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Optimization of Interlocking Structures Made of Flax Fibre Composites to Improve Its Energy Absorption Capability

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ABSTRACT

This study presents an investigation about the effect of size variation on mechanical performance of square core interlocking structures, by using finite element analysis (FEA). The material used in this study is flax fibre reinforced polypropylene (PP) composite. Abaqus software was used for modelling and visualizing number of six interlocking honeycomb structures with different cell sizes and heights. In the first analysis, Abaqus/standard was performed on the perfect models by applying quasi-static loading to identify the imperfection shape and obtaining the buckling Eigen-modes for the models, then the Eigen-modes from abaqus/standard were imported to abaqus/explicit to run post-buckling analysis and simulate the overall imperfection behaviour of models. The numerical results from the finite element analysis simulation were used to plot load-displacement curve to each model. The area under the load-displacement curve represents the total absorbed energy, energy absorption per unit mass indicates the specific energy absorption, and the highest value of specific energy absorption represents the optimum size. The findings demonstrated that the square interlocking structure exhibits good energy absorption performance in some geometrical cases, and also revealed that the natural fibre composites have unique energy absorption capability under quasi-static loads.

1. Introduction

The use of interlocking concept in manufacturing of honeycomb structures offers a lot of advantages to overall performance of the systems and constructions, because it's characterized by simplicity of installation and provided great resistance to crack propagation, also, it is helpful to absorb large amount of crushing energy. Moreover, the interlocking structures having a unique ability to combine various materials within a single topologically interlocked [1]. Recently, due to contemporary environmental rules, massive researches on natural fibres composites have been performed. Natural fibres composite (NFC) are low cost materials offering a low density, extraordinary specific properties, bio-degradable characteristics and recyclability [2]. Furthermore, to improve the levels of safety and protection, researchers and engineers moved toward

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developing structures that having excellent ability to absorb crushing energy, and made of eco-friendly materials [3-4]. Hence, the interlocking structures which made of natural fibre composites comprised between the excellent properties of materials and the high mechanical performance of structures that make it desirable in high-tech applications [5].

The most optimized square interlocking honeycomb structure is that having the best specific energy absorption capability and the lowest peak stress when used as a shock absorption device. Honeycomb structure is very important for the safeguard structural design where the cell height and cell wall thickness of the material honeycombs are used as design variables [6]. Many researchers have revealed that the composites based on natural fibres can offer comparable properties to those based on synthetic fibres, this is because most natural fibres need a lesser amount of handling costs and lower energy, in addition possessing excellent environmental standards such as being renewable, ecological and sustainable compared to glass and carbon fibres [7]. For that reason, Mallaiah [8] studied the properties of bio-based and artificial based fibre sandwich structures, and proved that a hybrid structure based on bamboo and glass fibres offers higher values of core shear stress and face bending stress than those structures manufactured from either pure glass or carbon fibres.

Pandey [9] stated that the growth rate of natural fibres in the industries, constructions, and business market sectors has increased by13 %, for instance, the sector of automobiles industry has focused on natural fibre composites to be used in both interior and exterior parts. This is to minimize the gross weight of the car as well as improving the fuel efficiency and sustainability. The utilization of natural fibre in fabricating of automotive spare parts contributes 10% weight reduction of vehicle, and this leads to 80% energy consumption and 5% cost saving [10]. A number of automotive industries in the world have introduced natural fibre composites into their products [11]. Jaguar and Land Rover automobiles pioneers fabricated a car door prototype from flax/polypropylene and stated that the bio fibre composites offer higher performance comparing with to modern-day elements. The weight of this prototype is lighter than the corresponding steel component by about 60% for the identical stiffness, and is almost 35% lighter than a glass filled polypropylene issued at the equal thickness [12].

Likewise, the air craft and space technology have given great attention toward lightweight composite structures, because these materials are characterized as offering a high strength with light weight a long with high specific bending stiffness and strength resistance under distributed loads [13]. Similarly, Yin [14] reported that, the currently thin-walled honeycombs have been extensively used as energy absorption structures due to their extraordinary light weight, excellent energy absorption capacity, and relatively low price in automotive, aerospace, military and many other industries. Enhancing levels of safety and protection need to create an ideal energy-absorbing structure, an ideal energy absorber structure is the capability of the structure to deform partially or completely and absorbs as much as possible of crushing energy following compression. To manufacture these structures there are two essential parameters should be considered, firstly, the mechanical specification of the used material or composite, secondly, the geometrical dimensions and shape of the structure [15]. Moreover, the previous reported studies have revealed that the cell structure has a substantial effect on the mechanical performance of the honeycomb material. Therefore, it is crucial to studied and compared the stress-strain characteristics and energy absorbing capacities in large buckling for the engineering design purposes [16].

Interlocking structures are well-known for being offer a lot of characteristics to performance of the systems, whereas, the natural fiber composites (NFCs) offer many advantages that make them an appropriate alternative for many types of engineering materials, particularly, for those related to energy-absorbing structures where safety and enhancing levels of protection are among the main interests. Therefore, researchers and engineers have given much attention for interlocking structures which are made of natural lightweight composites, in order to optimize their efficiency and mechanical performance. Thus, to optimize the mechanical performance of interlocking structures which made of NFCs, there is an importance to study the influence of core design (size effecting) on the validity of structures, as a result many researchers studied this issue analytically or experimentally to determine the optimum geometrical shape and dimensions of structure relied on different methods. Those researches were depended on the mechanical properties (specific strength, energy absorption, and shape) this is more active and sensitive method to identify the optimum core design.

Dharmasena [17] mentioned that the square shape honeycombs are the best shape design core among all other core shapes in term of strength by about 27%. Yamashita [18] performed a numerical simulation with practical experiment on aluminum honeycomb, by applying quasi-static compression tests toward through-thickness direction they concluded that the best strength is achieved in case of a regular hexagon cell shape. Zuhri [19] studied the influence of design of honeycomb core on compressive strength of natural flax fiber composites, where they carried out a comparison between square and triangle honeycomb made of polylactide (PLA) polymers and reinforced polypropylene (PP) it was found that the (PP) based composites are offered tensile characteristics and energy-absorbing better than those based on (PLA) composites, furthermore, it was observed that the energy-absorbing and compression characteristics of square honeycomb were greater than corresponding triangular counterparts.

This study presents numerical investigation about the effect of changing the geometrical dimensions on mechanical efficiency of square interlocking honeycomb structures made of flax fibre reinforced polypropylene (PP). A finite element analysis was used to simulate six interlocking honeycomb models with different dimensions and subjected to ques-static loading, and then from plotting displacement–load curve, the specific energy absorption of each model was calculated and compared to identify the optimum size in terms of mechanical performance. The outcomes from this study could be used in industries that fabricate structures and spare parts that used to provide high levels of safety and protection such as automobiles and aeronautical industries, also it could be helpful to researchers and designers when use finite element techniques to estimate mechanical characteristics of materials.

2. Methodology

2.1 Techniques of using ABAQUS Simulation

In order to accomplish the objective of this study both ABAQUS/ Explicit and standard software version 6.14 are used, the analysis model consists of the following information: element geometry, section properties, material data, loads and boundary conditions, assembling, constraints, analysis type, and output requests. The outputs of successfully complete simulation are saved in field output and history output. A complete ABAQUS software analysis is carried out by three distinguished stages: pre-processing, simulation, and post-processing.

2.2 Pre-processing

Creating an ABAQUS input file is the first step, then sketching the frame of the model and assigning the type of material, weather deformable or sold rigid, following that the structural characteristic of the input keyed. The model is sketched graphically using ABAQUS sketcher, or it could be imported from another 3D modelling software. In other words ABAQUS is a graphical representation, defining the geometry, defining material properties, and generating a mesh, then visualizing the results. A lot of assumptions and techniques should be provided to get successful simulation and precise results.

2.3 Element Geometry

Creating the parts is the first task in modelling, in this study six models with different size dimensions and different heights are used to modelling the actual specimens, each model plotted individually in 2D frame work according to its dimensions, then the model is extruded to the desired width to become solid 3D deformable element, the partition process applied to the parts in order to control meshing and gain accurate results. Consequently, two rigid shell platens are plotted and extruded to be located at the top and bottom of each model, with assigning a reference point at the centre of each platen used to apply compression load and calculate results of the models. The platen model does not deform during the test. The thickness of all models is set to about 1.5 mm. 1st model dimension is 20x20x20 mm, 2nd model 20x20x40 mm, 3rd model 30x30x20 mm, 4th model 30x30x40 mm, 5th model 50x50x20 mm, and 6th model 50x50x40 mm.

2.4 The Units of Quantities

The ABAQUS software has not identified specific units to be used in plotting models dimension and inputting materials properties, except for angle measures and rotation motion, therefore, the units of quantities are specified by the user, which means that derived units of the chosen system can be expressed in terms of the fundamental units without conversion factors, to obtain precise results all quantities must be unified. The units which are used in this simulation are SI units.

Table 1
Units used in finite element simulation

No.	Quantity	Unit
1.	Length	Millimeter (mm)
2.	Force	Newton (N)
3.	Mass	Kilogram (kg)
4.	Time	Second (s)
5.	Stress	Pascal Pa (N/mm^2)
6.	Energy	Millimeter Joule (mmJ)
7.	Density	Kilogram per Millimeter (kg/mm^3)

2.5 Element Type and Meshing

For the honeycomb cores the used element is 3D deformable solid homogeneous with eight-node brick (C3D8R), the meshing control is structure hex with an 8-node linear brick and reduced integration hourglass control, the meshing size of element should be similar along every unit cell size [20]. The CPU time is affected by the meshing size of element; too large element size leads to a greater value of stress, while a finer mesh size leads to much memory usage and is time consuming. For both top and bottom platen the used element is 3D discrete rigid type S4R none deformable, the meshing control is set to be free quad with a 4-node 3D bilinear rigid quadrilateral. Hibbitt [21] reported that to avoid penetration between honeycomb core and platens during compressing process, the meshing size of platens should be assigned to be larger than the core structure meshing size.

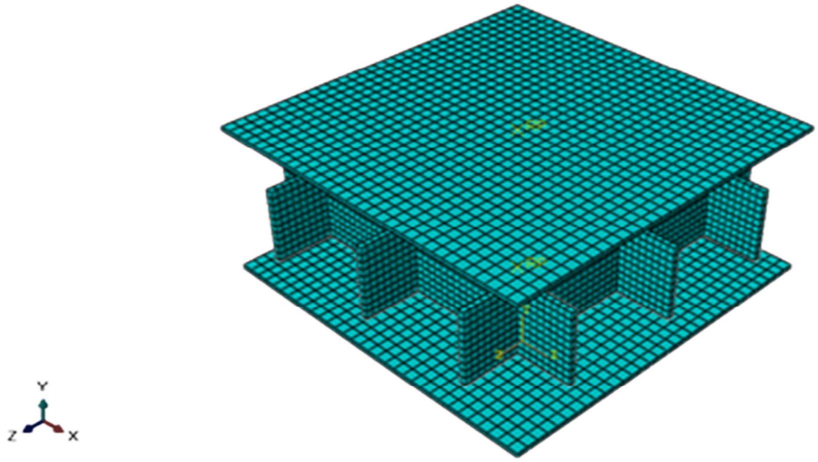

Fig. 1. Meshing of interlocking structure and platens

2.6 Assembling the Model and Interaction

All the parts of the honeycomb created earlier with both top and bottom platens are translated together in assembly stage to achieve the required model shape. Figure 2 shows the assembly process of interlocking core with top and bottom platens which are used to compress the model. To define the surfaces contact among the model parts, a general contact generated between the interlocking parts of model, and surface to surface contact generated between the honeycomb core and both top and bottom platen. The contact property will be hard contact and frictionless in the tangential direction in case of general contact, while in case of surface to surface contact the contact property will be with penalty friction. Moreover, a tie constraint is created between platen surface and honeycomb core surface with allowing for small sliding between surfaces. Tow reference points are created at the centre of each platen to use in applying loads and calculating results.

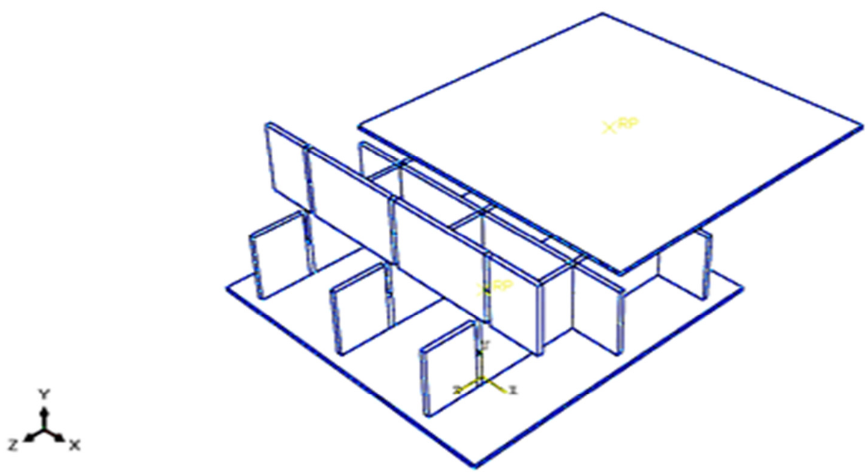

Fig. 2. The assembly of interlocking core with upper and bottom platens

2.7 Boundary Conditions and Loading

In current case, Abaqus/standard will be performed firstly to accurately simulate the perturbation behaviour of honeycomb. The step procedure type will be linear perturbation under buckling mode, with subspace Eigen-solver. For the boundary conditions the lower platen is fully fixed and upper platen moves toward y-direction at constant rate to compress the honeycomb core. Loading type is concentrated force assigned either to upper reference point or to upper surface of top platen; this force is distributed uniformly toward y-direction. Following that the imperfection pattern which produced of the previous abaqus/standard is imported into Abaqus/explicit by using Input file usage: *IMPERFECTION, FILE=results_file, STEP=step. Abaqus/explicit is applied to simulate the full imperfection of models, where the loading will change to be dynamic explicit load, and the boundary condition remained similar to that in abaqus/standard. The reference points at centre of platens are used to record the values of reaction force and crushing displacement, the field output and history output files are created either from particular point in model or from the whole model or over a part of model, those files used to define the required output from the overall analysis such as kinetic energy, forces, displacement, stress, strain, and soon. The numerical data obtained from abaqus simulation could be imported to Microsoft EXCEL to perform the calculations and plotting graphs.

2.8 Simulation

In this stage ABAQUS job file is created to solve the numerical problem which defined in the model and identified the case of analysis linear or nonlinear analysis. Complicated models could be simulated with this software with high level of flexibility workforce; the accuracy of outcomes from analysis is depending on many parameters such as the mesh refinement and type of element selected along with the accuracy of mechanical properties of used material. During analysis the CPU time, stable time, and step time are calculated along with number of increment and kinetic energy, warning and error messages established in case if any syntax error committed. This simulation technique may take interval from seconds to days to complete an analysis run, that is rely on the complexity of the problem being analysed and the specifications of the computer being used.

2.9 Post-processing

In this stage the results are evaluated as soon as the simulation has been accomplished successfully, and the necessary variables have been calculated. The evaluation is done by using the Visualization module of ABAQUS/explicit. The Visualization module, which reads the binary output database file, has a multi options for displaying the results, including, animations, deformed shape plots, colour contour plots, and X–Y plots. Once the model is complete, ABAQUS/explicit can submit, monitor, and control the products analysis jobs. The Visualization module can then be used to interpret the results.

2.10 Material Type and Specifications

The material which used as a sample in this research is natural flax fibre reinforced by polypropylene (PP), where the numerical analysis was carried out onto six samples having square shape honeycomb core design, the wall thickness is constant about 1.5 mm for all samples, and dimensions of cell size in the range between 20 mm and 50 mm, with height between 20 mm and 40 mm. Moreover, to conduct a successful study with tangible scientific values, the specifications and mechanical properties of selected material model defined appropriately, ABAQUS technique has capability to deal with various types of materials. In this study, a flax fibre /PP with properties: The Young's modulus is 3.7 GPa, the density is 800 Kg/m3, and Poisson's ratio is 0.3, [19].

2.11 Mesh Refinement and Model Sensitivity

Abaqus software is a technique depending on meshing principle in calculating the results, the meshing size of the model is very important factor to get the accurate results, that is why before obtaining the final results of the finite element analysis a meshing sensitivity investigation should be carried out to all the models, the meshing study is done by varying the approximate global size throughout the core geometry of each module. The concept of mesh sensitivity analysis stated that the maximum load for the model is relaying on refinement degree of the mesh and element size as well, by other mean time-force curve is used to identify the optimum meshing size of model with taking the CPU time in consideration [22]. Figure 3 shows the effect of changing meshing size on the reaction force of the 20x20 mm model. This variation occurred due to change of the approximate global size value in seed part window in Abaqus program. A gradual altering in the meshing size control starting from the smallest meshing size value where the ABAQUS program could start calculations, continued until the changing in meshing size values become insignificant, this step considers as evaluating process to determine the appropriate meshing size for the models. However, if a meshing size is refined to very small density, it will require long running CPU times, and large amount of computer memory. The extra-large meshing refinements lead to convergence in results [23]. The values of maximum reaction forces which results from changing meshing refinement, with CPU time for each running test, are used to plot the graph in figure 4 which included meshing size, maximum loads, and CPU times. The intersection point of the maximum loads line with CPU time curve is used to determine the optimum meshing size for the models. As shown in the figure the intersection point is approximately corresponding to meshing size 1 mm. As a result, the meshing size 1 mm is selected to be the refinement size to all models. To determine the appropriate duration to run a successful explicit analysis, a series of numerical runs with different time durations are carried out, until the dynamic effect became insignificant. Via this approach, the running time duration was assigned to 0.1 second [24].

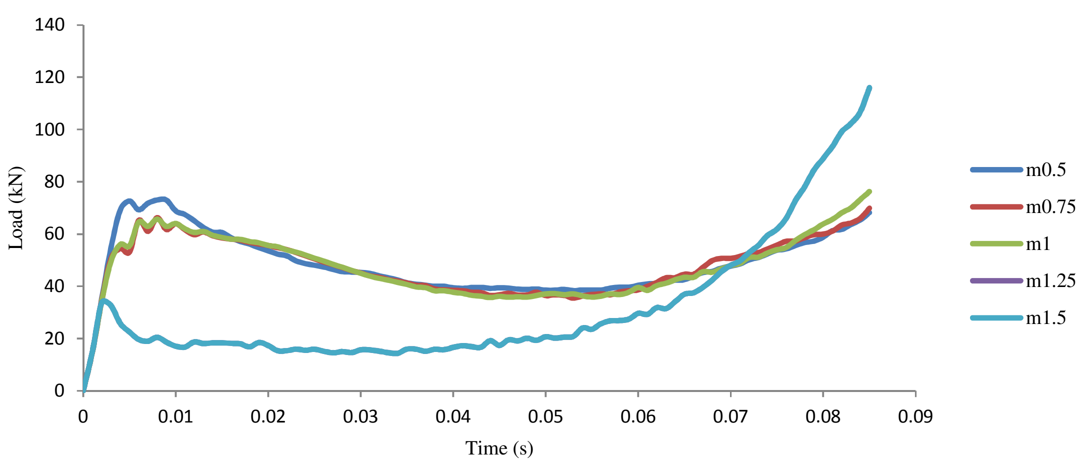

Fig. 3. Effect of changing meshing size on the reaction force

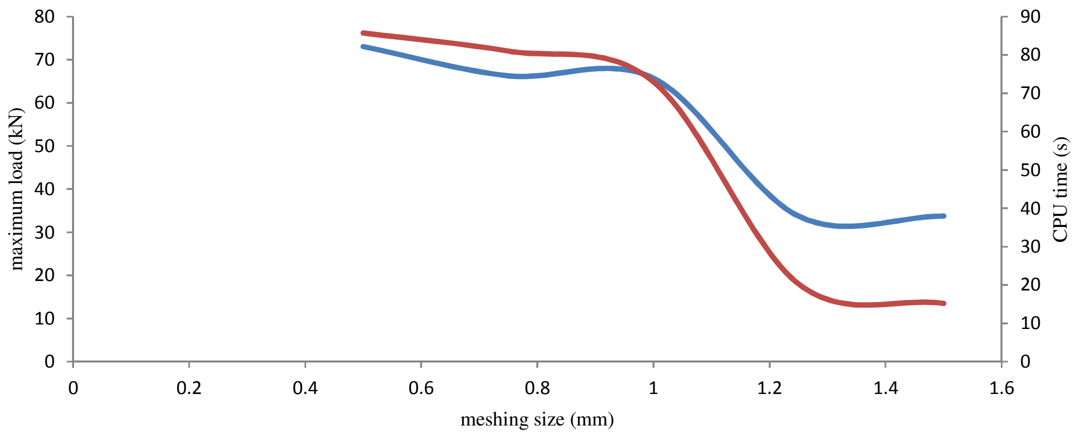

Fig. 4. Relationship between meshing size and both max load and CPU time

2.12 Energy absorption calculation

The law of Energy conservation states that the total energy contained by a substance or a structure cannot be destroyed or created, but it may be transferred from one form of energy to another. Therefore, in this study a compression test is conducted to analyse the energy absorption capability of interlocking structure, the absorbed energy by structure could be estimated from the load-displacement curves, where integration of the area under the curve up to densification point multiplied by average reaction force represents the capacity of absorbed-energy for the structure [25]. Figure 5 shows the area of absorbed-energy for structure. The energy absorption ability of material dependents on the shape and size of the specimen, as the amount of absorbed energy increased the rate of deformation will be larger, this absorbed energy usually transformed into plastic deformation [26].

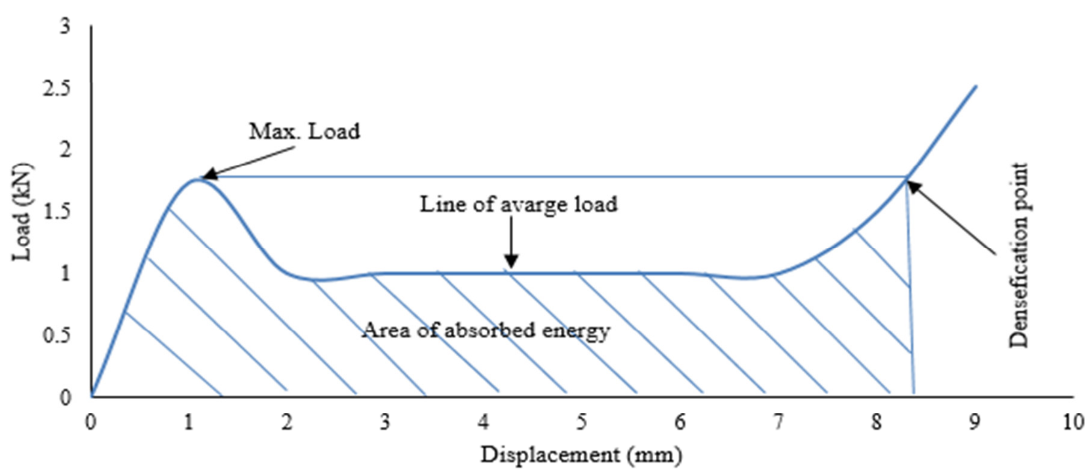

Fig. 5. Shows the area of absorbed energy in load-displacement curve [27]

2.13 Specific Energy Absorption

The term of specific energy absorption (SEA) in unit kJ/kg is used to differentiate between results of lightweight materials structures [28]. To achieve the optimum structure efficiency in designing of energy-absorbing structures a comparison study to models in terms of specific energy absorption should be performed [29]. Where the higher value of specific energy absorption represents the better energy absorption capability relative to unit weight of structure [30]. The specific energy absorption of material or structure is obtained by dividing the calculated value of absorbed energy below load–displacement curve up to densification point by the unit mass of material [26]. The mass of material (kg) is achieved by multiplying the density of material in the structure volume. Li [6] reported that when designing an energy absorber structure, different measures can be applied to evaluate the performance. These measures may be energy absorption per unit mass or per unit volume, which are often called the specific energy absorption. Reduction in the mass and volume are always desirable in the design of energy absorbing elements. Therefore, the specific energy absorption is used to characterize the energy absorption of metal honeycombs.

3. Results and Discussions

3.1 Geometry Imperfection and Buckling Mode

Due to the thin thickness of the interlocking cells, the flax/PP composite reveals buckling before the core fully crushed. For that reason, the geometrical imperfection pattern was included into the model to accurately predict the failure behaviour of the interlocking core structure. The geometric imperfection pattern is defined as a linear superposition of buckling Eigen-modes achieved from a prior eigenvalue buckling prediction performed with Abaqus/Standard [21]. The process of calculating and identifying the full geometric imperfection behaviour of the structures in ABAQUS/explicit simulation is achieved by adding linear buckling (perturbation) mode by using abaqus/standard first, then the post-buckling (nonlinear buckling) is carried out [31]. In the linear buckling process abaqus/standard will calculate eigenvalues for buckling mode of structure, and by adding the Input file: *NODE FILE U in edit keywords file for the model, consequently, the abaqus/explicit will import these values of Eigen-mode to the perfect geometry in order to introduce the final imperfection shape of structure. To define the imperfection of weighted mode shapes, specify the results job file and step number from eigenvalue buckling calculation analysis. The importing of Eigen-mode data for identified node set is done by using the input file *IMPERFECTION FILE=results_file, STEP=step. Figure 6 shows the initial imperfection behaviour of the model with size of 20x20 mm, at displacement of 2 mm this imperfection is done by Abaqus/standard simulation, by applying quasi-static load, the step manger is linear parturition buckling mode.

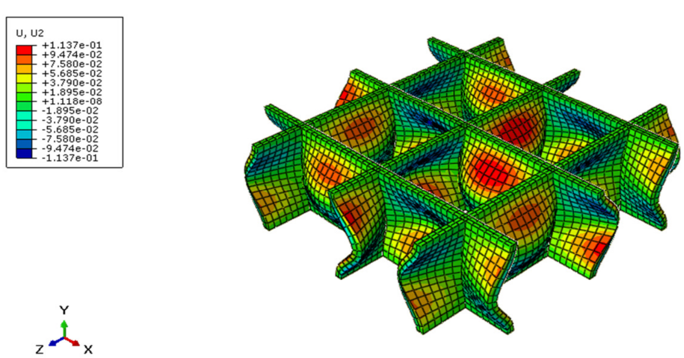

Fig. 6. the initial imperfection behavior of the model with size of 20x20 mm

3.2 Core Size of 20x20 mm

The volume of this model equals to 11205 mm^3, and the total mass is about 89.64x10^{-4} kg. Figure 7 shows the load-displacement curve of the model under compression load, in the linear transition region the curve starts with a speedy increase until reach the peak load at about 1mm displacement, then the load drops abruptly to crushing zone, where the structure is continuously compressed until reaches the point of densification at 13.60 mm displacement. The amount of absorbed energy by this model is calculated from displacement-force curve it found to be 0.65 kJ and the corresponding specific energy is 72.61 kJ/kg.

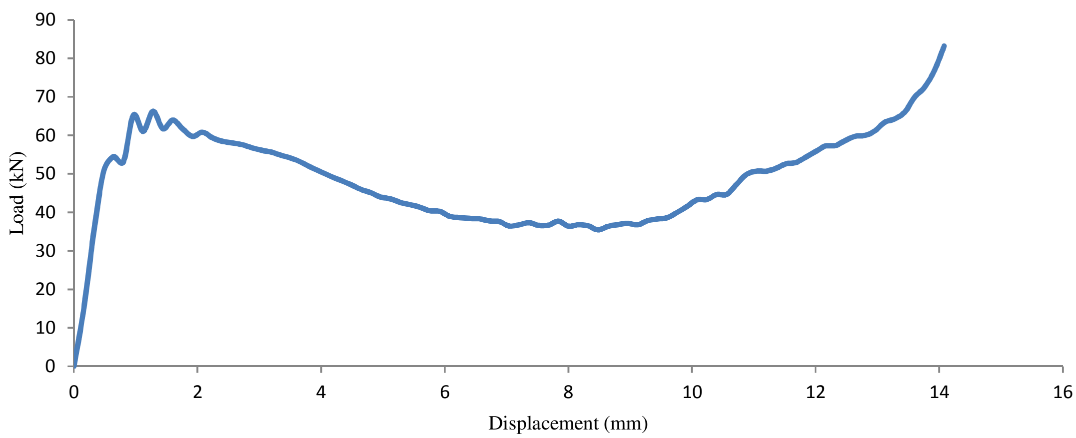

Fig. 7. Load-displacement curve for core cell size 20x20 mm

3.3 Core Size of 20x40 mm

The deformation stages of this model under compression load are as following, the curve line in the linear transition zone reached the maximum load at 1.2 mm displacement, then as the model starts collapsing the load decreased rapidly to crushing region, where, the curve appeared a fluctuated movement resulted of the resistance of structure to crushing, the complete collapse occurred at 29.40 mm displacement. The volume of this model is about 22410 mm^3, with mass of 179.28x10^{-4} kg. Figure 8 shows the deformation shape of the model at different crushing displacements along the height of its core. The amount of absorbed energy from this model is about 0.841 kJ, while the specific energy absorption is 46.93 kJ/kg.

3.4 Core Size of 30x20 mm

The results obtained from the preliminary analysis of core size of 30x20 mm are shown in Figure 9 the curve rose up rapidly to record maximum load equals to 112.80 kN in linear region. Thereafter, the curve declined gradually to the crushing area with a noticeable resistance to the applied load, the load continued compressing the structure until the fully crush occurred at densification point which is corresponding to about 14.25 mm displacement. The volume of this model is 16605 mm^3, and its mass 132.84x10^{-4} kg. The amount of absorbed energy is estimated to be 0.79 kJ, and according to the total mass of the model the specific energy absorption is estimated to be 59.14 kJ/kg.

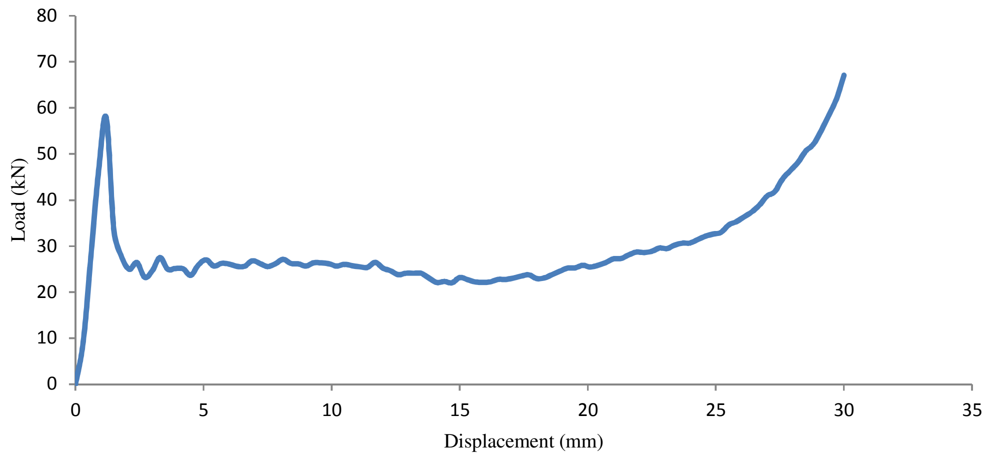

Fig. 8. Load-displacement curve for core cell size 20x40 mm

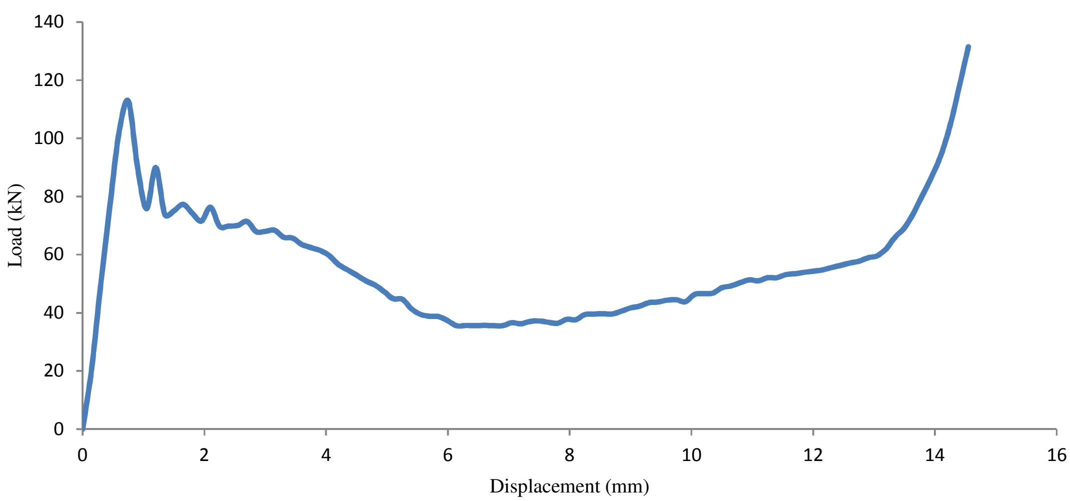

Fig. 9. Load-displacement curve for core cell size 30x20 mm

3.5 Core size of 30x40 mm

The load-displacement graph in Figure 10 shows the crushing behaviour of the model size of 30x40 mm under compression load, in the linear transition zone the maximum load reached at 1.2 mm displacement, then the load decreased rapidly until reached the crushing region, where, the curve appeared an oscillatory motion resulted of the resistance of the structure to crushing, the fully collapse occurred at 29.71 mm displacement. The volume of this model is about 33210 mm^3, with mass of 265.68×10^{-4} kg. The amount of absorbed energy from this model is about 1.08 kJ, while the specific energy absorption is 40.71 kJ/kg.

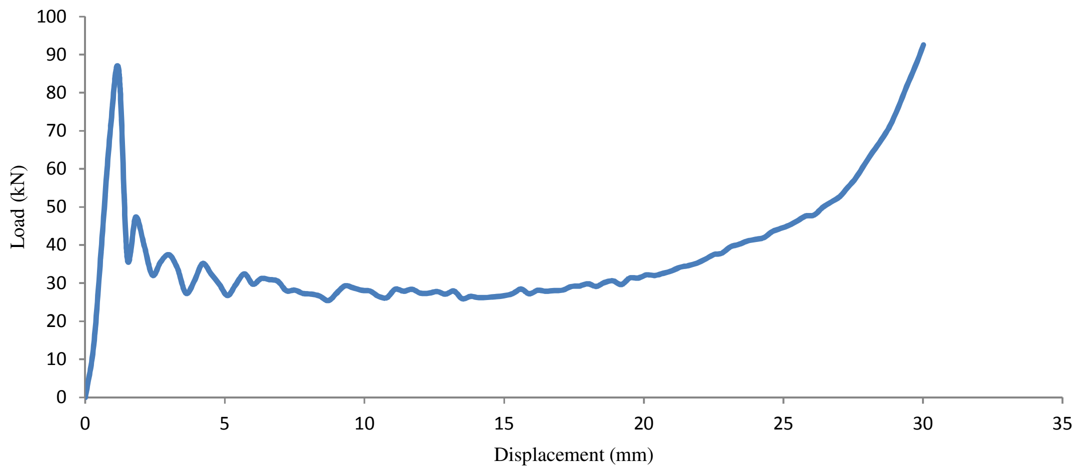

Fig. 10. Load-displacement curve for core cell size of 30x40 mm

3.6 Core size of 50x20 mm

As shown in Figure 11 the first phase of the load-displacement curve for this model starts with a rapid increase in region of linear transition until reaches the maximum load by 172 kN. Following that, the load decreased slightly created a sustained crushing region, where the load continued compressing the structure until the sustained crushing completed at densification point corresponding to about 15 mm displacement. The mass of model is 219.24×10^{-4} kg, and its volume is 27405 mm^3. The amount of absorbed energy according to the area under the curve is 1.29 kJ; meanwhile, the value of specific energy absorption relative to the total mass of model is 58.66 kJ/kg.

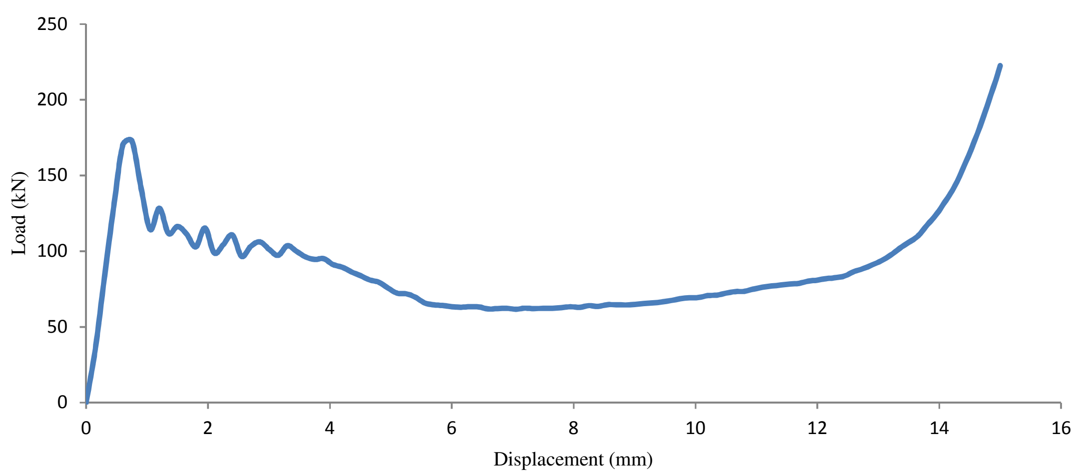

Fig. 11. Load-displacement curve for core cell size 50x20 mm

3.7 Core size of 50x40 mm

The entire volume of this model is roughly equivalent to 54810 mm^3 and its total mass about 438.48×10^{-4} kg. Figure 12 shows the load-displacement graph for this model, the curve starts with a prompt increase recorded the highest reaction force at 1.4 mm displacement, then the load decreased steadily to stabilize temporary in crushing region where, the structure is continuously compressed until reaches the point of densification at 31.50 mm displacement when the crushing is completely finished. Due to it is large volume this model absorbed the highest amount of energy by about 1.6 kJ; and the specific energy absorption is 36.54 kJ/kg.

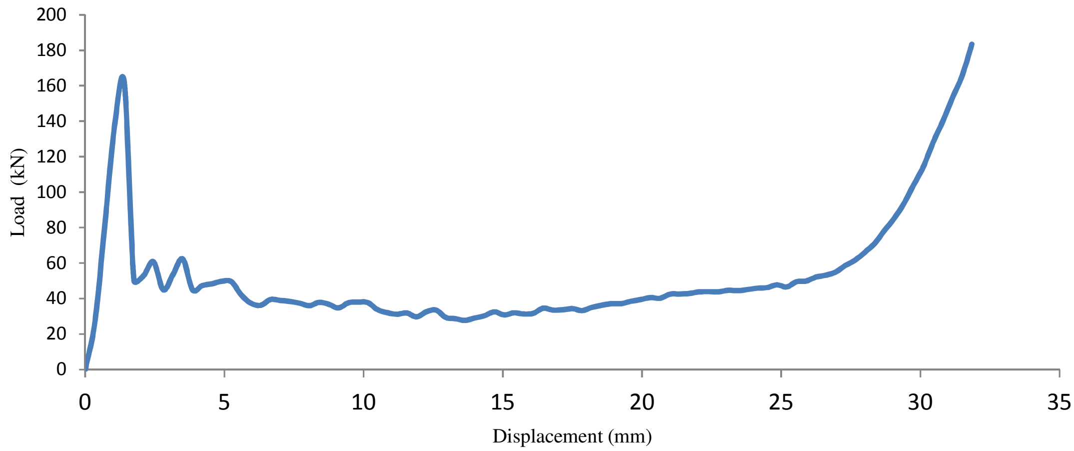

Fig. 12. Load-displacement curve for core cell size 50x40 mm

3.8 Energy Absorption Capability

Figure 13 shows the values of energy absorption for the tested models; these numerical values were calculated from the graphs of displacement-force for each model. The ideal energy-absorbing structure creating large area under the curve of load-displacement, and transfers the kinetic energy or part of it into another form of energy, and establishing a permanent plastic deformation to structure, that depends on the magnitude of load and material properties [32]. It is clear from the bar graph that the models with the greater structure sizes are having capability to absorb the higher amount of crushing energy, and then will expose to higher plastic deformation.

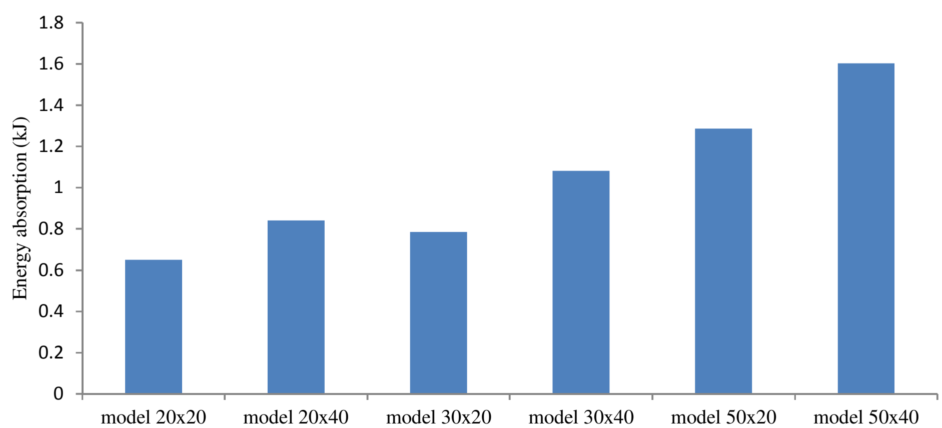

Fig. 13. Values of energy absorption for the models of study

3.9 Specific Energy Absorption

The mechanical performance of the thin wall and lightweight structures does not evaluate by the amount of absorbed energy via the model according to its size. Therefore, to compare the results among different analyses of lightweight structures the specific energy absorption (SEA) is generally used. Where, the higher value of SEA points out to the optimum performance in absorbing energy relative to unit mass [28]. Figure 14 demonstrates the values of specific energy for the six models, the model with size of 20x20 mm recorded the highest magnitude of SEA by about 72.62 kJ/kg. Meanwhile, the model size of 50x40 mm recorded the lowest value with around 36.54 kJ/kg. The models with sizes of 30x20 mm and 50x20 mm recorded approximately close values of specific energy absorption by 59.14 kJ/kg and, 58.66 kJ/kg respectively.

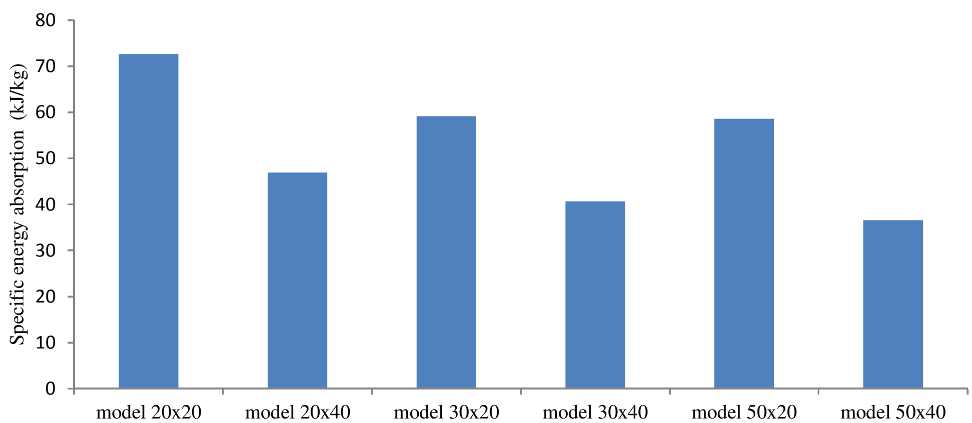

Fig. 14. Values of specific energy absorption for the models of study

Table 2
Specifications of the models of study

Model	Volume (mm3)	Mass (kg)	EA (kJ)	SEA (kJ/kg)
20x20	11205	89.64X10-4	0.65	72.62
20x40	22410	179.28X10-4	0.84	46.94
30x20	16605	132.84X10-4	0.79	59.14
30x40	33210	265.68X10-4	1.08	40.71
50x20	27405	219.24X10-4	1.29	58.66
50x40	54810	438.48X10-4	1.60	36.54

3.10 Comparison with Previously Published Data
3.10.1 Comparison of deformation behaviour

A previous experiment study conducted by Wu [33] concluded an identical description to this research results about the deformation behavior of honeycomb under compression load; where, six types of honeycomb structures were subjected to quasi-static loading. The findings revealed that, all honeycomb specimens showed a sharp peak load at beginning of applying force, followed by an oscillatory decreasing to crush load with a nearly constant mean value in crushing region, then the load rose up after the full crushing occurred at onset densification point. Likewise, a lately study by

Zuhri [19] mentioned the same trends of deformation stages for square and triangular honeycombs subjected to compression load. Furthermore, Li [6] described the three phases of deformation when honeycomb mechanics properties are studied. The first phase is linear elastic region where the honeycomb structures absorb energy through the elastic buckling of cell walls and the stress inside the wall reach to the peak value during the initial compression. The second phase is the stable plastic crushing phase; here the compressive stress is almost constant and the honeycomb structure absorbs energy through the plastic collapse of the cell walls. The third phase is the compaction phase described as follows. The walls of honeycomb are plastically collapsed, further deformation compresses the core tightly and leads to a sudden increase in the load-displacement curve. This phase represents the deformation ability of the honeycombs.

3.10.2 Comparison of SEA values

The outcomes of the current study showed that, the shorter heights of honeycomb core structure offer better specific energy absorption than longer height structures counterpart, these results are validated by previous study carried out by Roslan [5] when they conducted a compression tests to square and triangular honeycomb core structures based on bamboo-epoxy composites, to study their specific energy absorption. The findings indicated that the smaller cell height of honeycomb is able to absorb more energy than the bigger cell height one.

4. Conclusions

The compression response of the square interlocking structures made of flax fiber reinforced polypropylene (PP) composite has been successfully investigated using ABAQUS software. The simulation was carried out on six models with a different cell heights and sizes and same wall thickness. Initially, Abaqus/standard was applied to introduce the imperfection behavior of the models then, this imperfection is imported to Abaqus/explicit to simulate the final deformation of the models. Following this a few conclusions has been made:

- The optimum mechanical performance of lightweight interlocking structures is evaluated according to the values of specific energy absorption. Hence the core structure with cell size of 20x20 mm exhibited the highest value of specific energy absorption, and the lowest value is obtained from the cell size of 50x40 mm.

- The models with shorter cell heights appeared better specific energy absorption than the models with higher cell height counterpart. By other mean, the mechanical performance of the interlocking structures is inversely proportional to the height of cell.

- Despite their low density and lightweight the flax/PP composites showed outstanding mechanical performance and good energy absorption capabilities under compression loads.

References

[1] Estrin, Yuri, A. V. Dyskin, and Elena Pasternak. "Topological interlocking as a material design concept." *Materials Science and Engineering: C* 31, no. 6 (2011): 1189-1194.

[2] Benyahia, Azzedine, and Abdellah Merrouche. "Effect of chemical surface modifications on the properties of alfa fiber-polyester composites." *Polymer-Plastics Technology and Engineering* 53, no. 4 (2014): 403-410.

[3] Ahmad, Furqan, Heung Soap Choi, and Myung Kyun Park. "A review: natural fiber composites selection in view of mechanical, light weight, and economic properties." *Macromolecular Materials and Engineering* 300, no. 1 (2015): 10-24.

[4] Amina, Z., Roslina Mohammad, S. Abdul Azizc, and N. Othmand. "Workers' Safety Awareness Level on Hand Related Injury Accident in Metal Fabrication Industry." *Journal of Advanced Research in Applied Sciences and Engineering Technology* 1: 1-12.
[5] Roslan, S. A. H., M. Z. Hassan, Z. A. Rasid, S. A. Zaki, Y. Daud, S. Aziz, S. Sarip, and Z. Ismail. "Mechanical properties of bamboo reinforced epoxy sandwich structure composites." *International Journal of Automotive and Mechanical Engineering* 12 (2015): 2882.
[6] Li, Meng, Zong-quan Deng, Hong-wei Guo, Rong-qiang Liu, and Bei-chen Ding. "Optimizing crashworthiness design of square honeycomb structure." *Journal of Central South University* 21, no. 3 (2014): 912-919.
[7] Umar, A. H., E. S. Zainudin, and S. M. Sapuan. "Effect of accelerated weathering on tensile properties of kenaf reinforced high-density polyethylene composites." *Journal of Mechanical Engineering and Sciences* 2 (2012): 198-205.
[8] Mallaiah, Sripathy, Krishna Vinayak Sharma, and M. Krishna. "Development and comparative studies of bio-based and synthetic fiber based sandwich structures." *Int J Soft Compos Eng* 2 (2012): 332-335.
[9] Pandey, Jitendra K., S. H. Ahn, Caroline S. Lee, Amar K. Mohanty, and Manjusri Misra. "Recent advances in the application of natural fiber based composites." *Macromolecular Materials and Engineering* 295, no. 11 (2010): 975-989.
[10] Loh, X. H., M. Ahadlin M. Daud, M. Zulkefli Selamat, and UniversitiTeknikal Malaysia Melaka. "Study on Fibre Length and Composition of Kenaf-Polypropylene (K-PP) Composite for Automobile Interior Parts." *Applied Mechanics and Materials* 695 (2014): 36.
[11] Holbery, James, and Dan Houston. "Natural-fiber-reinforced polymer composites in automotive applications." *JOM Journal of the Minerals, Metals and Materials Society* 58, no. 11 (2006): 80-86.
[12] WEAGER, Brendon. "High-performance biocomposites: novel aligned natural fibre reinforcements." *JEC composites* 55 (2010): 31-32.
[13] Abrate, Serge. "Localized impact on sandwich structures with laminated facings." *Applied Mechanics Reviews* 50 (1997): 69-82.
[14] Yin, Hanfeng, Guilin Wen, Shujuan Hou, and Kai Chen. "Crushing analysis and multiobjective crashworthiness optimization of honeycomb-filled single and bitubular polygonal tubes." *Materials & Design* 32, no. 8 (2011): 4449-4460.
[15] Aziz, Alia Ruzanna. "The energy-absorbing characteristics of novel tube-reinforced sandwich structures." PhD diss., University of Liverpool, 2015.
[16] Xue, P., T. X. Yu, and X. M. Tao. "Effect of cell geometry on the energy-absorbing capacity of grid-domed textile composites." *Composites Part A: Applied Science and Manufacturing* 31, no. 8 (2000): 861-868.
[17] Dharmasena, K. P., D. T. Queheillalt, H. N. G. Wadley, P. Dudt, Y. Chen, D. Knight, A. G. Evans, and V. S. Deshpande. "Dynamic compression of metallic sandwich structures during planar impulsive loading in water." *European Journal of Mechanics-A/Solids* 29, no. 1 (2010): 56-67.
[18] Yamashita, M., and M. Gotoh. "Impact behavior of honeycomb structures with various cell specifications—numerical simulation and experiment." *International Journal of Impact Engineering* 32, no. 1 (2005): 618-630.
[19] Zuhri, M. Y. M., Z. W. Guan, and W. J. Cantwell. "The mechanical properties of natural fibre based honeycomb core materials." *Composites Part B: Engineering* 58 (2014): 1-9.
[20] Smith, M., Z. Guan, and W. J. Cantwell. "Finite element modelling of the compressive response of lattice structures manufactured using the selective laser melting technique." *International Journal of Mechanical Sciences* 67 (2013): 28-41.
[21] Hibbitt, Karlsson and Sorensen. (2012) Abaqus/CAE User's Manual (6.12): Dassault Systèmes Simulia Corp., Providence, RI, USA.
[22] Rejab, Mat, and Mohd Ruzaimi. "The mechanical properties of novel lightweight structures based on corrugated-cores." PhD diss., University of Liverpool, 2013.
[23] Wallace, John R. "Introduction to meshing algorithms for radiosity." *SIGGRAPH'92 Radiosity Course Notes* (1992).
[24] Al Galib, D., and A. Limam. "Experimental and numerical investigation of static and dynamic axial crushing of circular aluminum tubes." *Thin-Walled Structures* 42, no. 8 (2004): 1103-1137.
[25] Farley, Gary L. "Energy absorption of composite materials." *Journal of composite Materials* 17, no. 3 (1983): 267-279.
[26] Hamada, H., and S. Ramakrishna. "Impact performance of glass cloth/epoxy composite tubes with different surface treatment." *Composite Interfaces* 4, no. 1 (1996): 35-44.
[27] Li, Q. M., I. Magkiriadis, and John J. Harrigan. "Compressive strain at the onset of densification of cellular solids." *Journal of cellular plastics* 42, no. 5 (2006): 371-392.
[28] Heimbs, Sebastian. "Energy absorption in aircraft structures." In *International Workshop on Hydraulic Equipment and Support Systems for Mining, Huludao, China*, pp. 17-18. 2012.

[29] Thornton, P. H., J. J. Harwood, and P. Beardmore. "Fiber-reinforced plastic composites for energy absorption purposes." *Composites Science and Technology* 24, no. 4 (1985): 275-298.

[30] Li, Meng, Zong-quan Deng, Hong-wei Guo, Rong-qiang Liu, and Bei-chen Ding. "Optimizing crashworthiness design of square honeycomb structure." *Journal of Central South University* 21, no. 3 (2014): 912-919.

[31] Kazemahvazi, Sohrab, Daniel Tanner, and Dan Zenkert. "Corrugated all-composite sandwich structures. Part 2: Failure mechanisms and experimental programme." *Composites Science and Technology* 69, no. 7 (2009): 920-925.

[32] Alghamdi, A. A. A. "Collapsible impact energy absorbers: an overview." *Thin-walled structures* 39, no. 2 (2001): 189-213.

[33] Wu, Enboa, and Wu-Shung Jiang. "Axial crush of metallic honeycombs." *International Journal of Impact Engineering* 19, no. 5-6 (1997): 439-456.