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Finite element modelling of steel beams with web openings under impact load

[a]Maryam Jebur Al-Sultan and [a]Ali Al-Rifaie

[a]Department Civil Engineering / College of Engineering / Al-Muthanna University / Al-Muthanna, Iraq
**Corresponding author Email: maryamjabr168@gmail.com and maryam.j.k@mu.edu.iq*

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Abstract

In this study, the dynamic response of steel beams with hexagonal web openings (SBHWOs) is numerically examined. ABAQUS was used to create precise 3D nonlinear finite element models (FEMs). The impact forces, displacement histories, and failure shapes from published experimental tests were used to verify the FEMs built in the current study. Both the numerical and experimental results were found to be in good agreement in terms of displacement and failure shape, in addition, to impact force. It has been established that the FE models proposed were capable of addressing the entire response of the samples in elastic, plastic, and damage stages, despite the slight variation in the level of accuracy that was observed. Furthermore, the current study examined the relationship between impact energy, opening spacing, and opening height to determine how these factors affect the dynamic responses of SBHWOs. The results showed that both the magnitude of the displacement and the duration of the impact increase as the impact energy does. The maximum impact force was higher, but the impact duration and after-impact displacement were both lower when the opening spacing was increased. Increasing in opening height led to decreases in maximum impact force and average plateau impact force corresponding to an increase in impact duration and post-impact displacement.

***Keywords**: Dynamic response, finite element method, hexagonal web openings, impact, steel beams.*

1. Introduction

Openings in the structural steel beams of multi-story constructions allow ducts, wires, and pipes to flow through. Beams' strength and serviceability requirements are severely altered when web apertures are present. Such pores' presence may drastically impair beams' load-carrying capacity [1,2]. Lowering the moment of inertia also has an effect on Deflection. The interplay of the moment and shear causes plastic deformation, which is crucial for the lifespan of beams containing web holes. Because the beam flange provides the majority of the moment resistance, the moment capacity of a perforated beam is significantly reduced near the aperture. On the other hand, a part within the apertures has substantially reduced shear resistance [3]. To compensate for the strength loss, each opening has its own unique manner of reinforcing its outer borders.

The finite element methods (FEMs) [4,5] are one of the most efficient and precise numerical methods for dealing with the problem of dynamic analysis of structures under impact. Numerous engineering problems can be approximatively solved using the FEMs, a numerical analysis technique. The field of continuum mechanics has benefited from this method, which was initially developed for studying stresses in intricate airframe structures. There is a lot of interest in it in engineering programs and the business world as a result of its versatility and adaptability as an analysis tool [6]. Some numerical studies have been done to better understand the response of steel beams with web openings (SBWO$_S$) under impact loading. Srivastava et al. [7] ran a numerical study to look into what happens when steel beams with rectangular web openings are shaken. It was determined that the natural frequency is slightly affected by the configuration of the web opening. The stress and deflection distributions in SBWO$_S$ were studied by El-Dehemy [8]. According to the findings, the steel beam's deflection value grew larger as the number of holes increased. Moreover, a steel beam's stresses will rise as the number of its openings grows. When compared to static analysis, dynamic analysis has been shown to have higher values. Furthermore, the presence of openings decreases the rigidity of the beam when compared to SBWO$_S$ with bare steel beams (BSB$_S$). These results are in agreement with those obtained by R.R. Jichkar et al. [9].Alaa S. Al-Hussainy et al. [7] were among the researchers who used the FEMs to analyze the impact behavior of steel beams with circular apertures. The impact response of steel beams is studied by conducting parametric studies, with the impact energy, number of openings, and impact location all being studied as potential influences. According to the numerical findings, the presence of a hole will decrease the impact force and increase the displacement. On the other hand, changing the number of openings does not drastically affect the way impacts play out. In addition, the impact force and displacement of the beams are maximized at higher impact energies. Steel beams with square or rectangular web apertures were investigated by Ali Al-Rifai et al. [10] to ascertain their flexural impact strength. The number, area, depth, and reinforcement of web openings were among the many variables investigated using the ABAQUS-created 3D nonlinear FEMs under varying impact velocities (2.214-7 m/s). As can be seen from the results, the narrow openings are more resistant to bending impacts than the wider ones. Moreover, it has been found the opening depth has little effect on the bending impact response of the steel beams. Horizontal steel reinforcement of perforated beams is also very effective. The investigation is still in progress, and the issue of impact remains the focus of attention of the majority of researchers in recent years. The impact loading effect on the dynamic response of steel beams with hexagonal web openings (SBHWOs) was studied experimentally and numerically by Fengxuan Wang et al. [11] in 2022. To analyze the effects of impact energy, opening height, and opening spacing on the dynamic responses of SBHWOs, employ FEMs to study the dynamic response of such beams subjected to impact loads. Peak force, displacement, and impact duration were found to grow in proportion to the square of the impact energy. Opening spacing increased the maximum impact force but also decreased the impact duration, web-post buckling, and post-impact displacement. When the opening size was increased, the impact length, web-post buckling, and post-impact displacement were all larger, while the maximum impact force and the average plateau impact force were smaller. As stated in their paper, Huiyun Qiao et al [12] proposed a new principle with the intent of satisfying the rotation capacity and realizing the second route for the development of catenary action. A frame substructure made of kinked reinforced bars was the subject of both experimental and numerical research. It was discovered that the bearing capacity decreased along with the length of the reinforced bars. Comparing openings of varying diameters, it has been found that maximum bearing capacity varied by less than 5% but that failure modes varied greatly. The bearing capacity and ductility also decrease as the kinked height increases past two diameters. The experimental findings of Fengxuan Wang et al. [11] were the basis for the numerical analysis conducted by Caisong Luo et al. [13] into the effects of dynamic loads on castellated steel beams (CSBs). Opening height, impact velocity, opening spacing, impact mass, beam height, impact location, boundary conditions, and span-height ratio were all studied. The results demonstrated that the deflection of such beams and the time needed to dissipate the impact energy increased with both impact velocity and mass. Additionally, the ratio of opening size to beam height was found to have a minor impact on the deflection. Furthermore, the deflection was found to be proportional to the ratio of the opening's height to the beam's height. Impact location also had a sizable effect on the shape of the deflection curve. With the impact mass and velocity serving as the primary control parameters, a damage assessment curve was established using the value of the rotation of the support as the damage evaluation index.

This paper provides an overview of the numerical methods and techniques used to model the response of steel beams with openings to an impact load. For this study, the dynamic responses of SBHWOs were analyzed using the commercial FEMs software ABAQUS/Explicit. All aspects of the link's geometry, such as the kinds of elements used and the size of the mesh, are presented in full. Loading and boundary condition modeling are also described. Moreover, methods for modeling steel materials at the elastic, plastic, and damage stages are provided. The nature of the reaction and the characteristics of the interaction between the various steel components are also discussed. In addition, the effect of some factors affecting SBHWOs was shown, including spacing between openings, impact energy, and opening height effect.

2. Methodology

Little experimental work has been done to investigate the dynamic response of SBWOs subjected to impact loading. Additionally, the high-cost tag associated with running experiments makes the FEM$_S$ a potentially useful alternative that can help you avoid the hassles associated with running experiments. However, the outcomes of FEM$_S$ cannot be taken into account unless they have been verified by theoretical calculations or experimental data. SBHWOs were subjected to impact loading experiments, the results of which were presented by Fengxuan Wang et al. [11]. In this study, numerical models were created and validated against the related experimental results in this investigation. Many variables were then examined.

3. Experimental work

In this paper, Fengxuan Wang et al [11] experimental results have been used to check the accuracy of our FEMs. Q235 steel was used to create eight different beam samples SBHWOs. The beam had dimensions of (30 x 15 x 0.8 x 1) cm, measured 240 cm in length (L), and had a calculated length of 212 cm (L_0). The standard dimensions are depicted in Figure 1's notation. spacing between openings (29 cm, 31 cm, and 33 cm), impact energy (16.5 kJ, 21.5 kJ, 26.5 kJ, and 30.96 kJ), and opening height (16 cm, 18 cm, 20 cm). To easily produce SBHWOs, the cut-out web opening method is recommended. The following three categories describe the various stages of production. Initial web and flange cuts were made using the dimensions listed in Table 1. At strategic points, the web was sliced away to reveal a series of hexagonal openings. At last, the web was welded onto the flange. Table 2 provides a quick summary of the steel characteristics of the web and flange plates. The apparatus and setup used for the test are depicted in Figure 2. Since the expected impact-induced deformations on both sides of the SBHWOs are the same, the displacement gauge was only installed on the left side. Midspan, S-distance from midspan, and 2S-distance from midspan were the points used for displacement measurement.

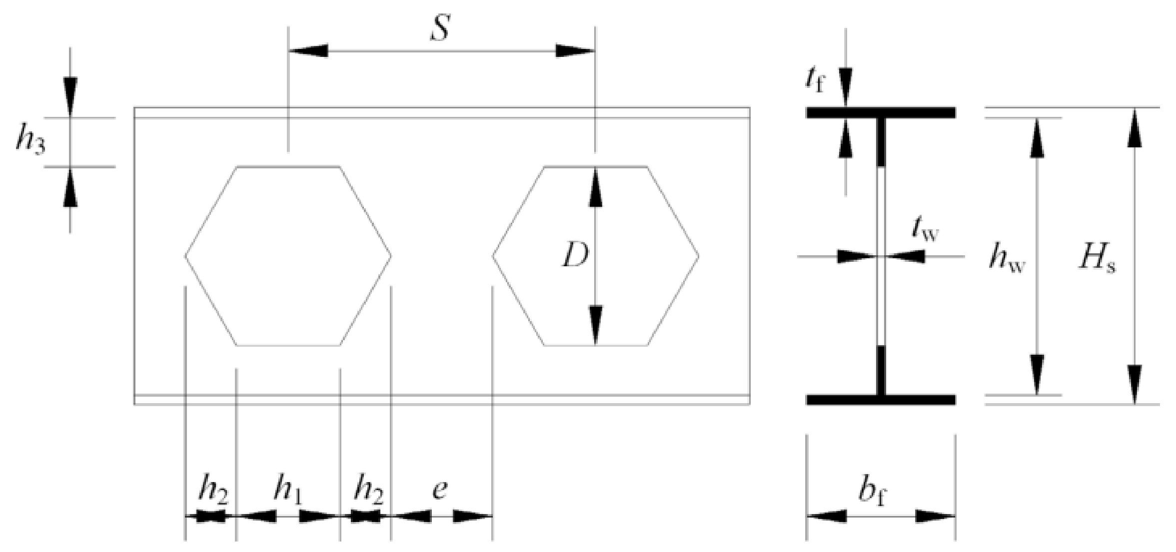

Fig. 1: The SBHWO$_S$ dimensions are in standard notation[11].

Table 1: The Specimen Design Parameters [11].

Specimen No.	Spacing between openings (cm)	Depth (cm)	h_1 (cm)	h_2 (cm)	Velocity (m/s)	Mass (ton)	Energy (kJ)
1	31	18	10.4	5.2	10	0.43	21.5
2	31	18	10.4	5.2	1۲	0.43	30.96
3	31	18	10.4	5.2	10	0.33	16.5
4	31	18	10.4	5.2	10	0.53	26.5
5	29	18	10.4	5.2	10	0.43	21.5
6	33	18	10.4	5.2	10	0.43	21.5
7	31	16	9.2	4.6	10	0.43	21.5
8	31	20	11.6	5.8	10	0.43	21.5

In the notes, h_1 and h_2 stand for the opening sizes of the hexagonal web.

Table 2: Steel characteristics[11].

Component	Average thickness (cm)	Yield strength (GPa)	Ultimate strength (GPa)	Elastic modulus (MPa)	Elongation (%)
Web plate	0.733	0.30443	0.44288	199470	40.84
Flange plate	0.929	0.32949	0.4645	200360	39.37

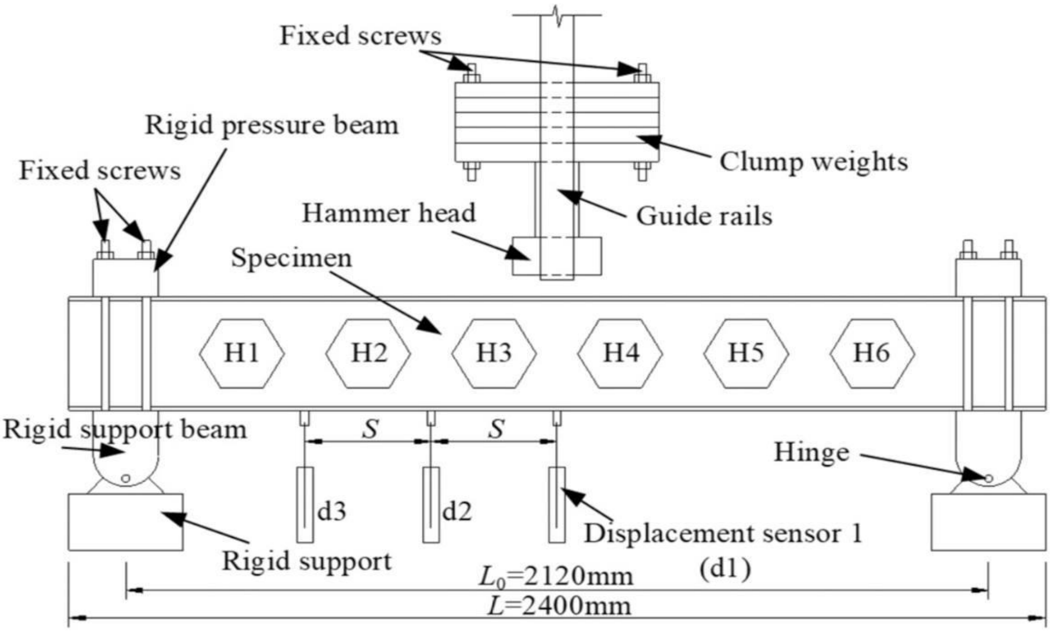

Fig. 2: Experimental test setup adopted by Fengxuan Wang et al. [11].

4. Finite Element (FE) modeling

Fengxuan Wang et al. [11] detail the examples selected for beams with web apertures subjected to impact load and the numerical methodologies and techniques utilized to model the tested reference beams. The explicit technique was utilized to create numerical models in ABAQUS since it is more appropriate for simulating a dynamic event. Further, such a technique could help avoid issues with convergence [14]. You'll find information about the element type, meshing, contact interaction, boundary conditions, geometry, material properties, and FE model verification here.

4.1. Boundary conditions and geometry

The geometric specifics and boundary conditions of the FE model used in this investigation are displayed in Figure. 3. To mimic the simply supported conditions, translational motion in the x and y axes was disabled. To simulate a vertical impact, the impactor was treated as a rigid body with all its axes of motion constrained except for the y-axis. Various projectile masses (330, and 430 kg) and launch velocity (10 m/s) were modeled.

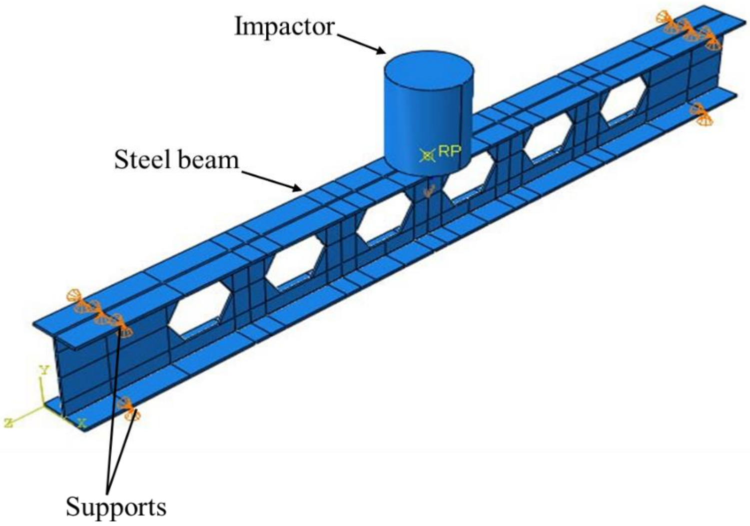

Fig. 3: Boundary conditions and geometry.

4.2. Contact interactions, element type, and mesh size

The Eight-nodded solid elements with reduced integration (C3D8R) were used because of how well they represent impacts. Figure 4 depicts the numerical modeling of the bundle with the selected element type. A sensitivity analysis was performed in order to determine the best mesh size. Although the complete model was solved with a mesh size of 20 mm, it was revealed that utilizing a mesh size of 10 mm for the flange and web near the midspan of the beam produces close results with an appropriate computing time. The 4-noded 3D bilinear rigid quadrilateral elements (R3D4) with a mesh size of 10 mm were used for impactor modeling, as illustrated in Figure 5. Surfaces in contact were represented using tie constraints and surface-to-surface contact formulae. To connect the weld to the flange and web, the earlier procedure was used. The impactor and the upper flange of the beams, on the other hand, made direct, surface-to-surface contact. A penalty friction formulation with a coefficient of friction of 0.2 between the contact surfaces was used to describe the tangential behavior of the contact, whereas the normal direction of contact was assumed to be linear. It was also explored to treat the stiffer section as the master surface and the less rigid section as the slave surface [14].

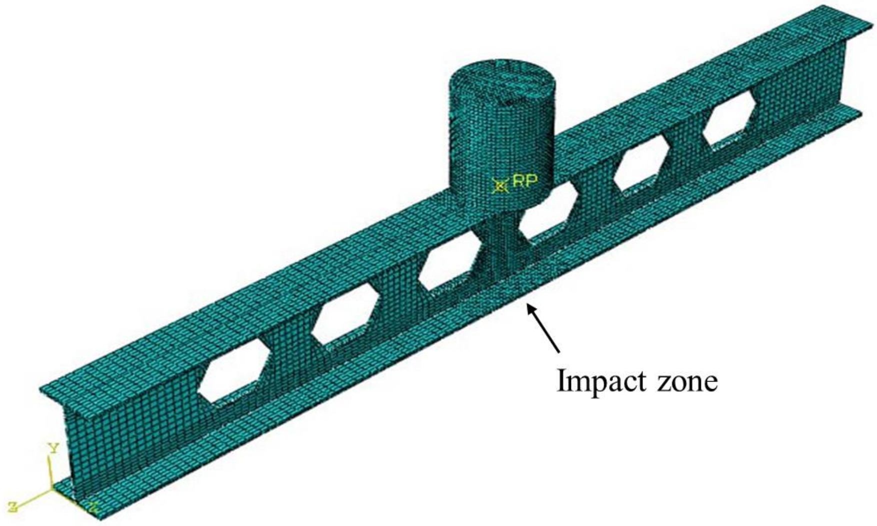

Fig. 4: FE model for steel beam mesh.

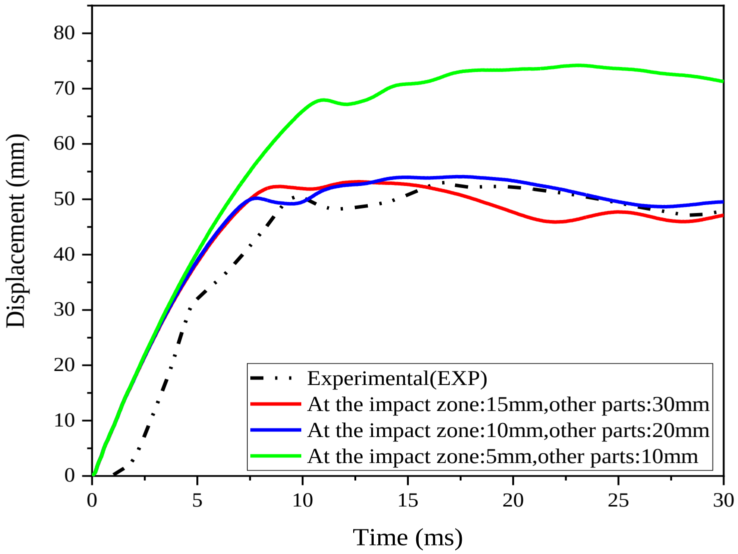

Fig. 5: Sensitivity of the SBHWOs displacement history for different mesh sizes to sample No. 1(mid-span).

4.3. Steel material constitutive models

Steel's elastic and plastic properties were determined from experimental results obtained by Fengxuan Wang et al. [11]. Table 2 also includes these items. Mechanical properties vary depending on the strain rate exhibited by the material, which can be caused by an impact or explosion. When analyzing the dynamic performance of structures and components, it is important to have a clear understanding of the material's dynamic constitutive model [15,16]. The Cowper Symonds (C-S) model is commonly used in the dynamic study of metallic materials subjected to high strain rates [17–19] because of its ease of use and accurate prediction results. The C-S model can be expressed in terms of a dynamic enhancement factor (DIF) by the following:

$$\mathrm{DIF}=1+\left(\frac{\varepsilon^{*}}{D}\right)^{1/q} \qquad (1)$$

Using the C-S model with D = 40 and q = 5, the effect of a high strain rate on yield strength in low-carbon steel can be accurately predicted.[15]. **Here:** *The plastic strain rate is denoted by* ε^{*}, *While D and q are the parameters of the C – S model.*

In addition, the strain rate is ignored when calculating ductility and shear parameters in ABAQUS[20]. Haitham Al-thairy [21] .'s findings in Tables 3 and 4 on the relationship between triaxial stress and fracture stress on the basis of shear and ductile failure form the basis for the steel fracture model used in this investigation.

Table 3: The numerical model's parameters for the ductile failure of the material[21].

Plastic strain at Damage initiation	Maximum triaxial stress	The maximum rate of strain (sce^{-1})	ε_f^{pl}	u_f^{pl}(mm)
0.115	0.7	14.2	0.145	1.45

Notes:ε_f^{pl}: The comparable plastic strain at the element's full failure,u_f^{pl}: The total plastic displacement at the failure point.

Table 4: The numerical model's parameters for the shear failure of the material[21].

Plastic strain at Damage initiation	Maximum shear stress ratio	Maximum rate of strain (sce^{-1})	ε_f^{pl}	u_f^{pl}(mm)
0.172	1.8	120	0.83	8.3

5. Verification of FE models

To evaluate the validity of the ABAQUS, FE program for simulating the dynamic response of SBHWOs, a comparison was made between the numerical results of the current study and the experimental results of Fengxuan Wang et al. [11]. As shown in Figures 6 and 7, the results of the numerical simulation of the FE were almost in agreement in terms of displacement, and also in terms of impact force results with the experimental study, shown in Figures 8 and 9. Moreover, there is a good agreement between the failure of FE with the detection of beams that are tested experimentally, as shown in Figures 10 and 11. Besides that, the area connecting the beam and the dropped hammer is where the vast majority of the damage is done. In spite of this minor discrepancy, it is established that the proposed FE model was able to address the full response of the chosen samples. There could be a number of factors at play in the discrepancies between the experimental and numerical results. The discrepancy between FE and experimental results may be due to the numerical representation of the interaction and support conditions or maybe the result of assuming that the dropped hammer did not show any deformation during the tests and was used as a rigid body. In this study, a FE model of SBHWOs was presented, and it was found to be in good agreement with experimental results. A parametric study of the parameters affecting the behavior of the examined beams is thus conducted using the developed FE model.

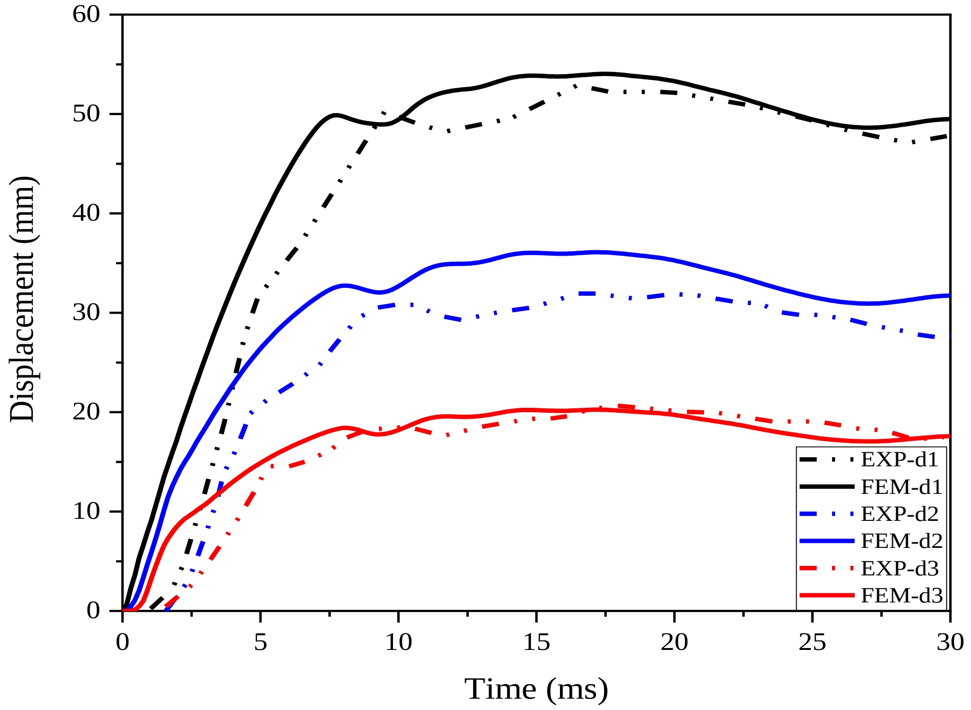

Fig. 6: Differences in displacement time histories between numerical simulations and experiments to sample No. 1.

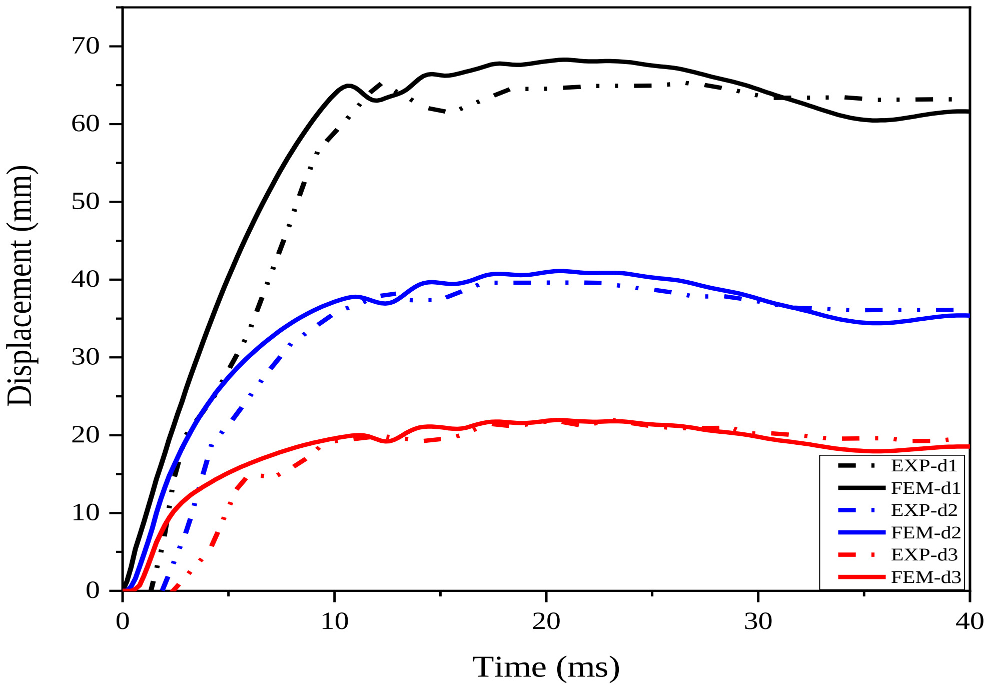

Fig. 7: Differences in displacement time histories between numerical simulations and experiments to sample No. 8.

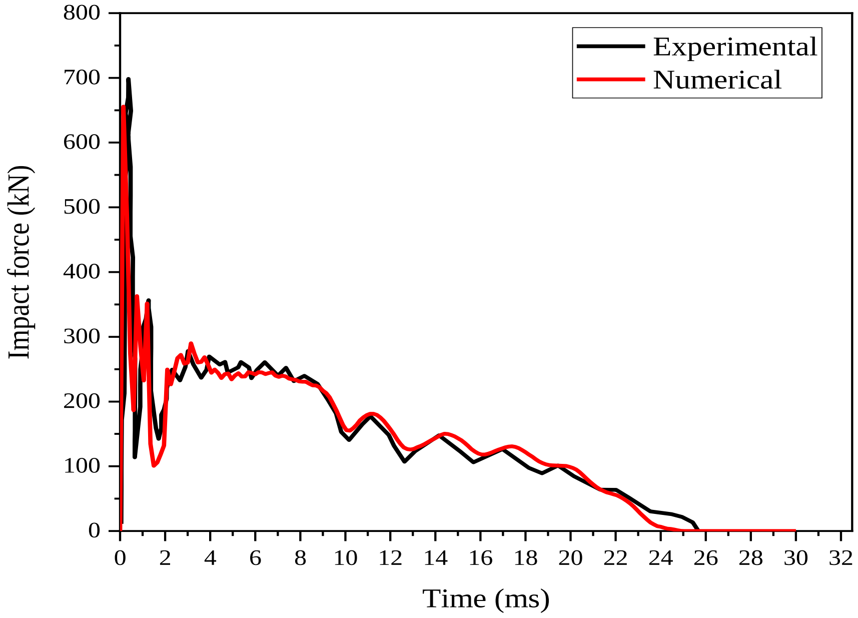

Fig. 8: Differences in impact force time histories between numerical simulations and experiments to sample No. 1.

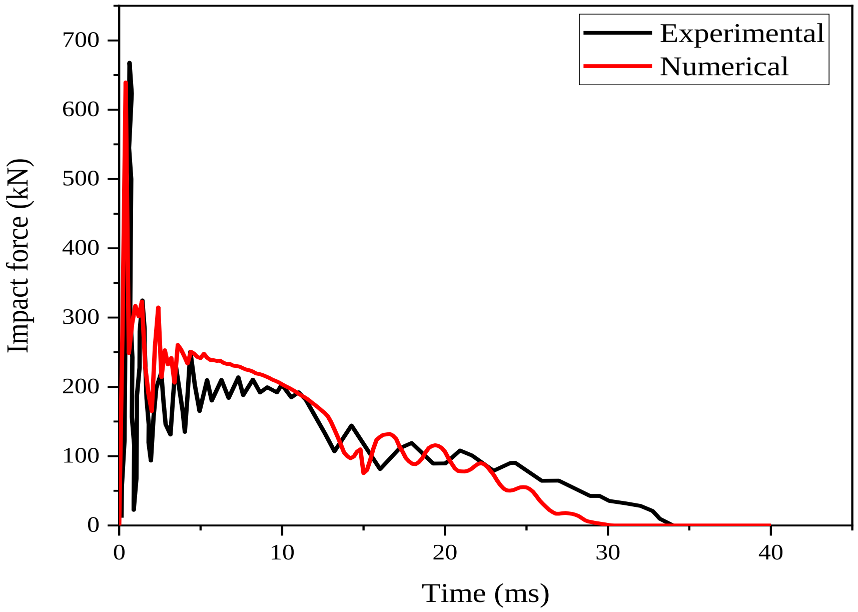

Fig. 9: Differences in impact force time histories between numerical simulations and experiments to sample No. 8.

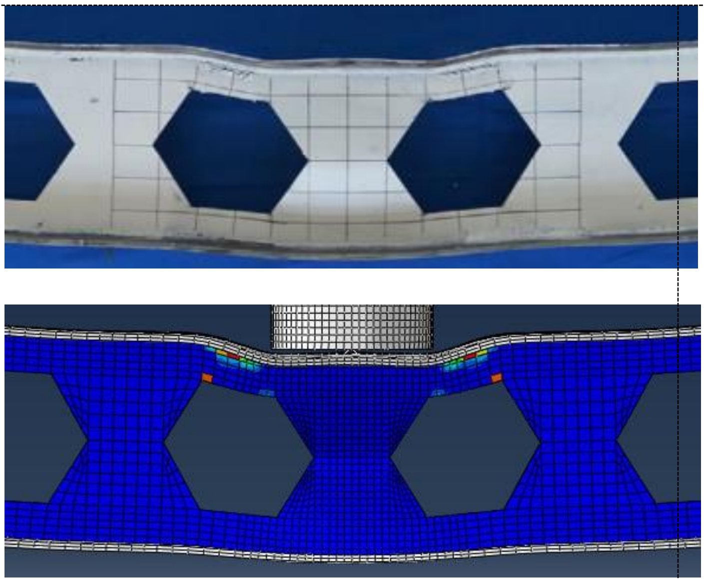

Fig. 10: Patterns of SBHWOs deformation as measured experimentally and calculated numerically are compared to sample No. 1.

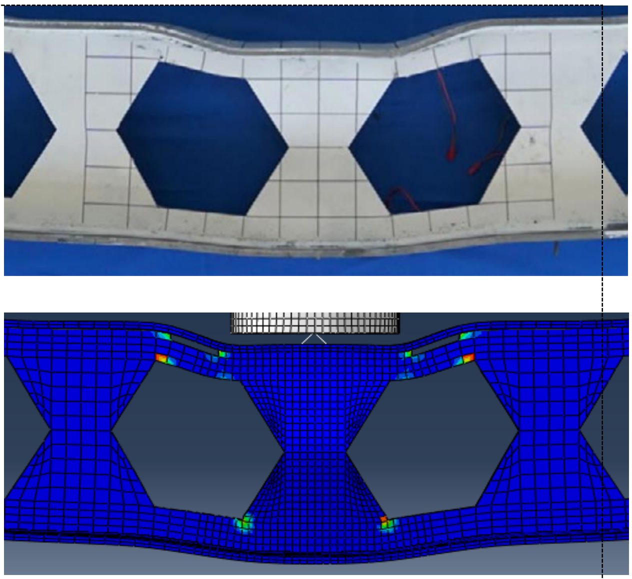

Fig. 11: Patterns of SBHWOs deformation as measured experimentally and calculated numerically are compared to sample No. 8.

6. Conclusions

The current study aims to build finite element models capable of better understanding how SBHWOs respond to impact. The associated experiment was used to develop and validate the numerical models. The dynamic responses of SBHWOs in dropped hammer testing can be predicted with high accuracy using a FE model. The FE model presented in the current study showed good agreement with experimental results regarding failure mode and displacement, in addition to impact force. The concave upper lip in contact with the dropped hammer, the web shaft laterally convex in the impact zone, the pressed hexagonal holes on both sides, and the net loosened away from the impact zone are all results of the impact on SBHWOs. Also, it is found that as the impact energy increases, so do both the amount of displacement and the time it takes for the impact to occur. However, the maximum impact force started to rise as the impact energy increased. While the maximum impact force increased as the opening spacing widened, the impact duration and post-impact displacement all decreased. As the opening height increased, so did the impact duration and post-impact displacement, while the maximum impact force and average plateau impact force decreased.

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