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Numerical Study for Crashworthiness of FSAE Vehicle Chassis via Biomimetic Approach

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ABSTRACT

In the automotive context, a vehicle's crashworthiness represents its ability to protect the occupants in case of accidents or collisions. This paper documents the design and topology study process of the prototype FSAE (Formula of Student Automotive Engineers) vehicle regarding the crashworthiness aspect. This project aims to generate design for the chassis of prototype FSAE vehicles through a biomimetic approach to simulate the feasibility of biological systems integration in engineering design. Studies on different biological structures good in compression loading resistance and distribution have been conducted according to the selected biomimicry approach. Quasi-static finite element analysis with dynamic loading analysis was implemented in studying the axial, lateral and bending deformation of the designed chassis concerning the specific energy absorption of the model. The following biomimicry approach has successfully shown potentiality in creating a satisfactory solution for automotive problems. The final chassis of the prototype FSAE vehicle shows specific energy absorptivity of up to 130 kJ/kg upon normal to critical impact conditions. CAD design of the expected prototype is produced, along with the presentation of a scaled-down fabricated 3D model. Considering the performance aspect of the prototype FSAE vehicle, the weight of the vehicle chassis has been successfully minimised by 30.8%.

1. Introduction

Due to the finite resources on earth, natural resources are gaining massive attention in material science research [1-4]. Another critical aspect of compacting against finite resources is biomimicry studies. Biomimicry studies the imitation of natural biological design for engineering or invention purposes [5,6]. In modern-day industries, various intelligent applications of biomimicry can be found in different research fields, such as applying biological structure orientations into architectural design in ecstatic and improving structural integrity in buildings [7]. Biomimicry is not often limited to engineering designs and modelling, as the elementary level of materials is also included in the range of biomimetic approaches. Applications such as tissue engineering and regenerative medicine production are being studied and synthesised through biomimetic materials [8]. The automotive

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industry often implements the biomimicry philosophy in vehicle design to enhance fuel efficiency and aesthetics. Limited literature research on the correlations between the biological aspect and chassis structural formation is the secondary level of biomimicry, i.e. imitation of how an organism relates to its larger context [9]. Thus, this study aims to fill in the identified knowledge gap.

In conjunction with biomimicry in automotive designs, a few biological structures or processes can be included to improve vehicular design and performance. Implementing the trabecular network structure within the cortical and cancellous bone is a well naturally defined structure for compression load resistance. Studies have shown that the bone structure overall has an elastic modulus of within 3-18 GPa, with their porous structure acting as shock absorbers and dampeners [10-13].

Concerning impact absorbers, spider webs are also unique in their energy dissipation and absorption mechanism through damping effects [14]. The unique mechanism of spider webs is further alleviated through the natural strength of the spider silk and its structural orientation [15]. Design enhancement can be further alleviated by incorporating biological concepts and engineering perspectives. In correspondence to the implemented approach, extensive studies on how the biomimicry of bone structure on automotive chassis occurrence to the effectiveness of the biological model being able to induce dissipation and absorption of collisional compression loading. Such application would then raise further questions and aspects to provide an in-depth understanding of how biomimicry can enhance automotive engineering design at a particular aspect. The onward usage of biomimicry in the crashworthiness study of the prototype FSAE vehicle chassis can also provide a justifiable comparison in terms of reliability based on common numerical solutions. While biomimicry is still in its early stages of development in the realm of automotive design research, its future implementation has the potential to encourage automotive manufacturers and researchers to create hybrid vehicles that integrate principles from various fields of knowledge. This approach could lead to optimal automotive solutions that prioritize protection, performance, and sustainability, rather than just physical principles.

The current study focuses on designing the chassis of prototype FSAE vehicles through a biomimetic approach to simulate the feasibility of biological systems integration in engineering design. There is currently a scarcity of information on the numerical study for crashworthiness of FSAE vehicle chassis via biomimetic approach. Therefore, this paper incorporates the aforementioned aspect to address the identified knowledge gap.

2. Methodology

2.1 Mathematical Model

The specific energy absorption is a critical parameter to evaluate the vehicle structure during a collision or crashworthiness analysis. The specific energy absorption only provides a component's energy absorption efficiency, not a structural mechanical efficiency. Given an object which is compressed due to crushing forces resulting in a collision, the object is said to be absorbing energy in the form of compressive work. Hence the energy absorbed by the object can be governed by Eq. (1).

$$E = \int_0^{S_f} F \cdot ds \tag{1}$$

where E = Energy absorbed by the object due to collision (J), F = Force exerted onto the object during collision (N), S_f = Final compressive displacement of the object or final crush length (m); ds = Deformation of the object based on compressive displacement (m).

The work equation relates the total work an object does as the product of the force applied, F and the distance the object moves, s. The chassis model is often projected at certain speeds before colliding into a boundary in dynamic models. Therefore, specific interpretation of the total energy transmitted during the collision is from the kinetic energy of the moving chassis if no additional energy is generated upon impact. By using the rudimentary principle of kinetic energy written in Eq. (2), it is possible to determine the chassis model's specific energy absorptivity. The total kinetic energy in Joules (J) of the moving chassis can be denoted as half of the product of its mass, m and square of the projected velocity, v.

$$E = 0.5 \, x \, m \, x \, v^2 \tag{2}$$

The specific energy absorptivity (J/kg) in Eq. (3) is defined under the principle in which it is the total energy absorbed by the chassis (E) per kilogram mass of the deformed chassis material (m_c) [16].

$$\text{Specific Energy Absorption}, SEA = E/m_c \tag{3}$$

The mass of the deformed chassis material (kg) in Eq. (4) is calculated as the product of the linear mass per meter length of the overall chassis structure, m_l and its maximum compressional deformation, S_f.

$$m_c = m_l \cdot S_f \tag{4}$$

By combining Eq. (3) and Eq. (4), the summarised specific energy absorptivity equation (J/kg) can then be derived, as shown in Eq. (5).

$$\text{Specific Energy Absorption}, \; SEA = E/mc = \int_0^{S_f} F \cdot ds / m_l \cdot S_f \tag{5}$$

2.2. Initial Model

The structure of the initial chassis network (Figure 1) was drafted using SOLIDWORKS 2019 through 3D sketch and weldment features. The primary chassis network structure was modelled with square beam elements with dimensions of 25 mm x 25 mm and a thickness of 1.2 mm [17]. Different beam elements will be replaced per the study of different energy-absorptive structures based on the bone and web structure.

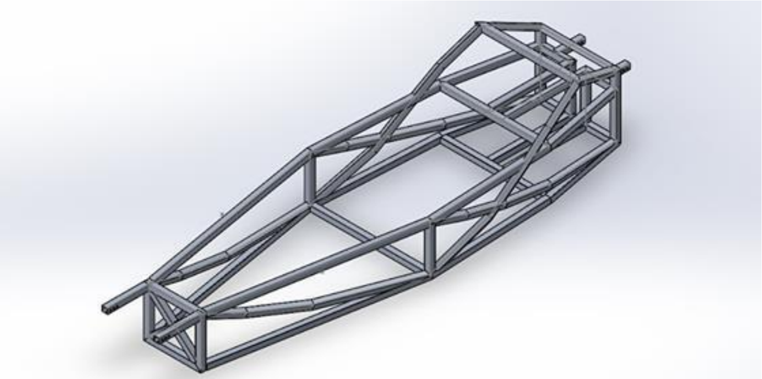

Fig. 1. Initial chassis model of the prototype FSAE vehicle

2.3 Material Selection

The required materials for the chassis as the main integral in optimising the model were selected by analysing its structural properties and studying its specific energy absorptivity. Material properties such as the elastic modulus, compression yield strength and ultimate yield strength are analysed in the process. Each material was applied onto a sample circular beam with an outer diameter of 50.80 mm and thickness of 2.4 mm and tested dynamically to determine its specific energy absorptivity. The suitable material was selected from the SOLIDWORKS material library in terms of its suitability and reliability in automotive construction.

2.4 Beam Design and Testing

In conjunction with the biomimicry approach, four structural beams have been designed based on the web and bone trabecular structure. Two of the beams comprised a circular base of 50.80 mm outer diameter with a thickness of 2.4 mm, and the latter two beams were constructed with a square base of 25 mm by length and width and thickness of 1.2 mm [16] (Figure 2).

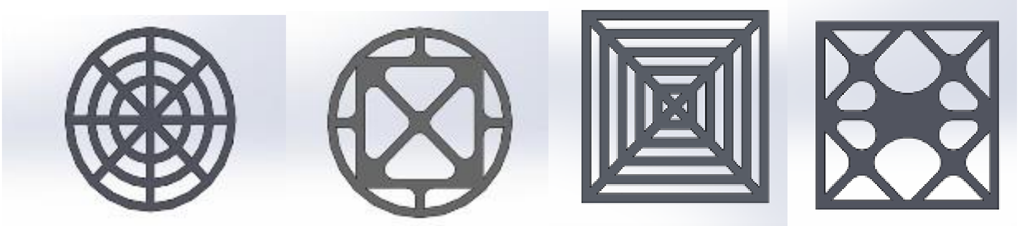

Fig. 2. Designed beam geometries based on biomimicry. From left: web circle, trabecular circle, web square and trabecular square

Void fraction to total cross-sectional area of the four different designed structural beams. The parameter represents the porosity level of the beams on a cross-sectional surface level rather than the entire volume. The void fraction to the total cross-sectional area of each beam is calculated in conjunction to analyse its effects on the specific energy absorption of the structure (Table 1). The beams are tested through simple crash test analysis using ANSYS EXPLICIT DYNAMICS.

Table 1
Void fraction to cross-sectional area of structural beams

Beam geometry	Void surface area, mm^2	Void fraction to total cross-sectional area, %
Web circle	910.92	44.94
Trabecular circle	1031.95	50.92
Web square	242.96	38.87
Trabecular square	301.06	48.17

2.5 Topology Study

The initial chassis model was simulated with the selected construction material set, in which its initial weight was considered. As part of the weight reduction efforts in addressing contradictions with crashworthiness and aerodynamic performance, the overall weight of the chassis model is constricted to a target reduction of approximately 30% of the total weight, with an acceptable tolerance of 3%. SOLIDWORKS TOPOLOGY STUDY is used in conducting topology study with the preservation of the main entities of the frame. The initial chassis was subjected to a stress study before conducting topology study on its structure by simulating occupancy with a distributed load of 58 kg representing an average weight of a female driver acting onto the bottom hoop of the chassis [18]. The final model is then smoothened in geometry using SOLIDWORKS computer-aided design.

2.6 Boundary Conditions and Meshing

The crash test analysis of the chassis model was conducted through SOLIDWORKS 2019. The collision speed for a full-frontal collision will be set at 10 m/s to 90 m/s onto a stationary barrier. Side collision simulation conducted using standard speeds with a collision speed of 17.78 m/s complies with ANCAP standards, and 25 m/s or above would correspond to the speed of a prototype FSAE vehicle [19]. Velocity extremities are also included under high-velocity impacts to study the difference in chassis behaviour upon critical impact conditions. The crash test analysis was mainly studied under quasi-static modelling conditions with the assumption that the impact force will be applied gradually throughout the contact area of the chassis upon any collisional speeds. The study was considered explicit with known boundary conditions. An approximate deviation percentage of 5% in analytical results would be expected compared to dynamic impact analysis. In real life, high-speed impacts occur spontaneously, except for low-speed collisions [20]. The meshing of the chassis models was conducted through SOLIDWORKS 2019 and ANSYS 2019 Explicit Dynamics using tetrahedral meshes upon simulation. A mesh independence study was undertaken to ensure an absolute convergence in results disregarding the mesh element size.

2.7 Validation through Grid Independent Testing

Grid independent testing has been used mainly in validating the feasibility of the crash test analysis result through numerical simulations. Refinement of mesh is done during the post-convergence simulation, where all imbalances and monitor points are considered. The refinement is done repetitively and of necessity until the critical solutions are altered into a state independent of the mesh resolution. Regarding the research, a mesh independent study based on the percentage difference of simulated solutions of both successive mesh sizes is observed throughout the simulation, as shown in Figure 12. At a finer mesh size of 7mm and below, the percentage difference falls below the range of 0.5%, which can be considered negligible and thus independent of the mesh resolution. A mesh size of 4.051 mm to 6.785 mm is used in conjunction with the simulated model for the crash test simulation within SOLIDWORKS 2019.

2.8 Verification

Physical testing on the bending capacity of the benchmark and selected biomimicry design beams were conducted to verify the results (Figure 3).

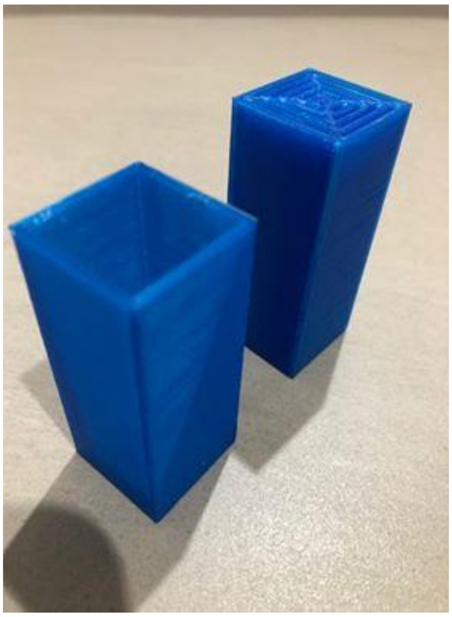

Fig. 3. Beam specimens for the three-point bending verification test

The beam specimens are fabricated on a scale-down model with a printed length of 120 mm. The bending test was conducted with GoTech universal testing machine (Model: AI-7000L), studying force and deformation over time (Figure 4).

Fig. 4. GoTech universal testing machine AI-7000L used for the compression loading test

3. Results and Discussion

3.1 Finalised Model on Prototype FSAE Vehicle Chassis

The chassis model has meshed with SOLIDWORKS through tetrahedral meshing with an element size of 4.051 mm to maximise mesh independency on the perceived solution. Through biomimicry, the final chassis model of the prototype FSAE (Figure 5) was enhanced by integrating web square beams as its individual beam elements and aluminium 2018 alloy as the base material.

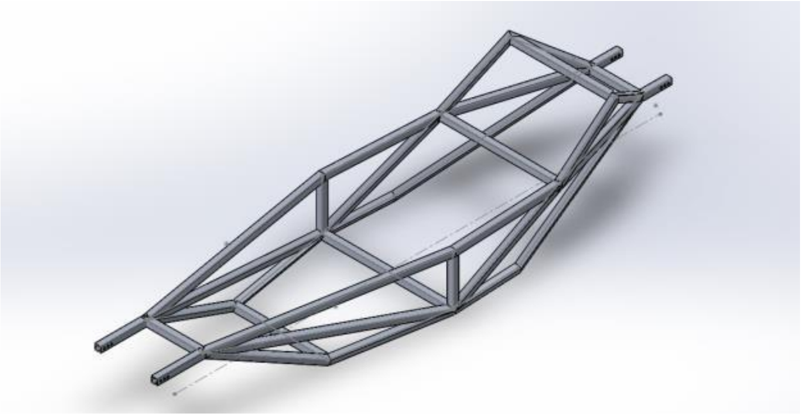

Fig. 5. Isometric view of chassis model of Peregrine Falcon 1

Through selective comparison to the other selected automotive materials, the aluminium 2018 alloy possesses the highest specific energy absorptivity, and its high deformability allows maximal energy absorption. The material is also lightweight, with a mass density of 2.80 g/cm^3 (Table 2).

Table 2
Mass density and specific energy absorptivity of different automotive materials

Materials	Specific energy absorption, kJ/kg	Mass density, g/cm^3
AISI 4340 (Annealed)	57.95	7.85
AISI 4340 (Normalized)	58.15	7.85
ASTM A572 Grade 50	59.95	7.80
Aluminium 2018 alloy	75.66	2.80
Aluminium 7079 alloy	71.74	2.70

A total of six chassis models have been included in the crash test analysis through frontal crash test simulation. Two chassis models were made with benchmark thin-walled beams, with the remaining four models constructed through the biomimicry design thin-walled beam structures (Figures 6-8). Compared to the other designed chassis structures, the web square chassis fulfils the conditional requirements in the crashworthiness element. The structure must undergo plastic deformation to convert the collision energy to internal energy. Due to its internal flanges, the web square beam can sustain a significant compression load resistance and greater load impacts as concurrent to diagonal diaphragm studies onto S-beam structures show strengthening effects and bending resistance [21]. The web square chassis shows high deformability for specific energy absorptivity with maximal deformation of 200 mm and above compared to other relevant biomimicry-designed beams (Figure 8). The deformational trend (Figure 6) suggests low deformability for the circular chassis due to their uniformly distributed mass on high deformation resistivity, as expected in conjunction with their high void fraction to the cross-sectional area as well [22] .

An observable trend can be seen in Figure 7, where the web square chassis would have sustained permanent deformational fracture under impact loading of more than 100 kN (that is 130 kJ/kg), with benchmark circular and trabecular square chassis having a fracture resistance below impact force of 80 kN. The benchmark square chassis has recorded the lowest fracture resistivity, where imminent fracture on the chassis would deliberately occur beyond the impact range of 30 kN. Note that the plastic region (represented with red colour line in Figure 7) occurs between the yield strength and the ultimate yield strength of the material applied.

Fig. 6. Deformation trend of different biomimetic designed chassis

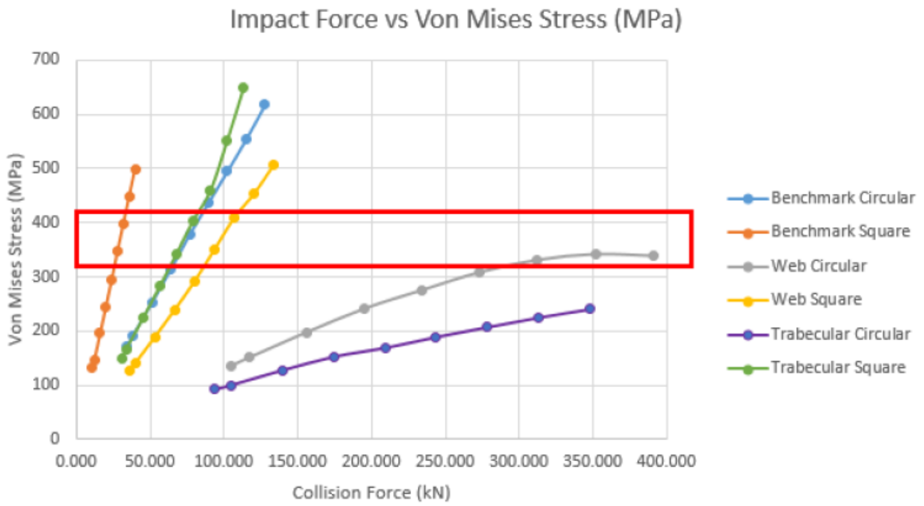

Fig. 7. Von Mises stress distribution of different biomimetic designed chassis

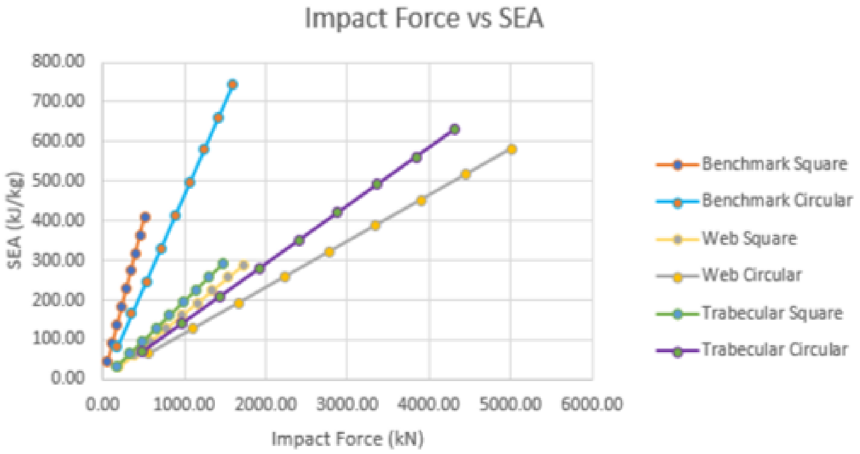

Fig. 8. Specific energy absorptivity trend of different biomimetic designed chassis

The stress level of the enhanced web square chassis is low in bending behavioural studies through side collision simulation in which structural fracture of the chassis, especially on the main roll hoop, can be deliberately avoided upon collision (Figure 9).

The web square chassis records the lowest equivalent stress upon collision, preceding the web trabecular and web circular chassis. However, among the other square beam chassis counterpart models, the web square chassis shows the highest specific energy absorptivity of 2.07 kJ/kg under bending conditions (Figure 10), with respective enhancement percentages of 113% and 13% compared to the benchmark and trabecular square chassis. Specific energy absorptivity trends on frontal collision simulation (Figure 8) suggest otherwise, where the biomimicry-designed chassis have a lower energy absorbance per unit mass than the conventionally designed chassis. In concurrent to the variation in void fraction to the cross-sectional area of the biomimicry designed and conventional thin-walled beams, a low void fraction to the cross-sectional area is suggestive of where the structure is capable of implementing energy distribution and dissipation properties, as can be seen in the graphical trend where a wide impact loading range to low specific energy absorptivity exhibited by the biomimicry designed chassis (for the case of the square web beam in the front collision simulation).

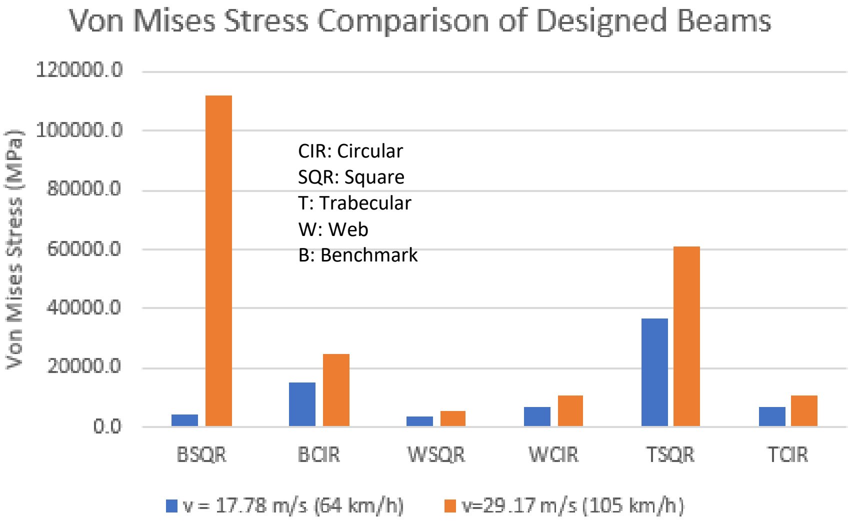

Fig. 9. Von Mises stress levels of different biomimetic designed chassis based on side collision simulation

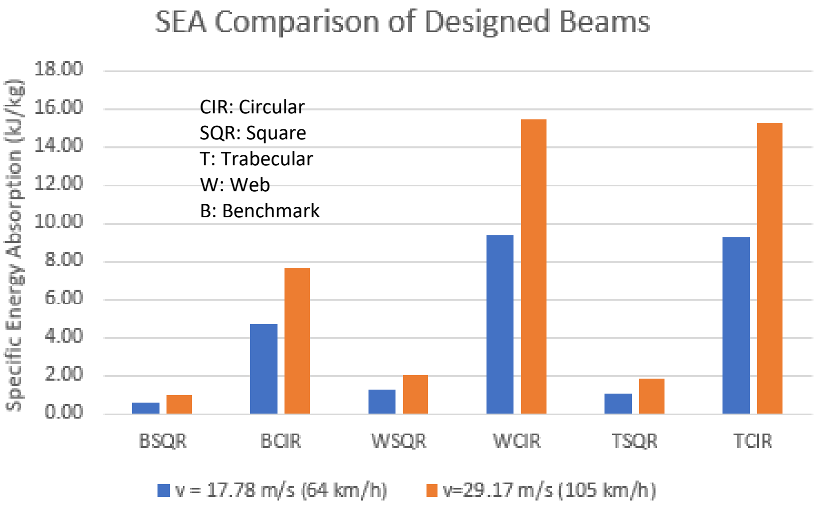

Fig. 10. Specific energy absorptivity of different biomimetic designed chassis based on side collision simulation

3.2 Result Validation

The benchmark square and web square beams were fabricated through 3D printing using polylactic acid (PLA), with dimensions of 25 mm in width and height and 120 mm in length. The resultant beam specimens were printed under an infill strength of 100% to simulate maximal structural integrity with normalised cubic cells. An optimal layer height of 0.3 mm and shell thickness of 2.0 mm is embedded into the printing configuration for medium-scale fabrication of a beam test specimen. Upon the three-point bending test on both specimens, the web square beam possesses greater material strength, suggested to be concurrent to the simulation results obtained. The bending strength is 43.40% greater in web square beam than in benchmark hollow square beam (Figure 11). The three-point bending result, therefore, accepts the outcome of the simulation results in which the web square beam composed of diagonal flanges within internal cross-sectional layers would increase the bending strength of the material itself. The resulting property can also allow the material to sustain higher loading forces without being subjected to permanent deformation or fracture.

Following the simulated study of the void fraction to the cross-sectional area on effects of structural behaviour, a low void fraction to the cross-sectional area of structural beams thus enables improvements in impact resistivity on prolonging the plastic deformation region for increased deformation without implementing fractures.

In conjunction with the topology study, the finalised model has successfully achieved approximately 30.8% weight reduction. The final chassis model now weighs 15.51 kg, compared to the initial weight of the chassis of 22.41 kg.

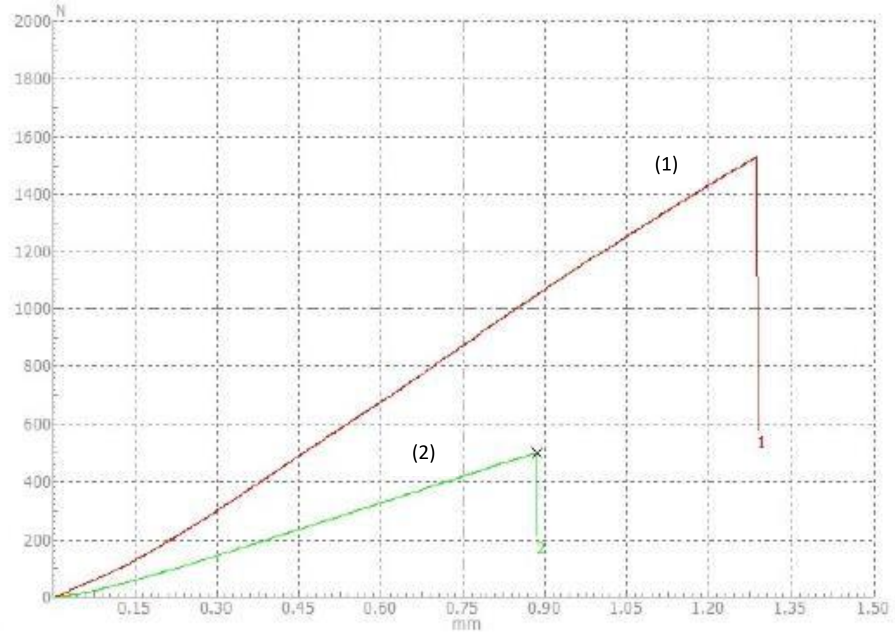

Fig. 11. Force over deformation of web square beam (1) and benchmark square beam (2)

3.3 Limitations

Fabrication and crash test analysis of a full-scale prototype could not be achieved due to financial and time constrictions in this study. The obtained numerical results should be validated with a full-scale experimental prototype. Nevertheless, the obtained mesh-independent study showed the deformation result is converged (Figure 12) as the difference is less than 5%.

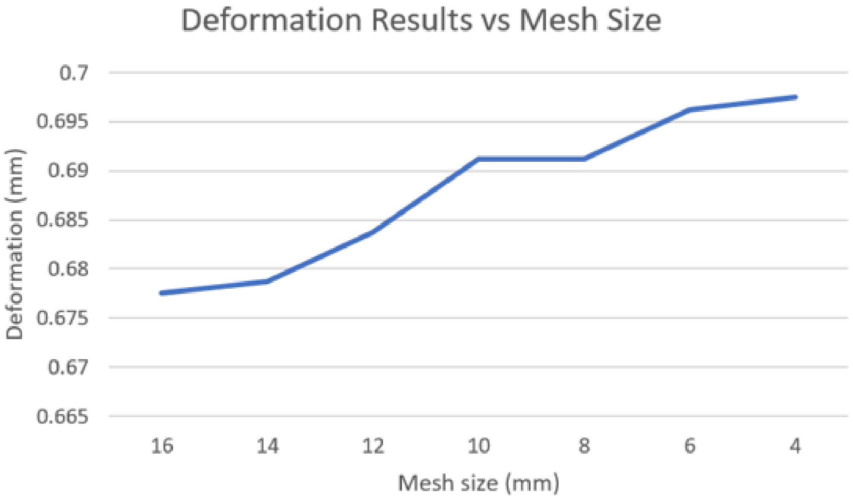

Fig. 12. Mesh independent study on mesh elements to the convergence of deformative result

4. Conclusions

The final chassis prototype FSAE vehicle shows desirable results in terms of crashworthiness and weight reduction improvements. Implementing biomimicry beams such as the web square beams based on spider web orientation suggested a range of impact conditions in maintaining optimal occupancy protection and a considerable specific energy absorptivity range of up to at least 130 kJ/kg. Performance trade-off between the amount of specific energy absorption and chassis weight was accounted for within the study. Further improvements in crashworthiness performance based on progressive biomimicry efforts and weight reduction will be a construct for future work in this research.

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