IN-PLANE DYNAMIC CRUSHING BEHAVIOR AND ENERGY ABSORPTION OF METALLIC HONEYCOMB CORE WITH UNIQUE COMBINATION OF TWO REGULAR HEXAGONAL CELLS AND THEIR ARRANGEMENTS

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ABSTRACT

The densification, energy absorption and deformation mode patterns for a honeycomb core under dynamic in-plane axial crushing is governed by its cell geometry, cells arrangement and impact velocity. In this study, two regular hexagonal cells are combined in such a way that without major modifications in manufacturing process, the in-plane dynamic crushing characteristics of a specific specimen are controlled with major focus on standard deformation modes those are X, V and I deformation modes. The cell geometry itself and arrangement of modified cells pattern in a specimen which may include functional gradient and auxetic features, are numerically studied by means of explicit dynamic finite element simulations using ABAQUS. A cell having a controllable auxetic nature for a period of time along with the regular cell honeycombs (hybrid cell) can give better impact and crushing response. A comparative study of in-plane uniaxial compression loading behavior of regular honeycomb and hybrid cell was performed and deformation and failure modes are investigated under in-plane loading conditions. The effect of cell shape and the negative Poisson's ratio is evaluated for different impact speeds and energy absorption results are plotted.

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INTRODUCTION

The honeycomb is a kind of cellular materials which is widely applied as core of sandwich structures or filler of energy absorbers due to its excellent mechanical and energy absorption properties with high specific strength to weight ratio. As the safety requirements are increasing, the need for honeycomb structures to be optimized with better crashworthiness with increased energy absorption efficiency, have become the cry of the day [Zhang et al., 2015; Fazilati and Alisadeghi, 2016]. Honeycomb structures have applications in multiple fields of engineering such as aerospace, mechanical and packaging engineering because of their strength, toughness and energy absorption [Bitzer, 1997; Cutler and Liber, 2005]. Specific application for the honeycomb structures demands complete understanding of the mechanical properties with deformation patterns under static and dynamic loadings. Gibson and Ashby [Gibson and Ashby, 1999] used the discrete cell structural models to find out the in-plane and out of plane mechanical properties of the honeycombs under static case of loading. The experimental findings of the Wu and Jiang [Wu and Jiang, 1997] showed that the dynamic crushing strength is higher than quasi-static crushing for aluminum honeycombs.

Honeycomb structures show three distinct regimes under in-plane loadings in their stress-strain curves may called as an elastic regime which is linear, a plateau regime with almost constant stress value and finally a densification regime in which the stress rises sharply [Jang and Kyriakides, 2009a,b]. The plateau regime is mostly responsible for energy absorption capacity of a honeycomb structure and this regimes experiences elastic and plastic buckling and unit cell's plastic collapse [Gibson and Ashby, 1999]. The mechanical properties of the honeycomb structures are sensitive to cell topology [Liu and Zhang, 2009; Oftadeh et al., 2014; Galehdari et al., 2015; Ruan et al., 2003]. One may alter the mechanical properties and hence energy absorption of the honeycomb structure by changing cell shape, size, cell angle, wall thicknesses and so on [Liu and Zhang, 2009]. The most popular cell type is regular hexagonal cell, though square, triangular, diamond and many other cell shapes have been under investigation in scientific research and engineering applications. Honeycombs have been investigated for their mechanical properties numerically [Ruan et al., 2003; Hu and Yu, 2013], theoretically [Hu et al., 2014; Hu and Yu, 2010] and experimentally [Hu and Yu, 2013; Xu et al., 2012].

The in-plane crushing of the honeycombs to determine the energy absorption capacity with different kinds of cells have been great research during last decade. Researchers have also tried to come up with optimized and improved microstructures of conventional honeycombs to get higher impact resistance [Wang et al., 2019]. Various honeycomb's microstructures can be characterized as positive, zero and negative (auxetic) Poisson's ratio honeycombs. The in-plane deformation modes for regular honeycombs were investigated by Zhu and Mills [Zhu and Mills, 2000] experimentally and theoretically and by Papka and Kyriakides [Papka and Kyriakides, 1994a, 1998b, 1999c] experimentally and numerically. The FE simulations to determine the dynamic behavior of regular hexagonal honeycombs [Ruan et al., 2003; Sun and Zhang, 2009; Ali et al., 2008], irregular honeycombs [Li et al., 2007; Zheng et al., 2005] and triangular cells honeycomb [Liu and Zhang, 2009] have been carried out by many researchers. Hierarchical honeycombs' crashworthiness against in-plane loading through theoretical and FE simulations was investigated by Qiao and Chen [Qiao and Chen, 2016]. The various cell shapes

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and arrangements show different properties in different planes of loading. Naveed et al., [Naveed et al., 2017] showed that insertion of different sized cells in otherwise a regular hexagonal cells arrangement have a definite effect on the deformation and energy absorption.

Under dynamic in-plane loading, the deformation mode is guided by the initiation of collapse from the weakest row or band of cells and gradually spreads to strong area [Hu et al., 2008]. Shape of the cell and their arrangements have a major impact on the dynamic response of the honeycombs. Ruan et al. [Ruan et al., 2003] showed that for regular hexagonal honeycomb, under in-plane dynamic loading, deformation may occur as X, V and I shape of patterns for low, medium and high impact velocities as shown in Figure 1. One being able to play with the deformation modes would be able to control the energy absorption of the honeycomb for a specific velocity case.
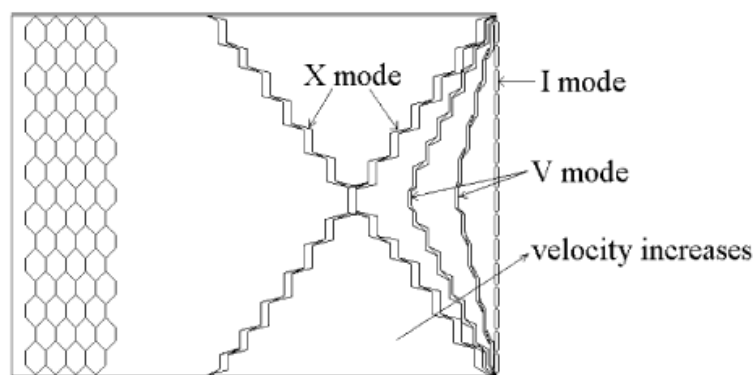

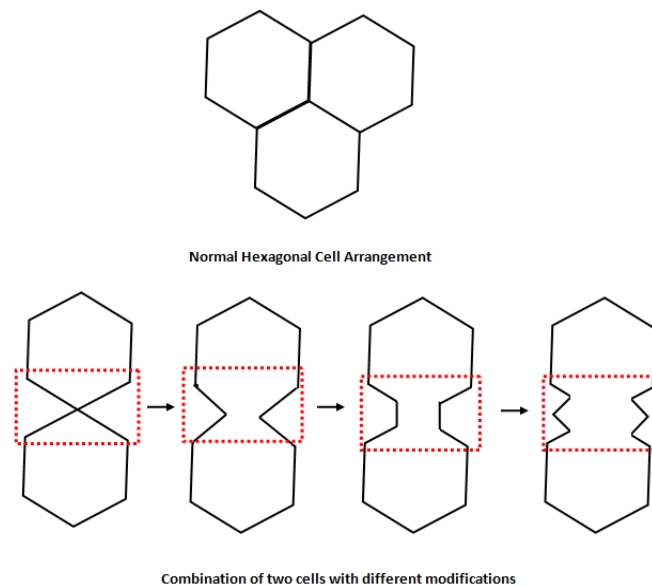Figure 1. Three types of the deformation modes [Ruan et al., 2003]

Figure 2. Proposed cells (MMC-A, MMC-B, MMC-C and MMC-D)

The cell shape and its topology being the guiding parameter for characterization along with material definition needs special consideration for controlling the response of honeycomb panel. However, another aspect is the arrangement of cells with different shapes and topology to control the performance of honeycomb under various loading conditions. In this study, two regular hexagonal cells are combined in one, in a way that its inherent characteristics, the cell may show auxetic behavior for a specific time of load application and then can behave as a positive Poisson ratio cell as shown in Figure 2. A honeycomb core specimen is then formulated with multiple arrangements of this cell in rows and columns of the specimen, in order to get gradient feature of geometry as well. The said honeycomb panel is numerically crushed at multiple velocities varying from low to moderate to high for in-plane directions to observe the change in deformation modes and its ability to define the user command on deformation patterns and energy absorption curves. The results are compared with standard X, V and I deformation modes and energy absorption parameters in published research [Ruan et al., 2003].

DESIGN APPROACH

Reference Model

The proposed reference uniform regular hexagonal cells honeycomb panel consists of 15 rows (R1-R15) and 16 columns (C1-C16) as shown in Figure 3. The regular uniform cell geometry is represented with capital letters H, S and L describing thickness, distance between two vertical walls and vertical wall height respectively. The parameters used for the definition of geometry are compiled in Table 1.
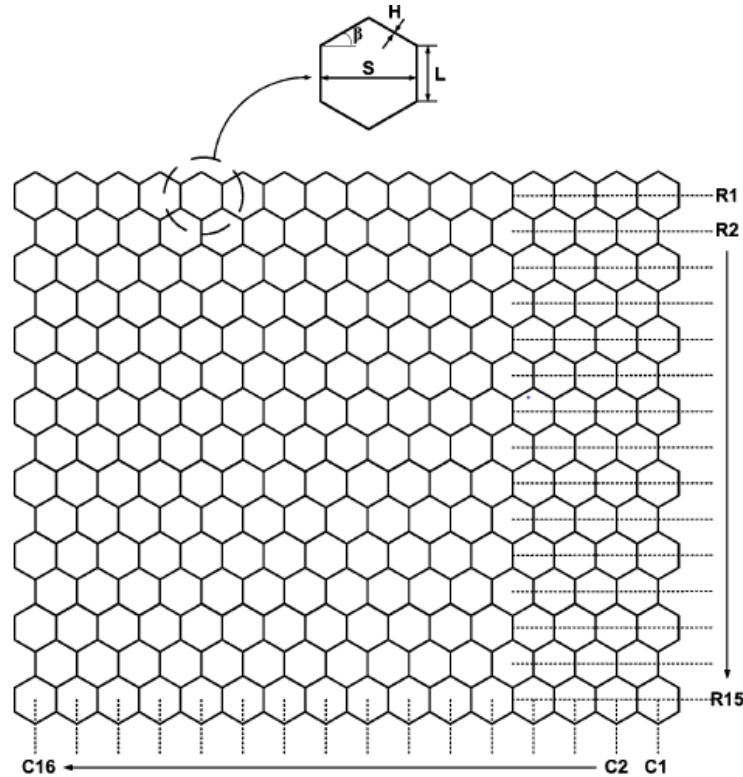

Figure 3. Regular hexagonal cells arrangement (reference model)

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Table 1: Geometry parameters of the proposed regular uniform and modified hexagonal cell

Parameter	Value	Units
H	0.2	[mm]
S	4.7	[mm]
L	2.7	[mm]
B	120	[Deg]

Honeycomb Panels with Different Arrangements

The combined cells as shown in Figure 2 are placed in a way that the overall dimensions of the new panels are unchanged in comparison to the earlier uniform regular cell honeycomb panel. The modified cells are named as **Modified Combined Cell-A** (MCC-A) to **Modified Combined Cell-D** (MCC-D), from left to right in Figure 1. They are arranged in different patterns to investigate the effect of geometry and arrangement of cells in defined specimen of honeycomb core; the cases made are defined in Table 2. The nomenclature of the cases is MCC-A to MCC-D for Case#2 to Case#5 respectively. For Case#6 to Case#10, the nomenclature is defined as MCC-X(R/C n)-Reg-HC, in which MCC represents Modified Combined Cell, (R/C n) defines row or column number in which the MCC are being placed and Reg. HC defines regular honeycomb core. In Modified Combined Cells, the geometric dimensions i.e thickness (H), wall length (L) and Width of a cell (S) are same as of regular cell. The geometric parameters vary only in the region where two regular cells are combined to form the MCC-n cell. Case#2 to Case#5 schematic arrangements is shown in Figure 4.
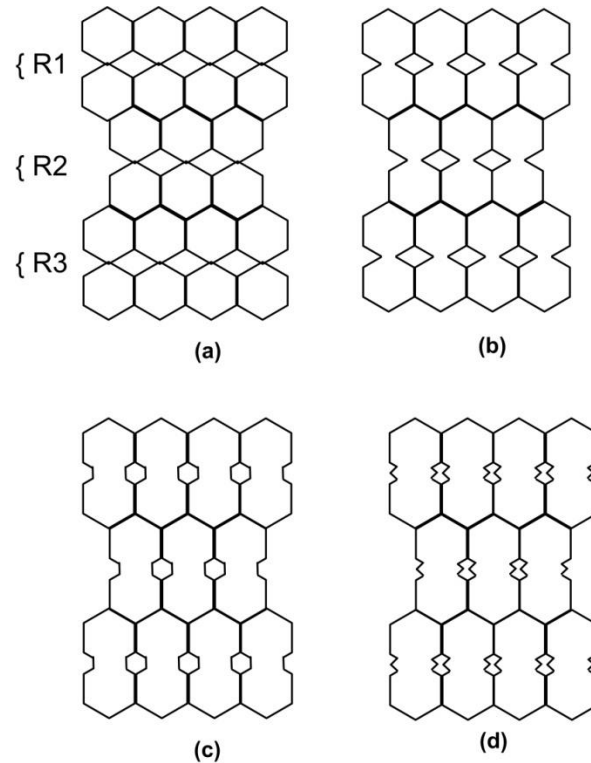

Figure 4. Proposed cells arrangements (a)Case#2 (b)Case#3 (c)Case#4 (d)Case#5

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Table 2: Proposed configuration of cases

Case#	Nomenclature
1	Reg. HC
2	MCC-A
3	MCC-B
4	MCC-C
5	MCC-D
6	MCC-A(R1)-Reg. HC
7	MCC-B(R1)-Reg. HC
8	MCC-C(R1)-Reg. HC
9	MCC-D(R1)-Reg. HC
10	MCC-A(C1)-Reg. HC

The combination of proposed cells for MCC-n where 'n' is from 'A' to 'D' with regular hexagonal cells is shown for Case#7 i.e. MCC-C(R1)-Reg. HC is shown in Figure 5 below:
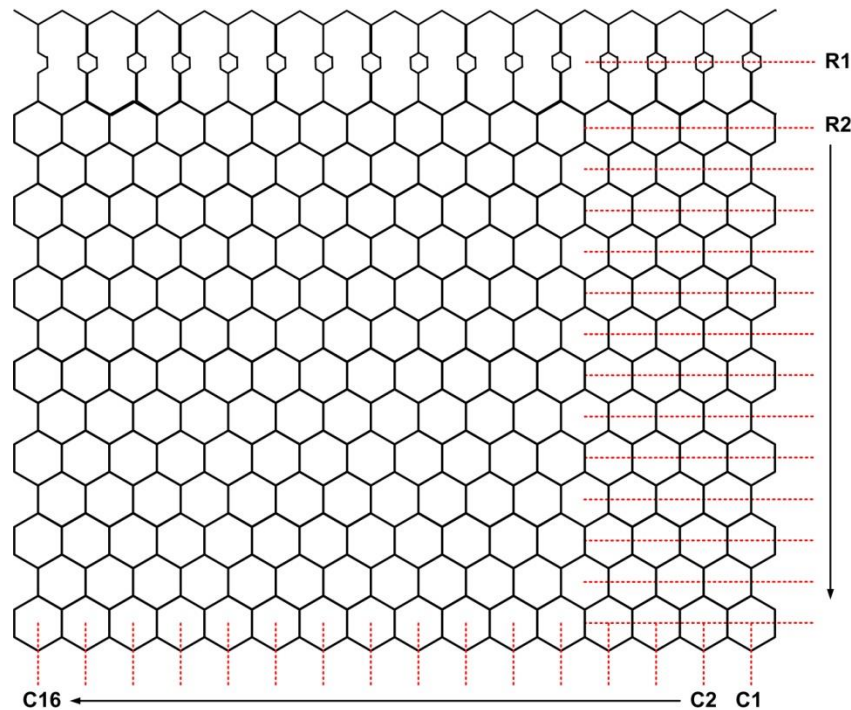

Figure 5. Case#7

FINITE ELEMENT MODELING

The in-plane crushing of the proposed honeycomb configurations are performed in ABAQUS explicit dynamics for different velocities i.e 3.5m/s, 14m/s and 70m/s corresponding to low, medium and high velocity impacts, in order to figure out the energy absorption in different configurations. The honeycomb panel is sandwiched between two rigid plates; one plate is moving in the axial direction while the opposite plate is fixed in all directions of motion. Honeycomb is modeled by using the shell S4R element. It is a 4-node doubly curved thick or thin shell element with reduced integration, hourglass

control and finite membrane strains. Impact mass of 50 Kgs is used for the moving rigid plate and rigid plates are modeled using discrete rigid element. Reference material properties for the honeycomb are taken from the Aluminum honeycomb used in the in-plane crushing research of Ruan et al., [Ruan et al., 2003]. After mesh convergence studies, an element size of 0.8mm are selected with five integration points through thickness. A general explicit contact with tangential behavior being frictional using frictional coefficient of 0.3 is used between the moving rigid plate and the honeycomb panel. The fixed rigid plate and the honeycomb had tie contact and self contact was defined for all bodies to avoid inter-penetration. Figure 5 describes the adopted boundary conditions for the current study.
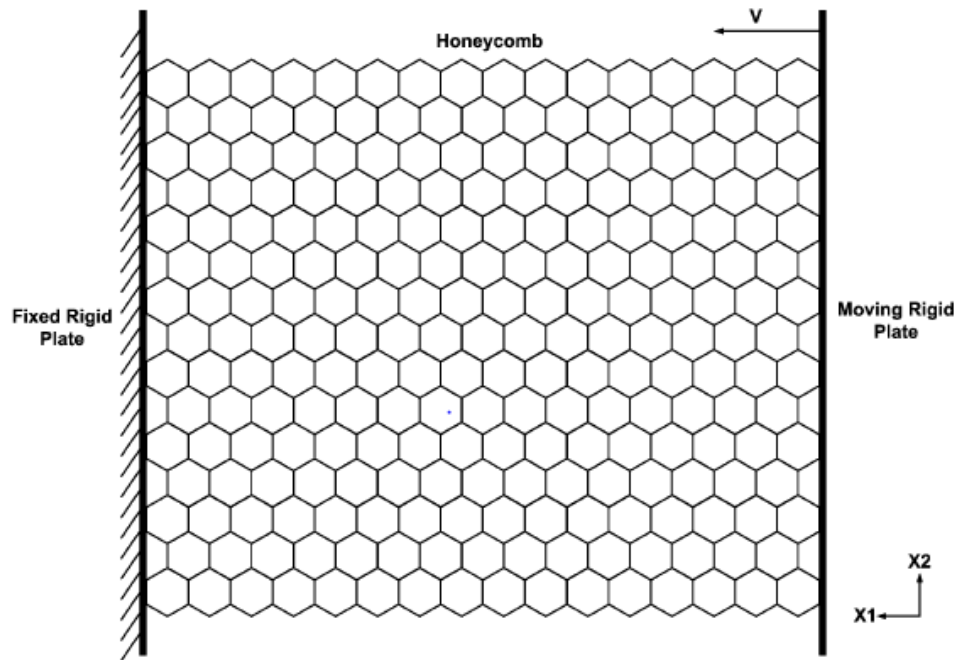

Figure 6. Boundary conditions

In order to validate the FE model for current study, deformation plots and force-displacement curves from the in-plane dynamic crushing of regular hexagonal honeycombs [Ruan et al., 2003] and current FE study for Case#1 i.e. regular hexagonal cells arrangement, with similar simulation parameters, are compared in Figure 7. The results show quite acceptable and close behavior with reference study. The same parameters are adopted for the all of the cases in present FE work.
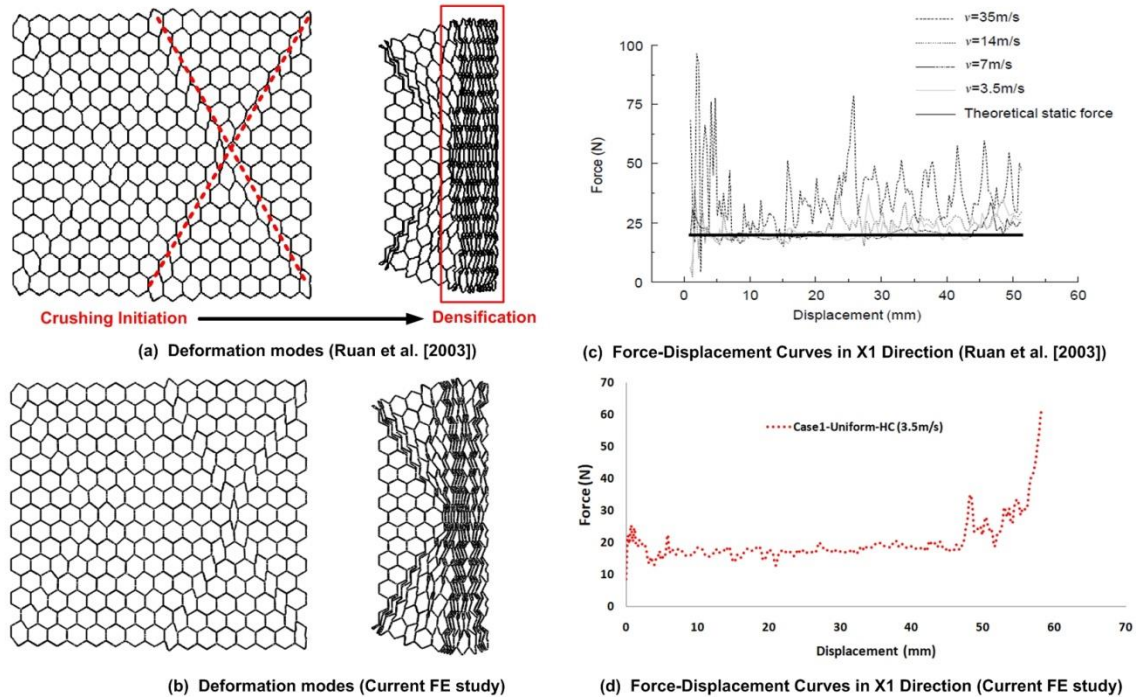
(a) Deformation modes (Ruan et al. [2003])

(c) Force-Displacement Curves in X1 Direction (Ruan et al. [2003])

(b) Deformation modes (Current FE study)

(d) Force-Displacement Curves in X1 Direction (Current FE study)

Figure 7. Deformation Mode (a) [Ruan et al., 2003] (b) Current study
Force-Displacement Curve (c) [Ruan et al., 2003] (d) Current study

RESULTS AND DISCUSSIONS

Single Cell Deformation

Initially the deformation patterns for the proposed cells are investigated. Figure 8 shows the unit cell's deformation at very low velocities for all of the proposed cells.
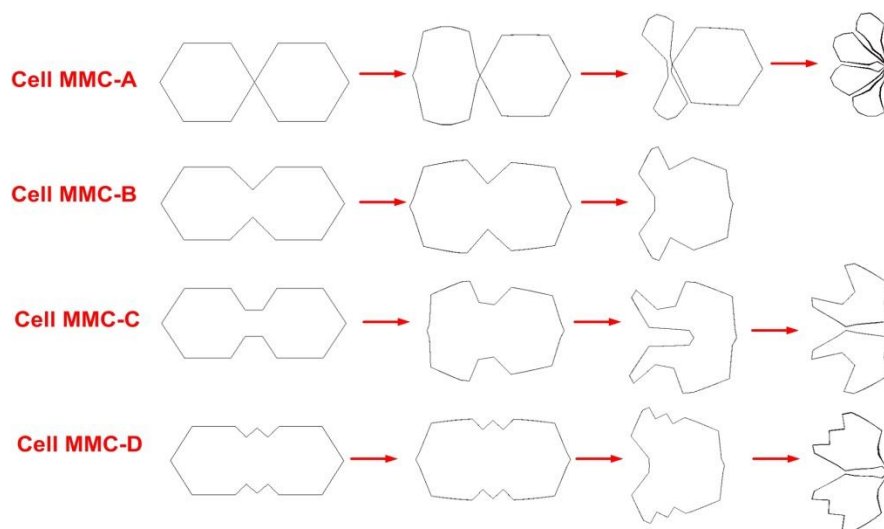

Figure 8. Proposed Cells' Deformation: X2 Loading

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Different cells behave differently during different phases of their deformation. MMC-A allows both hexagonal parts of the cells to be deformed simultaneously against X1 loading as shown in Figure 9 while against X2 loading, one hexagonal part is deformed completely before second parts come into play. The comparative deformation at same instant of time for different cells is also different. MMC-B behave as an auxetic structure for some period of time against initial load application, which later on behaves as positive Poisson's ratio structure in the later part of the deformation against X1 loading. Against X2 loading, MMC-B , C and D starts expanding, however, densification is different for different cells allowing the densification curve slope to be governing parameter. MMC-C and D are also auxetic in nature for some period of initial loading, giving unique advantage of energy control as per requirement.
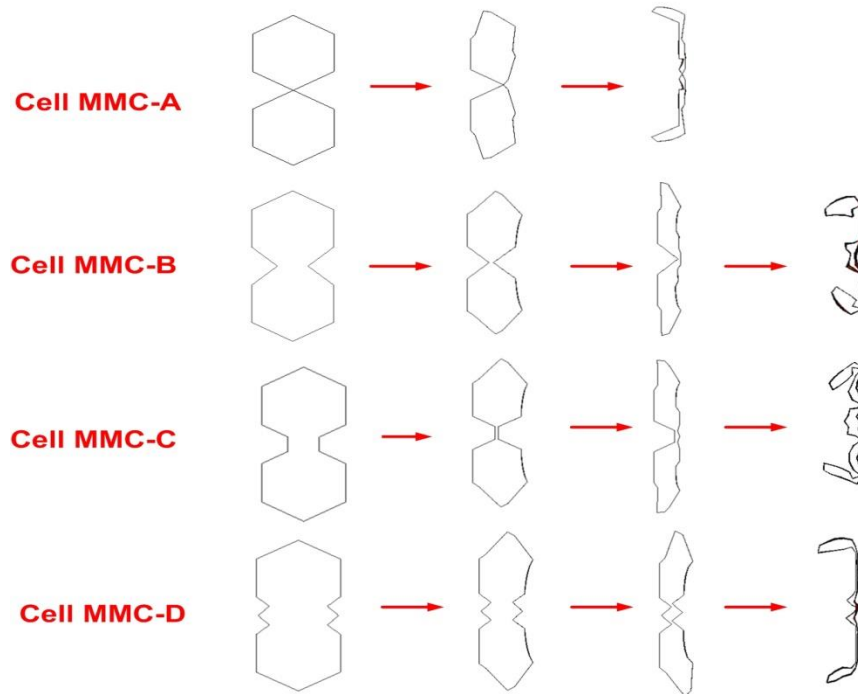

Figure 9. Proposed Cells' Deformation: X1 Loading

Proposed Configurations Deformation Modes

The standard hexagonal cells arrangement called as Case#1, in this study, shows X, V and I deformation modes as the structure starts collapsing against the 3.5, 14 and 70m/s crushing velocity as described by Ruan et al. [Ruan et al., 2003]. The deformation modes are vital to govern the energy absorption as well as to control the specific structure application against impact loading. Proposed cells are unique in nature to show partly auxetic nature of behavior and densification approach as described in the previous section. The very same characteristics of the proposed cells play a vital role in leading the deformation modes. Multiple combinations of the proposed cells with regular hexagonal cells may provide an arrangement which can be an application specific, like a sandwich panel may be deformed as per requirement of application.
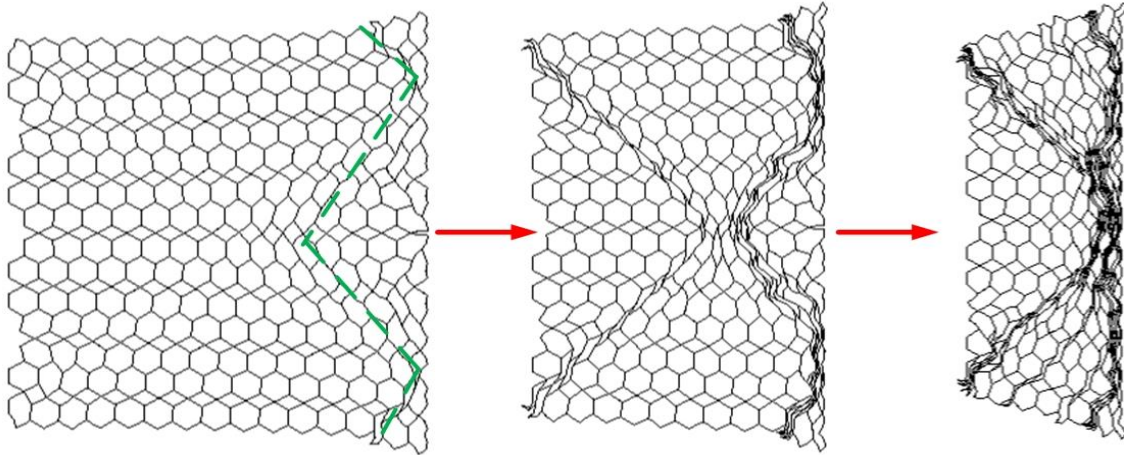
Figure 10. Proposed Case#2 Low Velocity Deflection Modes: X1 Loading

Figs. 10-13 show the deformation modes for some selected Cases as described in Table 1. The deformation modes are dependent on velocity, size of cells, cells characteristics and their formations. Contrary to hexagonal cells arrangement i.e. Case#1, showing X mode of deformation against X1 direction loading at low speed, Case#2 shows 'W' mode of deformation leading to a 'V' formation on the opposite end as the crushing proceeds. Case#4 does not show any known alphabetic deformation pattern, instead it starts deforming for three to four columns simultaneously at the impacted end in the start which ultimately repeats itself on the fixed end as the crushing proceeds as shown in Figure 11. For X2 loading, the cells buckle for second row from the impacted end and second last row on the fixed end, giving a wavy collapse for the said rows, approaching to other rows as well as shown in Figure 12.
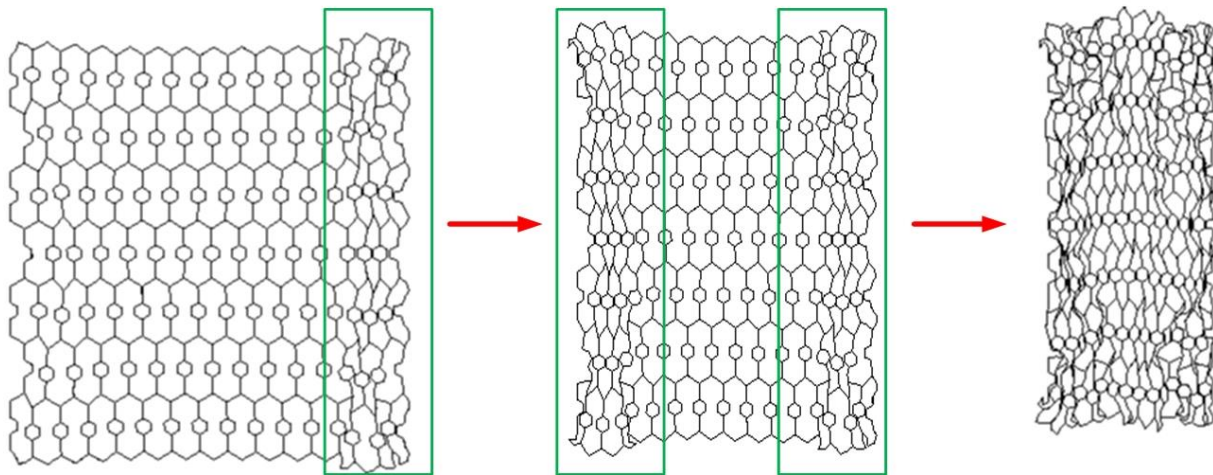

Figure 11. Proposed Case#4 Low Velocity Deflection Modes: X1 Loading
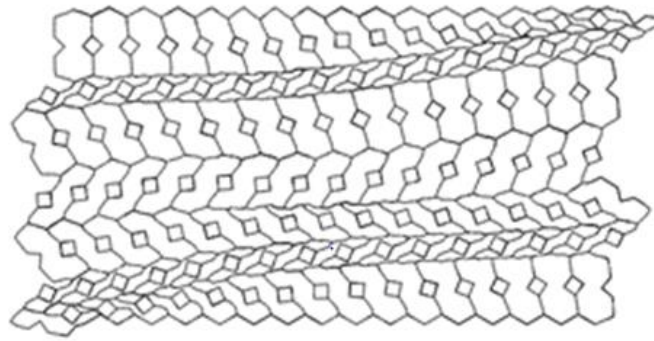
Figure 12. Proposed Case#4 Low Velocity Deflection Modes: X2 Loading

At lower velocities, the insertion of modified cells row, column, diagonal or a mixed combination can significantly control the formation of deformation modes especially. These behave as triggering agents; hence providing the freedom to control the specific deformation mode shape or its initiation. The deformation modes for configuration of Case#6 are shown in Figure 13. At low speed, a 'Y' mode which later converts to 'X' mode of deformation is observed. At moderate velocity of 14m/s, 'X' mode of deformation is visible at the start of crushing. At higher velocity of 70m/s, the 'I' mode is observed forming a localized band in the direction perpendicular to impact direction; however a 'V' formation ahead of 'I' mode would control the energy absorption as shown in Figure 13.
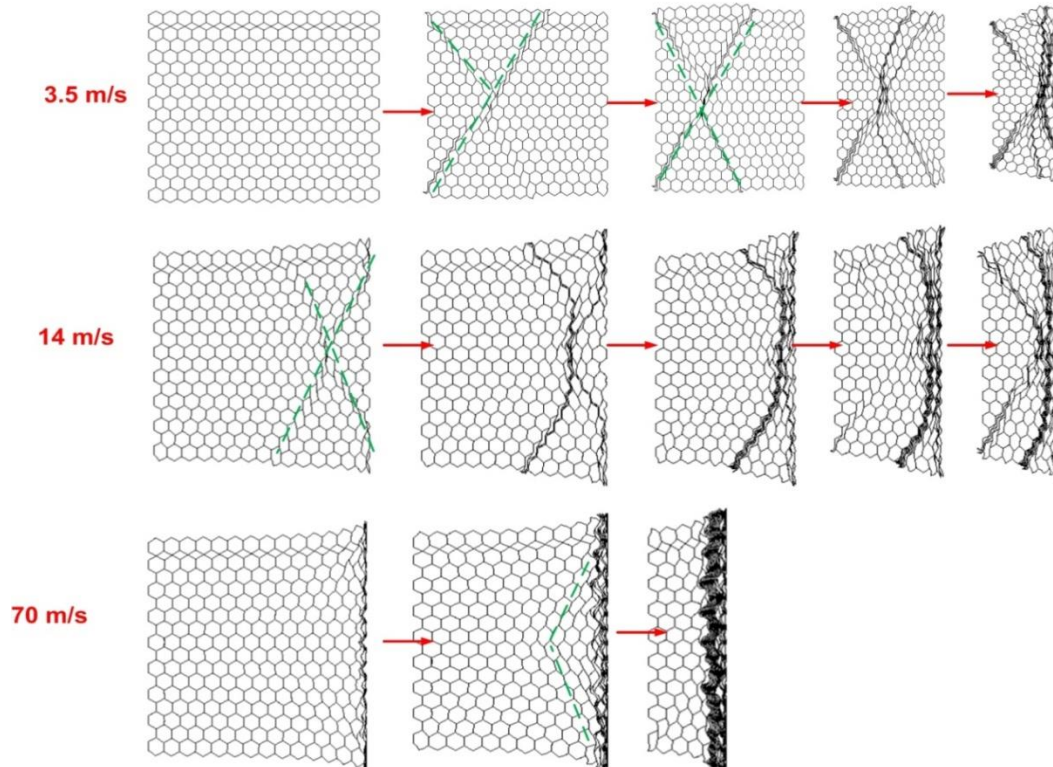

Figure 13. Proposed Case#6 Deflection Modes: X1 Loading

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Energy Absorption

Mode of deformation would play a vital role in the overall energy absorption of the configuration. It would govern the peak force and energy absorption. Force displacement curves for the proposed configurations are shown in Figs. 14-15. Proposed cells arrangement shows higher area under the curve with less initial peak force. In general, the plateau region is much smoother in comparison with Case 1. The peaks at different distances along the panel length can be seen in figures; however, the location of peaks is changing, giving more control on applications of such panels.
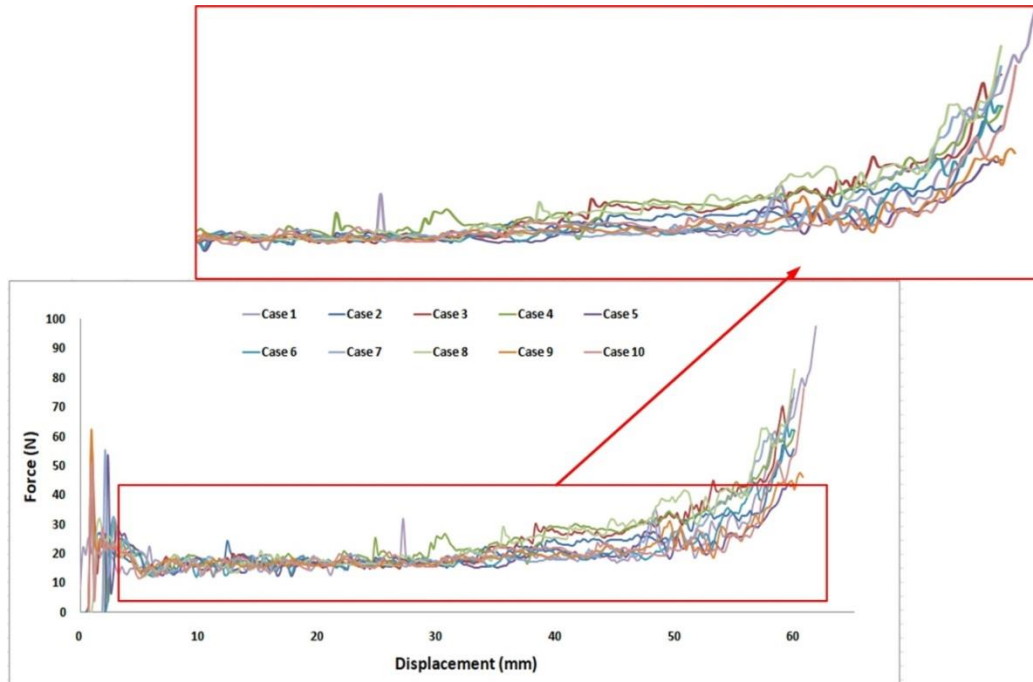

Figure 14. Force displacement curves for proposed configurations: X1 Loading (3.5m/s)

Figures 14 and 15 shows the force displacement response of proposed configurations at low speed of 3.5m/s and moderate speed of 14m/s respectively. It is evident from the curve that the peak force, curve smoothness and densification time and its behavior is hugely dependent on the cells arrangement. As velocity increases, the area under the curve increases with high initial peak value. The proposed cells hierarchal arrangement shows low initial peak force while cells configuration with auxetic behavior inside otherwise regular hexagonal arrangement would support in delaying densification process. As velocity increases from 3.5m/s to 14m/s, an approximate 40% increase in force is observed. The area under the curve is observed to be increased in column addition in comparison to rows addition for X1 loading while in X2 direction; rows addition would experience the similar behavior.
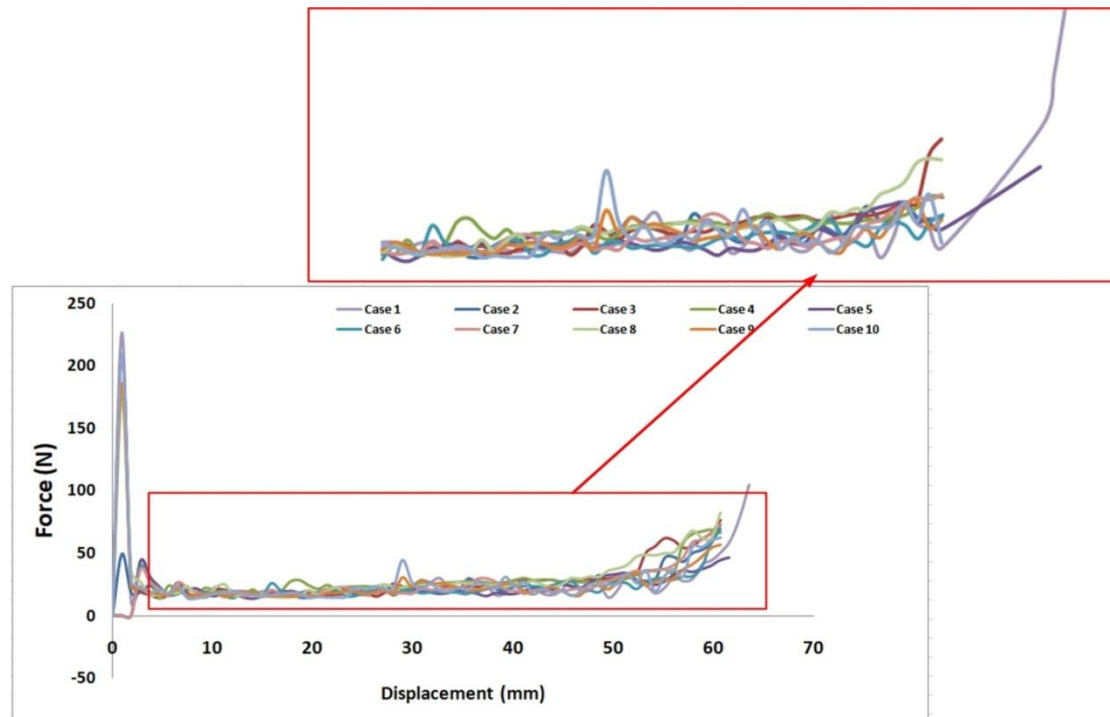
Figure 15. Force displacement curves for proposed configurations: X1 Loading (14m/s)

The energy absorption for all of the configurations in X1-direction is shown in Figure 16 while Figure 17 shows the energy absorption for some selected cases in X2-direction. The addition of rows or columns can guide the behavior of honeycomb panel which can clearly be seen for X1 and X2 cases; however the behavior varies with increasing velocity for different cases. At low velocity, the highest energy absorption was noted as 13.56kJ/kg in Case 8 (X1-direction) and 14.92 kJ/kg in Case 10 (X2-direction) respectively. At higher velocities, Case 10 (X1-direction) showed energy absorption of 13.56kJ/kg for a velocity of 14m/s while Case 2 (X2-direction) showed energy absorption of 16.8kJ/kg for a velocity of 14m/s. The energy absorption is dependent on the impact conditions and geometry of the honeycomb; hence an optimized position can be decided for different energy levels.
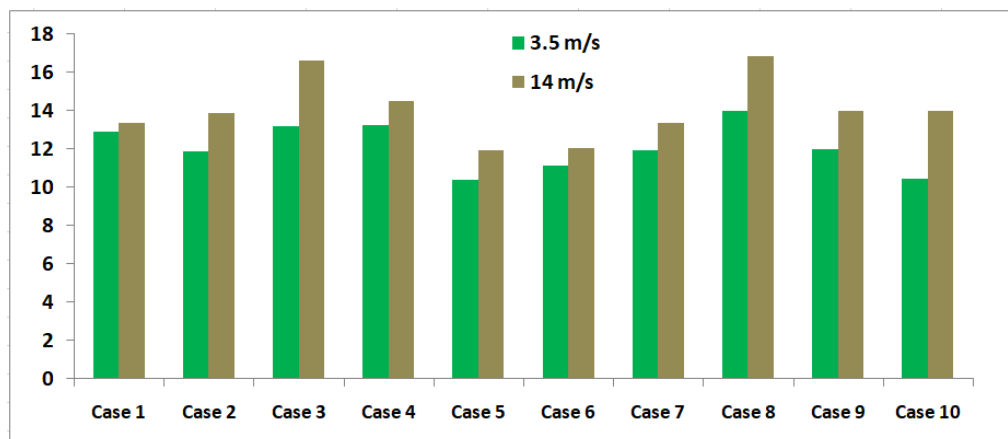

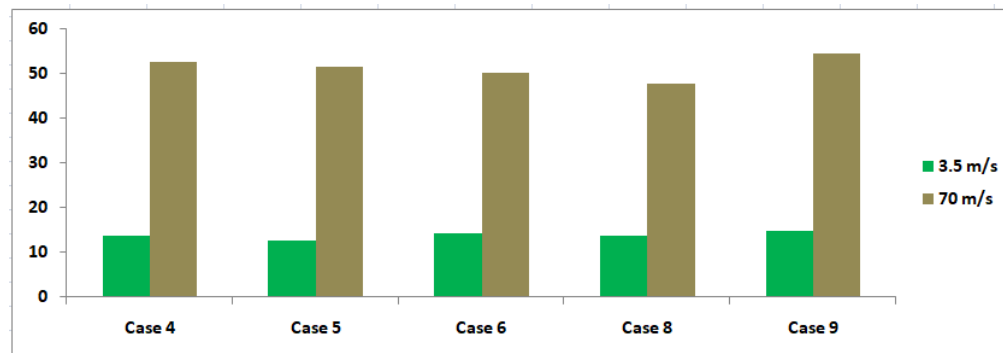Figure 16. Energy absorption (kJ/kg) : X1 direction

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Figure 17. Energy absorption (kJ/kg) : X2 direction

CONCLUSION

A new cell with combination of two regular hexagonal cells is proposed in different forms to get the auxetic behavior and their some structural arrangements with self repetition and in rows and columns additions inside otherwise a regular hexagonal cells arrangements are described. The cells arrangements are axially crushed under different velocities. The deformation patterns and their energy absorption are studied. The crushing showed some useful results which can be concluded as:

1. The size of a cell has no major effect on energy absorption enhancement but can control the initiation and propagation of the deformation patterns. The specific mode shapes under a specific velocity can be delayed, brought earlier or theoretically speaking, can be avoided using an optimized arrangement of such cells insertion.

2. The row insertion showed much more significant effect in the direction of loading. However, a mixed insertion can give a better control along with enhanced energy absorption.

3. The smoothness of the force-displacement curve of crushing can be controlled with providing relatively weaker cells along the path and can be controlled with appropriate columns and rows insertion.

4. At higher velocities, 'I' modes of collapse is so fast that generally next row does not feel the effect but inserting such small sized cell can give the direction of collapse for next rows, hence this method can also be helpful under high speed of impact.

5. The controlled deformation and energy absorption can be utilized in future aero and auto systems to avoid the damage to human beings and costly equipment.

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