Experimental and Simulation Study of Honeycomb Core under Dynamic Loading

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Abstracts: The objective of this project is to get the energy absorption of aluminium honeycomb core through experimental work and simulation analysis. The force-displacement behavior and energy absorb are studied for two different cell sizes of honeycomb core, which are 0.0127 m and 0.01905 m, respectively. The out-of-plane dynamic compression tests are conducted for the specimens by using INSTRON CEAST 9340 drop tower machine with an impact mass of 25 kg at 800 mm height and generate an impact velocity of 3.96 m/s. The linear elastic regime, flat plateau force regime and densification regime are observed in the force-displacement behavior in the crushing of aluminium honeycomb core. In finite element simulation, the model of honeycomb structures with 0.0127 m cell size is created in ABAQUS 6.12 in explicit environment. Several parameters such as mesh sizes, time intervals and plasticity models with Isotropic hardening and Johnson-Cook hardening are investigated in the simulation and validated with the experimental results. Isotropic plasticity model with 1 mm mesh size and 500-time interval is the optimum parameters in modelling aluminium honeycomb core with 0.0127 m cell size where the buckling mode of the specimen is similar with the experimental work.

Keywords: Aluminium Honeycomb Core, Energy Absorb, Isotropic Plasticity and Johnson-Cook Model.

1. INTRODUCTION

The honeycomb structures have been adopted as a part in the aerospace industry throughout the past few decades. The honeycomb structures are popularly used due to its high strength to weight ratio. Nowadays, the honeycomb sandwich panel have widely used in aerospace, transportation, marine and automotive industries. The honeycomb sandwich panel provides better properties than other material because a core with excellent mechanical properties will enhance the performance of the panel. For example, higher performance of the panel can absorb more energy and directly reduce the seriousness when the accident happened. Hence, the analysis of honeycomb sandwich panel is critically needed to understand the energy absorption and crush stiffness to improve the safety of honeycomb sandwich panel that use in various engineering applications.

This paper focuses on the effect of cell size of honeycomb core to the energy absorb of the structure under low velocity impact via experimental and finite element analysis. Two types of cell size are tested which are 0.0127m and 0.01905m cell size. In finite element analysis (FEA), the effect of Isotropic plasticity model and Johnson-Cook model are used respectively to describe the nonlinear behavior of aluminium honeycomb core under low velocity impact in terms of peak force, plateau force, stopping distance, and energy absorption. The FEA buckling mode of honeycomb core will be validated with experimental work.

2. LITERATURE REVIEW

Aluminum honeycomb is manufactured primarily by the expansion method where the adhesive is applied to the printed adhesive node lines followed by stacking the sheets. The aluminum honeycomb core has been used in transportation, marine, aerospace and automotive industries. The main reason why the honeycomb core has been used compared to the single thin wall structure is that the cells in the honeycomb core are able to absorb high compressive energy and absolutely contribute to the better specific energy absorption (SEA) compared with the single thin wall structure(Palomba et al., 2019).

Pokaad et al. had studied the effect of cell size dimension of aluminum honeycomb core under quasi static loading through experimental work. They found the energy absorb of the structure will be increased if the honeycomb cell size dimension is smaller (bin Pokaad et al., 2015). This is because the small cell size dimension will make the structure become more strength and rigid compared to the big cellsize. G. Tiwari et al. studied the response of aluminium hexagonal honeycomb with 45° apex angle under quasi static loading through experimental and simulation works. The LS-DYNA is used as the simulation platform. From the result, the relative density of honeycomb core with 45° apex angle is higher 1.5 times than relative density of regular honeycomb core. The energy absorb value of honeycomb core is increased with the higher value relative density of honeycomb core (Tiwari et al., 2018).

Aluminum honeycomb structure also exposed to the dynamic loading. The main purpose of the researchers to test it is to analyze the crushing behaviour of aluminium honeycomb core with the effect of strain rate. Xu et al. found that the energy absorb of honeycomb core is 50% larger during dynamic loading compared to quasi-static loading especially at plateau region. The test is made with the strain rate up to 10 m/s that applied to the honeycomb core (Xu et al., 2012). The same result was also recorded by Zhai et al. (Zhai et al., 2019). Some researchers had studied the behaviour of aluminum honeycomb core filled with natural or synthetic fiber under quasi static or dynamic loading. Radzai and Zulfakar had investigated the energy absorb of aluminum honeycomb core filled with natural fiber, kenaf and merbau sawdust (Radzai Bin Said & Zulfakar Bin Pokaad, 2016) . Mohamadi et al. investigated the failure mode of honeycomb core filled with synthetic fiber, elastomeric polyurethane foam(Mohamadi et al., 2021). Pietras et al used graphene-reinforce polyurethane foam as the filler for honeycomb core (Pietras et al., 2020). While, Zhanget al. used expanded polypropylene foam as the filler for honeycomb core (Y. Zhang et al., 2019).

Finite element analysis (FEA) has been performed by many researchers to study and investigate the mechanical behavior of honeycomb structure. However, the crushing test simulation can be done by several types of finite element (FE) software which are ABAQUS, ANSYS, NASTRAN, and so on. Sun etal. had used Altair and Hypermesh software to model the surface and honeycomb core damage in adhesively bonded aluminum sandwich panels subjected to low-velocity impact. They used 2D geometry to model theadhesive fillet height bonded into the sandwich panel (Sun et al., 2022). Zhang et al. modelled the dynamicresponse of multilayer curved aluminum honeycomb sandwich beams under low-velocity impact via Abaqus software. Johnson–Cook constitutive model is used to describe the nonlinear behavior of plastic metals, and its yield stress of aluminum honeycomb sandwich beams (J. Zhang et al., 2022). Yuelin et al. presented finite element models to simulate the uniaxial compressive performance of an aluminum honeycomb sandwich structure. They proposed the simplified method by converting the honeycomb core to a cube with equivalent material properties due to the aluminum honeycomb is too complex to be modeleddirectly, for there are too many contact relations among the honeycomb edges and the rear panel (Y. Zhanget al., 2023).

Many researchers use simplified methods to model the honeycomb core either quasi static or dynamic loading. Sun et al. used 2D model method for honeycomb core (Sun et al., 2022), Yuelin et al. converting honeycomb core to a cube method (Y. Zhang et al., 2023) and Yamashita & Gotoh simplified the honeycomb core into one Y-cross sectional column (Yamashita & Gotoh, 2005). Simplified the model will reduce time consumption to running the simulation. Unfortunately, they were not able to compare the buckling mode for all cells in honeycomb core with the experimental result.

Thus, this paper, the simulation is run using the 3D model of honeycomb core which is exactly similar with the experimental specimen. The validation of the buckling mode in simulation can directly validate to the experimental result.

3. METHODOLOGY

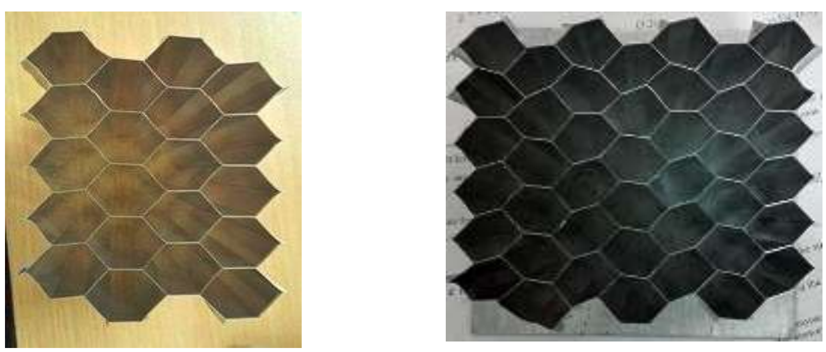
3.1. Preparation of specimen

The aluminium alloy AA3003-H18 honeycomb core with a thickness of 0.063 mm is chosen as the testing material. Alloy 3003 is commercially pure aluminium with the addition of manganese to enhance its strength by about 20% and is one of the most commonly used aluminium alloys. Two types of specimens, which are 0.01905 m and 0.0127 m in cell size, were chosen and prepared for the experiment. Figure 1 shows the original honeycomb core, steel plates (face sheets), and adhesive glue. While both specimens are cut into the desired cell numbers, which are 4x5 and 7x6 for 0.01905m and 0.0127m cell size honeycombs, respectively, as shown in Figure 2, Thereafter, the specimen is placed centrally and bonded between the face sheets by using the adhesive glue as shown in Figure 3.

The weight and dimension of each aluminum honeycomb core are measured by using the digital weighing scale and Vernier caliper, respectively. In addition, the cross-sectional area for each honeycomb core as shown in Figure 4 is obtained from Autodesk Inventor 2016 software. The total volume of each honeycomb core is calculated to determine the nominal density by using Equation 1 and Equation 2. The honeycomb core geometry and cell parameter are depicted in Figure 5 while the dimension and calculated data for each honeycomb specimen are tabulated in Table 1 and Table 2, respectively.

(a) (b) (c)

Figure 1: (a) original 0.01905m cell size honeycomb core, (b) steel plate, and (c) adhesive glue



(a) (b)

Figure 2: (a) 22 number of cells with 0.01905 m cell size honeycomb core, and (b) 42 number of cells with 0.0127 mcell size honeycomb core

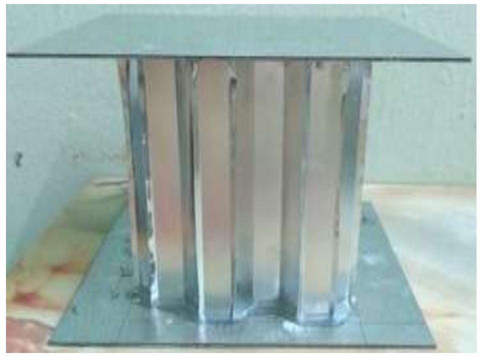


Figure 3: 0.01905 m cell size of honeycomb core glued with face sheets

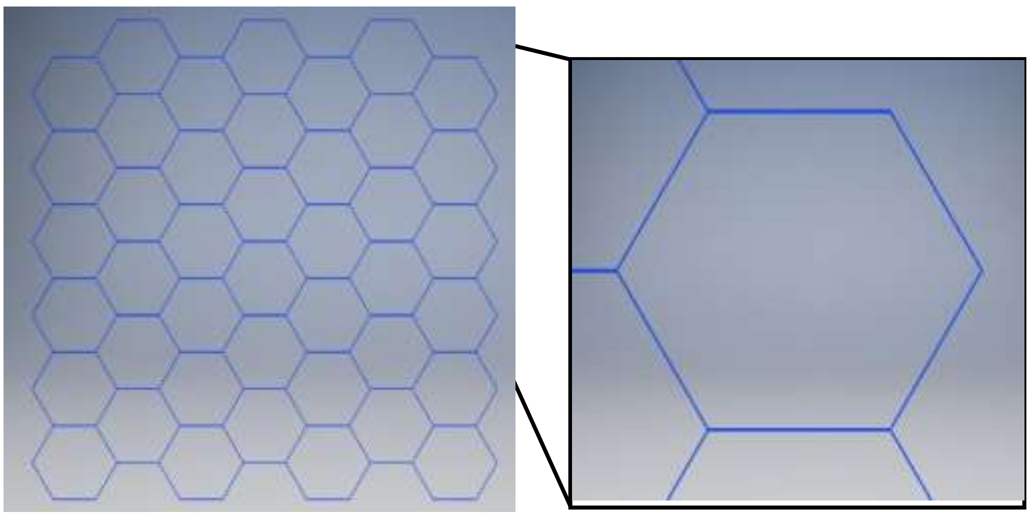


Figure 4: Cross-sectional view of 0.0127 m cell size honeycomb core

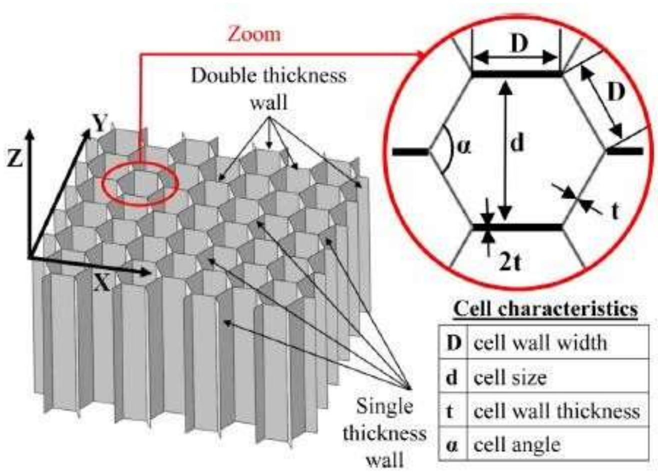


Figure 5: Honeycomb specimen geometry and cell parameter

Table1: Detail of each specimen dimensions

Cell size, d (m)	0.0127	0.01905
Cell wall thickness, t (m)	0.000063	0.000063
Cell wall width, D (m)	0.007332	0.01010
Cell angle, α (degree)	120	120
Height, H(m)	0.1	0.1

Volume of aluminum honeycomb is calculated by：

$$\mathbf{V} = \mathbf{A} \times \mathbf{H} \tag{1}$$

Nominal density of aluminum honeycomb is calculated by:

$$\rho = \frac{M}{V} \tag{2}$$

where M is the mass of honeycomb core.

Table 2: Additional data of each specimen

Cell size, d (m)	Mass, M (kg)	Area, A (m^2)	Volume, V (m^3)	Nominal density, ρ (kg/ m^3)
0.01270	0.0215	0.000089	0.00089	36.305
0.01905	0.0160	0.000061	0.00061	26.229

3.2. Experimental Setup

The dynamic compression test is conducted by using the INSTRON CEAST 9340 drop tower machine. CEAST 9340 is a floor standing impact system and suitable for a range of impact applications such as Charpy tests, tensile impact test, penetration tests on plate and films, and Izod test. Photography equipment such as Olympus i-speed 2 camera with 1000 fps resolution, lighting kit and tripod set are used during the experiment as shown in Figure 6. The high-speed camera is used to record and capture all the deformation photography during the impact test. The specimens are placed centrally between the fixed and adjustable height stand which is shown in Figure 6. In addition, the specimens are crushed by 25 kg dropping mass at 0.8 m height with initial impact velocity of 3.96 m/s. The data acquisition system is employed to collect the data and plot the force versus displacement.

3.3. Simulation Method

In the finite element analysis, ABAQUS 6.12 software with explicit model type is employed to simulate the crushing behavior of aluminum honeycomb core. During the analysis, all the modules should be completed accordingly, which start from part, property, assembly, step, interaction, load, mesh, and finally end with visualization module. The part drawings of honeycomb core and plate are created in deformable and rigid type, respectively. Furthermore, the honeycomb core is determined as a homogeneous shell shape with two different types of wall thickness which are single and double wall thickness, respectively. While the red portions as shown in Figure 7 denoted as the single-wall thickness with 0.063 mm and the rest portions are denoted as the double-wall thickness with 0.126 mm. The specimen model which is shown in Figure 8 shows the assembly by honeycomb core and two plates. Other than that, the mechanical properties, engineering stress-strain value, and Johnson-Cook parameter of 3003 aluminum alloy as shown in Table 3, Table 4, and Table 5, respectively, are used in the finite element analysis.

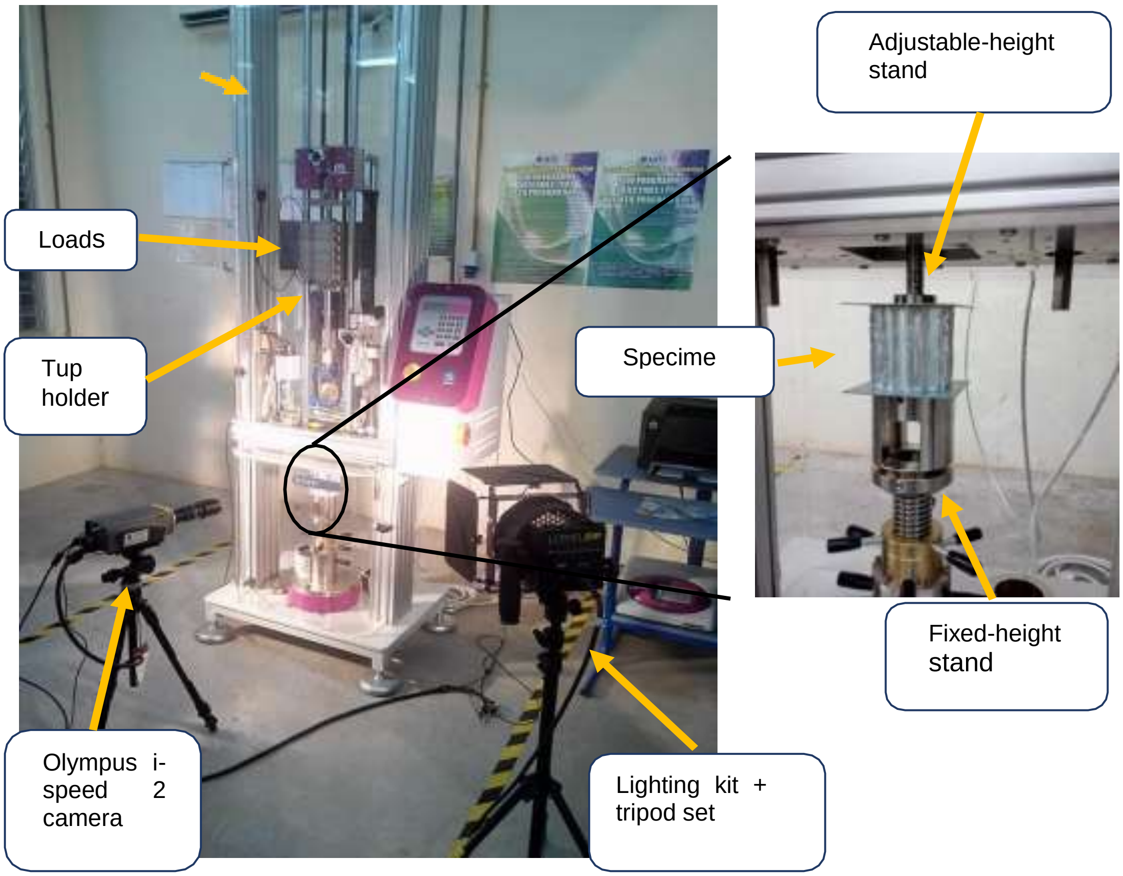


Figure 6: CEAST 9340 drop tower for compression tests

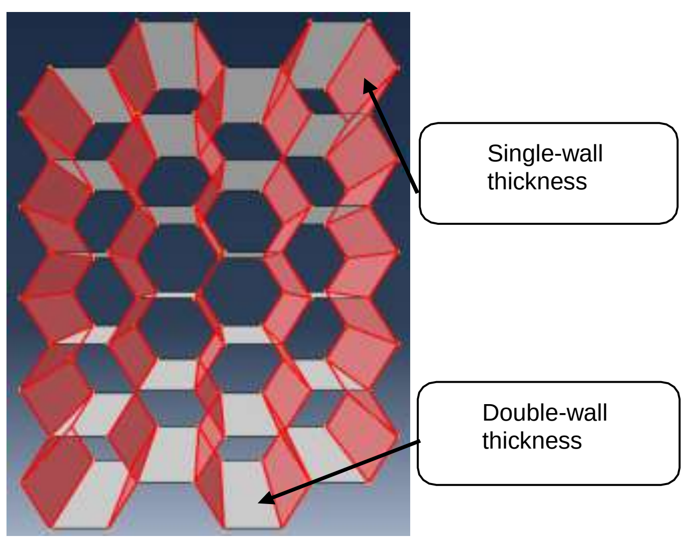
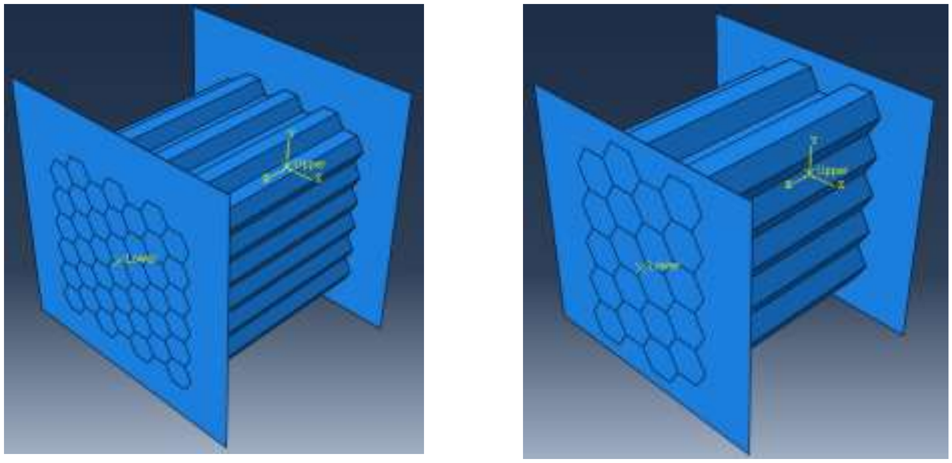


Figure 7: Homogenous shell shape of honeycomb core with single and double wall thicknesses



(a) (b)

Figure 8: Specimen model of (a) 0.0127m cell size of honeycomb core, and (b) 0.01905m cell size of honeycombcore

Table 3: Mechanical Properties of AA3003-H18 (X. Zhang et al., 2014)

Material	Density (kg/m^3)	Young's modulus (GPa)	Initial yieldstress (MPa)	Ultimate Stress (MPa)	Poisson ratio,v
3003-H18	2730	69	115.8	154.5	0.33

Table 4: Engineering stress-strain curve of AA3003-H18 (X. Zhang et al., 2014)

Yield stress (MPa)	Plastic strain (%)
115.8	0.10
116.0	0.20
133.0	0.30
142.0	0.40
148.0	0.50
150.0	0.60
152.0	0.70
154.0	0.80
154.5	1.00
154.5	1.46

Table 5: Johnson-Cook parameter of AA3003-H18 (Huang et al., 2016)

Yield stress constant A (MPa)	Strain hardening coefficientB (MPa)	Strain rate dependence coefficient C	Strain hardening exponent n	Reference Strain rate $\dot{\varepsilon}$	Temperature dependence coefficient M
85.2	170.0	0.038	0.44	1	1.37

There are two types of boundary conditions applied to the reference point at bottom and upper platewhich are "encastre" and "displacement" as shown in Figure 9. The "encastre" implies that the bottom plate is fixed in all directions while "displacement" means that the upper plate is moving along Z-direction witha downward velocity and a dropping mass which are 3.96 m/s and 28.245 kg, respectively.

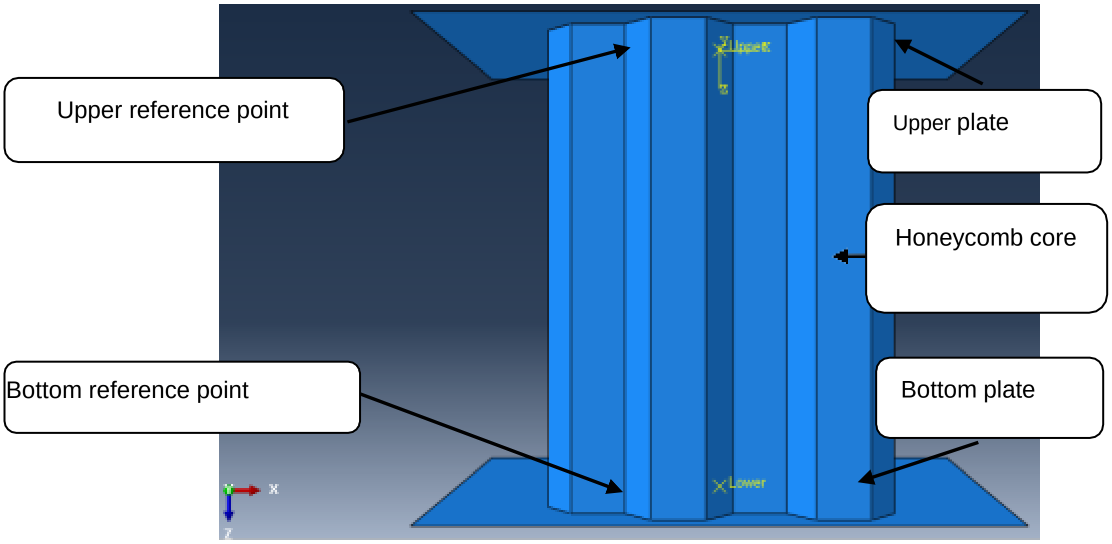


Figure 9: Model of specimen with boundary condition

For the constrains, friction coefficient and coupling interactions are applied to create a relationship between the honeycomb core and two plates which shown in Figure 10. Apart from that, a time interval of 500 is used during the analysis and a mesh size of 1 mm is applied to the honeycomb core. However, the sensitivity of mesh sizes and time intervals will be analysed and compared with the experimental result.

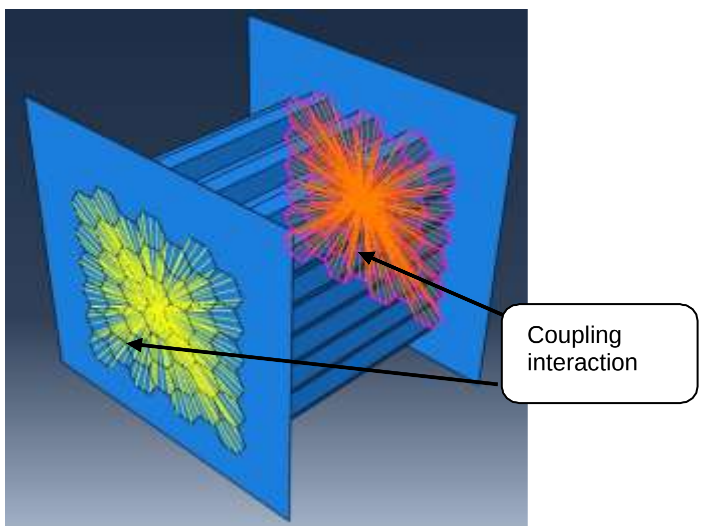


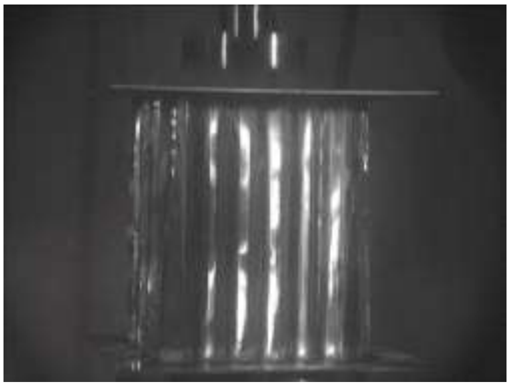
Figure 10: Coupling interactions between honeycomb core and two plates

There are some effects need to be studied and investigated in the simulation in order to compare the differences such as mesh sizes and time intervals are the critical issues that will affect the results of the simulation (bin Pokaad et al., 2015). Therefore, three different type of mesh sizes which are 1.2 mm, 1 mm, and 0.8 mm are applied to the 0.0127 m cell size of honeycomb core. Moreover, five different types of time intervals such as 100, 200, 300, 400, and 500 are used during the simulations.

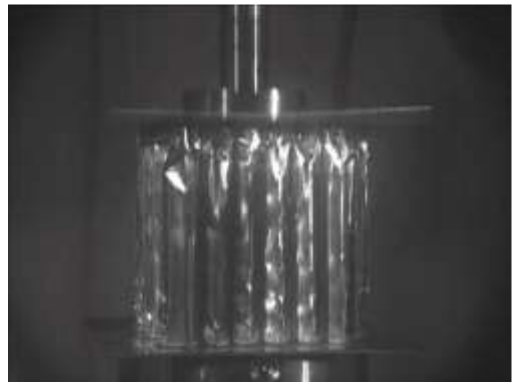
4. RESULT AND DISCUSSION

4.1. Experimental result

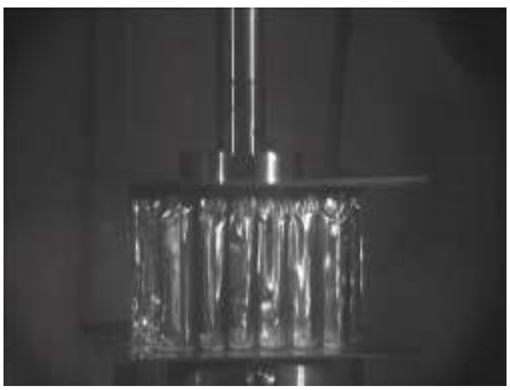
Two specimens with different types of cell sizes are conducted under dynamic loading. Figure 11 and Figure 12 show the photographs of progressive buckling deformation of for cell size of 0.0127 m and cell size of 0.01905 m respectively. In the photographs, the honeycomb core with cell size of 0.01905 m shows higher deformation compared to the honeycomb core with cell size of 0.0127 m. The number of cells for honeycomb with cell sizes of 0.01905 m and 0.0127 m are 20 cells and 42 cells, respectively. The higher number of cells will make the honeycomb core structure become more stiff and able to absorb more impact energy compared to the smaller number of cells of honeycomb core. Thus, the dropping mass is able to crush or deform the honeycomb core until 56.17 mm for 0.0127 m cell size as shown in Figure 11 and 82.3mm for 0.01905 m cell size as shown in Figure 12.



(a) 0.00 mm



(b) 10 mm



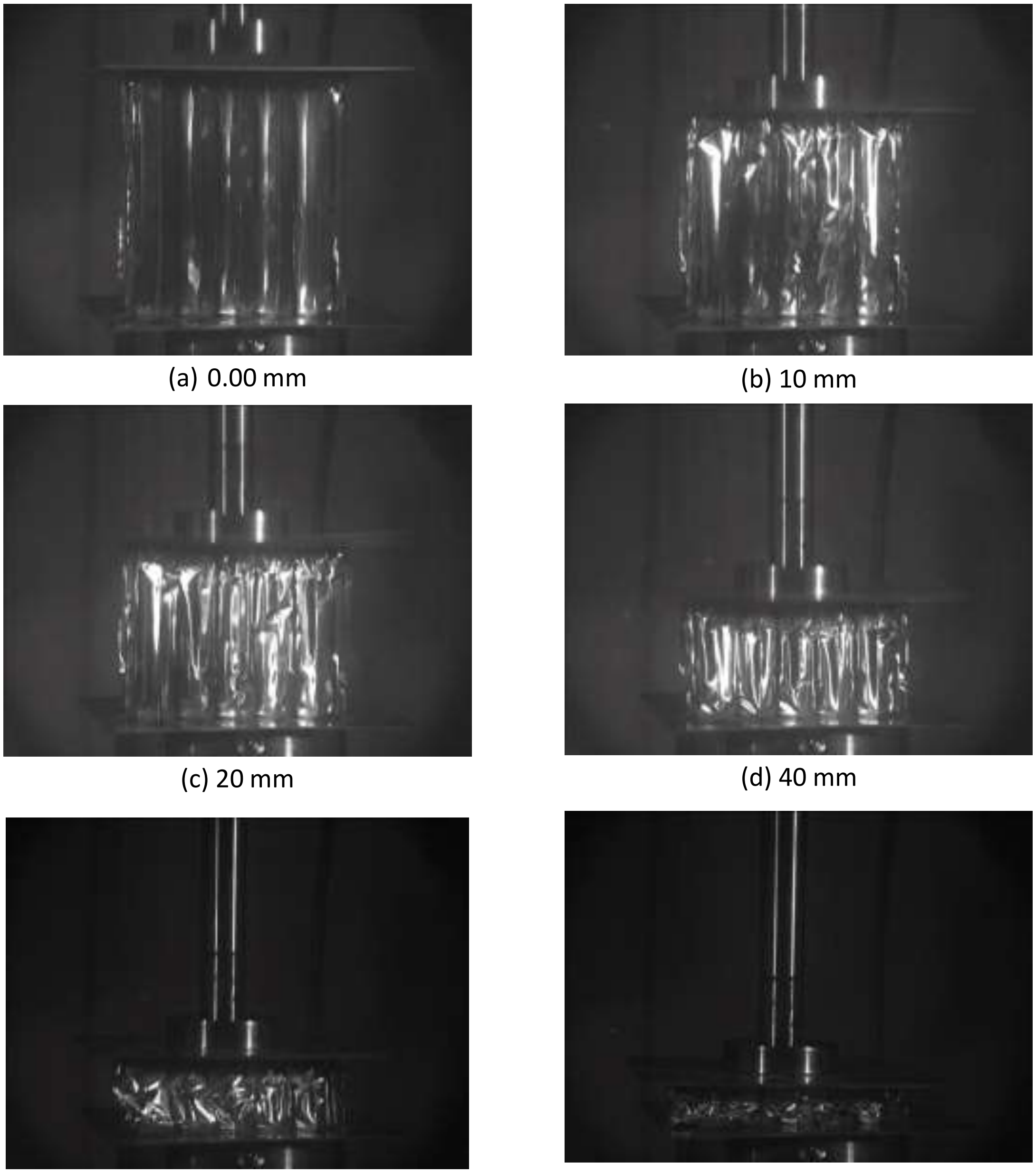
(c) 20 mm

(d) 40 mm

(e) 50 mm

(f) 56.17 mm

Figure 11: Photographs of the progressive buckling deformation of 0.0127 m cell size of honeycomb specimen atdifferent displacement



(a) 0.00 mm (b) 10 mm (c) 20 mm (d) 40 mm (e) 60 mm (f) 82.3 mm

Figure 12: Photographs of the progressive buckling deformation of 0.01905 m cell size of honeycomb specimen atdifferent displacement

Figure 13 shows the force-displacement graph for 0.0127 m cell size. The graph shows the linear elastic region and plateau force region. The cell wall of honeycomb begins to buckle due to the increasing of crushing force where point 1 to point 2 show the linear elastic region. Point 2 is the peak force or maximumcompressive strength of the structure before the cell wall starts to collapse. Apart from that, the plateau force region is started from point 3 to point 4 where the force is nearly constant. The peak force, plateau force and stopping distance of 0.0127 m cell size of honeycomb are 8396.08 N, 4288.84 N, and 0.05617 m,respectively.

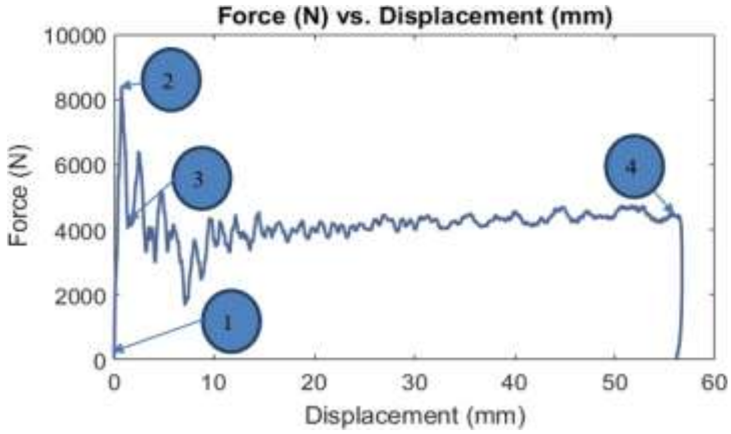


Figure 13: Experimental force-displacement for 0.0127 m cell size of honeycomb core under dynamic loading test.

In Figure 14, a densification region that indicated from point 4 to point 5 is occurring in the force- displacement graph. The occurrence of densification is due to further compression when the honeycomb cell wall is collapsed sufficiently. However, the pattern from point 1 to point 4 for 0.01905 m cell size is similar with 0.0127 m cell size of honeycomb. The peak force, plateau force and stopping distance of 0.01905 m cell size of honeycomb are 5498.08 N, 2573.63 N, and 0.08283 m, respectively.

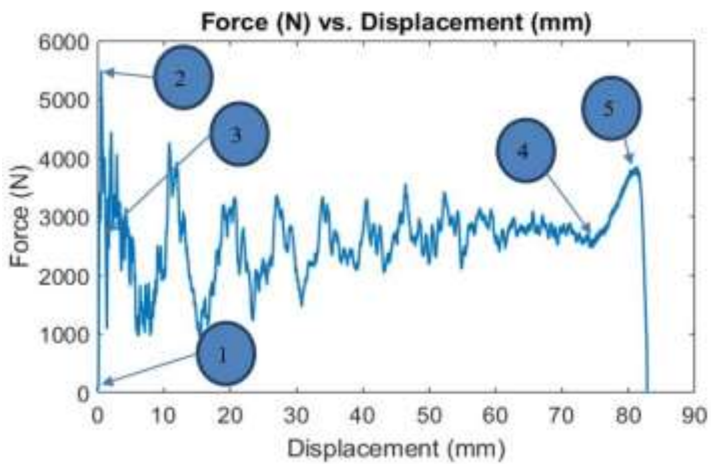


Figure 14: Experimental force-displacement for 0.01905m cell size of honeycomb core under dynamic loading test.

4.2. Simulation Result

In the analysis of finite element simulation, three types of parameters such as plasticity models, mesh sizes,and time intervals are applied to the honeycomb structure in order to investigate the sensitivity, followed by comparing and discussing with the experimental results. Two types of plasticity models are applied to 0.0127 m cell size of honeycomb structure which are isotropic and Johnson-Cook plasticity model respectively. In Figure 15, the progressive buckling deformation at different compressive strain for isotropic plasticity model is nearly same as the experiment as the structure is mostly buckling at the layer adjacentto the upper face sheet.

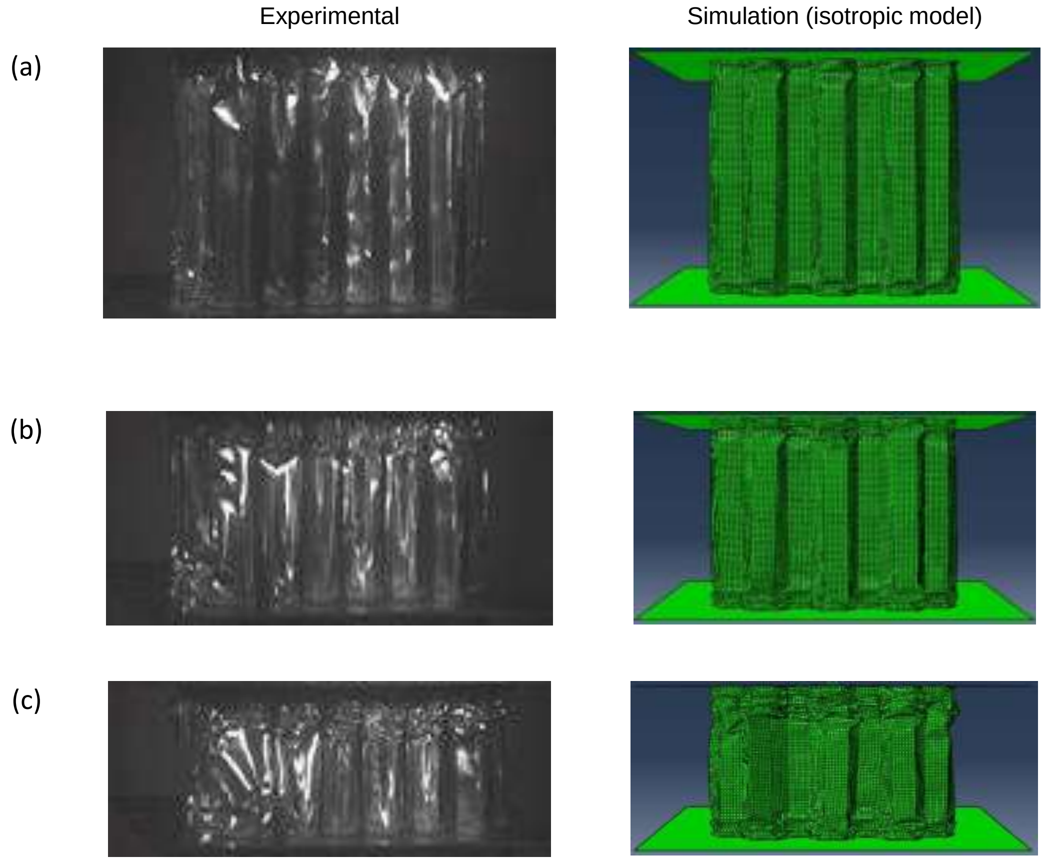


Figure 15: Structure deformation of 0.0127 m cell size of aluminium honeycomb core between experimental and sotropic model at (a) 10% compressive strain, (b) 30% compressive strain, and (c) 50% compressive strain

On the contrary, Figure 16 shows the progressive buckling deformation at 50% compressive strain for Johnson-Cook plasticity model which is different compared to isotropic plasticity model and experiment result. This is because it focuses to buckle at the layer adjacent to the lower face sheet.

In addition, Figure 17 shows there is a difference in peak force for both plasticity models when compared to experiment. However, isotropic plasticity model shows similar plateau force and stopping distance as the experiment result compared to Johnson-Cook plasticity model.

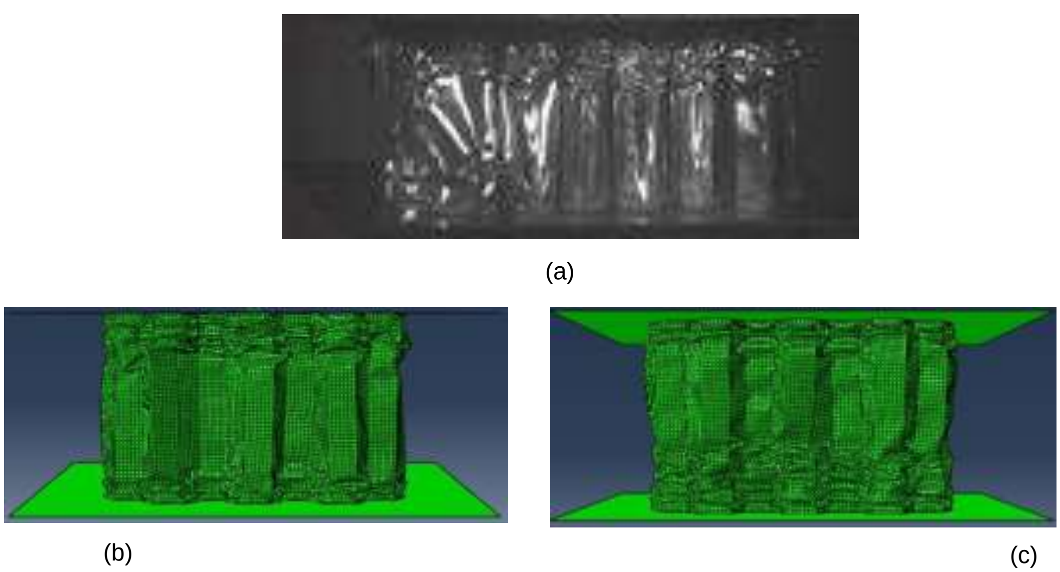


Figure 16: Structure deformation of 0.0127 m cell size of aluminium honeycomb core at 50% compressive strain: (a) experiment, (b) isotropic plasticity model, and (c) Johnson-Cook plasticity model

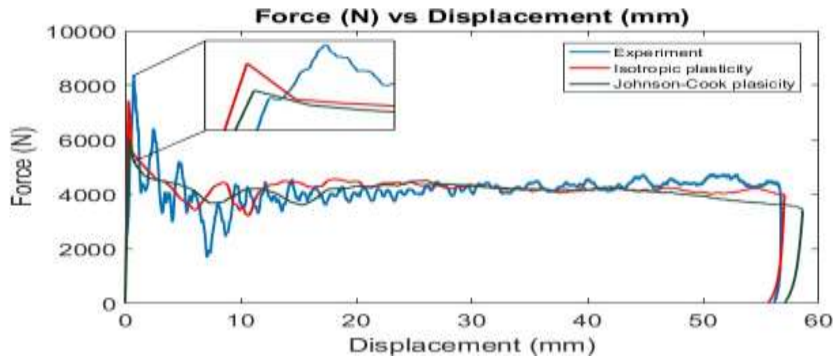


Figure 17: Comparison of force-displacement between experimental and finite element analysis with two different plasticity models of 0.0127 m cell size of honeycomb core

In summary, the isotropic plasticity model is more suitable to be used in the simulation compared to Johnson-Cook plasticity model as presented in Figures 16 and 17. From the study, Johnson-Cook plasticity model is more suitable to be used for the strain rate deformation of material is between 10^2 s^{-1} and 10^4 s^{-1} (Kaliat Ramesh, 2008). However, the strain rate used in the experimental test is 39.6 s^{-1} which is lower than 10^2 s^{-1}. Equation 3 is used to calculate the experiment strain rate where the impact velocity and original length of specimen, are 3.96 m/s and 0.1 m, respectively.

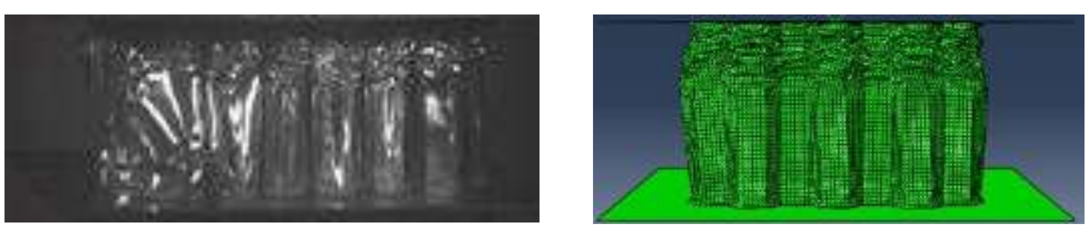
The equation of strain rate is defined as:

$$\dot{s} = \frac{v(t)}{l_0} \quad (3)$$

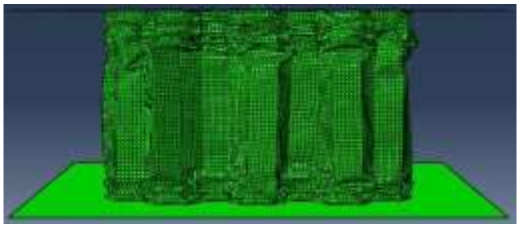
where $v(t)$ is the impact velocity and l_0 is the original length of specimen.

4.3. Sensitivity Studies of Mesh Sizes And Time Interval

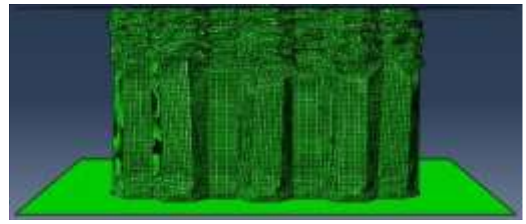
Figure 18 shows three different meshing sizes, which are 1.2 mm, 1 mm, and 0.8 mm that are applied to the 0.0127 m cell size honeycomb structure followed by comparing with the experimental result. In 0.0127m cell size of honeycomb structure, the number of nodes for 1.2 mm, 1 mm, and 0.8 mm mesh sizes are 74400, 104658, and 168714, respectively. In finite element analysis, the larger the mesh size will make thestructure stiffer. In addition, the smaller mesh size will increase the time required for the analysis in Abaqus.



(a) (b)



(c)



(d)

Figure 18: Structure deformation of 0.0127m cell size of aluminium honeycomb core at 50% strain: (a) experiment, (b) 1.2 mm (c) 1 mm, and (d) 0.8 mm meshing size

For instance, Figure 19 shows 1.2 mm mesh size has the highest peak force and plateau force, followed by the lowest stopping distance due to lesser nodes are counted and leaded to increase the stiffness of structure. By comparing three mesh sizes, 1 mm mesh size has similar plateau force and stopping distance as the experiment. Therefore, 1 mm mesh size is most suitable to be used for the following structures.

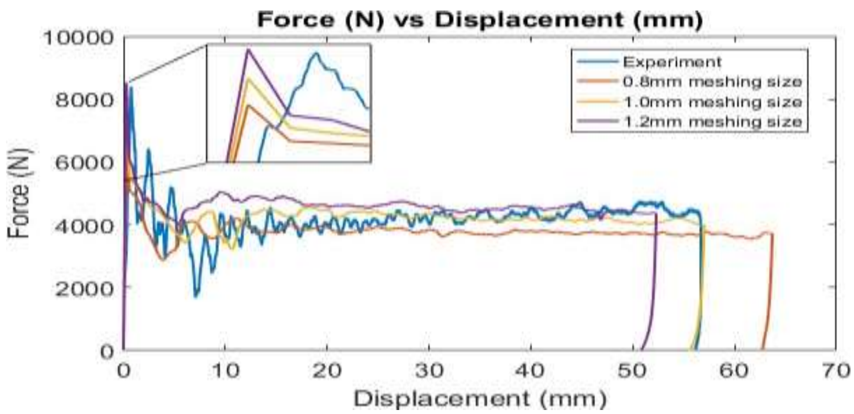


Figure 19: Comparison of force-displacement between experiemntal and finite element analysis with three differentmesh sizes of 0.0127 m cell size honeycomb core

Alternatively, different types of time intervals which are 100, 200, 300, 400, and 500 are applied to the simulation analysis which is shown in Figure 20. From the force-displacement graph above, the plateau force region and stopping distance for different time intervals are nearly the same as the experiment. Conversely, there is a difference in peak force between the experiment and different time intervals. However, the time interval of 500 shows the most similar force-displacement graph to the experiment resultcompared to other time intervals. Thus, time interval setup in simulation is used to get the similar experimental peak force.

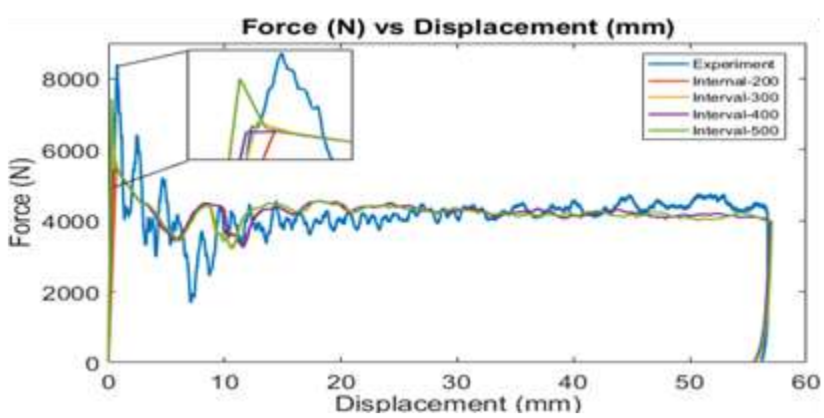


Figure 20: Comparison of force-displacement between experimental and finite element analysis with four differenttime intervals of 0.0127m cell size of honeycomb core

CONCLUSIONS

In this paper, the behavior of aluminium honeycomb core under dynamic loading is studied experimentally and the result is used as the benchmark for the simulation analysis such as the buckling mode and the force-deformation of the structure. The finding of the results as follows:

1) In experimental result shows the higher number of cells will make the honeycomb core structure become more stiff and able to absorb more impact energy compared to the smaller number of cells of honeycomb core.

2) Based on analysis area under the graph for Figure 13 and 14, the energy absorption for 0.0127 m cell size of honeycomb is 237.2 Joule. While the energy absorption for 0.0905 m cell size of honeycomb is 206.68 Joule. The fact is the small cell size of honeycomb can absorb more impact energy compared to the big size of honeycomb. The high plateau force is the main factor to absorbmore impact energy.

3) Both honeycomb core cell sizes show the progressive buckling mode where the buckling is started from the top surface until the bottom surface of honeycomb core. But, the end of deformation high is different. The stopping distance or end of deformation high after the impact for 0.0127 m cell size is 56.17 mm and 0.0905 m cell size is 82.3 mm. The small cell size has short stopping distance compared to big cell size after the impact occurred. The fact is, the small cell size is more strength due to the higher number of cells compared to the big cell size.

4) Due to the strain rate in this experimental is lower than 10^2 s^{-1}, the isotropic plasticity model is more suitable to use in modelling compared to Johnson-Cook plastic model. The buckling mode for isotropic plasticity model is almost similar with the experimental result.

5) In sensitivity study, the mesh size plays the important role to make the buckling mode of the structure similar with the experimental result. The big mesh size will make the structure become stiffer and the folding size of honeycomb core becomes bigger. But, the small mesh size will increase the time consumption of simulation. Thus, 1 mm mesh size is the optimum value for the simulation.

6) Time interval is introduced in this simulation. Based on the observation, time interval setup will not change the buckling mode of the structure. But, the time interval is play importance role for the Abaqus solver to catch the peak force value during the impact. Thus, a 500 time interval is the optimum value in this simulation.

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