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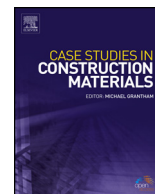
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Flexural impact resistance of steel beams with rectangular web openings



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ABSTRACT

This paper focuses on the flexural impact behaviour of steel I-beams with rectangular web openings. Published studies on impact resistance and design requirements of perforated steel beams are limited. To shed light such a topic, detailed non-linear three-dimensional finite element models (FEMs) were developed using ABAQUS. Rigorous validation process was employed to verify the FEMs built against published experimental tests in terms of force and displacement time histories. Reasonably good agreement was obtained between the numerical results and the corresponding experimental ones. Then, the validated FEMs were exploited to investigate the flexural impact resistance of perforated steel beams with rectangular openings. The factors examined in the current study were the area, depth, number and reinforcement of web openings under different impact velocities ranged between 2.214–7 m/s to provide comprehensive understanding on the flexural impact response of steel beams perforated with rectangular openings. It was observed that increasing the number of narrow web openings negligibly effected the flexural impact resistance of steel beams. Moreover, using wide openings significantly reduced the dynamic flexural resistance of such beams. Besides, slight effect on the flexural impact resistance and mid-span deflections were obtained if the depth of openings increased. Moreover, a considerable improvement was observed by providing perforated beams by horizontal steel reinforcement particularly for those with wide openings. The perforated steel beams showed similar mode of failure by generating four plastic hinges around the edges of an opening, which is the failure mode produced for perforated beams under quasi-static loading.

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1. Introduction

Providing web openings in steel and concrete beams has significant importance in structural building frames. Such openings work as appropriate access for services like ducts and cables to pass through such openings. Besides, the entire weight of the beam compared with solid beams is reduced. Also, high stresses produced in the beam to column connections may be alleviated if the perforated beams replace the solid ones. Furthermore, the provision of openings in the beams has also been considered for architectural requirements. Generally, the stiffness of beams with different shapes of web openings is lower than those for solid beams, which leads to producing higher deflections. The existence of the web openings in a beam

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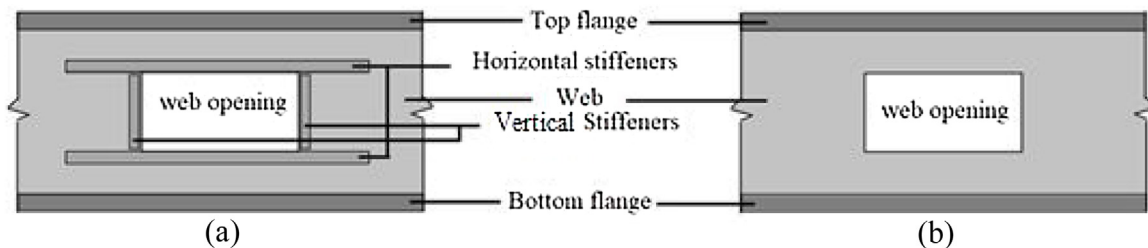


Fig. 1. Steel I-section beam with (a) Horizontally and vertically reinforcement and (b) without reinforcement.

also reduces its shear and flexural strength. Thus, stiffeners may be welded horizontally and/or vertically around the openings to enhance the shear and flexural capacity in the opening sections as shown in Fig. 1.

Different studies were conducted to investigate the behaviour of perforated steel beams under static loading conditions. Some studies concluded that providing web openings may lead to significant disadvantages in terms of load-carrying capacity [1–3]. Theoretical study on steel beams having rectangular and circular openings has been performed by Chung et al. [2] and a design procedure was proposed. The effect of moment to shear ratio on the resistance of the opening section was realised, therefore, an empirical shear to moment interaction curve at the circular perforated section was proposed. More recently, Sweedan [3] developed a simplified approach based on experimental and numerical investigations to predict a moment modification factor for cellular beams. The complex behaviour accompanied by the combined effect of shear and moment of perforated steel beams resulted in expanded the studies to the recent time. However, experimental tests were recently performed by Al-Dafafea et al. [4] to evaluate the behaviour of stiffened and unstiffened web openings on the beam subjected to shear and bending. The results showed that significant improvement in the ultimate carrying capacity of the beam was obtained using sufficient anchorage length of stiffeners. Feng et al. [5] presented an experimental tests to investigate the high-strength H-shaped steel beam perforated with circular openings with different configurations. The test results were compared with the current design guidelines and it was found that the Eurocode 3 is non-conservative while both Australian and Chinese guidelines were conservative. Recently, the work on providing analysis procedures and design guidelines to predict the behaviour of perforated steel beams under quasi-static loading is continuous [6–8]

In addition to static loading, steel frames should be designed to resist seismic loading. Goel et al. [9] used the web openings to create a ductile zone in the beams of moment resisting frame to absorb the energy induced by ground motion. The beneficial effect of providing a steel beam with web openings was concluded by Erfani et al. [10] when subjected to seismic loading. It was found that seismic resistance of moment-resisting steel frames was enhanced by the presence of openings in beams web, due to alleviation in stress concentration of beam-to-column connections of such frames.

During the service life, structural frames may experience dynamic loadings such as impact and blast, in which a force is produced within a short time such as vehicle impact or explosions. However, researches were intensively presented to investigate the response of beams and other structural members to such loading regimes [7–16]. Limited studies were carried out to investigate the response of metal beams under high loading rates. The earliest study was carried out by Menks et al. [21], in which a clamped solid aluminium beams were investigated against explosion. The tested specimens experienced tearing at the extreme fibres and shear near the support. Some studies were carried out to investigate the effect

Table 1
Details of the specimens tested by Antimo et al. [20].

	Impact test	Test CODE	h (mm)	m (kg)
1 st specimen	IT B01	M1 H250	250	211
		M1 H500	500	211
		M1 H500	500	211
		M1 H1000	1000	211
		M1 H1000	1000	211
		M1 H3000	3000	211
2 nd specimen	M2 H250	M2 H250	250	460
		M2 H500	500	460
		M2 H1000	1000	460

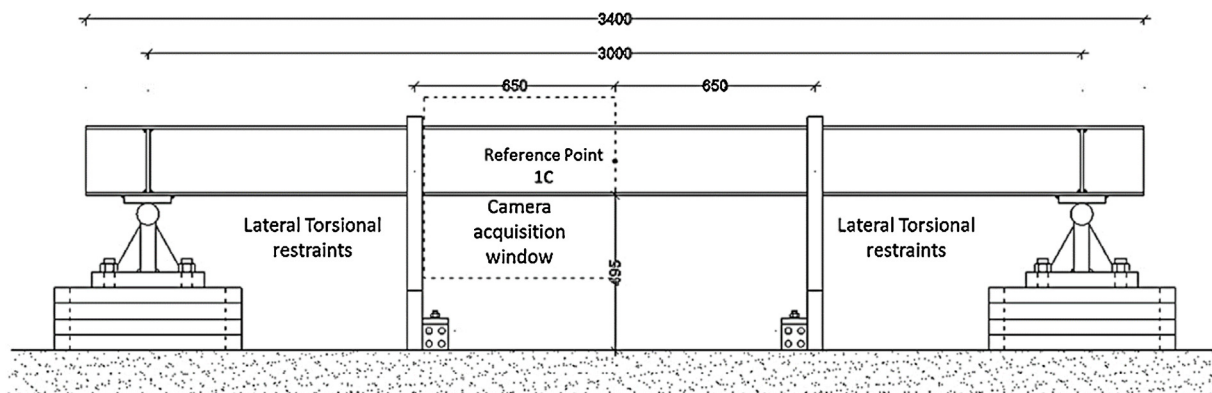


Fig. 2. Test setup for the experimental work conducted by Antimo et al. [24].

of different parameters on the aforementioned failure modes such as type of beam material and impact location [18,19]. Recently, Antimo et al. [24] investigated the impact resistance of a solid steel beam subjected to multiple impact loading. Two simply supported beams were tested and the results were obtained then finite element models were developed for further investigation. It was found that using an appropriate strain rate model enhanced the validation of FE models against the test results.

The previous studies indicated that the focus has been made on investigating the behaviour of perforated beams under static and seismic loading. Also, it showed that the attention was paid to understand the response of solid steel beams under impact loading. However, in the current study, it will be beneficial to investigate the impact behaviour of steel beam with web openings to cover this gap of knowledge. The methodology adopted to achieve this task is based on developing Finite Element (FE) models then verifying such models against the available experimental results of solid beams. After that the verified FE models of solid beams could be provided by rectangular openings with different cases to investigate the impact resistance of perforated beams. This methodology seems to be efficient in terms of accuracy and cost. It was used in different studies and acceptable results were obtained. For example, finite element models were developed by Degteyareva et al. [25] for cold-formed steel slotted channel sections then validated against experimental results of solid channel sections.

It should be mentioned that the current study represents a part of a project to investigate the response of perforated steel beams under impact loading. It was started by investigating the impact response of steel beams with circular web openings. The results indicate that providing circular openings lead to a reduction in the impact force and increase in the displacement measured at mid-span [26].

In this study, published experimental tests were used to verify the numerical models developed, which were built using the finite element package ABAQUS. The developed FE models were used to investigate the impact response of steel beams with rectangular web openings and the effect of several parameters on such response.

2. Experimental studies

The FE models developed were verified against the experimental test results of two previous studies. The first study was conducted by Antimo et al. [24] and the second one by Cho et al. [27]. The beams in both aforementioned studies were tested under repeated impact. However, the results of only the first of four tested specimens were considered for validating the FE models. Then, the geometrical and material properties of the beam tested by Reference [24] were considered to perform the parametric studies.

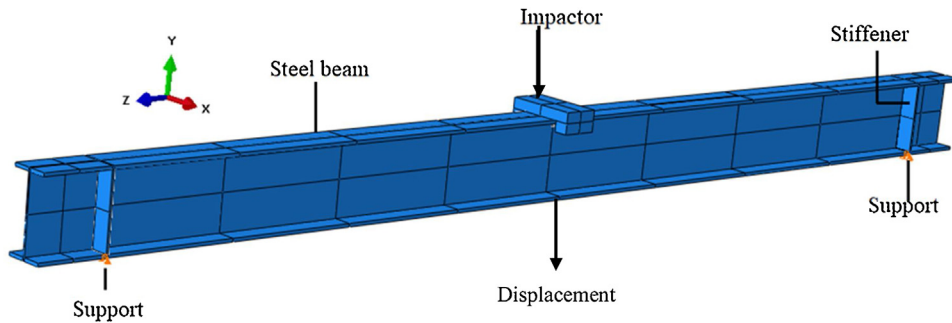
An experimental study was carried out by Antimo et al. [24]. The tests included two specimens with IPE 220 section, which has dimensions of (220 × 110 × 5.9) mm. The beams were simply supported and exposed to multiple impact loading and the details of the tested specimens are listed in Table 1. The first and second specimens were exposed to six and three multiple impacts, respectively. The applied impact energy was generated using a range of height from 250 to 3000 mm corresponding to two different values of mass, i.e. 211 and 460 kg. The grade of steel for both specimens was S275. During the

Table 2
Tensile test results of steel profiles used in experimental tests of Cho et al. [27].

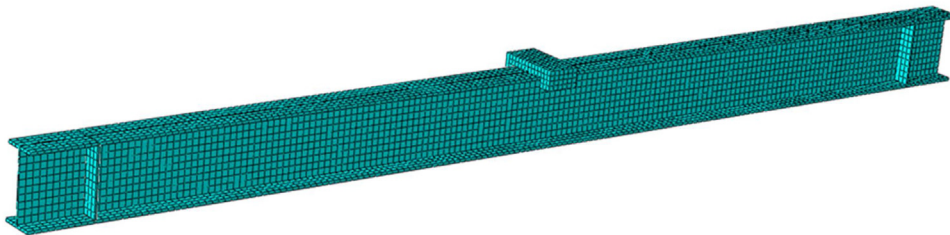
Profile	Yield stress (MPa)	Ultimate stress (MPa)	Modulus of Elasticity (GPa)
Flange	356.8	526.9	189.3
Web	390.1	527.0	220.4
stiffener	399.9	530.6	221.1

multiple impact tests, the global deflection was measured at the mid-span of the specimens regardless of the local deformation of the beams. The instrumentation and the test setup used in this study is shown in Fig. 2.

Another test results carried out by Cho et al. [27] were also selected to enhance the accuracy of the validation of FE models obtained against tests of Antimo et al. [24]. Four steel beams with T-section were fabricated and tested as indicated in [27]. Two of them were impacted under room temperature, while the others were tested under combined elevated temperature and impact loading. Only those beams impacted under room temperature were used in the current study to validate the FE models. The beams tested have equal web and flange thickness of 10.2 ± 0.1 mm, while the web height was 50 mm and the flange width was 100 mm. The span length of the beam was 1.068 m, fixed at its both ends to a ground rigid frame using steel stiffeners, bolts and plates. The tensile tests were carried out to obtain the engineering stress-strain relationships of steel profiles involved and the summary of the test results can be seen in Table 2. A drop hammer machine was used to apply the impact loading using knife-edge impactor configuration. The first specimen was impacted by a mass of 193.8 kg with an initial velocity of 4.85 m/s while the mass and the initial velocity of the second specimen tested were 295.7 kg and 3.96 m/s, respectively.



(a) Geometry and boundary conditions



(b) Meshing

Fig. 3. FE model details of the solid beam.

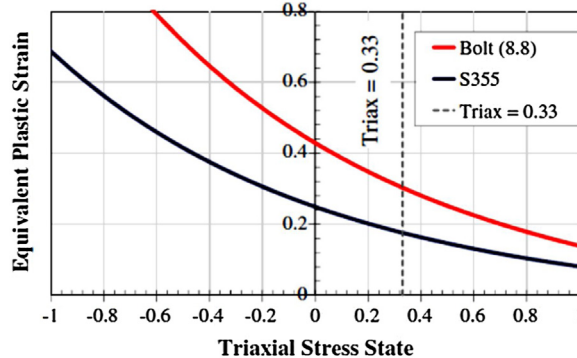
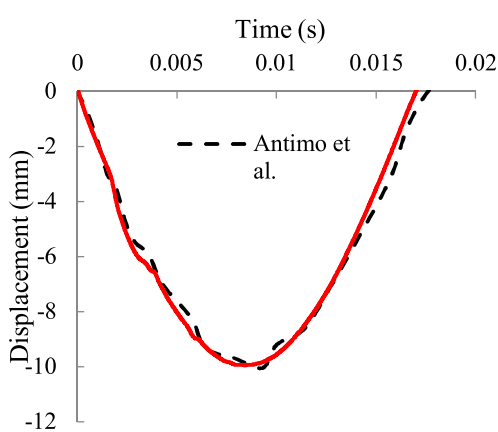
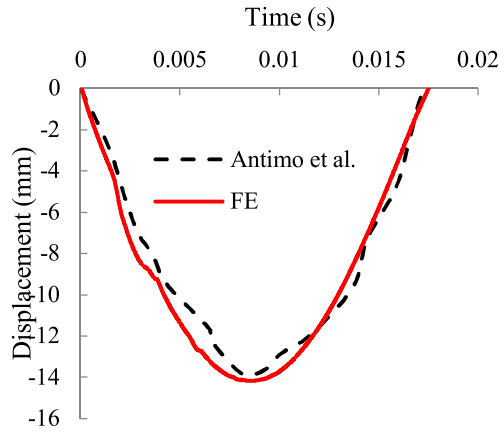


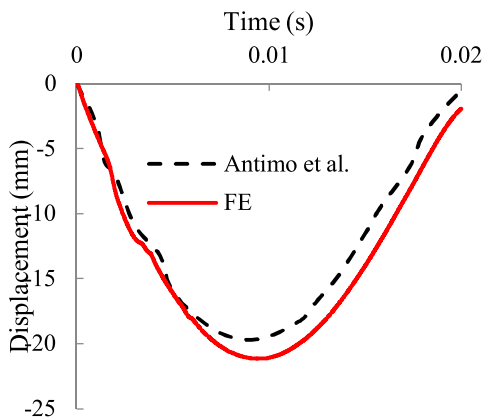
Fig. 4. Triaxiality-plastic strain envelope proposed by Ribeiro et al. [29].



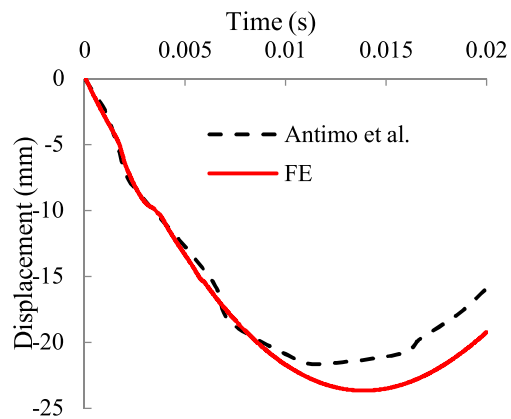
(a) M=211 kg, V= 2.214 m/s- Specimen (ITB01 M1 H250)



(b) M=211 kg, V= 3.132 m/s-Specimen (ITB02 M1 H500)



(c) M = 211 kg, V= 4.429 m/s-Specimen (ITB05 M1 H1000)



(d) M = 460 kg, V = 3.132 m/s-Specimen (ITB08 M2 H500)

Fig. 5. The validation of FE models against tests carried out by Antimo et al. [24] (M: Mass, V: Velocity).

3. FE modelling and verification

This Section presents the numerical procedures and techniques that are used to simulate the reference beams tested by Antimo et al. and the cases selected for beam with web openings under impact load. Here, ABAQUS was employed to develop numerical models using the explicit procedure, which is more appropriate to simulate a dynamic event. Also, convergence issues could be avoided using such procedure [28]. Geometry, boundary conditions, element type, meshing, contact interaction, material properties in addition to the verification of the FE models are presented in this Section.

3.1. Geometry and boundary conditions

Fig. 3 (a) shows the geometrical details of a FE model and boundary conditions utilized in the current study. Translational movements were prevented in x and y directions to simulate the simply supported conditions. The impactor was simulated as a rigid body and all its degrees of freedom was restrained, except for the vertical movement (y-axis) to allow for vertical impact. The projectile was modelled with a mass of 211 and 460 kg and different initial velocities of 2.214, 5 and 7 m/s were employed.

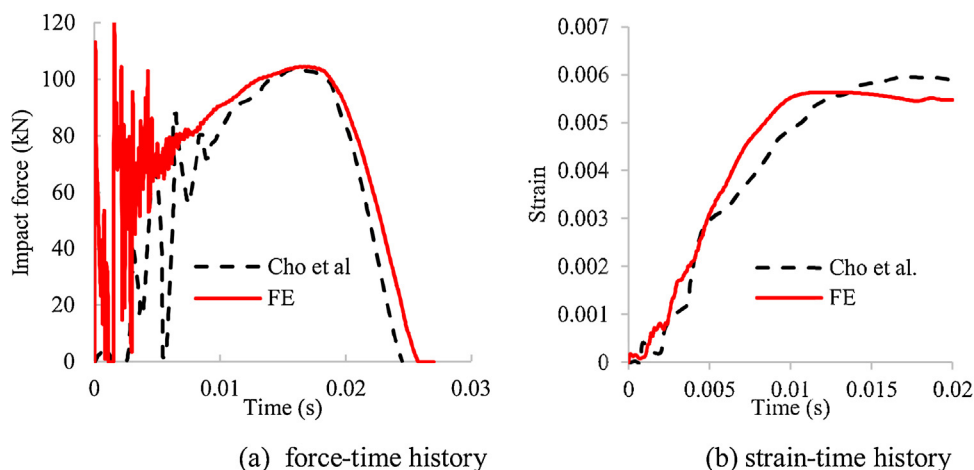


Fig. 6. The validation of FE models against tests carried out by Cho et al. [27].

3.2. Element type, mesh size and contact interactions

C3D8R element with reduced integration was used due to its efficiency to model the impact events. Fig. 3 (b) shows the numerical model of the beam with the selected element type. A mesh sensitivity study was performed to identify the proper mesh size. It was found that using the element size of $20 \times 20 \times 5$ mm gives reliable results with appropriate computational time. The rigid quadrilateral element (R3D4) was used to model the impactor with finer mesh size compared to the mesh size used for the impacted beam. This is to avoid contact penetration of the impactor into the impacted beam. Normal hard and frictionless contact was assumed for the contact surfaces of the impactor and the beam. Whilst, tie constrain was employed to model the weld used to connect horizontal stiffeners to the web of the beam. It was also considered using the stiffer part as a master surface and the other part as a slave surface [28].

3.3. Constitutive models of steel material

Both elastic and plastic properties of steel materials were obtained from the experimental engineering stress-strain relations provided by Antimo et al. [24] and Cho et al. [27]. Then, such stress-strain relations were converted to the true stress-strain relations, which in turn were used as input data in ABAQUS. Strain rate effect was considered using Johnson-Cook dynamic magnification approach as follows:

$$(DIF)_{JC} = 1 + C \ln \text{ ENTITY NOT DEFINED !!!}^* \quad (1)$$

Here, C is a constant; ENTITY NOT DEFINED !!!^{*} is the ratio of the current strain rate to the reference quasi-static strain rate. The constant C was assumed to be 0.039 as recommended by Ribeiro et al. [29]. Beyond the strain hardening stage, damage criteria need to be modelled to allowing for strength degradation and avoiding overestimation of such strength. The onset of ductile damage was modelled using the envelope of triaxiality-plastic strain proposed by Ribeiro et al. [29] as shown in Fig. 4. Afterwards, the damage evolution stage begins producing the stiffness degradation of the element until the total failure. A linear relationship was then assumed between the element size (L_e) and the equivalent plastic strain ϵ_{pl} as follows:

$$U_{pl} = L_e \epsilon_{pl} \quad (2)$$

Also, shear damage of steel beam was modelled by assuming a value of the equivalent plastic strain at the onset of shear damage. Such strain is a function of strain rate and shear stress ratio. Hence, the value of equivalent plastic strain, strain rate and shear stress ratio was taken as 0.172, 120 and 1.8 as proposed by Al-Thairy [30]. These values were validated by the aforementioned study against experimental tests [22] for a solid rectangular mild steel beam under impact load.

3.4. Verification of FE models

3.4.1. Test carried out by Antimo et al. [24]

To perform a parametric study, the FE models were calibrated against four experimental tests presented by Antimo et al. [24]. Fig. 5 shows the convergence between the experimental and numerical displacement-time histories obtained. The highest discrepancy between the experimental displacement and the predicted one among the four cases was less than 8.5%,

which reflects a very good correlation between the FE models and test results. Such correlation can be exploited to perform a parametric study in which different parameters effect can be examined.

3.4.2. Cho et al. Tests

As mentioned in Section 2.2, these tests were selected to enhance the validation of the FE models developed to predict the impact response of the steel beams with rectangular perforations. Here, the predicted traces were correlated reasonably well to the corresponding experimental tests. The maximum deflections measured for the two specimens selected were 30 and 33 mm, while the corresponding predicted deflections acquired from FE models were 29.15 and 32.05 mm, respectively. The predicted results were compared also in terms of force-time histories and strain time histories for the experimental data provided by Cho et al. very good correlations were obtained as can be seen in Fig. 6 for a sample impacted under a mass of 295.7 kg and a velocity of 3.96 m/s. However, a considerable difference can be noticed between the peak force obtained from the experimental and FE model as can be seen in Fig. 6a. It is attributed to the assumption of the rigid projectile that has much higher contact stiffness than the deformable steel projectile used in the test. Besides, peak forces are difficult to be measured precisely as stated by Birch et al. [31] as it has a short duration. Such difference in peak force has a negligible effect on the flexural impact behaviour of the specimens selected in the current study as the beams reach their maximum bending moment and maximum deflection in a time different than that of peak forces.

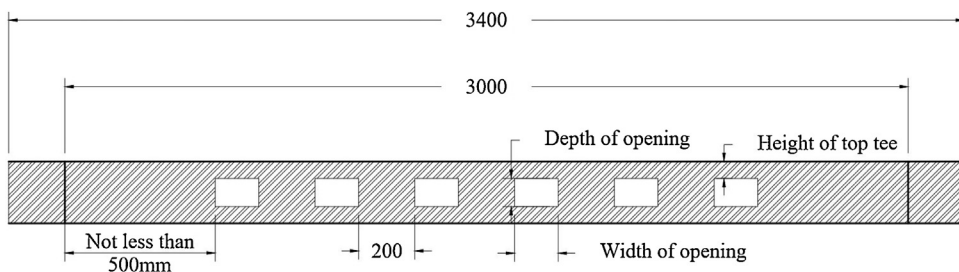


Fig. 7. Typical steel beam with rectangular web openings.

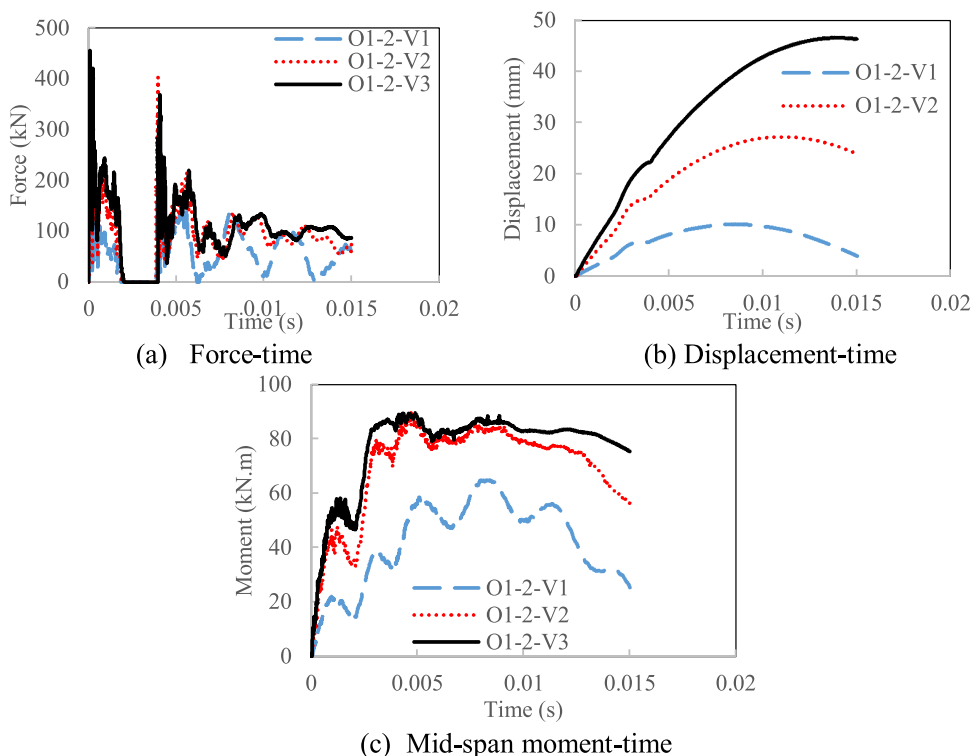


Fig. 8. Effect of impact velocity (two openings with the size of (155 × 100) mm).

4. Parametric study

To study the impact behaviour of steel beams with rectangular web openings, numerical FE models were developed with different parameters based on the verified ones. Rectangular openings with different numbers and areas were provided into the solid steel beams. The dimensions and boundary conditions of the steel beams which utilized by Antimo et al. were kept constant to study the influence of the depth, number and reinforcement of the openings under impact loading. The impactor mass was not changed and kept at the value of 211 kg.

The effect of impact energy was also examined by employing a range of impact velocities increased from 2.214–7 m/s. The parametric study details with the corresponding numerical results are tabulated in Table 2. Typical steel beam with rectangular web openings is shown in Fig. 7. The details of web openings such as the distance between the support and the nearest web opening, the distance between two openings, dimensions of openings and height of top and bottom tees were selected as per SCI-P355, which was in accordance with Eurocode and the UK National Annexes [32]. Such details are required to design steel beams with web openings under static loading. Finally, it should be mentioned that the terms “narrow openings” and “wide openings” have been used in the current parametric study to refer to openings of size (155 × 100) and (310 × 100) mm, respectively.

4.1. Effect of impact velocity

Three different values of impact velocity were selected to study its influence on the impact response of the steel beams with rectangular web openings, i.e. 2.214, 5, and 7 m/s. The other parameters such as the impactor mass and boundary conditions were kept constant. The samples were divided into five groups. The first three groups were for beams with narrow openings while the others were with wide openings. The first, second and third groups included beams with two, four and six openings, respectively while the beams in the fourth and fifth groups were perforated with two and three openings, respectively.

Figs. 8, 9 and 10 show the effect of the impact velocity for the first three groups. In general, the figures reveal that increasing the impact velocity has approximately the same trend regardless of the number of openings. Within the models' conditions, the impact force, displacement and moment at the mid-span section of the beam increased using higher impact velocity. It could be noted that the difference in the bending moment and the force-time curves when the impact velocity raised from 5 to 7 m/s is relatively smaller than that increase from 2.214 to 5 m/s. This could be attributed to the plastic response of the beam under velocities of 5 and 7 m/s. As the beam started its plastic deformation, the change in the strength

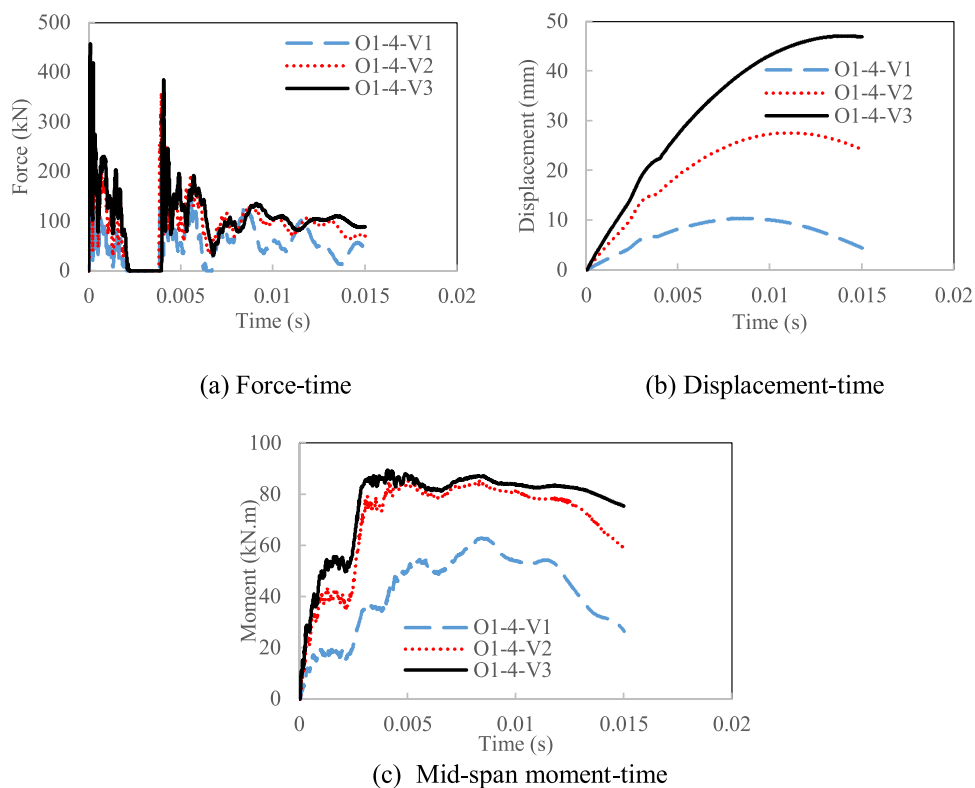


Fig. 9. Effect of impact velocity (four openings with the size of (155 × 100) mm).

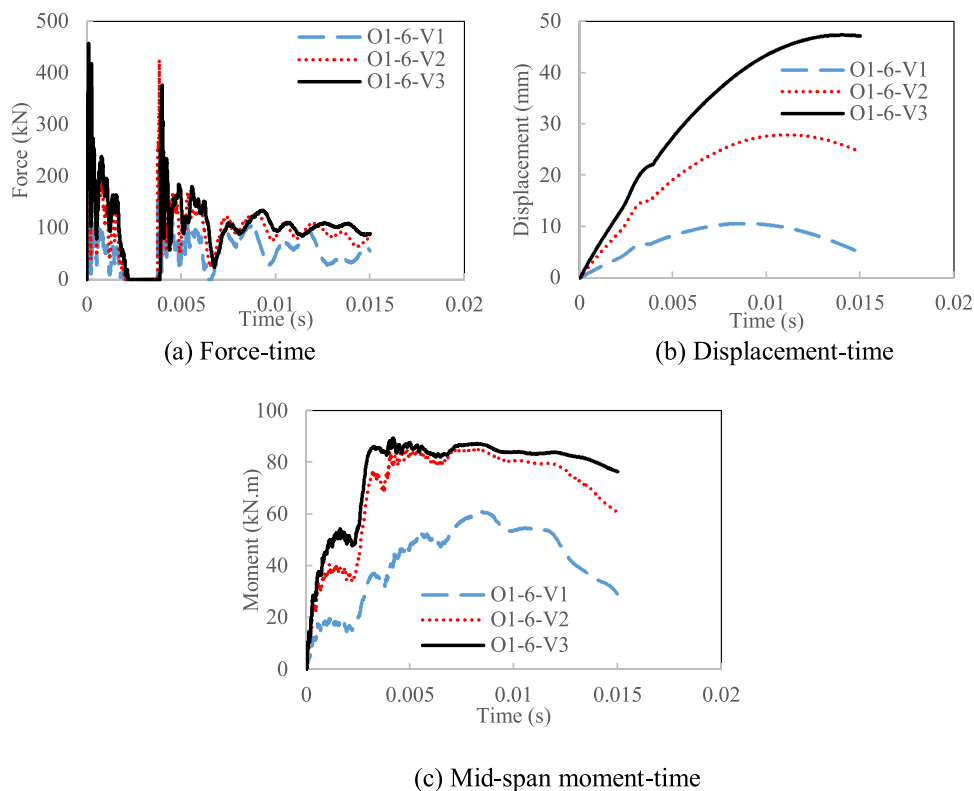


Fig. 10. Effect of impact velocity (six openings with the size of (155×100) mm).

will be slight because the beam experienced stress hardening, in which low increase in stress is produced. Whilst, a considerable change in displacement can be noticed as the beam supposed to experience higher displacement in the plastic stage compared with elastic stage.

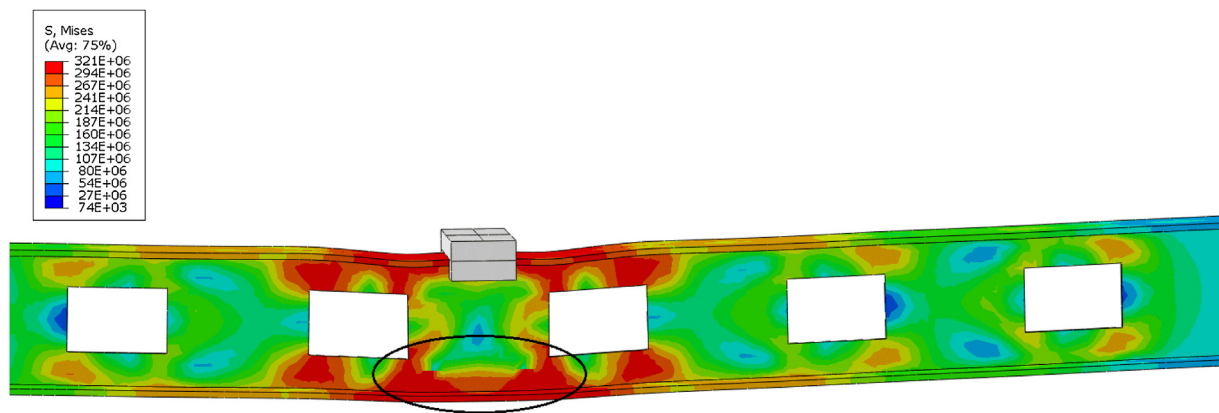
For the steel beam with two openings, raising the impact velocity from 2.214–7 m/s led to increase the impact force, displacement and moment by 152%, 357% and 38%, respectively. However, the beams with different number of openings show almost the same increasing percentage when the impact velocity increased from 2.214–7 m/s. The considerable reduction in the moment of inertia of the perforated beam induced the beam to dissipate more energy in terms of local and global deformation as shown in Fig. 11. Clearly, increasing the impact energy influenced the response of the beam and caused higher stress at edges of the openings and higher deformation as shown in Fig. 11(b).

Again, Figs. 12, 13 and 14 manifest that the impact velocity has the same effect on the steel beams with different number of wide openings. The impact force, mid-span moment and mid-span displacement increased with the rise of the velocity. With increasing the impact velocity from 2.214 to 7 m/s, the mid-span moment increased from 58.1–83.3 kN.m for the beams with two openings for wide openings beams, whilst it raised from 53 to 85.5 kN.m for the models with three openings with the same size.

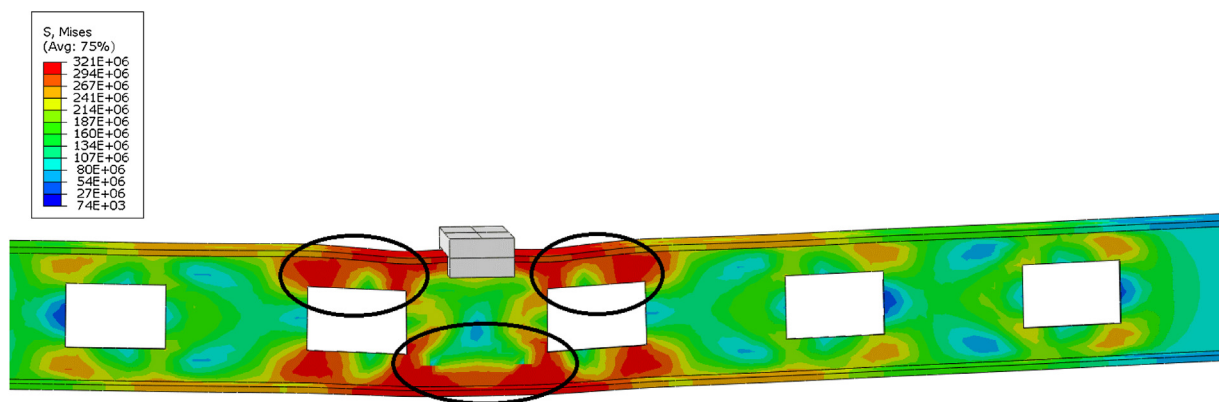
The mode of failure for the perforated steel beams with two wide openings is shown in Fig. 13. Vierendeel plastic hinges started to develop by applying impact velocity of 5 m/s and such failure mode magnified by applying a velocity of 7 m/s. Also, the upper and bottom edges of the openings were highly affected in the same manner of the beams with narrow openings, which could refer to the same failure scenario as for the same sample conditions adopted in the current study under quasi-static loading. It could be noticed that all beams with wide web openings experienced only one peak force followed by a plateau force while two peak forces were propagated in the beams with narrow ones and also followed by a plateau force. This reflects the higher stiffness that beams with narrow openings have compared with others with wide ones. Such a high stiffness plays important role in generating multiple peak forces during an impact event [33].

4.2. Effect of number of openings

The effect of the number of web openings was examined in this section. Only the number of openings was increased, while the impact velocity, boundary conditions, impactor mass and material properties were kept constant. For the beams impacted by a velocity of 5 m/s, the results showed that the impact force reduced by 20% when the beams were perforated



(a) O1-6-V2



(a) O1-6-V3

Fig. 11. Deformation shape of the steel beam with six openings with the size of (155 × 100) mm.

with six narrow openings as shown in Fig. 15 (a). Fig. 15 (b) illustrated that the displacement of the beam was increased by 13% when the beam provided with six narrow openings. The mid-span moment is also affected by increasing the number of openings. Fig. 15 (c) illustrates that the trend of the mid-span moment-time trace for the solid and perforated beams with different number of openings are almost the same. Increase the number of openings from zero to six leads to reduce the moment from 99.7–85.2 kN.m.

Impacting the perforated steel beams with three wide openings, i.e. (310 × 100) mm with impact velocity of 7 m/s led to reduce the impact force and mid-span moment by 61% and 30%, respectively compared to solid beam. As in narrow openings, the displacement increased as the number of wide openings increased. However, the specimens provided with three wide openings under impact velocity of 5 and 7 m/s exhibited less global displacements compared with solid beams and the ones with narrow openings. This can be attributed to formation of high local deformation underneath the impactor in addition to the global one as can be seen in Table 3.

Clearly, providing web openings reduced the load-carrying capacity of the beams and the impact force due to the reduction of the web area which in turn reduced the beam strength. In general, those results are similar to the outcomes of the behaviour of the steel beams with openings under static flexural loadings presented by Abdo et al. [34] who concluded that the increasing the number of opening induced the beam to exhibit higher deflection. The only difference between the results obtained here under impact loading and the results obtained by reference [34] under quasi-static loading was the higher local deformation that perforated beams exhibited under impact loading compared with that under quasi-static

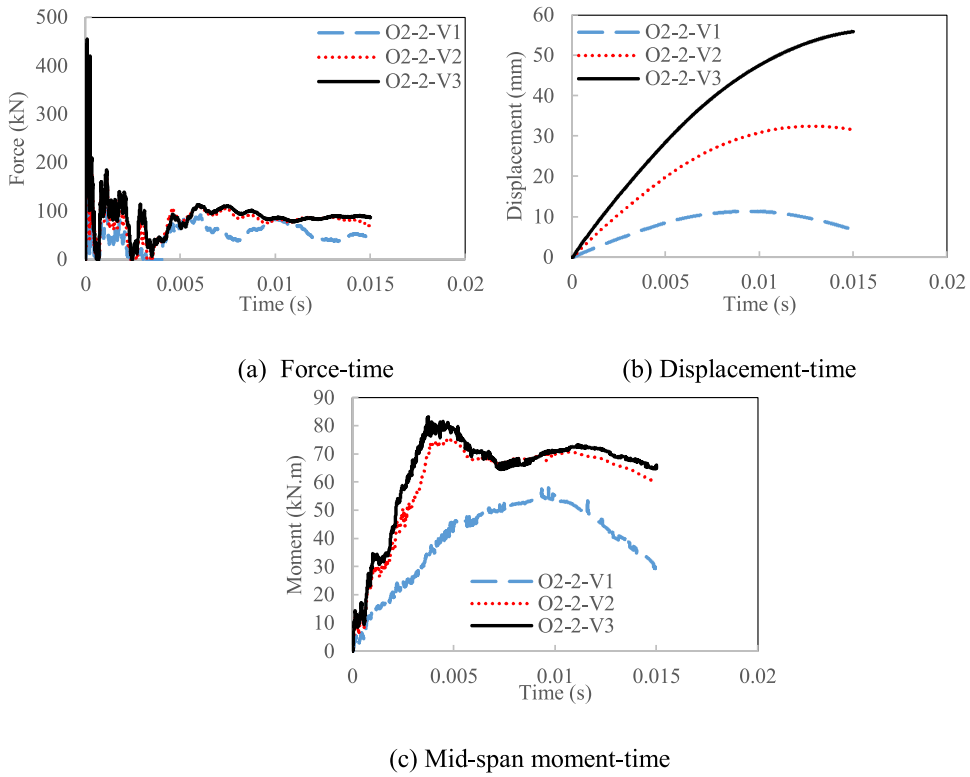


Fig. 12. Effect of impact velocity (two openings with the size of (310×100) mm).

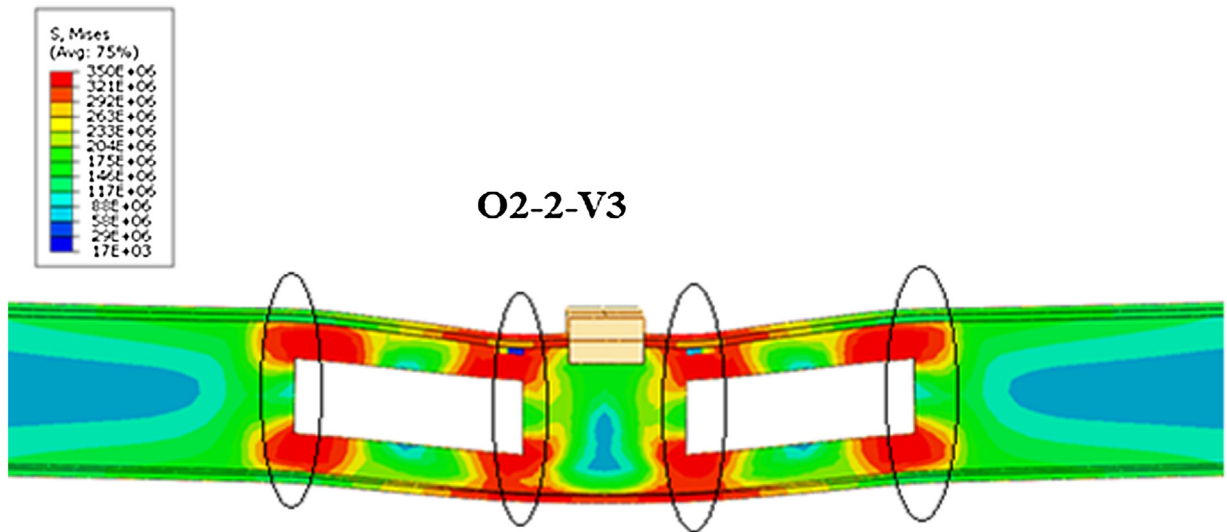


Fig. 13. Deformation shape of the steel beam with two openings with the size of (310×100) mm.

loading. This could be attributed to the dynamic effect in which higher forces are produced within short period leading to provide the local deformation.

4.3. Effect of area of openings

The effect of area of openings were investigated by comparing results of beams having different number of openings with similar area. However, each two narrow openings of size (155×100) mm was replaced by one wide opening of size

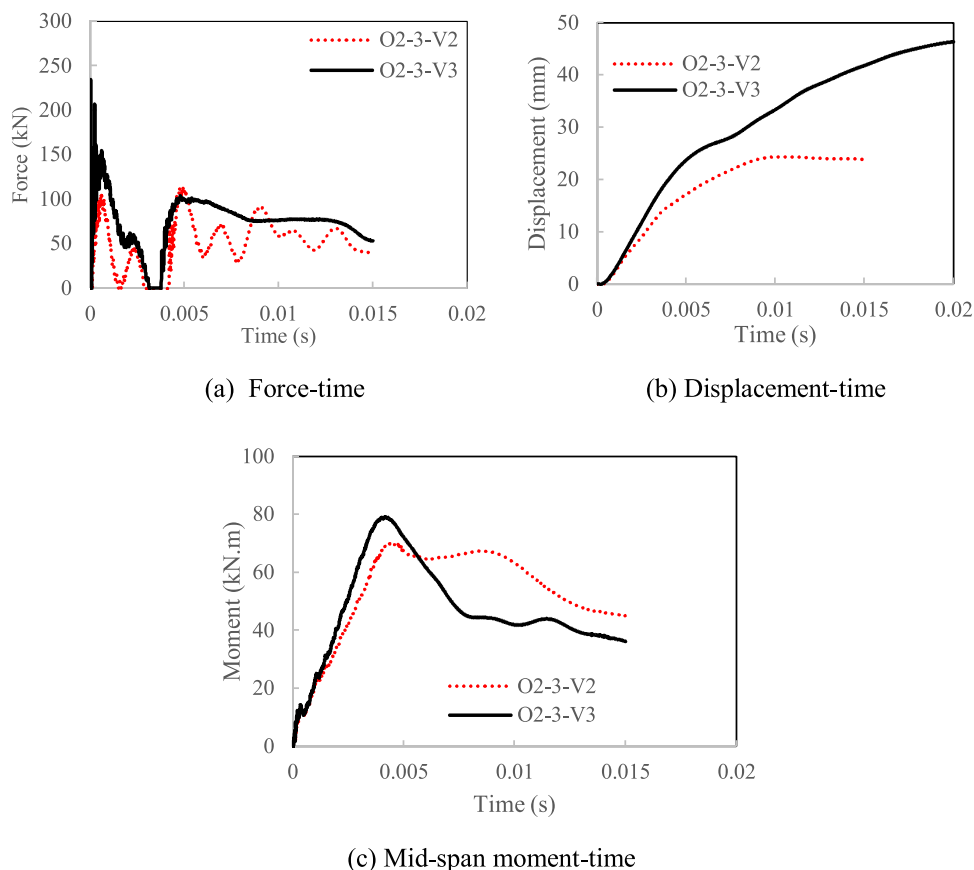


Fig. 14. Effect of impact velocity (three openings with the size of (310×100) mm).

(310×100) mm. Then, the total opening area in both samples was equivalent. The results obtained can be shown in Fig. 16 for force, displacement and moment-time histories up to a time of 0.015 s. The mid-span moment reduced from 89.5–83.3 kN.m when the area of openings increased from 31,000 to 62,000 mm². Fig. 16 (b) shows that increasing the opening area slightly affected the displacement of the beams. This is because of the number and depth of openings are the same regardless of the opening area. In contrast, the impact force reduced by 11% with increasing the opening area from 31,000 to 46,500 mm².

The area of four (62,000 mm²) and six (93,000 mm²) narrow openings is equal to the area of two and three wide openings, respectively. In general, the comparison between the specimens with an equivalent area manifests that increasing width of the opening significantly affected the impact response of the beams. For the specimens with openings area of 62,000 mm² and subjected to impact velocity of 2.214 m/s, the impact force and mid-span moment reduced by 14% and 8%, respectively, and the displacement increased by 8.5% when the opening width increased from 155 to 310 mm. Under impact velocity of 7 m/s, the reduction of the impact force was 50%, while the mid-span moment decreased from 89.4–70.4 kN.m for the beams perforated with wide openings are of 93,000 mm² in comparison with the ones provided with narrow openings with same area of openings. However, the comparison between the above specimens showed that the overall displacement which represents the displacement of the bottom fibre at the mid-span of the beam decreased from 28 to 10.8 mm and from 47.4–24.4 mm for the specimens under impact force of 5 and 7 m/s, respectively. This is due the high local deformation at the impactor area.

Within the conditions of the study, the obtained results from the numerical models reveal that the area of the opening plays a vital role on the impact response of the steel beam and increasing the opening area lead to decreasing the stiffness and load-carrying capacity of the steel beam. Besides, the beams perforated with narrow openings exhibited better impact response than those with the wide ones having an equivalent area.

4.4. Effect of depth of openings

The top and bottom tee depth (See Fig. 7) were considered in the previous studies [1,4,35] to estimate the static flexural capacity of steel beams. However, the flexural capacity of perforated beams is significantly affected if the beam perforated

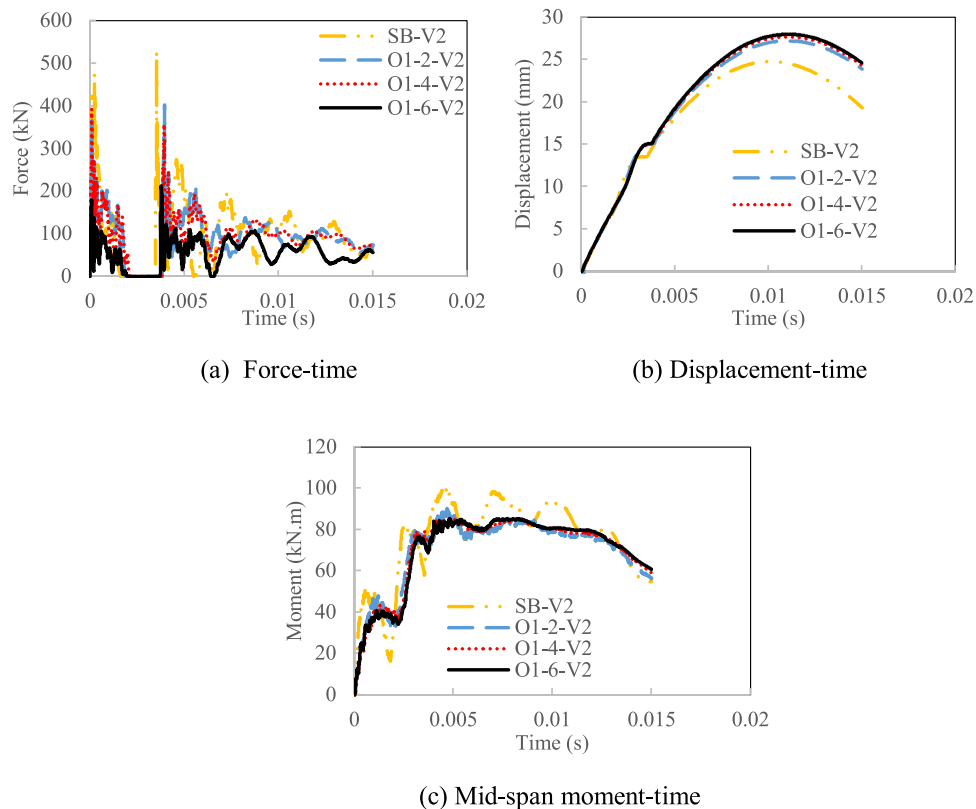


Fig. 15. Effect of the web openings number on the impact behaviour of steel beam.

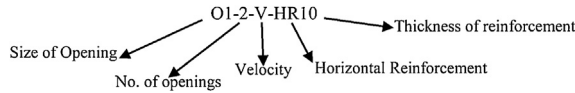
with deeper openings. In this section, the results obtained was used to show the effect of opening depth on the flexural impact capacity. Under impact loading, the results reveal that the corner of the rectangular openings is critical and the area around the corners exhibited higher stress concentration as shown in Figs. 11 and 13. However, four plastic hinges were started to develop leading to Vierendeel failure mode. The moment of inertia is a very important parameter affecting the stiffness of the beam, and therefore, reduction the depth of the beam lead to reduce the moment of inertia and then the load-carrying capacity and beam strength. Three different values of opening height were examined, i.e. 100, 125 and 150 mm. When the opening height increased from 100 to 150 mm the displacement increased by 24%, whilst the mid-span moment reduced from 89.5–80 kN.m. The impact force was also affected by the depth of the opening as it reduced from 455.9 kN to 406.3 kN with increasing the opening height from 100 to 150 mm, respectively. It can be observed that increasing the depth height from 125 to 150 mm led to raise displacement by only 13% and reduce the mid-span moment by 6.5%. The impact results obtained reveal that increasing the depth of opening up to around 70% of the total depth of the beam has a slight effect on the flexural impact strength of steel beams with rectangular web openings. More studies may be required to further investigate such results considering different cases to evaluate such slight effect obtained under impact loading compared to the higher one under quasi-static loading.

4.5. Effect of reinforcement of openings

Steel beams with rectangular web openings are usually strengthened by horizontal stiffeners to enhance their statically flexural capacity. Here, such stiffeners were used to examine whether it can improve the impact of flexural capacity. Hence, three perforated beams were strengthened by horizontal stiffeners with two thicknesses of 8 and 10 mm. Constant width of 40 mm with appropriate anchorage length were used for stiffeners. In order to investigate the effect of reinforcing the perforated beams horizontally, four models were used for this comparison. Solid beam, perforated beam (with small two openings) and two reinforced perforated beams impacted under a velocity of 5 m/s were selected. Both the reinforced and unreinforced perforated beams exhibited lower flexural characteristics than solid beam as can be seen in Fig. 17. The effect of using different reinforcement thicknesses has a negligible effect on the maximum displacement and moment capacity. Whilst, an improvement can be observed by providing such reinforcement to perforated beams. It was found that the maximum deflection and bending resistance were enhanced by 6.8 and 5%, respectively as shown in Fig. 17. (a, b). Another

Table 3
Summary of the parametric variation for the steel beam with rectangular web openings.

No.	Sample ID	Number of openings	Size of openings (mm)	Velocity (m/s)	Opening Reinforcement	Reinforcement thickness (mm)	Maximum Impact force (kN)	Maximum displacement (mm)	Maximum moment at midspan (kN.m)
1	SB-V1	0	0	2.214	none	none	217.8	9.8	72
2	SB-V2	0	0	5	none	none	529.6	24.8	99.7
3	SB-V3	0	0	7	none	none	590.1	41.5	100.2
4	O1-2-V1	2	155*100	2.214	none	none	180.7	10.2	65
5	O1-2-V2	2	155*100	5	none	none	402.9	27.2	90.3
6	O1-2-V3	2	155*100	7	none	none	455.9	46.6	89.5
7	O1-4-V1	4	155*100	2.214	none	none	210.8	10.5	63
8	O1-4-V2	4	155*100	5	none	none	393.6	27.7	85.6
9	O1-4-V3	4	155*100	7	none	none	456.8	47.1	89.4
10	O1-6-V1	6	155*100	2.214	none	none	211.4	10.7	61.1
11	O1-6-V2	6	155*100	5	none	none	426	28	85.2
12	O1-6-V3	6	155*100	7	none	none	457.0	47.4	89.4
13	O2-2-V1	2	310*100	2.214	none	none	180.8	11.4	58.1
14	O2-2-V2	2	310*100	5	none	none	395.6	32.5	75.3
15	O2-2-V3	2	310*100	7	none	none	455.1	56	83.3
16	O2-3-V2	3	310*100	5	none	none	113.1	24.4	71.7
17	O2-3-V3	3	310*100	7	none	none	228.9	46.4	78.5
18	O3-2-V3	2	155*125	7	none	none	404.8	51	85.5
19	O4-2-V3	2	155*150	7	none	none	406.3	57.8	80
20	O1-2-V2-HR10	2	155*100	5	horizontal	10	430.5	25.5	94.9
21	O1-2-V2-HR08	2	155*100	5	horizontal	8	424.9	25.6	94.4
22	O2-2-V2-HR08	3	310*100	5	horizontal	8	262.0	18.4	84.5



SB: Solid beam.

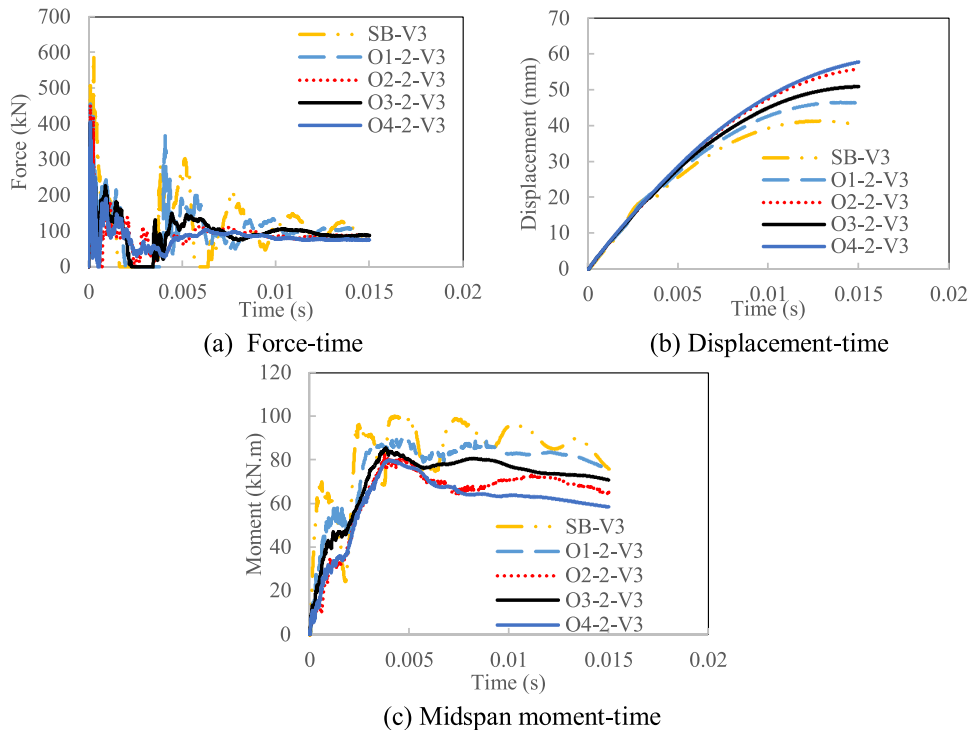


Fig. 16. Effect of the web openings area on the impact behaviour of steel beam.

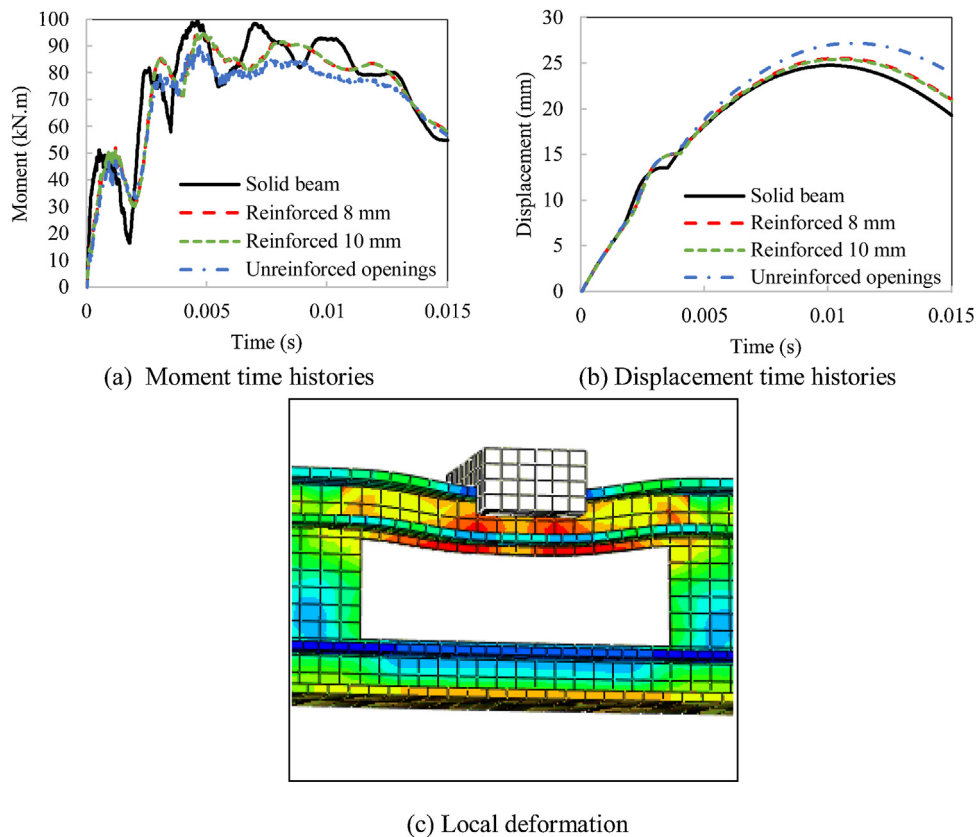


Fig. 17. Effect of providing horizontal reinforcement to web openings.

comparison was made using beams with three large openings. Again, lower bending moment resistance produced in perforated beams compared with the solid one. Besides, providing the reinforcement enhanced the impact bending resistance by about 20%. Moreover, high local deformation was noticed on the perforated beams under the impactor, which show the vulnerability of impacting such beams in the centre of an opening, see Fig. 17. (c). The local deformation can be justified by the higher concentration of impact wave in the top tee of the openings compared to the bottom one as the reinforcement plays a significant role to push the stresses away from the bottom tee. Therefore, the mid-span opening behaves to some extent as a simply supported beam producing such local failure. Under quasi-static loading, the deflection at mid-span for a tested steel beam with three horizontally reinforced web openings (each one 50×100 cm) was about 51% of the corresponding unreinforced one [34] while it was 75% under impact load but with considerable local deformation as mentioned above in this section.

5. Conclusions

The experimental results of the response of steel beams under impact loadings were used to verify the FE models of steel solid beams and then those models were utilized to investigate the impact behaviour of steel beams with rectangular web openings. The strain rate effect, ductile and shear damage were considered in the modelling. Several parameters were examined to study their effect on the impact response of steel beams with rectangular web openings. However, for simply supported steel beams with rectangular web openings under low velocity impact loading located in the mid-span of the beam, the conclusions below can be drawn.

- Very good correlations between the numerical results and the corresponding experimental ones were obtained. The difference in the maximum displacement did not exceed 8.5% corresponding to the compatibility between the numerical and experimental results of force and strain-time history. This provides strong evidence that the materials and damages properties are well modelled and the models are robust and can be utilized to conduct pragmatic study to investigate the impact behaviour of steel beams with openings.
- The beams having narrow web openings offered better flexural impact resistance than those with the wide ones having an equivalent area.

- Changing the depth of opening up to around 70% of the total depth of the beam has slight effect on the flexural impact response of steel beams with rectangular web openings.
- The effect of using different reinforcement thicknesses has a negligible effect on the maximum displacement and moment capacity. Whilst, an improvement was observed by providing such reinforcement to perforated beams.
- Regardless of the openings area, depth and number as well as the impact velocity, the steel beams showed similar mode of failure in which four plastic hinges were generated around the opening's corners due to the stress's concentration in this area.

Declaration of competing interest

The authors declare no conflict of interest.

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