Behaviour of steel beams with circular web openings under impact loading

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Abstract. This paper presents a 3D nonlinear finite element analysis on simply supported steel beams subjected to impact load. The modelling was developed to simulate the beams and the models developed were validated against the corresponding experimental results with good correlation. Parametric studies were achieved to study the steel beam with web openings and to investigate the effect of several parameters such as the number of openings, impact energy and impact location on the impact response of the steel beams. The numerical predictions show that the opening presence reduced the impact force and increased the displacement. In contrast, increase the number of openings has insignificant effect on the impact behaviour within the conditions of this study. Also, higher impact energy induces the beams to exhibit higher impact force and displacement.

1. Introduction
Openings are frequently provided in the structural steel beams of multi-storey buildings to enable pipes, ducts and electrical cables pass through. The strength and serviceability requirements of beams affect negatively if web openings are provided. The presence of such openings may have a considerable reduction in the load-carrying capacity of beams [1,2]. The deflection is also affected as the moment of inertia in openings sections reduced. The plastic deformation occurred due to the interaction of moment and shear plays an important role in the strength of beams with web openings. The moment capacity of a perforated beam is slightly reduced where the opening located as most of the moment resistance is gained by the beam flange. Nevertheless, the reduction in shear resistance at a section within the openings is substantial [3]. To regain the strength lost, the openings are reinforced along their peripheries in different ways. As a general rule, openings should not be placed in locations with high shear stresses, nor should they be closely spaced.

Different studies were conducted to investigate the response of steel beams with web openings under quasi-static loading. Jichkar et al. [4] investigated the buckling resistance of steel beams with several types of support conditions and opening configurations. It was found that increasing beam section enhanced the buckling resistance while providing web openings leads to decrease in the buckling load. A design method of composite steel beams with large web openings against Vierendeel mechanism was presented by Chung et al. [5]. The effect of the web openings was also investigated under seismic loads. Kazemi et al. [6] showed that the presence of web openings in beams may enhance the seismic response of moment-resisting frames by placing the plastic hinge away from the beam-column joints. Tsavdaridis
et al. [7] emphasized the results obtained by Kazemi et al. In addition to the possibility of controlling the story drift provided the proper usage of opening configurations. It was indicated that the main parameters in evaluating the structural behaviour of steel beams with web openings were the length of the top and bottom T-sections produced above and below the openings. As per the design guidelines of steel beams with I-section having web openings shear resistance, bending resistance, Vierendeel bending resistance, local and web buckling in addition to additional deflection should be considered [3].

In addition to static loads, the structural members may expose to dynamic loads such as impact and blast. Hence, many studies were conducted to investigate the response of different structural members to such loading regimes [8]–[12]. On the other hand, and according to author knowledge, limited studies were presented to investigate the dynamic response of steel beams with openings. Among such studies, a numerical study to investigate the behaviour of steel beams having rectangular web openings subjected to vibration was conducted by Srivastava et al. [13]. It was concluded that changing the web opening configurations has a slight effect on the natural frequency. Another related research was conducted by El-Dehemy [14] to compare the dynamic and static response of steel beams with web openings using finite element analysis. Higher stresses and mid-span deflections were obtained in dynamic analysis than those in static one.

However, it will be worthwhile to cover such a gap of knowledge and introduce the current study, in which the impact response of perforated steel beams is examined.

2. Methodology

Limited experimental researches were carried out to study the dynamic response of steel beams without web openings. Whilst, no experimental data is available for steel beams with openings under such loading type. Besides, due to the high cost of conducting experimental tests, Finite Element (FE) method can be considered as an efficient substituted tool, in which the complications of conducting experimental tests can be avoided. However, the finite element modelling results cannot be considered unless it was validated against theoretical calculations or experimental data. Antimo et al. [15] presented an experimental data of steel beams without openings tested under impact loading with different energies. In the current study, the numerical models were built and validated against the corresponding experimental findings obtained in the aforementioned study. Then, several parameters were examined, as is discussed in the next section, to evaluate the impact resistance of the perforated steel beam.

3. Previous experimental test details

The experimental results obtained by Antimo et al. [15] is used here as a reference to verify the FE models. Table 1 shows the specimens tested in the aforementioned study. The experimental tests were carried out on two IPE 220 (220 x110 x5.9) simply supported steel beams of grade S275. Six multiple impacts were applied on the first specimen while only three multiple impacts were submitted to the second specimen. The specimens were impacted by two different masses of 211 and 460 kg from heights of 250, 500, 1000, and 3000 mm. Figure 1 shows the test setup and the instrumentation used. The displacement time histories for both the impacted mass and a point located at the mid-span were obtained in the experimental tests. Such results can be used for the verification of FE models.
Table 1. The specimens tested by Antimo et al. [15].

| Test Code | Impact Test | Beam Test | Mass 1 [Kg] | Mass 2 [Kg] | Dropping Height [mm] |
|-----------|-------------|-----------|-------------|-------------|----------------------|
| ITB01 M1 H250 | ITB01 M1 H250 | ITB01 M1 H250 | 250 | 211 |
| ITB02 M1 H500 | ITB02 M1 H500 | ITB02 M1 H500 | 500 | 211 |
| ITB03 M1 H500 | ITB03 M1 H500 | ITB03 M1 H500 | 500 | 211 |
| ITB04 M1 H1000 | ITB04 M1 H1000 | ITB04 M1 H1000 | 1000 | 211 |
| ITB05 M1 H1000 | ITB05 M1 H1000 | ITB05 M1 H1000 | 1000 | 211 |
| ITB06 M1 H3000 | ITB06 M1 H3000 | ITB06 M1 H3000 | 3000 | 211 |
| ITB07 M2 H250 | ITB07 M2 H250 | ITB07 M2 H250 | 250 | 460 |
| ITB08 M2 H500 | ITB08 M2 H500 | ITB08 M2 H500 | 500 | 460 |
| ITB09 M2 H1000 | ITB09 M2 H1000 | ITB09 M2 H1000 | 1000 | 460 |

Figure 1. Experimental test setup adopted by Antimo et al. [15].

4. FE modelling
Abaqus / Explicit was employed to perform the finite element analysis, which is a preferable approach for simulating dynamic events [16]. Figure 2 presented the FE model developed to be used for verification purposes. Eight-nodded solid elements with reduced integration (C3D8R) were utilized to model the properties of steel beams and the impactor was assumed as it did not show any deformation during the tests and modelled using the 4-noded 3D bilinear rigid quadrilateral elements (R3D4). The boundary conditions were restrained against and lateral ration, whilst movement was only permitted in the “Y” direction to the condition of the experimental work.

The steel behaviour was modelled as an elastic perfectly plastic material with a yield strength of 275 Mpa, whilst the modulus of elasticity and the Poisson’s ratio were 200 GPa and 0.3, respectively. The impact force was captured using the interaction between the impactor and the steel beam. The strain rate effect on the steel material was taken into account by using Johnson-Cook material law with the C parameter value of 0.038 [17].
5. Verification of FE models
In order to conduct a parametric study, the FE models were verified first against the experimental tests presented by Antimo et al. [14]. Figure 3 shows the numerical and experimental displacement-time curves of the tested beams. All displacement sets were located at the bottom fiber of the beam mid-span. It can be seen that the predicted traces are correlated reasonably well to the corresponding experimental ones. For the tests (ITB01M2 H250) and (ITB02M1 H500), the measured displacements were 10.04 mm and 13.84 mm, respectively, whilst the numerical ones are 9.95 mm and 14.16 mm, respectively. The experimental displacement for (ITB05M1 H1000) and (ITB08M2 H500) is lower than the predicted ones by 7% and 8.5%, respectively.
In general, the agreement between the numerical predictions and the measured data is very good. This proves that the associated geometry, material and contact properties which implemented in this model are appropriate and performed well. Thus, the numerical model will be employed to carry out a parametric study to study the impact response of the steel beam with circular web opening with different loading location, impact energy and opening configuration.

6. Parametric study
The validated FE model presented earlier were adopted to carry out parametric studies to investigate the effects of several parameters on the behaviour of steel beams with circular opening under impact loading.
Figure 4 shows the typical steel beam with a circular opening which is adopted in the current study. The Circular opening diameter is 165 mm and the clear distance between the openings is greater than 165 mm. The influence of the number of openings, impact energy and impact location were examined. The FE models’ matrix is tabulated in table (2).
The first letter of the specimen designation refers to the impact location, i.e., “M” at mid-span and “E” at the edge of the beam. The first and second number represents the opening number and the impact velocity, respectively. The small letter “e” indicates that the specimen impacted by different energy with a value of 2.1, 6.8, and 10.6 kJ for “e1”, “e2”, and “e3”, respectively.
Figure 3. The FE and experimental displacement-time traces: (a) ITB01M2 H250 (b) ITB02M1 H500 (c) ITB05M1 H1000 (d) ITB08M2 H500

Figure 4. Typical steel beam with opening
Table 2. The numerical models’ matrix.

| Specimen No. | Specimen designation | Impact location | No. of openings | Velocity (m/s) | Mass (kg) | Energy (kJ) | Displacement (mm) | Force (kN) |
|--------------|----------------------|-----------------|----------------|----------------|-----------|-------------|-------------------|-----------|
| 1            | M0V1-e1              | M               | 0              | 4.43           | 211       | 2.1         | 21.00             | 465       |
| 2            | M3V1-e1              | M               | 3              | 4.43           | 211       | 2.1         | 21.99             | 323       |
| 4            | M5V1-e1              | M               | 5              | 4.43           | 211       | 2.1         | 23.20             | 315       |
| 4            | M7V1-e1              | M               | 7              | 4.43           | 211       | 2.1         | 23.78             | 314       |
| 5            | E7V1-e1              | E               | 7              | 4.43           | 211       | 2.1         | 17.81             | 311       |
| 6            | M7V2-e2              | M               | 7              | 6              | 375       | 6.8         | 60.89             | 377       |
| 7            | M7V3-e2              | M               | 7              | 8              | 211       | 6.8         | 58.69             | 409       |
| 8            | M7V4-e2              | M               | 7              | 10             | 135       | 6.8         | 56.00             | 442       |
| 9            | M7V4-e3              | M               | 7              | 10             | 211       | 10.6        | 87.60             | 447       |

7. Results and discussion

7.1. Opening configuration

Three different opening configurations were considered to study the influence of the circular web openings on the impact response of the steel beam. Three models with three, five and seven openings were studied and compared with the one without opening as shown in figure 5. The impact velocity, the impactor mass and the boundary conditions were kept constant. The displacement and corresponding impact force for all models are listed in table 2. It can be seen that the load-carrying capacity of steel beam significantly affected by the presence of the openings and it reduced by about 32.5 %. This is because of the reduction of the cross-section area and moment of inertia at the opening location. However, increasing the number of openings from three to seven, slightly decreased the impact force and increased the displacement by 3 % and 7.5 %, respectively.

The failure modes of the steel beam with a different number of openings are shown in figure 6. Clearly, it can be observed that the local deformation of beam flange underneath impactor is almost the same regardless of the number the opening configurations. However, the stress concentration near openings increased. Thus, it is recommended to strengthen the openings to avoid that kind of deformation and this will be considered in the next study of authors.
Figure 6. The mode of failure of steel beam with openings: (a) M3V1-e1 (b) M5V1-e1 (c) M7V1-e1 (d) E7V1-e1.
7.2. Impact location
To study the effect of the impact location on the impact behaviour of steel beam with seven openings, two locations were adopted, i.e. at the mid-span and a distance of 1025 mm from the mid-span of the beam, while the other parameters were not changed. The impact location has a limited influence on the impact behaviour of the steel beam, with the impact force being decreased by only 1% and the displacement being decreased by 25% when the impactor hit the beam near the support. The impact force normally increases if the impact location is close to the support due to the high stiffness of beam in this area. However, the impact force decreased because the impactor hit the beam directly on the opening location which also leads to an increase in the stresses and local deformation as can be seen in figure 6-d. The short distance between the impact location and the support induces the beam to exhibit less deformation at the mid-span of the beam as can be observed from table 2.

7.3. Impact energy (IE)
The effect of the impact energy (IE) on the steel beam behaviour with seven openings under impact loading was examined by using several values of impact velocity and mass. The velocity range of the impactor was from 4.43 m/s to 10 m/s, whilst the mass of the impactor raised from 135 kg to 375 kg. The impact energy is directly related to the mass of impactor and impact velocity can be expressed as follows:

\[ IE = \frac{1}{2} mv^2 \]  

where, \( m \) and \( v \) are the mass and the impact velocity, respectively.

The results for models M7V1-e1, M7V3-e2 and M7V4-e3 in figure 7 and table 2 manifest that the impact energy has a significant effect on the impact force and the displacement. Increases the IE lead to rise both of displacement and impact force. The impact force raised from 314 kN to 447 kN, while the displacement increased from 23.78 mm to 87.60 mm when the IE increased from 2.1 kJ to 10.6 kJ. The impact energy was increased by raising the velocity only from 4.43 m/s to 10 m/s, whilst the impactor mass was 211 kg. Increasing the initial impact energy up to a certain level, i.e. before the ultimate failure induces the beam to exhibit higher energy dissipation because of increasing the local deformation, displacement and the corresponding impact force. This clearly can be seen from figure 8-a, 8-c, and 8-e.

![Figure 7. Comparison between displacement-time curves for steel beams with seven openings under different impact energy.](image-url)
Figure 8. The mode of failure of steel beam with openings: (a) M7V1-e1 (b) M7V2-e2 (c) M7V3-e2 (d) M7V4-e2 (e) M7V4-e3.
Increasing the impact velocity with keeping the impact energy constant will slightly increase the deformation resistance of the beam as can be seen for models M7V2-e2, M7V3-e2, and M7V4-e2. However, the impact force increased by about 15% only when the impact velocity increased from 4.43 m/s to 10 m/s. Figure (8-b), (8-c), and (8-d) show that the stresses and local deformation reduced with increasing the impact velocity due to the reduction of the impactor mass to keep the impact energy constant.

8. Conclusions
This study aims to investigate the impact behaviour of the steel beams with openings. Numerical models were developed and validated with corresponding experimental findings. Based on the numerical modelling outcomes, the following conclusions can be drawn.

- The results showed that experimental displacement-time histories are well simulated and the models developed are capable of predicting the impact forces, displacements and the mode of failure of the steel beam with web opening subjected to impact loading.
- The comparison between the numerical displacement-time curves for the steel beams with different opening configurations show that the impact force and displacement were significantly affected. However, increasing the number of opening leads to increase the displacement and decrease the impact force by 7.5% and 3%, respectively within the conditions of the current study.
- The results reveal that the impact behaviour marginally affected by the impact location. However, this area of research requires more investigation.
- The numerical models have well captured the deformation shape caused by increasing the impact energy which induced the beam to exhibit higher force, displacement and local deformation.
- The modes of failure of the FE models manifest the importance of strengthening the openings to reduce the high stresses and deformation in the opening area. Thus, it is recommended to study this gap of knowledge about the influence of the reinforcing of the beam openings on the impact behaviour of the steel beams.

9. References
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