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Numerical Analysis of Bio-Hybrid Crashworthiness Design and Investigation of Energy Absorption Performances Under Oblique Impact

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Abstract
Designs inspired by nature are used in several areas as automotive, aerospace and defence industry. In studies on the axial crushing analysis of thin-walled structures such as crashworthiness, a critical role of developments of design aspects have been achieved by the bioinspired perspective. The energy absorption performance of the crashworthiness which shapes the basis of the crushing analysis is the main aspects of the numerical and experimental solution methods. In order to verification of finite element model, the energy absorption characteristic specifications were performed the square tube under axial loads. Using the proposed of lotus-inspired design performances of axial load condition, the newly design was prepared square tube included lotus bifurcation as called "bio-hybrid". To compare the axial and oblique loads performances of the L (lotus) and BH (bio-hybrid) structures, force-deformation curves was evaluated with characteristic properties as EA, CFE, SEA, MCF and PCF. The numerical analysis showed that the square outer frame included lotus bifurcation of crashworthiness is suitable than natural circular lotus configuration under oblique loads. However, the lotus-inspired configuration is determined advantageous under axial loads.

Key Words
"Crashworthiness, energy absorption, bio-inspired design, oblique impact"

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1. Introduction

Crashworthiness is one of the main parts that ensure the safety of passengers and drivers in automobile accidents. There are two crashworthiness behind the bumper that distributes the kinetic energy released by the impact (San Ha et al., 2023). It is based on reducing the energy absorption by converting kinetic energy into plastic deformation energy. For this reason, studies have determined that geometric factors play a critical role as well as material selection. The studies carried out, it was aimed to increase the stiffness of structures by dividing the thin-walled polygonal and circular outer frame into multi-cells with different patterns (Nia et al., 2013; Nia et al., 2014; Fang et al., 2015; Ahmed et al., 2017; Shen et al., 2017; Xu et al., 2018; Wang et al., 2018). To investigate the behaviour of crashworthiness under impact loads, the sequential folding has achieved of the scaffold that consist of different corner geometries (Chen et al., 2018; Albak et al., 2021; Chen et al., 2019). From the shapes designed to increase the energy absorption capacity of the scaffold, it was seen that significant improvement was achieved in the high order hierarchical structures (Fan et al., 2018).

The adaptation of plants and animals living in nature is an important source of inspiration for designers in the fields of architecture and engineering. The numerical and experimental results indicated that the energy absorption is high efficiency for considered on bio-inspired properties (San Ha et al., 2020). Gong et al. (2022) carried out the energy absorption performances of the crashworthiness in a lotus-like and multi-cell structure. However, the optimum design parameters were determined by numerical simulations. Bamboo, plant stem, pomelo peel and horsetail-inspired structures provides an advantageous structure which is prepared with the definition of bionic energy absorber under axial loads (Zou et al., 2016; Zhang et al., 2019; Qin et al., 2022; Cheng et al., 2022). The design parameters such as multi-cell number and structural hierarchy, outer and inner diameter of the circular structure that was designed by bioinspired crashworthiness were more effectively in the SEA (specific energy absorption) (Zhang et al., 2018; Gong et al., 2020; Zhang et al., 2019). According to the experimental and numerical analysis studies, the best results were obtained with the increase in the number of multi-cells in the horsetail bionic structure (Xiao et al., 2016). Similarly, in the bionic conch-like crashworthiness, the effect of inner and outer diameter of structures on PCF (peak crashing forces) was greater than other geometric parameters (Zhang et al., 2019; Song et al., 2019) Xu et al, (2022) determined that in the pinus sylvestris hierarchical scaffold, which they designed as a square profile that was prepared the multi-cells of the inner parts of the corners, more suitable by means of sequential folding during deformation (Albak, 2021; Xu et al., 2022). In another design related to edge shape of bioinspired designs, the SEA significantly increased on the honeycomb frame with a triangular hierarchy (Yin et al., 2021). Song et al. (2022) determined the three cell shape of pine cone inspired structures was better energy absorption than other configurations. In bioinspired crashworthiness designs, analysis is also made on the basis of shell animals. In one of these, beetle elytra-like modelling, the SEA and CFE (crushing force efficiency) values determined that the wall thickness plays an important role for the best efficiency (Du et al. 2020). For the crashworthiness performance improvement, the behaviour of these structures under oblique loads has also been investigated in many studies (Fang et al., 2015; Zhang et al., 2021; Zhu et al., 2023). Huang et al. (2019) discussed that the most suitable EA (energy absorption) was obtained with the five-cell model in their optimization according to the O. scyllarus-like structure design.

The main purpose of this study is to design a square outer frame of crashworthiness that is used the hierarchical interior bifurcation pattern of a lotus inspired structure. However, the energy absorption parameters of the newly crashworthiness lotus-liked structure were investigated to improve the design. Our proposed methodology, for the designs defined as lotus (L) and bio-hybrid (BH), analysis was carried out under oblique and axial loads that is executed the numerical analysis method.

2. Material and Methods

In main crashworthiness analysis, the area under the force-deformation curve is evaluated as the total energy absorption of the structure. The deformation caused by a plate impacted on the structure in an axial or angular position is executed in numerical and experimental analysis. When the moving plate impact on the structure, the kinetic energy is transformed into plastic deformation energy. In this process, the geometric characteristic of the crashworthiness plays an important role for excellent energy absorption. Several equations in the literature are used to calculate the performance indicators of structure. The main indicators calculated in performance are respectively: PCF, mean crushing force (MCF), SEA, EA, CFE (Zhang et al., 2018; Qin et al., 2022;). The energy absorption of the whole system during deformation as:

$$\mathrm{EA(d)} = \int_{0}^{\mathrm{d}} \mathrm{F(x)dx} \tag{1}$$

where d is the axial displacement and F is the axial compression force. The maximum point on the force-displacement curve in numerical and experimental analyses is called PCF. The SEA is calculated by dividing EA by the mass of the structure. Based on the force-deformation graph, the MCF is given as:

$$\mathrm{MCF(d)} = \frac{\mathrm{EA(d)}}{\mathrm{d}} \tag{2}$$

CFE, which is the stability of the structure against the maximum impact force, can be explained as:

$$\mathrm{CFE} = \frac{\mathrm{MCF}}{\mathrm{PCF}} \text{ x } 100\% \quad (3)$$

To improve the design of crashworthiness, it is aimed to provide the optimal value of PCF and CFE with large cross-section area. In this case, the crashworthiness design is desired to have a low initial peak force at the crash. Based of crashworthiness studies in literature are focused on improving one or more parameters, it is basically aimed to reduce the fluctuation of force-displacement.

2.1 Finite Element Validation

Multi-cells are obtained that is placed panels in various hierarchies inside the square and circular tubular structure. Wu, (2016) designed the structures for multi-cell and square cross-section of crashworthiness and studied experimental and numerical analysis. The square section structures are 200 mm length and various wall thickness as given in Figure 1. The boundary conditions of plates (moving and fixed) and crashworthiness of FE assembly are set up for reference FE model (Wu et al., 2016). The moving and fixed plates was designed 100 x 100 mm^2 steel which is used material properties are follows; density $7.8x10^3$ kg/m^3, Poisson's ratio 0.3, Young's modulus 200 GPa. As seen in Figure 1(b) and 1(c), the C1 and C4 are designed 3D deformable in the Solidworks software then was imported into the FE assembly. The structures bottom surface and fixed plate outer surface are constrained each other. For this study, the design of which was verified the FE model was set in Abaqus software considering the material properties of AI6063-T5 as follows: density $2.7x10^3$ kg/m^3 , Young's modulus 68.2 GPa, Poisson's ratio 0.3(Wu et al., 2016). A static friction coefficient of 0.2 for surface-to-surface contact is defined in quasi-static conditions. The C1 and C4 structures was meshed C3D8R and for moving plates S4R, despite the shell structures which is used crashworthiness analysis generally performed in LS-DYNA (Xiao et al., 2016; Gong et al., 2020; Gong et al., 2022).

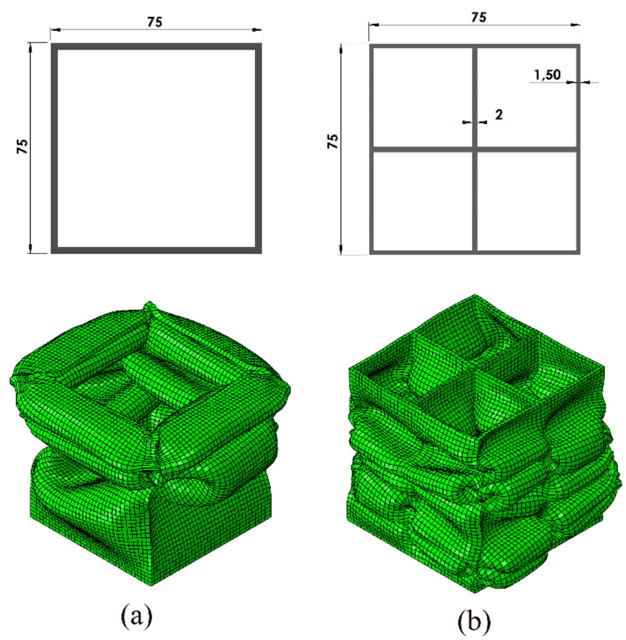

Figure 1. The deformation and lobe shapes during compression in **(a)** C1 and **(b)** C4 designs.

The number of mesh elements dimension is taken as 1.5 mm considering the validation model. The moving plate velocity is 10 m/s and deformed the structures from 0 to 120 mm. According to the quasi-static analysis solution, the ratio of kinetic energy to internal energy is below 5 % for validation of FE (Figure 1). The force-deformation curve of C1 and C4 which were designed in the same mass is showed in the Figure 2. It was ensured closed to FE model (Wu et a., 2016).

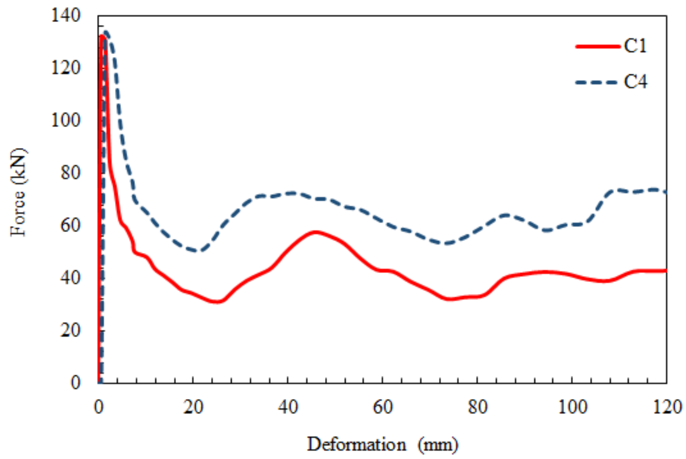

Figure 2. The force-deformation curves of C1 and C4 for convergence of FE model

The cross-sectional areas of C1 and C4 structures are equal, thus the PCF are 132.21 kN and 133.77 kN respectively. Until the sustained deformation to 120 mm, C4 collapse modes more uniform than C1 (Wu et al., 2016).

Table 1. FE analysis results vs. C1 structure verifications of FE model for performance parameters

Performance Parameters	C1*	C1 (Wu, 2016)	Error (%)
PCF(kN)	132,21	131,37	0,63
MCF(kN)	44,75	42,66	4,67
SEA(kJ/kg)	13,7	12,64	2,81
EA(kJ)	5,37	5,11	4,67
CFE(%)	33,85	32,5	3,98

In the impact simulation applied to the C1 structure for FE model verification, C1* values were calculated by the force-deformation curve and the Equation (1), (2) and (3). According to the referenced results, as given in Table 1, the model validation was approved since the error in the simulation model was < 5%.

2.2 Geometry of Bio-Hybrid Design

Generally, a circular outer frame is prepared for crashworthinesses on the basis of bio-inspired. Numerical and experimental analyses of these designs, which are created with the inspiration are carried out under the most appropriate conditions with various parameters. In particularly, the grooves on the tubular scaffold with circular cross-section were observed to behave with the definition of "corcentina mode" (Wang et al., 2018; Gong et al., 2020; Cheng et al., 2022;). In axial loading, it is desirable to provide the deformation as collapse without bending of scaffold in the same direction.

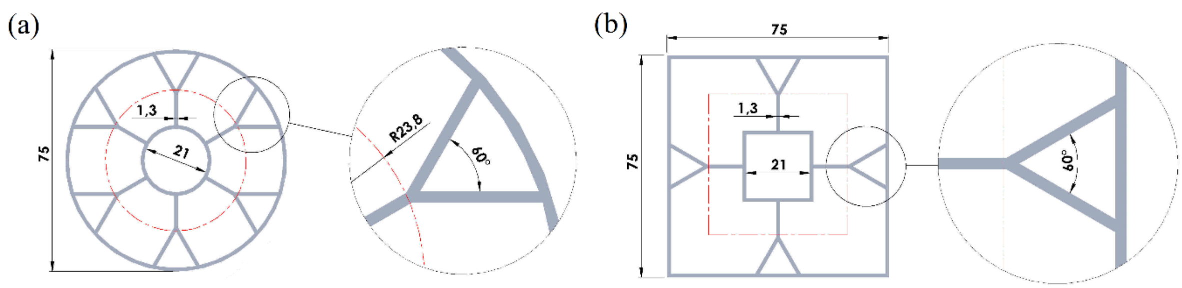

Figure 3. Design specifications of crashworthiness, **(a)** Lotus-liked, **(b)** Bio-hybrid.

When the kinetic energy is absorbed of the structure, dimension of structure is changed with corcentina mode under compression in square cross-section. Here, the newly crashworthiness created by the square outer frame with the bifurction panels which is inspired lotus-like structure is shown in the Figure 3. In this design idea, the wall thickness along with the inner and outer diameters for the L design was prepared by considering the reference model (Wu et al., 2016). It was prepared as 375 gr of L (Lotus) and BH (Bio-hybrid) designs with respect to C1 and C4.

2.3 Finite Element Simulations for Axial and Oblique Loads

The crashworthiness fixed behind the vehicle bumper can be deformed at different angles when there is an accident. As the load increases at the oblique angle, the crashworthiness is resisted to buckling (Huang et al., 2019). To investigate the buckling stiffness of multi-cell structures, studies were carried out single-cell polygonal and circular bio-inspired structures under oblique loads (Fang et al., 2015; Umeda & Mimura, 2019; Huang & Hu, 2019; Zhu et al., 2023). In this paper, numerical analy-sis was performed using Abaqus/Explicit software (Abaqus, 2014). The FE model prepared to examine the behaviour of the L and BH designs under axial and oblique loads is shown in the Figure 4. Moving plates are positioned on the structure at different angles (0°-15°-30°).

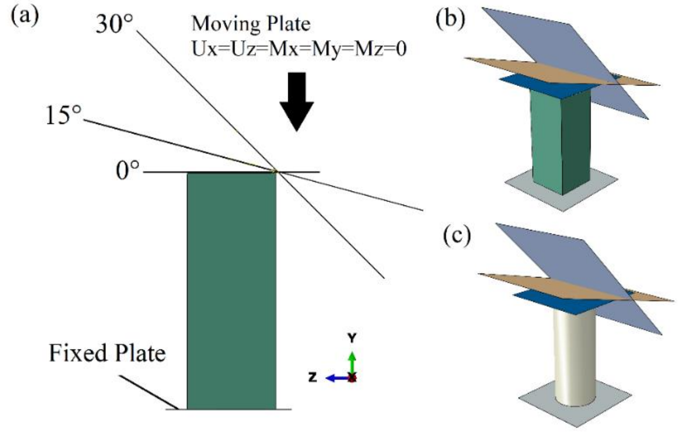

Figure 4. (a) FE models of designs assembly in all parts, **(b)** Bio-hybrid (BH), **(c)** Lotus-inspired (L).

Accordingly, the moving plates velocity is 10 m/s under quasi-static conditions at a low feed rate. The moving plate and structures have interacted to each other by surface-to-surface contact. The bottom of structures and fixed plate have constrained interaction. All parts in the simulation model are hard con-tact and static friction coefficient of 0.2 (Wu et al., 2016; Gong et al., 2022; Deng et al., 2023).

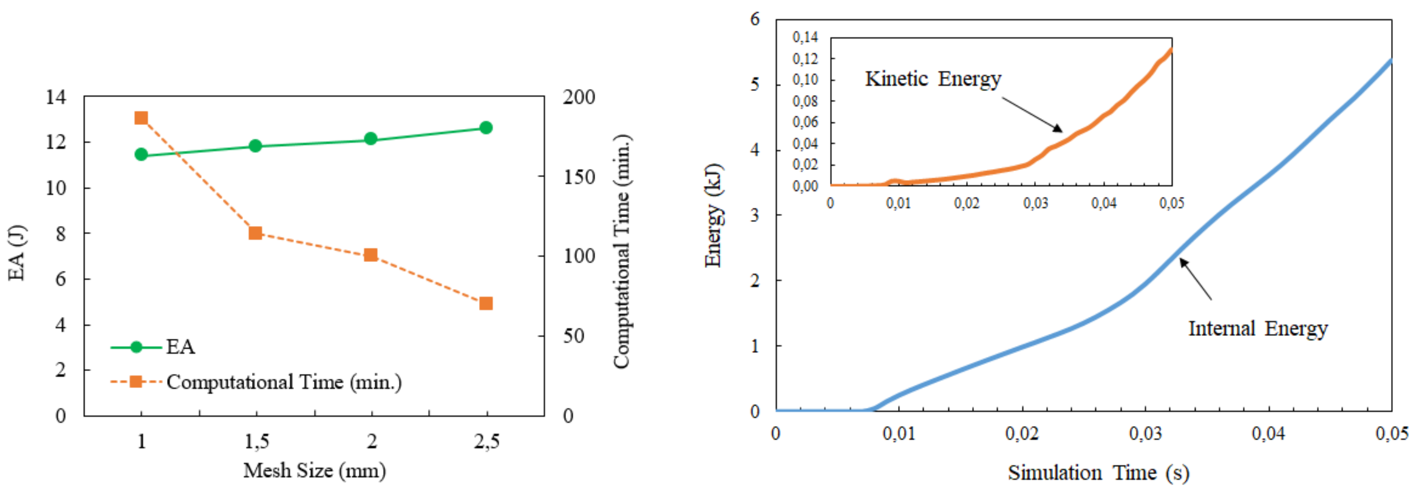

Figure 5. Mesh convergency and total energy curves of quasi-static analysis for the FE whole model verification.

The structures are designed in solid model, the element type of structures C3D8R and the fixed and moving shell plates are prepared 150 x 150 mm² and used S4R element type. To improve the mesh convergence of the FE model, simulations were performed by dividing structure into 1-1.5-2 and 2.5- mesh elements. As given in Figure 5, EA values of structure between 1 and 1.5 were close to each other. In the same study, PCF was determined as 125.1 kN, 125.61 kN, 126.75 kN and 127.31 kN, respectively. The mesh sizes of structures are set at 1.5 mm for reducing computation time and convergence of results. In order to investigate energy dissipation of simulations, the ratio of hourglass energy to total energy has been less than 1% and kinetic energy has been less than 5% of internal energy. Here, the quasi-static conditions were verified during the system analysis as given in the Figure 5. In addition, the sum of the reaction forces of the nodes on the fixed plate was used to obtain the force-deformation curves in these simulations.

2. Results and Discussion

In this section, force-deformation curves of L and BH crashworthiness were determined under axial and oblique loads includes EA, MCF, SEA and CFE parameters. The behaviour of the bio-inspired structure, which provides good energy absorption under axial load, has been determined as a result of the analysis under oblique loads. In addition, the energy absorption was investigated of the newly structure (BH) with a square outer frame, which was generated with a lotus plant-like interior panel pattern.

3.1. Force-Deformation Curves

To compare the characteristics of the L and BH structures, force-deformation curves were plotted as seen in the Figure 6(a). When the force-deformation curve for BH is evaluated, it is observed that the PCF reaches its maximum point at the beginning of the stage, and then the plateu stage occurs with the increase in folding with the deformation of structure. However, the reaction forces gradually decreased as the plastic deformation increased during deformation. In contrast, when the moving plate impacted on the L, the force-deformation curve has occurred by fluctuation with collapse mode. As seen in the first stage of the Figure 6(a) curve, the deformation of strucutures linearly increased with the impacted moving plate to the top of the strucutes. In the second stage, while the crushing by the moving plate continued, the force reached its peak value. The last stage of deformation curve, the corcentina mode began and plastic deformation increased in the walls of structures. Thus, the force-deformation curve continued as fluctuation in the densification stage.

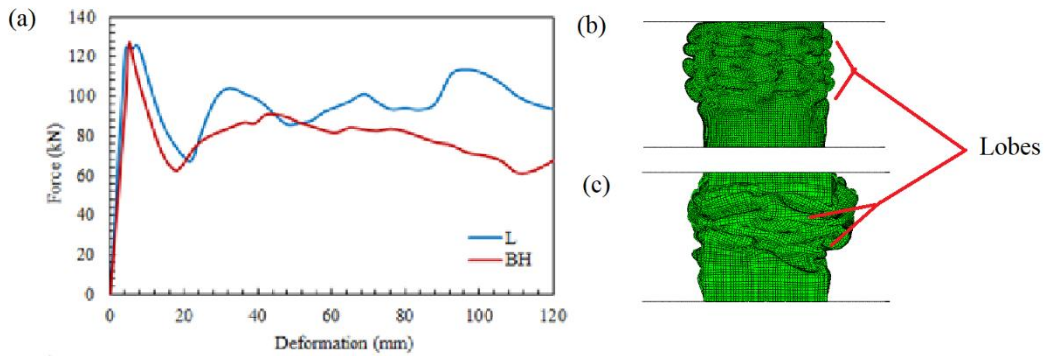

Figure 6. (a) The force-deformation curves of L and BH structures with deformation lobes, **(b)** L, **(c)** BH.

Comparing to L and BH structures, the energy absorption capacity of structures depends on force-deformation curves and these structures are evaluated from the numerical results in the literature. When structures are compressed on the axial direction by the moving plate, on the top of the structures wall has folded as seen in Figures 6(b) and (c). During this mode of deformation, lobes are formed on the structures for absorbing kinetic energy. Here, it is seen that L has more symmetrical lobes than BH against the applied axial load. In addition, 150 kN of PCF for L is characterized as the best crashwort-hiness performance (Gong et al., 2022). For the BH and L design, the PCF was determined 126.43 kN, 125.81 kN respectively. The force-deformation curve fluctuation of axial loading developed in a stable direction in BH. Here, the BH in terms of MCF was calculated 19.5% lower than L.

3.2. Crashworthiness Performances for Loading Angle

This section presents the behaviour of L and BH structures under oblique loads. Due to the crushing performance regarding the different oblique loads were conducted numerical analysis.

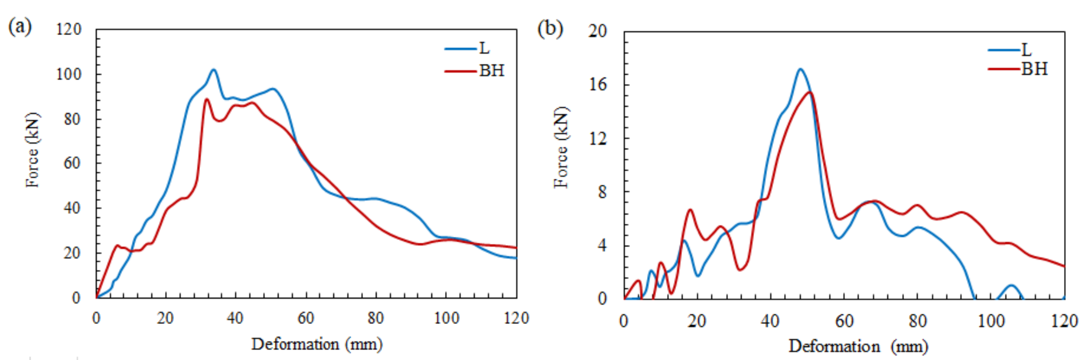

Figure 7. The force-deformation curves of L and BH structures for crushing **(a)**15° and **(b)** 30° under loads.

Figure 7(a) and (b) illustrates the L and BH structures force-deformation curve that is affected 15° and 30° angles. Although similar curve fluctuation was plotted in both structures, the PCF value of BH was lower compared to L. The PCF values obtained at 15°, L and BH structures were determined as 101.99 kN and 87.10 kN, respectively. Obviously, the maximum force point was reduced by 17% for BH, the square profile to which the lotus bifurcation pattern was adapted in square frame of structures. Compared of L and BH's PCF at 30°, it is seen that reduced by 12.19% with the BH design (Figure 7b). In MCF, which is one of the determining parameters of the crashworthiness performance, the improvement made at 15° and 30° was achieved to be 8.8% and 6%, respectively. The best energy absorption and MCF can be obtained with the appropriate arrangement provided in the topology of the structure (Fan et al., 2018).

Umeda & Mimura 2018 demostrated that PCF decreased between the angle of impact was 10° and 20° on polygonal structures in quasi-static conditions. During the angular collision, the folding of structure wall is formed at 0 - 60 and 120 mm deformation distances as seen in the Figure 8. Due to the plastic deformation of structures, the lobes shaped by folding are collapsed on top of each other. To compare the buckling performance of the mentioned structures for 15° under loading on L and BH as given in respectively Figure 8(a) and (c). The red line defined of simulated in Figure 8, the buckling conditions of both structures were examined. Therefore, it is seen that L is more resistance to plastic deformation than BH.

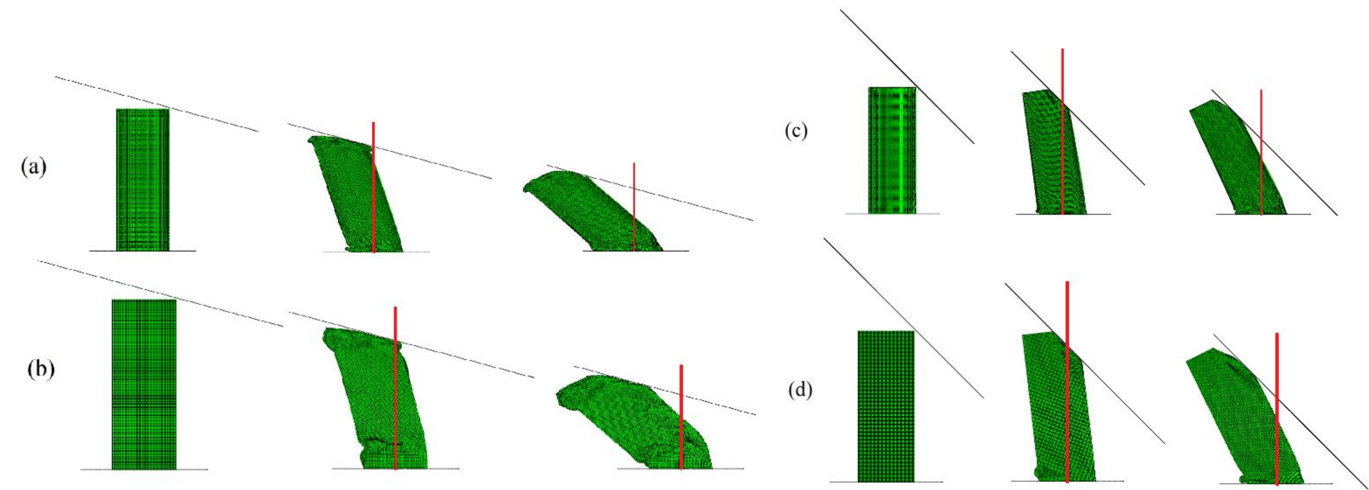

Figure 8. Collapse modes of structures under oblique loads with several displacement of moving plate, for 15° **(a)** L, **(b)** BH; for 30° **(c)** L, **(d)** BH.

Obviously, BH is more advantageous than the L design in inclined loads. Figure 8(b) and (d) are given the deformation of BH at an angle of 30° occured similarly to 15° impact. Huang and Hu, (2019) concluded that the circular crashworthiness design is more resistant to the possibility of buckling under oblique loads. When the multi-cell of structures are prepared by the walls in the crashworthiness, the resistance of the structures increase to the inclined load conditions.

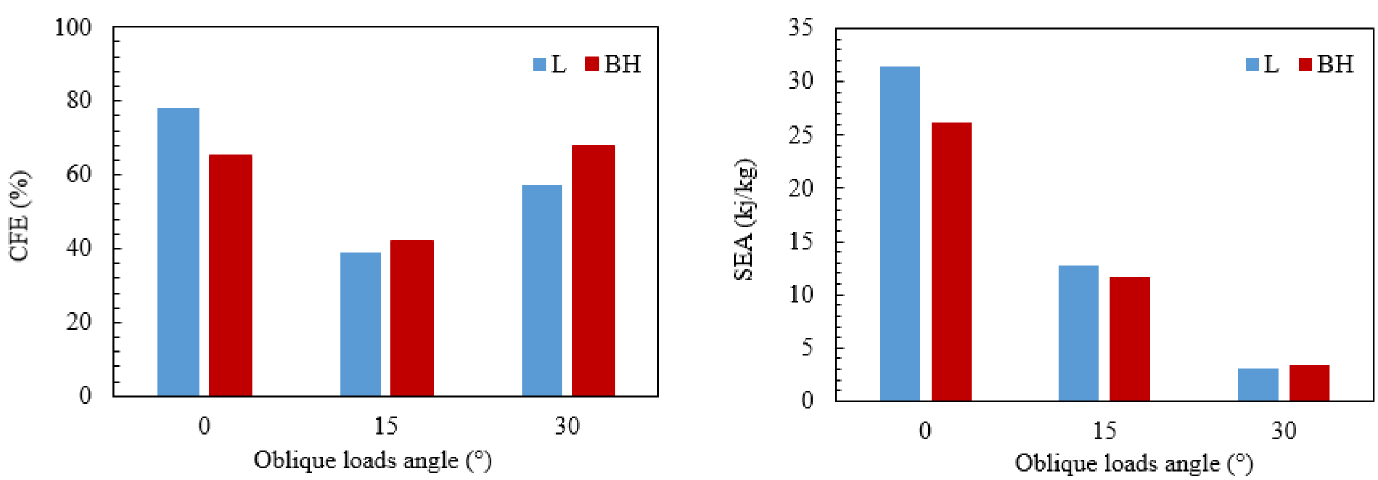

Figure 9. The comparison of structures main performance parameters, **(a)** CFE, **(b)** SEA.

For the crashworthiness performance evaluation, the basic parameters CFE and SEA comparisons are given in the Figure 9. It is evaluated that L performs better in terms of CFE and SEA when the moving plate impact on the structure in axial direction. In contrast to the axial direction of moving plate, the effect of oblique loads on the BH, SEA was found to be three times higher, especially loading at 15°. According to the simulation results calculated by dividing EA by the mass of the structure at the same angle, CFE was developed by 7.52% with BH design. Although there was no significant difference between the two designs for SEA at 30° loading conditions. The BH for CFE is 18.84% more efficient than L. Comparing to the L and BH structures performance criteria, the BH provided moresuitable performance under 15° and 30° loading than axial impact

3. Conclusion

Based on the numerical analysis of the lotus-inspired (L) and considered lotus bifurcation with outer square frame is called bio-hybrid (BH) was investigated in this paper. The convergence of the analysis results was ensured by conducting a validation study for the finite element model established in the first stage of the study. Although there is crashworthiness analysis under axial loads in the literature, oblique loads solution has not been adequately for generating of structural design. Based on the results from the numerical analysis of L and BH structures summerized as:

1- In terms of the CFE of the BH and L structure designs, there was a difference of 14.25% in the average of the CFE value in oblique angles. It has been observed that polygonal designs are more advantageous than circular geometry under oblique loads.
2- There was no significant change in SEA criteria for 10 m/s impact from axial to oblique loads in L and BH designs.
3- It was good agreement that the force-deformation curve was more stable in the BH design and the wavelength was less than the L design.

The results of the analysis showed that by improving the bioinspired design, it gives significant effect for oblique loads on the structures that consist of corner for controllable deformation. It has been executed that the square outer frame scaffolding prepared with the bioinspired approach is more efficient in inclined loads. The study shown that the strength of circular cross-section bioinspired designs can be increased not only under axial but also inclined loads by desinging them with equal weight and polygonal cross-sections.

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