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A new and lean finite element model to predict the out of plane crash behaviour of aluminium honeycomb structures

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Abstract. Aluminium honeycombs are well-known anisotropic structures which are commonly used as energy absorber units. In the past decades, several researchers have focused on developing finite element models credible enough to predict the crash behaviour of honeycomb structures. A number of modelling methodologies have been developed and validated to closely represent the structural behaviour under various boundary conditions. Due to the limitations with modelling the structure accurately as well as the adhesive failure and trapped air, presents a serious challenge to predict the crushing behaviour of honeycomb structures. This paper introduces multiple simplified FE models and the results from simulations are compared with experimental data to evaluate the most effective model. The results have also been compared with our existing article which used LSDYNA for numerical analysis. The techniques proposed in this paper show good correlation with the mentioned experimental data and the LSDYNA model. Thus, the simplified FE models are regarded as validated and credible enough to predict out-of-plane crash behaviour of aluminium honeycomb. Altair's HyperMesh and HyperCrash were used to create the FE models and the dynamic explicit code RADIOSS to solve the models.

1. Introduction

Aluminium honeycomb structures are used in a wide range of engineering applications such as rail, marine, automotive and aircraft industries due to its ability to absorb high impact energy and the highly desired strength to weight ratio. To ensure good prediction of their crushing behaviour, it is necessary to validate the FE models in order to accurately predict the physical and numerical results when the structure is subjected to variety of boundary conditions. However, due to the limitations with modelling the structure accurately as well as the adhesive failure and trapped air, presents a serious challenge to predict the crushing behaviour of honeycomb structures. Hence, current focus is to develop simplified FE models for honeycomb structure and assess its credibility to represent the crush strength.

2. Literature

2.1. Review

A study into the impact behaviour of honeycomb structures with various cell specifications [1, 2] investigated the effect of internal angles and foil thickness on the crash behaviour of aluminium honeycomb structures using the explicit FEA code DYNA3D. Impact tests using a drop hammer with a velocity of 10m/s⁻¹ and the corresponding quasi-static tests were also performed. The experiment showed that the compressive stress increases under impact due to the air enclosed in the



honeycomb cells. For the numerical analysis a simple “Y” cross-section column (double flange) was used due to geometric symmetry. Branch angles of the column were varied from 30° to 180°. The numerical work from their investigation shows the cyclic buckling mode occurs in every case and crash strength increases with smaller branch angle as well as increased foil thickness. The numerical results were reported to show good correlation with experimental data.

A simplified model was developed by researchers [3-6] who analysed the crash behaviour of a simple “Y” cross-section column (single flange) and compared the numerical results with experimental data. A total of fifteen samples of honeycomb cores produced by Cellbond were used in the experimental tests. The effect of adhesives, trapped air and curves at the cell corners were not considered in the model. In spite of the initial buckling phenomenon that resulted in a large instantaneous peak, the numerical results from this work shows close representation of the energy absorption, deformation behaviour as well as compressive strength.

A study on the yielding function of aluminium honeycomb [7] focused on developing a more accurate yielding function of aluminium honeycomb block. Experimental tests were done to evaluate the behaviour of honeycomb block under compressive load. Observations from the work show that the yielding stress of aluminium honeycomb highly depends on the direction of compression. Using the test data a new yielding function was proposed as a function of volumetric change and angle of compression. This newly developed yielding function was then introduced to MAT126 in LSDYNA. Frontal crash tests were performed with the yielding function and showed better correlation with the test results in comparison with MAT126 without the yielding function.

An investigation was carried out focusing on the mechanical behaviour of aluminium hexagonal honeycombs subjected to out-of-plane dynamic indentation and compression loads [8, 9]. The finite element models have been verified using experimental data in-terms of deformation pattern, stress-strain curve and energy absorption. The model reveals that for velocities of 5m/s⁻¹ under indentation, plastic buckling of the honeycomb cell walls from the end that is adjacent to the indenter, while under compression the buckling of honeycomb cell walls occurs from both ends of the honeycomb.

Analytical study conducted by a group of researchers [10, 11] focused on developing a beam element based aluminium honeycomb FE model with lateral and frontal crash load. The intention behind the work was to achieve realistic deformation behaviour of the anisotropic honeycomb structure. The models generated with beam elements showed reasonably good results with that of physical testing during the validation process. Initially the model was validated with cladding sheets; the corresponding force displacement curve seemed to be representative of the curves produced during the physical testing phase. The study concluded stating that special attention must be given to local phenomena such as sheet metal failure, glue failure and modelling the air trapped in the hexagonal pockets.

To improve the accuracy of the results with a shell element-based honeycomb barrier, a group of researchers carried out an investigation [12-14] and compared the results with a solid element model. Upon solving both shell and solid element models, the results were compared to the physical test. To approximate the real crash pattern, ends of the honeycomb core were bent locally to simulate the pre-crashed surface of the samples prior to solving the model. Modelling of the adhesive with the cladding sheet was also considered in the model. With regard to the bonding between aluminium honeycomb and cladding sheet, beam elements were used in order to simulate the rupturing of the adhesive. The study reports that the shell element model is capable of predicting the physical result more accurately than solid element model however the disadvantage is the higher computational cost.

Another investigation [15-18] examined the influence of cell wall thickness, node length, cell size and loading conditions. The crush patterns of the honeycomb structure have been studied in both out-of-plane and in-plane crash modes. Aspects such as geometrical core configuration and geometric property like cell size, cell wall thickness and node length have a significant importance in administering the potential of honeycomb according to this research. The study also reports that the cladding sheet material and thickness majorly affects the energy absorption credibility of the core during impulsive impacts.

Wide range of analytical and experimental work has been performed by researchers in-order to characterise the anisotropic behaviour of honeycomb structures. However, further study is essential to characterise the crash behaviour of honeycomb structures more accurately whilst not compromising computational cost.

3. Experimental Test

Data and results from our previous experimental tests and existing paper have been used to validate the proposed simplified FE models. The aluminium honeycomb samples used in the previous experiment was produced by Cellbond. The samples used are regarded as 1.8-3/4-3003 with a foil thickness of 0.06mm. The sample cores used were 250mm x 250mm x150mm in length, width and height respectively with a wall to wall thickness of 19mm.

Table 1: Specification of Aluminium A3003

Mass Density (ρ)	2100kg/m ³
Young's Modulus (E)	70GPa
Poisson's Ratio (ν)	0.33
Yield Stress (σ_{ys})	190MPa
Ultimate Tensile Strength	800MPa

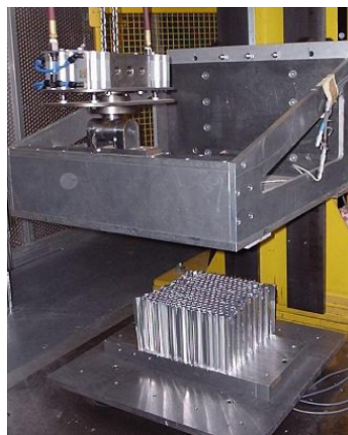


Figure 1: Experimental Test Set up – Honeycomb Out-of-Plane Crush Test

A drop trolley of mass 72kg was used to crush the honeycomb samples with an impact velocity of 5.24m/s⁻¹.

Aluminium honeycombs are hexagonal structures made of thin aluminium foils and due to the anisotropic behaviour, honeycomb structures are approximately ten times stronger in the principle “T” direction in comparison to “L” and “W” directions.

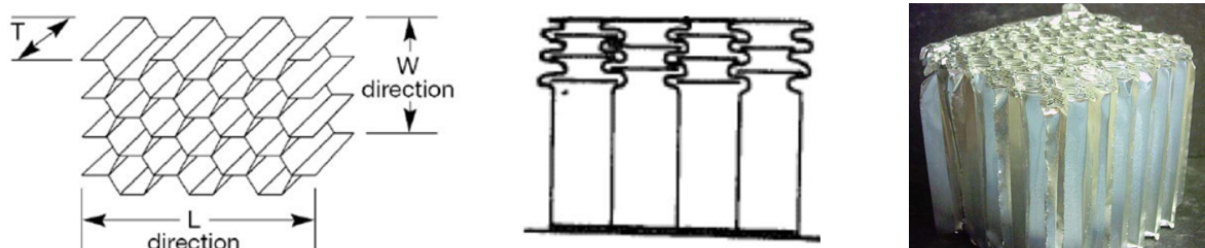
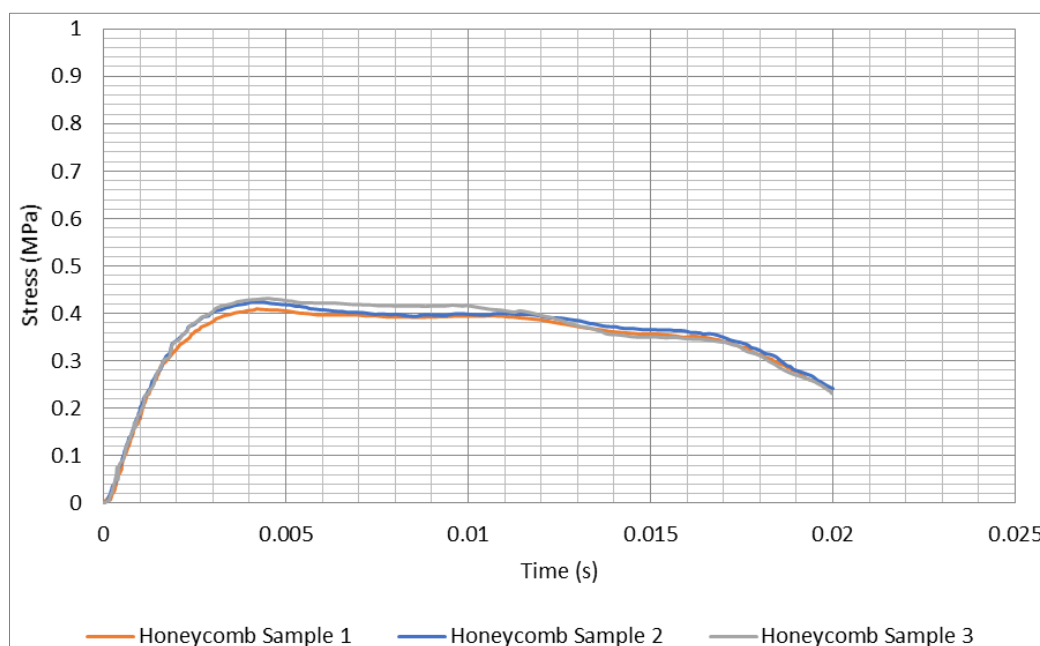


Figure 2: Deformation behaviour of Honeycomb Structures

When loaded in the T direction, the structure shows a particular buckling behaviour. Initially the structure buckles elastically and when the impact load reaches a critical point, the core buckles for the first time and is indicated by a distinct peak. Progressing past this first buckling point, the core then continuously buckles under constant load. It should be noted that the buckling behaviour of honeycomb structure is initiated from the top and progresses down the structure in “T” direction. During test, the impact force was measured and the compressive stress profile was calculated using the equation below,

$$\sigma = \frac{F}{A} \quad (1)$$

Where, σ is the compressive stress, F is the impact force and A is the out-of-plane cross-sectional area of the honeycomb samples.



Graph 1: Compressive stress as a function of Time – Honeycomb Samples

A total of fifteen crash tests were done, however, results of three samples are presented in this paper. The corresponding stress vs time curves for the three samples are shown above. The measured curves from the tests gives an average compressive stress which is defined in $\sigma = F/A$. The full cross-sectional area (A) of the honeycomb samples are 62500mm². A sharp peak appeared on all graphs immediately after the initial trolley contact, thereafter a smooth curve which gives an average crash strength of approximately 0.37MPa. In all samples, the deformation process was initiated at the top side progressing down the principle “T” direction. The curves shown in Graph 1 are filtered for visual clarity. Figure 2 shows one of the crushed honeycomb sample.

4. Finite Element Model

4.1. Simplified FE Model development

As shown in Figure 3, due to the geometrical symmetry within the structure, a “Y” cross-section was selected for this research. In doing so, the effects of trapped air and the marginal curvatures in cell corners are eliminated and thus the FE models simplified significantly. The three FE models based on the “Y” cross-section columns will be referred to from here on as “Unit Cell (UC)”. All three UC models are broken down into three surfaces and a localised co-ordinate system assigned to each surfaces.

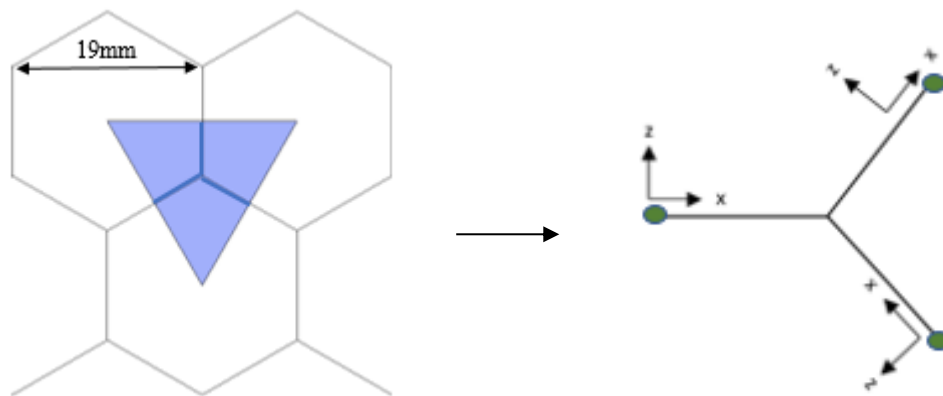


Figure 3: Geometric pattern in Honeycomb Structures

Constraints were applied to the nodes (labelled as green dots in Figure 3) of the three surfaces of the UC model. These constraints were applied to ensure that the UC behaves as if it was part of the overall honeycomb structure during an out of plane crash scenario. The applied constraints are described in Figure 10

4.2. Unit Cell FE Model

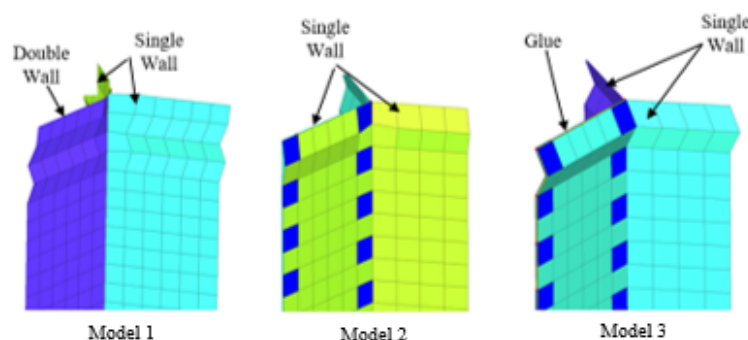


Figure 4: The proposed variants of the UC Model

The three FE models presented in this paper was developed using HyperMesh and HyperCrash and the models were solved using the explicit code RADIOSS.

4.2.1. Model 1: A “Simplified Single Flange Model” consists of a “Y” cross-sectioned column with two walls representing the single flanges and one wall is modelled as double sided to represent two foils joined by adhesive. This is achieved by controlling the thickness of the shell property.

4.2.2. Model 2: A “Simplified Double Flange Model” consists of two halves of a “Y” cross-sectioned column. All walls in this model are represented as single sided and a type 2 contact is utilised to define the adhesive connection between the two flanges. With the HyperCrash Type 2 tied interface contact, it is possible to rigidly connect a set of slave nodes to a master surface. Nodes belonging to the two neighbor walls are defined as slave and master with no priority. Sliding of the slave nodes is restricted and voids are not present in between contact either.

4.2.3. Model 3: A “Double Flange Model with Adhesive” consists of a “Y” cross-sectioned column with the walls modelled same as the Model 2. MAT LAW59 is applied between the neighbour walls to represent adhesive. MAT LAW59 is typically used to model the mechanisms of connection material in spot-weld, welding line or adhesive layers in laminated material. Normal tangential stress functions

were defined to characterise the elastic and plastic behaviour in the normal and shear directions of the adhesive layer.

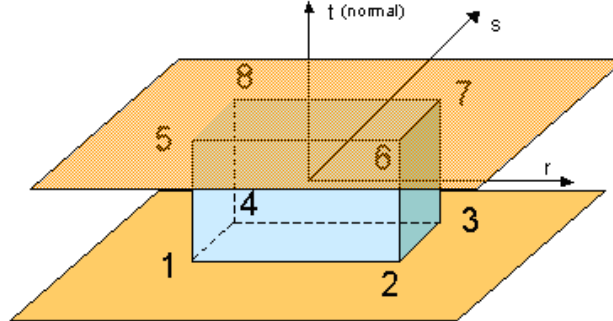


Figure 5: Illustration of adhesive modelling using Solid connection element (HyperMesh Theory Manual, 2018)

MAT LAW59 is only applicable to solid hexahedron elements and the material time-step does not depend on element height, therefore, the adhesive layer was modelled with a uniform thickness of 0.05mm solid 8-noded elements.

4.3. Description of Material Card

Walls in all three models are assigned the ELASTO-PLASTIC JOHNSON-COOK Plasticity Model LAW2. The strain hardening behaviour of materials is a major factor in material characterization and a robust definition of this parameter is imperative with large plastic strains. For a number of plasticity problems, the hardening behaviour of the material is simply defined by the stress-strain curve. Although the stress-strain curve is adequate for the linear loading phase, a more detailed definition is necessary to characterize the material's behaviour in its plastic deformation phase. Most isotropic elastic-plastic material laws in RADIOSS use Von-Mises yield criteria.

In JOHNSON-COOK LAW2, the material behaves as linear elastic when the stress is lower than the yield stress. As for higher values of stress experienced, the material behaviour becomes plastic. This law is valid for brick, shell, truss and beam elements. The relation between describing stress during plastic deformation is defined by the formulae,

$$\sigma = (\alpha + b\varepsilon_p^n) \left(1 + c \ln \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right) (1 - T^m) \quad (2)$$

where,

σ = Flow Stress (Elastic + Plastic Components)

ε_p = Plastic Strain (True Strain)

α = Yield Stress

b = Hardening Modulus

n = Hardening Exponent

c = Strain Rate Coefficient

$\dot{\varepsilon}$ = Strain Rate

$\dot{\varepsilon}_0$ = Reference Strain Rate

m = Temperature Exponent

$$T = \frac{T - 298}{T_{melt} - 298}$$

T_{melt} = is the melting temperature in Kelvin degrees. The adiabatic conditions are assumed for temperature computation

$$T = T_f + \frac{E_{int}}{\rho C_p (Volume)}$$

Where:

ρC_p = the specific heat per unit of volume

T_f = initial temperature (in degrees Kelvin)

4.4. Unit Cell Crush Analysis – Observations

Proposed FE model are validated by taking to consideration the crash pattern and the structure's compressive strength/stiffness.

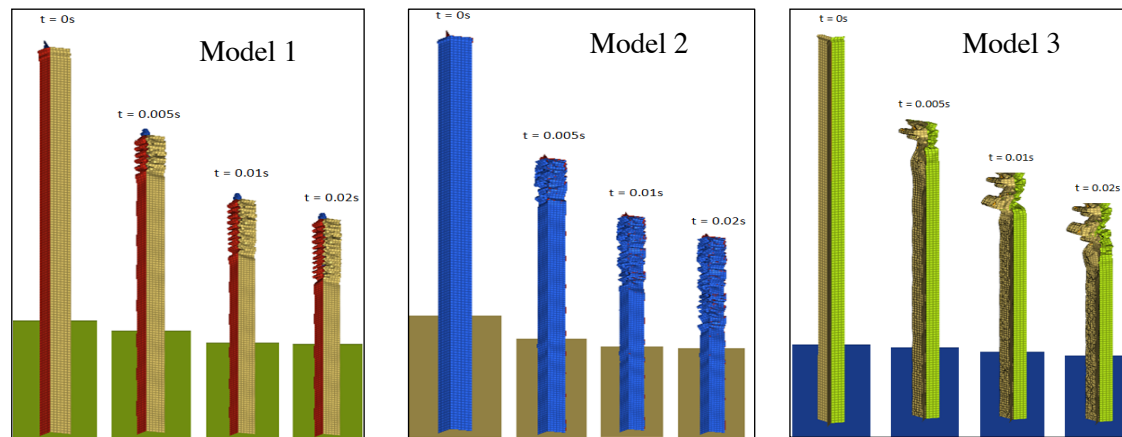


Figure 6: Deformation Pattern of the UC Models

Figure 6 shows the UC models being simulated through the experimental test scenario and the predicted deformation behaviour when crushed with the rigid mass (impacting at 5ms^{-1}). Identical deformation pattern between experimental test and simulation was observed: when the “Unit Cells” were impacted in the out-of-plane (T) direction, deformation of the structure was initiated from the top and propagated down the axis of compression which closely represents the deformation pattern of the crushed honeycomb samples.

Identical deformation patterns are found between the three proposed FE models as well. The “Unit Cell” models of the single and double flange deformed with regular crash pattern whereas the double flange model with adhesive deformed in a more irregular manner. Nevertheless, the realistic deformation pattern of the crushed honeycomb samples are closely predicted by all three models.

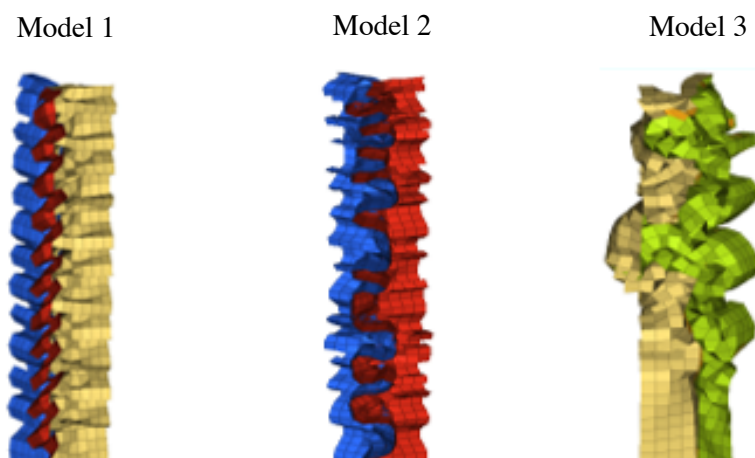
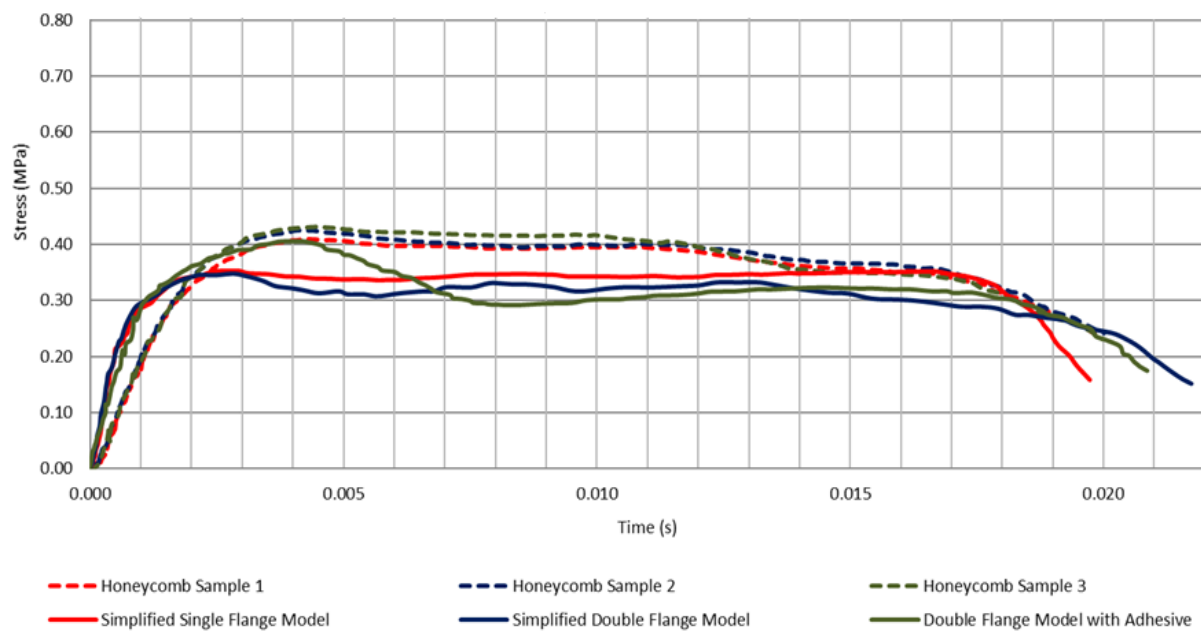


Figure 7 Deformation pattern of the Unit Cell Models

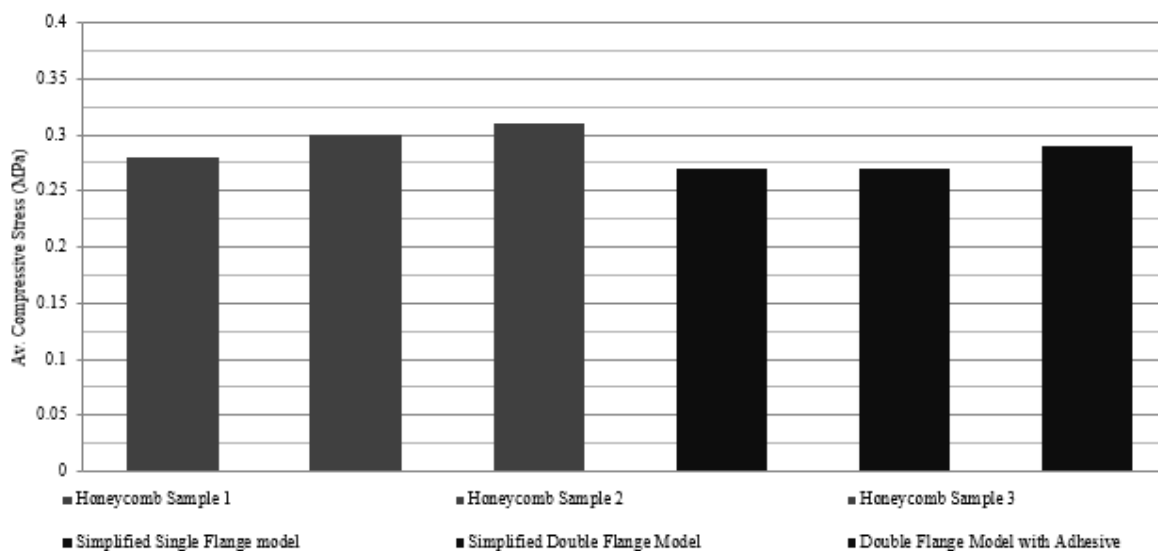
The average compressive strength of the three samples and FE models are also compared in Graph 2.



Graph 2: Compressive Strength Samples vs Unit Cell FFE Models

Generally, similar trends in stress curves were observed between the experimental data and FE simulations. The typical distinctive peak is not visible in the graph due to filtering of the data. It is suspected that modifying the coefficient of friction value between honeycomb and the baseplate could further represent the stiffness more accurately.

Comparing the average crash strength of all three FE models shows good correlation with test results. The Double Flange Model with Adhesive is more accurately predicting the real crash strength.



Graph 3: Average compressive stress

The Simplified Single and Double Flange models seem less stiff under compression. Nevertheless, the proposed FE models show good correlation with test results.

Comparison of computational time,

Variants of Unit Cell	Solve Time
Simplified Single Flange	10 minutes
Simplified Double Flange	19 minutes
Simplified Double Flange with Adhesive	21 minutes

Table 2: Comparison of solve time

Table 2 shows a breakdown of the solve time required by the three simplified UC models. With a clear indication in the reduced solve time, the computational cost is proved to be significantly lower for the “Simplified Single Flange” model.

4.5. Generalised Valid Discrete Model – Development of a New Modelling Approach for Aluminium Honeycomb Structures

In the current (conventional) FE models of honeycomb, the structure is modelled as a continuum shown in Figure 8 of layers of foils bonded together. After simulating the conventional model, it was observed that the compressive stress/stiffness is representative of the test data, however the deformation pattern was not predicted accurately. Deformation occurred at the bottom of the structure and an irregular deformation pattern was observed at the top of the structure.

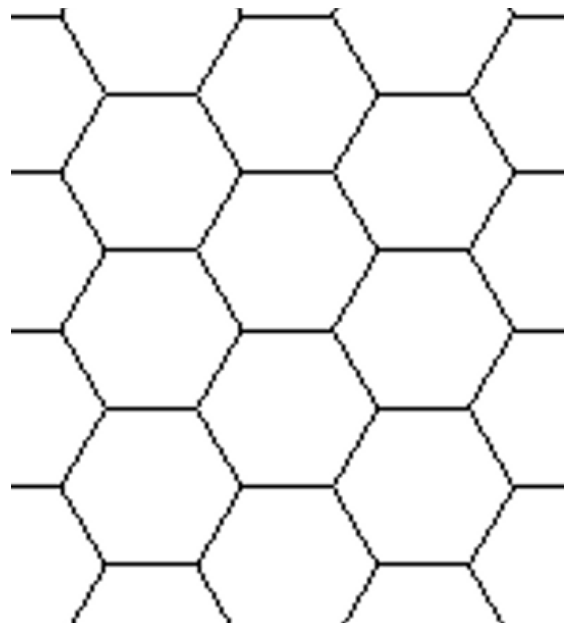


Figure 8: Conventional FE Modelling Approach

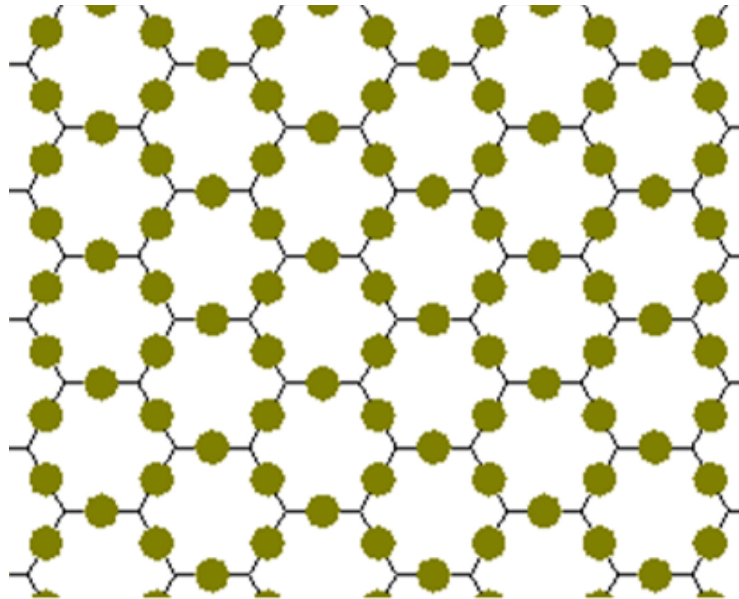


Figure 9: The New Modelling Approach with localised co-ordinate system and constraints

Based on the approach taken and findings from the Unit Cell models, a new modelling approach was identified. This method differs by two ways in comparison to the conventional method. The new approach is such that the validated “Unit Cell” model (with the local co-ordinate systems and the localised nodal constraints) is patterned in the “in-plane” directions to form the FE honeycomb model as shown in Figure 9.



Figure 10: Generalised co-ordinate system and Nodal constraints

The full scale honeycomb structure (representative of the samples used in testing) was generated by generalising the “Unit Cell” model in both the in-plane directions. The model was then modified into three series of parallel elements and each series were assigned a local co-ordinate system. Constraints were applied to the edge nodes as shown in Figure 10.

The model was then simulated in-order to compare the deformation pattern and crush strength/stiffness to test data.

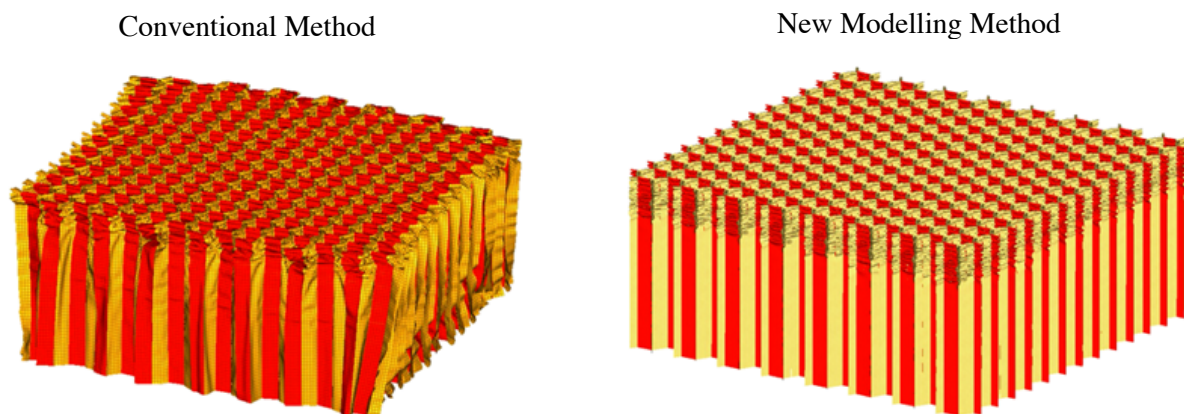
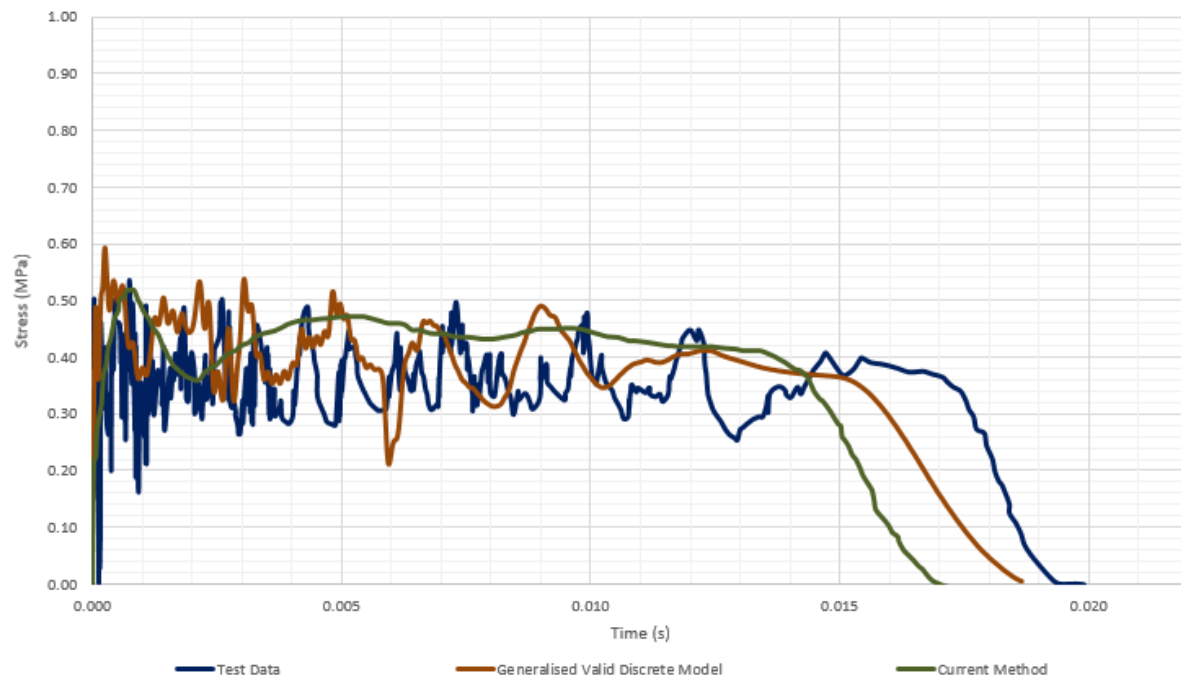


Figure 11: Comparison of the deformation behaviour

Figure 11 above shows a direct comparison of the deformation pattern between the current (conventional shell method) and the new FE method. From observations, it can be seen that the new method captures the realistic deformation pattern much more accurately and is more representative of the typical honeycomb deformation behaviour when subjected to impact loading. The new method shows a consistent regular deformation pattern and the deformation process is initiated from the top of the structure.

Graph 4 shows the compressive strength of the FE models as a function of time during the crash scenario and compares against test data. The distinctive peak anticipated at the initial stage is not visible in the graphs below due to filtering of the data.



Graph 4: Compressive Stress curve

Although the current FE model is capable of representing the stiffness characteristics reasonably well, the model still failed to capture the distinctive peak in stiffness right at the beginning of the crushing process.

However, the new method distinctively captured the sharp rise in stiffness at the very beginning of the crushing process and represents the stiffness characteristics quite accurately. It is anticipated that, by modifying the coefficient of friction values between the base plate and the structure could potentially improve the accuracy of the stiffness curves. Nevertheless the average crush strength of both FE models are around 0.37MPa and is comparable with test data.

5. Conclusion

Multiple simplified finite element models have been developed using the pre-processor HyperCrash. The intention was to evaluate the credibility of simplified models to represent the mechanical deformation behaviour of honeycomb structures under out-of-plane impact. The proposed FE models have been validated using previous experimental results in terms of crush pattern and compressive strength. Good correlation have been established between the FEA and experimental results.

The research showed that the simplified models are reasonably credible in predicting the crush behaviour of honeycomb structures. The “Simplified Single Flange” model was the most favourable due to the reduced analysis time, deformation procedure and pattern. Taking to consideration the approach taken with the “Unit Cell” model, the full honeycomb block was generalised to simulate the crash test scenario. Existing method and the new method has been compared against test data and the new model demonstrates the improved accuracy in predicting the deformation pattern and good representation of the stiffness characteristics.

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