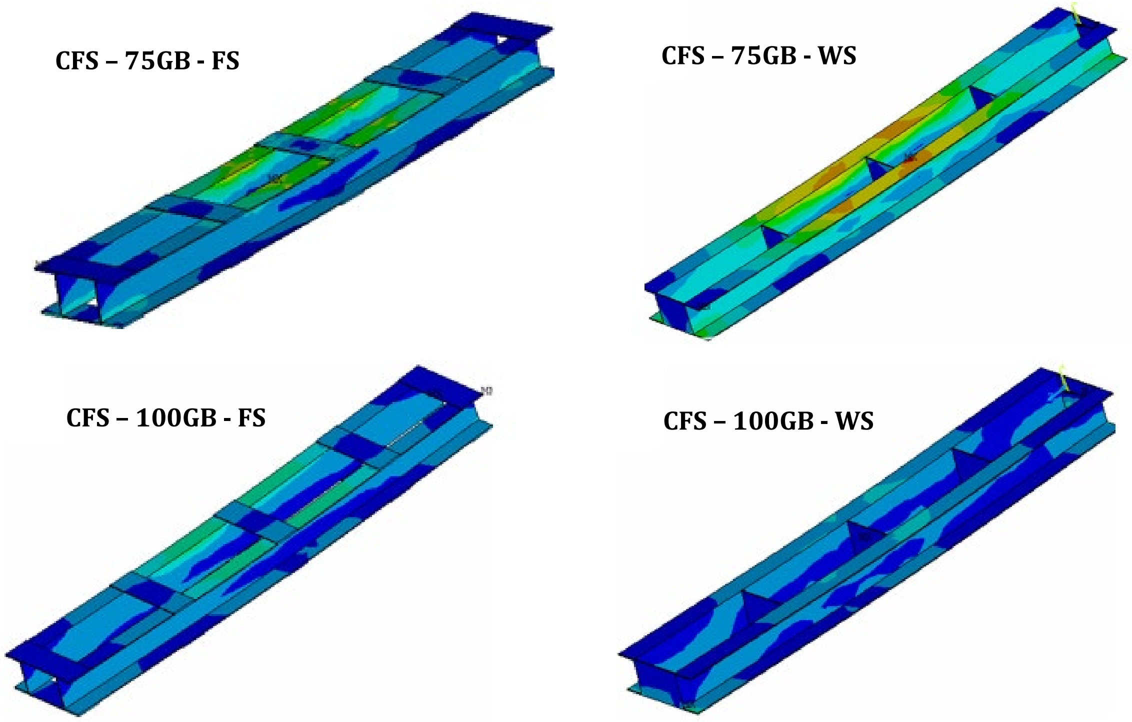


(a) CFS-gapped beam with flange stiffeners **(b) CFS-gapped beam with web stiffeners**

Fig. 10 *Tested CFS gapped beam with stiffeners*

The FE model reveals localized buckling in the flanges, particularly at load application points, where stresses concentrate. The flange stiffeners help in delaying this buckling in CFS built up gapped beam. Similarly, localized web buckling can appear in FE models, particularly in areas of high shear stress. The web stiffeners help mitigate this failure mode by increasing the gap between the back-to-back channel section. Fig. 11(a) and 11(b) shows the deformed shape of the FEA model of the CFS gapped beam with flange and web stiffeners respectively.



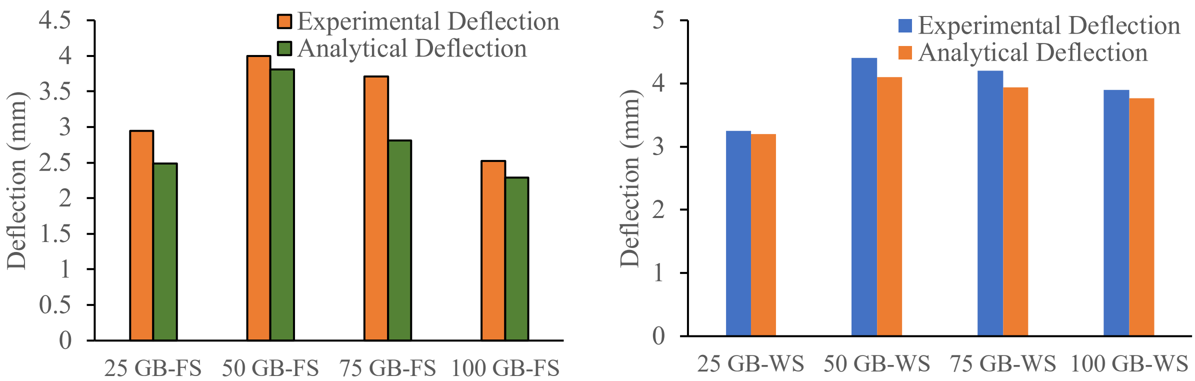


(a) CFS-gapped beam with flange stiffeners **(b) CFS-gapped beam with web stiffeners**

Fig. 11 *Deformed model of the CFS built-up gapped beam with stiffeners*

3.4 Comparison Between the Experimental and Numerical Results

The FE models of CFS gapped built-up beams often predict lower maximum central deflection than experimental results, particularly under controlled loading conditions. This can be attributed not only to idealised conditions such as perfectly symmetric loading, absence of residual stress, and assumed material homogeneity, but also to differences in material property assumptions. In the FE model, a nominal yield strength of 250 MPa with an elastic–perfectly plastic material model was used, and no strain hardening was considered. However, tensile coupon tests on the actual cold-formed steel used in the experiments revealed a higher average yield strength (260–270 MPa) and moderate strain hardening, which contributed to increased post-yield stiffness and lower deflection in the physical specimens. This explains the observed deviation where the FE model underpredicted deflection despite idealized assumptions. The percentage difference between the maximum central deflection of experimental and numerical results was found to be approximately 9% for flange-stiffened and 4% for web-stiffened beams, both within a reasonable range (<10%), indicating good agreement between the test results and FE predictions. Fig. 12 presents a bar graph comparing the central deflections obtained from both experimental and numerical analyses for different CFS gapped beam configurations.



(a) CFS-gapped beam with flange stiffeners **(b) CFS-gapped beam with web stiffeners**

Fig. 12 *Comparison between experimental and numerical results of CFS gapped bram*

4. Design Approaches

The design of back-to-back gapped built-up CFS channel section beams is not directly discussed in the current specifications [14], [15]. However, the finite strip analysis program Thin-Walled-2 [16], based on the Direct Strength Method (DSM), cannot be directly used to gapped built-up beams. The DSM equations were used to compute the moment capacity of a single channel segment, which was then doubled to determine its capacity of gaps between built-up beams.

The nominal flexural strength (M_{DSM}) for CFS structures, according to the DSM, is the minimum of lateral-torsional buckling (M_{ne}), local buckling (M_{nl}), and distortional buckling (M_{nd}), as shown below in Equation (1).

$$M_{DSM} = min\,(M_{ne}, \quad M_{nl}, \quad M_{nd}) \tag{1}$$

The lateral – torsional buckling strength (M_{ne}) is

For $M_{cre} < 0.56\,M_y$; $M_{ne} = M_{cre}$

For $2.78\,M_y > M_{cre} > 0.056 M_y$; $M_{ne} = \frac{10}{9} My\left(1 - \frac{10 M_y}{36\, M_{cre}}\right)$

Where , M_{cre} - Critical Moment Capacity

M_y - Yield moment capacity

M_{nl} - Lateral-Torsional Buckling coefficients

Table 2 summarise the moment capacities of the CFS gapped beam obtained by experimental, numerical and using design standards of AISI and AS/NZS. From the table it was observed that both flange-stiffened and web-stiffened specimens show M_{DSM} values lower than M_{Exp} and M_{FEA}, confirming that the design standards are conservative. This conservativeness is slightly higher for flange-stiffened beams, as reflected in the larger M_{Exp}/M_{DSM} ratio.

Table 2 *Comparison of the experimental and FE moment capacities with the current design predictions of AISI[14] and AS/NZS[15]*

Specimen ID	M_{Exp} (kNm)	M_{FEA} (kNm)	M_{DSM} (kNm)	M_{Exp} / M_{FEA} -	M_{Exp} / M_{DSM} -	M_{FEA} / M_{DSM} -
CFS-25GB-FS	3.63	4.03	3.12	0.90	1.16	1.29
CFS-50GB-FS	3.71	4.07	3.26	0.91	1.14	1.25
CFS-75GB-FS	3.80	4.12	3.31	0.92	1.15	1.24
CFS-100GB-FS	3.88	4.16	3.41	0.93	1.14	1.22
			Mean	**0.92**	**1.15**	**1.25**
			COV	**0.01**	**0.01**	**0.02**
CFS-25GB-WS	2.81	3.05	2.71	0.92	1.04	1.13
CFS-50GB-WS	2.89	3.10	2.73	0.93	1.06	1.14
CFS-75GB-WS	2.89	3.22	2.81	0.90	1.03	1.15
CFS-100GB-WS	2.81	3.08	2.75	0.91	1.02	1.12
			Mean	**0.01**	**0.02**	**0.01**
			COV	**0.02**	**0.02**	**0.01**

5. Conclusion

The experimental and numerical behaviour of gapped CFS beam with the stiffeners were studied. The gap between back-to-back channel sections of built-up beam was varied. The CFS gapped beam were stiffened by providing flange and web stiffeners. The maximum load carrying capacity, strain and overall central deflection was calculated and compared between the experimental and numerical model. From this study the following conclusions were arrived.

- The percentage increase in load carrying capacity of the gapped built-up beam with flange stiffeners is 24% when compared to CFS gapped built -up beams with web stiffeners.
- The percentage increase in load carrying capacity of the gapped built-up beam with flange stiffeners is 24% whereas CFS gapped built -up beams with web stiffeners is only 2 to 3% for change in the gap between the channel section from 25 mm to 100 mm.

- Variations in the gap size between back-to-back channel sections have an impact on load distribution and stability. A moderate gap size improves the interaction between channels, leading to increased load capacity and reduced deflection. However, excessively large gaps reduce this interaction, leading to greater deflection and lower load-bearing capacity, highlighting the need for optimal gap design in built-up CFS beams. Thus, the built-up beam with 50 mm gap were found to be optimum gap to resist more deflection than the beam with 25 mm, 75 mm and 100 mm respectively irrespective of the type of stiffeners (Flange and Web stiffeners).

- The numerical model showed less maximum deflection than the experimental specimen because it assumed perfectly rigid connections. In reality, slight flexibility in the joints and imperfections in the specimen cause higher deflections in experiments. Despite this, the overall deflection and load patterns matched well, showing that the numerical model closely reflects the experimental results. This means the FE model is reliable for predicting behavior of CFS gapped beam with flange and web stiffeners with minimal error of 9% and 4%, respectively.

- The gapped built-up beam with flange stiffener is found to be more effective in load carrying capacity and resist more deflection than the beam with web stiffeners.

- The prediction od moment capacities of CFS gapped beam was more than the experimental and numerical model, thus design standards are conservative. This conservativeness is slightly higher for flange-stiffened beams, as reflected in the larger M_{Exp}/M_{DSM} ratio.

A primary limitation of this study is that only one specimen was tested for each beam configuration, due to constraints in material, fabrication time, and access to experimental facilities. While the testing conditions were carefully controlled and all specimens were fabricated from the same batch of material with verified properties, the lack of repeated tests limits the statistical strength and generalizability of the experimental findings. However, the strong correlation observed between the experimental and finite element results adds confidence to the reliability of the trends reported. To enhance the robustness of the conclusions, future research would consider testing multiple specimens per configuration to assess variability and improve statistical confidence. Additionally, further studies would explore the long-term performance, fatigue behaviour, and optimisation of stiffener arrangements for different span-to-depth ratios and loading conditions, enabling more comprehensive design recommendations for cold-formed steel gapped built-up beams.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***conceptualization, methodology, visualization and review*** *P. Sangeetha,* **software & validation***, S. Dhanus, Ba J Hrushikesh & S T Sreeharini. All authors reviewed the results and approved the final version of the manuscript.*

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