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ENHANCING LOAD CAPACITY: A NUMERICAL INVESTIGATION OF CORRUGATED STEEL BEAMS WITH WEB HOLES

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Abstract

The main challenge of the construction beam is increasing its capacity without increasing weight and cost. Therefore, the beam with a corrugated web is considering a new structural system that has come out recently, which may satisfy that purpose. The research objective was to develop a 3D finite element model to simulate and investigate the structural behaviour of a steel corrugated beam with a hole in the web. The previous researchers' experimental results calibrated and validated the finite element model. The model properly agrees regarding load-deflection response, failure mode, and ultimate load capacity. The correctness of the numerical analysis was confirmed by a comparison with experimental data, which demonstrated a maximum difference ratio based on the ultimate load of less than 15% for all models considered. A parametric study was conducted on a hole shape and number in the web of the corrugated beam. The results showed that the presence or absence of a web hole significantly impacts the ultimate strength of the corrugated beam models. The ultimate capacity decreased by about 65 % when the hole in the web appeared. All models failed with the flexural mode.

Keywords: Corrugated beam; steel girder; corrugated web; beam; numerical investigation, circular openings.

1. Introduction

For decades, steel buildings have reliably withstood a variety of stresses. These buildings need to be more lightweight and stronger than before [1]. I-section members are typically subjected to bending moment, and the flanges and the web withstand shear stresses, making it difficult to reduce member thickness without sacrificing stability. In the design of broad flange beams, flexural demand often takes precedence over shear. Local buckling in the web of a broad flange beam can be mitigated primarily by increasing the web thickness. A very thin web can be made more robust by adding transverse stiffeners and corrugating the steel web, as shown in Fig. 1.

Nevertheless, residual stresses and non-uniform stress distribution may occur during the welding process of stiffeners to the member [2]. The web's corrugations might be employed in place of transverse stiffeners. This method increases the shear strength of the web [2]. Some examples of corrugation shapes are trapezoids, sinusoids, and others [3]. Bridges and structures both benefit from the use of corrugated web [4]. Depending on the number of folds in the web, one of three failure mechanisms can take place: local buckling, where buckles are contained within a single fold; global buckling, where buckles extend throughout the entire depth of the web; or interactive buckling, where local and global buckling interact to cause failure [5].

The major advantage of corrugated web girders is their reduced weight, which can be 30%-60% less than that of flat web girders with the same shear strength. As a result, less effort would be required to traverse greater distances [6]. Last but not least, the bending moment makes the corrugated web vulnerable to direct stress. Because just the flange is resisting the bending force, an interaction diagram is not necessary to determine the shear strength. When the elastic buckling stress is more than 80% of the yield stress, inelastic buckling will occur. For inelastic buckling calculations, Elgaaly et al. [7] suggested a reduction factor of 0.8. Li et al. [8] looked into the theoretical and experimental behaviour of the local stability of H-beams with the corrugated web. All three specimens were tested, but only half of each pair was subjected to the focused moment at either end. Daley et al. [9] examined twenty I-girder obtained by previous studies with experimental findings and formula computed results. In addition, seven test cases from additional experiments were conducted to fill up the blanks.

Fig. 1. Some buildings have corrugated beams.

Raiza Ashrawi et al. [10] studied the semicircular shape of a corrugated web by using a three-dimensional finite element analysis (Solid 185) element from the ANSYS program library used for modelling corrugated steel beams. They concluded that a semicircular corrugated web might hold (18.41%) loading capacity higher than a flat web steel beam under three-point loads. An experimental study was carried out by Elamary et al. [11] to examine the flexural behaviour of flat web beams compared with similar properties and dimensions of beams with corrugated webs. Trapezoidal corrugated web full scale (four beams CW and FW with the same web thickness of 2.1 mm). Hashem [12] conducted an experimental and numerical investigation to investigate trapezoidal corrugated web behaviour subjected to biaxial load. Jáger et al. [13] collected several available previous investigations on the flange buckling resistance for trapezoidal corrugated web girders and also executed a new experimental research program on 16 large-scale specimens. A numerical analysis was proposed to develop the performance of the imperfection sensitive. Chen et al. [14] investigated the buckling behaviour of the stainless steel hot-rolled plate girder under shear stress. Ghadami and Broujerdian [15] modelled fourteen girders to study the behaviour of the initial imperfection of the web, flange to web thick-ness ratio, and web slenderness.

From previous studies, it can be concluded that there is a slight or no contribution of corrugated web in the moment capacity of the steel beam, and that benefit in reducing construction cost and providing lighter members. However, many studies focused on (trapezoidal and sinusoidal) shapes, and the main conclusions were that the magnitude of the out-of-plane unsupported flange or the depth of corrugation fold controls the mode of failure. Furthermore, there is a lack of studies concerning the corrugated web beams with rectangular and limited literature on triangular corrugations. Also, most studies focused on optimizing the angles of corrugations, and as noticed, few studies have been carried out to improve corrugated web beams to avoid instability.

The study's relevance is that it improves the efficiency of cross section bending capacity by producing geometrical shapes with a considerable amount of material positioned in the furthest zone from the neutral axis. Furthermore, lowering the web slenderness ratio caused by a low thickness to depth ratio. Additionally, increased load bearing capability, more cost-effective construction, and lighter than a flat web beam stiffened with stiffeners. This study focuses on the ultimate strength of a corrugated beam with openings in the web. Rectangular, circular, and triangular openings with a base downwards and triangular openings with a base upwards were studied. The presence of more than one hole in the web has also been studied. The models were evaluated based on the load-displacement curve, the type of failure, and the amount of failure load.

2. Specimens' Description

In this research program, six full-scale steel corrugated beam specimens were used; each specimen has a clear span of 3000 mm, as shown in Fig. 2. The thickness of the flange and stiffener is 10 mm, and the thickness of the corrugated web is 1 mm. Table 1 summarizes the specimen details. Three codes labelled all specimens. For instance, in the CBR1 label, where the first symbol (CB) refers to the corrugated beam, the second symbol refers to the hole shape, where symbol R refers to rectangular, and the third symbol refers to the number of holes on each side. Consider the model without holes in the web as the reference model for the study.

The holes in the web were chosen to have a total area of 90,000 mm2 for all shapes. The holes area represents approximately 6% of the web area for all models. The web ripple shapes were chosen to be easy and quick to manufacture as they are arranged at right angles. As for the dimensions of the holes in the web, they were chosen to be of an acceptable area for the passage of services in buildings, as the passage of water pipes and cooling ducts always conflicts with the presence of the beams. Therefore, the area of the openings was taken to simulate the area of these services. The corrugated shape of the web was as shown in Fig. 3.

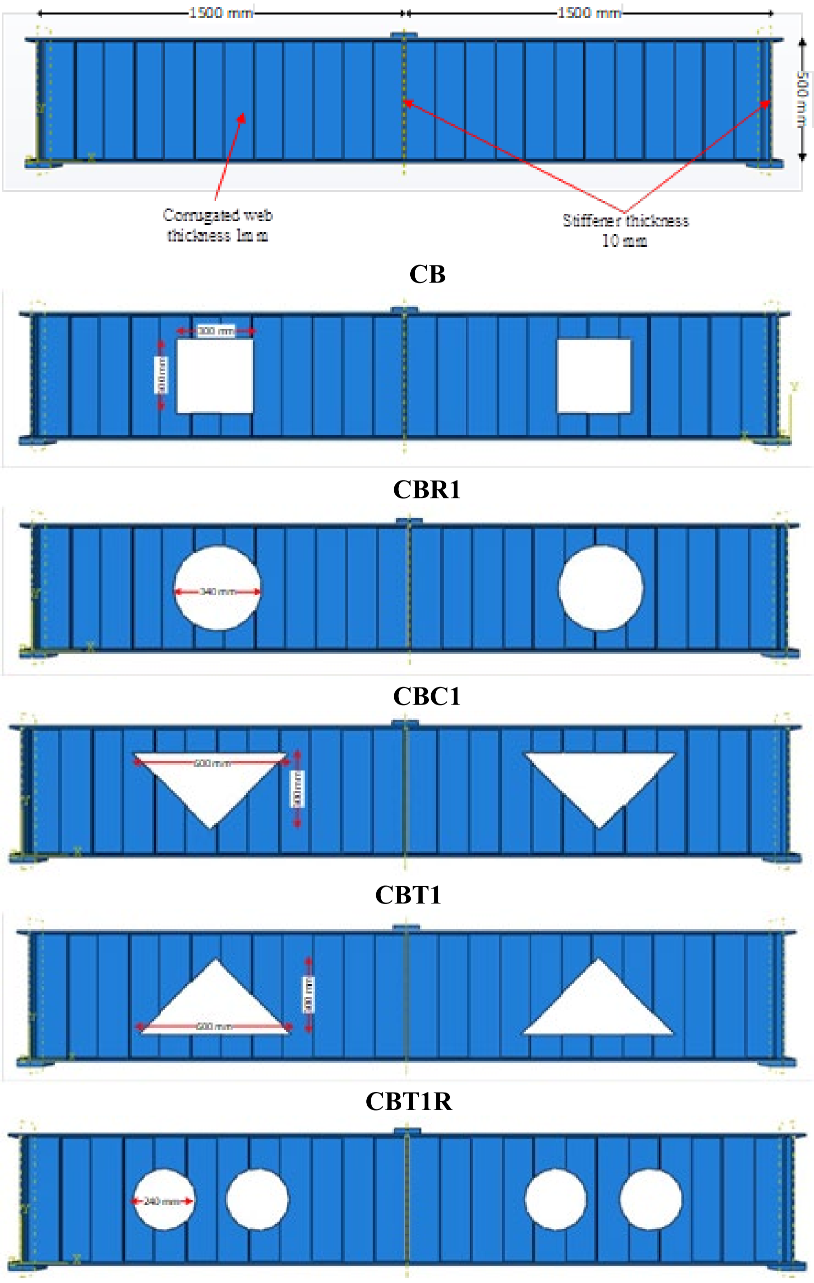


Fig. 2. Models' parameters details.

Table 1. Models' dimensions.

Specimen Designations	Total span (mm)	Total height (mm)	Hole shape	Notes
CB	3000	500	Non	Reference model without hole
CBR1	3000	500	Rectangular	Rectangular hole with a total area of 90,000 mm^2
CBC1	3000	500	Circle	Circular hole with a total area of 90,000 mm2
CBT1	3000	500	Triangle	A triangular hole with its base downwards, with a total area of 90,000 mm^2
CBT1R	3000	500	Triangle	A triangular hole with an upward base, with a total area of 90,000 square mm
CBC2	3000	500	Circle	Two circular holes with a total area of 90,000 mm^2

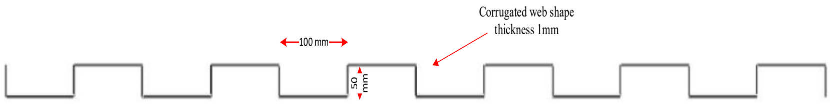


Fig. 3. Corrugated web shape and dimension.

3.Corrugated Beam FE Model

A 3D FE model was created with ABAQUS / CAE version 6.12-3 technology. The model consisted of three components: a corrugated beam, two bottom fixing plates, and one upper plate, as shown in Fig. 4. A ten-node quadratic tetrahedron modelled the corrugated beam and plates of fixation with improved visualization of the surface stress. Using connection constraints, the lower and upper plates were fixed to the flange of the corrugated beam. The corrugated beam simulated as a simply supported. The load was applied uniformly on the upper plate. The analysis method used is Static Riks, considering all major abnormalities that occur during the simulation.

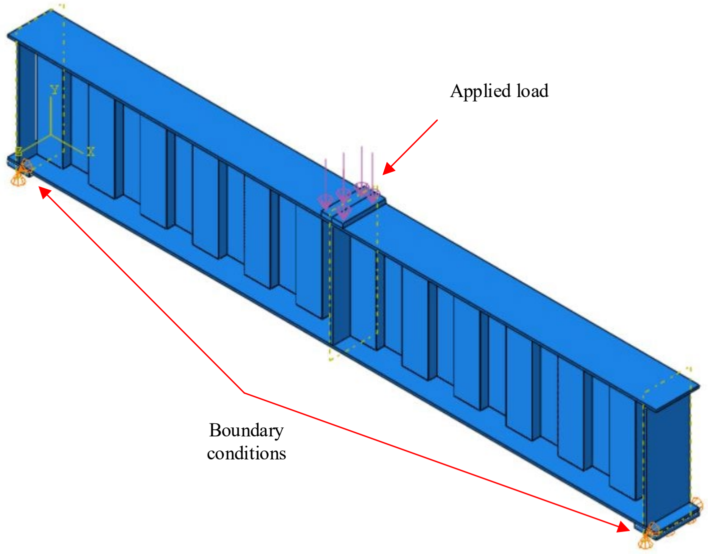


Fig. 4. Corrugated beam FE model.

3.1. Materials properties and meshing

In order to get close results, the properties of the defined models have to conform exactly with the test specimens. The stress-strain curve of the materials is defined, as shown in Fig. 5. Based on previous tests carried out by the author, the steel modulus has been taken at 200 GPa for a corrugated beam and the supporting plate. However, Poisson Ratio has been taken at 0.3 for all steel materials. The element size selection is essential to obtain convergence of results. This study changed the number of elements to obtain the same behaviour for the models and tested specimens in terms of failure mode and failure mid-span deflection. A convergence study on the model of the corrugated beam was carried out to determine an appropriate mesh density. This is practically achieved by decreasing the mesh size to have a negligible effect on the results. The corrugated beam of the same material properties was modelled with a decrease in the mesh size (from 100 to 10 mm), as shown in Fig. 6, and the best dimension was 30 mm. The amount of increase in deflection in the middle of the model has become very small and imperceptible. Therefore, the size 30 mm was chosen. The mid-span deflection for all corrugated beams was observed for the same applied load level.

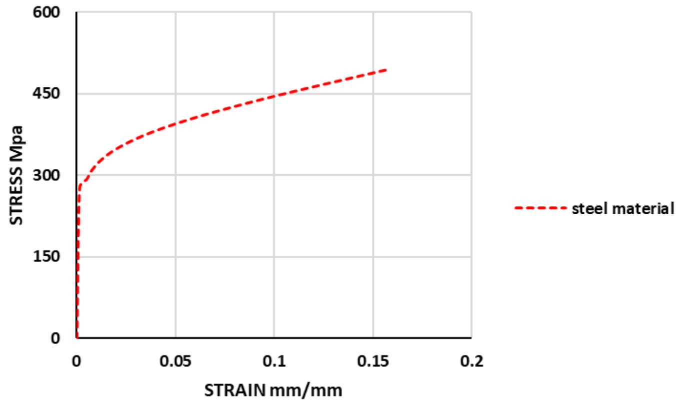


Fig. 5. Stress vs. strain curves used in the FE models.

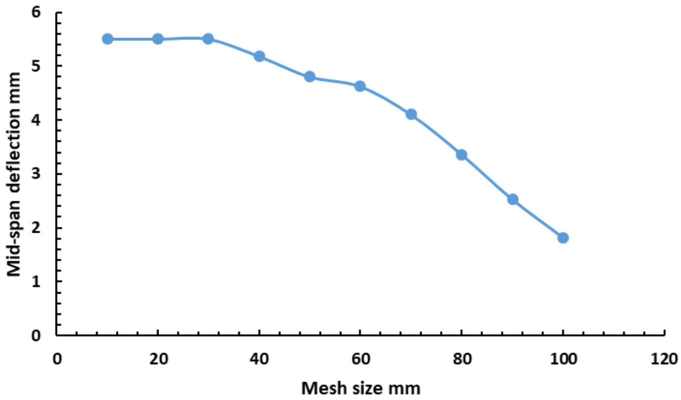


Fig. 6. Convergent study for mish size.

3.2. Calibration of models

The finite-element model was calibrated using previous researchers' results in the load-deflection response, ultimate load, and failure mode [16, 17]. A tensile strength parameter was considered to calibrate the load-displacement response of the corrugated beam model. Khamees and Shadhan [18] showed that this parameter and steel module significantly affect FE's results. The reason for this is the direct effect of the tensile strength of the steel material on the endurance of the model. Likewise, the steel module coefficient has a noticeable effect on the amount of deflection in the model. After several tests, the experimental and FE results were agreed upon since the specimens showed the same deflection response. The same failure mode was observed in both the experiments and the corresponding FE simulation. The tested and simulated corrugated beam experienced a lateral buckling failure that started at the flange and then developed into the web. Furthermore, the ultimate load of the calibrated specimens were compared to those experimentally tested by the previous researchers. The difference between the experimental and FE ultimate load ranged less than 15 %, making the FE model more conservative than the experiment.

The calibrated models were validated using load-deflection response and ultimate load capacity. A good agreement was observed in the elastic and plastic stages. The validity of the model was verified after verifying the conformity of all previously represented models by other researchers

4. Results and Discussions

4.1. Load-displacement response

Load -displacement curve for all corrugated beam models is shown in Fig. 7. When looking at the model, the load-displacement response consists of two stages. In the first phase, there is a straight line of proportionality between the applied force and the resulting deflection. The load-displacement curve at this point had a sharp decline. As the load is increased to the maximum failure value, the load-displacement curve changes shape, indicating that the corrugated beam has entered a plastic phase. The plastic zone of the specimens is rapidly expanded by changing the slope of the load-displacement curve since a small charge increase leads to a great increase in displacement. In general, the behaviour of the corrugated beam changes when there are openings in the web, where the elastic stage decreases and deflection increases, which makes the models fail ductile. Regarding the plasticity stage, it has been observed that it increases as the number of openings increases for the same total area. The reason for this could be the decrease of steel material from the pattern over a greater distance, as is observed in the difference between the opening of the circle and the two circles.

4.2. Failure load and failure deflection

To study other factors influencing the behaviour of corrugated beams, models with different hole shapes were simulated to determine the ultimate strength. This research was performed for rectangular, circular, and triangular hole-shaped models. Models with two holes are also represented to find the ultimate strength. The hole area was maintained at 90,000 square mm for all shapes. Table 2 shows the study results. When adding the hole in the web, the ultimate strength decreased significantly by about 64%. This decrease because the weak point in the web is due to the hole's presence.

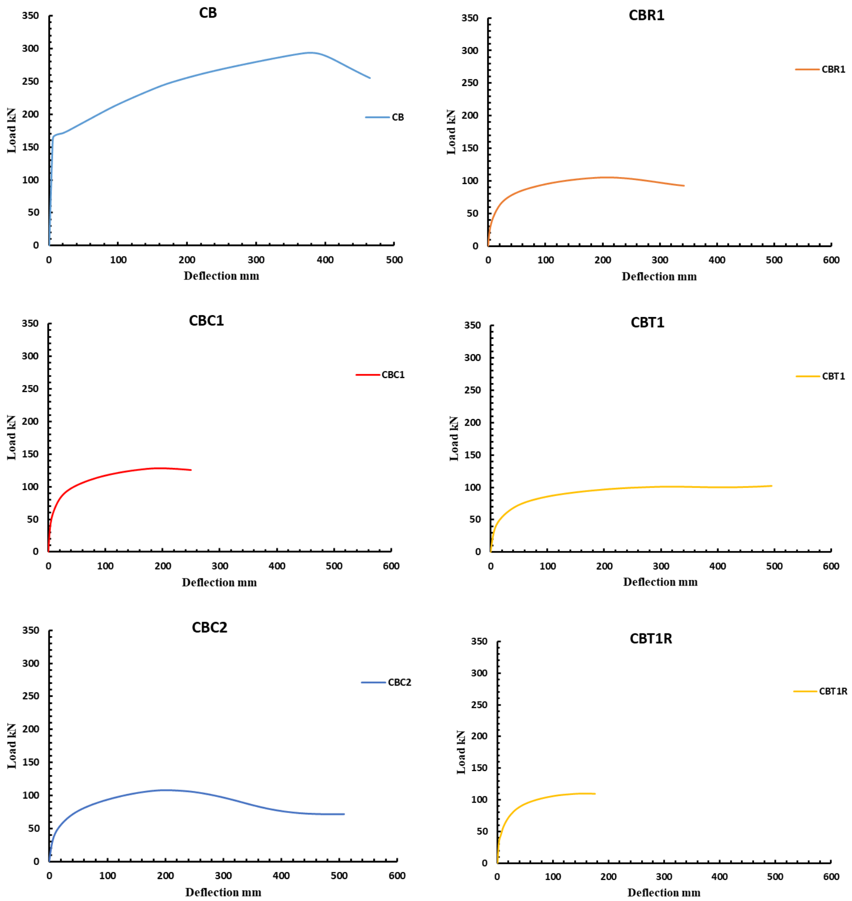


Fig. 7. Load deflection curves for models.

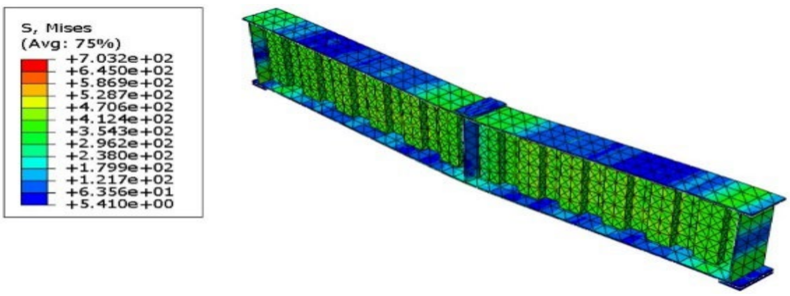
Also, when changing the shape of the hole in the web from rectangular to a circular shape, the ultimate strength of the beam decreased by about 56 % due to the stress distribution around the hole. In addition, using the triangular hole shape reduced the ultimate strength by about 65%, which indicates that the rectangular and triangular hole shapes are similar in affecting the ultimate strength. In the case of an equivalent area of the circular shape with two circuits, the ultimate strength of the corrugated beam is decreased by 63% than the strength of the reference beam, and at the same time, it is less by about 16 % than in the case of using a single circle. This decrease in the strength of the models must be taken into account when designing corrugated beam, as the passage of services in buildings requires the presence of openings. Therefore, it is preferable for the number of openings to be more than one to distribute the stresses to more than one place. Also, avoid maximum stresses in the middle of the beam as much as possible. The failure deflection decreases when there are holes in the web due to a decrease in the failure load of models. After examining the model with the triangle hole, however, it is found that the specimen's vertical displacement has grown significantly. All models have vertical displacements that are smaller than the reference model.

Table 2. Results of the study.

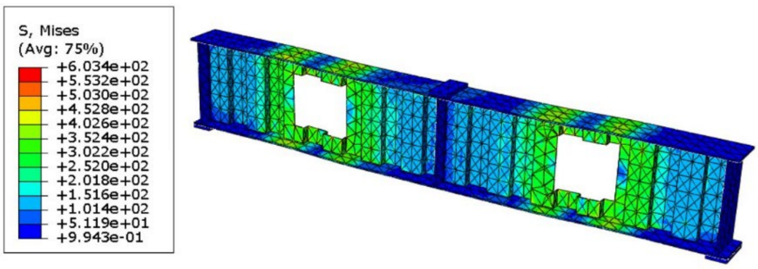
Specimen Designations	Ultimate load (kN)	Failure deflection (mm)
CB	294	377
CBR1	106	206
CBC1	128	194
CBT1	101	320
CBT1R	110	162
CBC2	107	200

4.3. Models failure mode

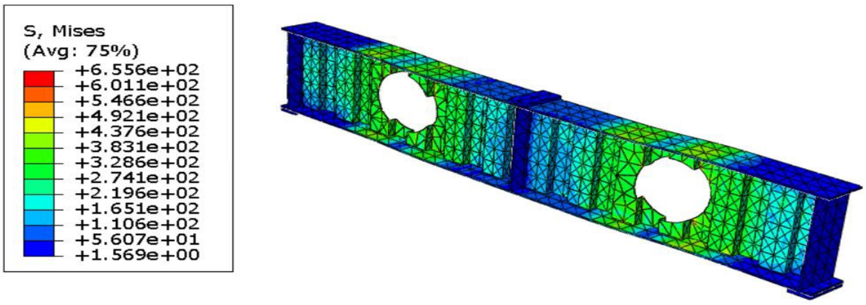
The failure mode for all models was generally a bending failure, as shown in Fig. 8. This type of failure occurred due to increased stresses in the lower layer of the models, especially when there were holes in the web. The failure of the web buckling has been avoided by using three stiffeners, as web buckling can occur even with the presence of corrugated. It has been noted that the parts under the holes, under the supports and under the load are reached to yield stress. The failure mode of the reference model was the yielding of the steel in the middle of the model, where the yielding began from a point in the middle and then began to spread to the top of the model cross section. As for the models with rectangular and triangular holes, the steel began to be yielded from the corners of these holes and then spread to the top of the model cross section. As for the models with circular holes, the performance was much better, as the steel yield started at the circumference of the circle from the bottom and then spread.



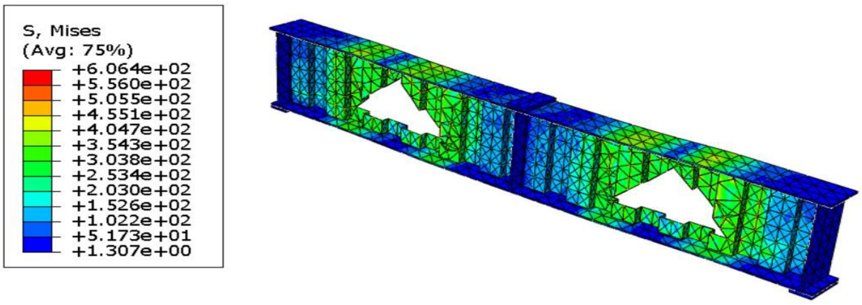
CB



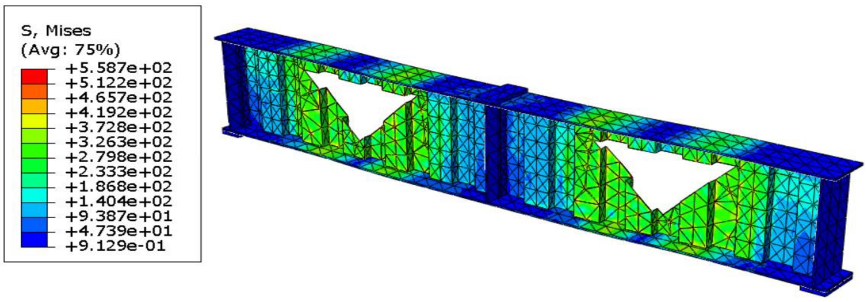
CBR1



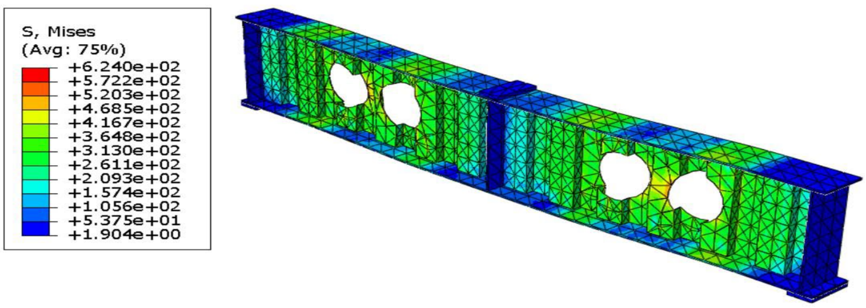
CBC1



CBTR1



CBR1



CBC2

Fig. 8. Failure mode of FE models.

5. Conclusion

In the scope of this study, based on results derived from the finite-element simulation with an ABACUS method for corrugated beam models subject to one concentrated load, the following conclusions could be drawn:

- The 3D finite element model used in the present study can simulate the corrugated beam, and it has a good agreement regarding load-deflection response, failure mode, and ultimate load capacity. The comparison between the numerical and the experimental results showed good validity of the numerical analysis, where the maximum difference ratio based on the ultimate load was less than 15 % for all analysed models.
- Using corrugated plates significantly increases the resistance of the web to buckling failure. Moreover, the presence of holes in the corrugated web greatly affects the overall ultimate strength of the model and its general behaviour. Also, the failure mode is usually bending failure for all models.
- When adding square and triangular holes, the ultimate strength of the model is 64% less than the reference model, while when circular holes are added, the ultimate strength decreases by 56%. Furthermore, when the area of a hole circle is equivalent to the area of two hole circles, the ultimate strength of the model decreases by 16.5 %. So, for practical purposes, it is recommended to use more than one circular holes in corrugated beam.
- For future studies, researchers can investigate the effect of other types of holes, such as rhombic and elliptical, on the strength capacity of the corrugated beam. In addition, the non-prismatic corrugated beam can be studied. The effect of holes on the deep corrugated beam can also be studied.

Conflict of interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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