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Sub-structure Geometry Effect on Energy Absorption Ability of Hierarchical Honeycomb under Crushing

Rakesh Kumar Singh[1,*], Rakesh Saxena[2]

Abstract

Honeycomb structures are stiff and light weight composite structures which show good energy absorption. Hierarchical honeycomb structures which are bio-inspired innovative form of honeycomb structure, are used for energy absorption applications. The crashworthiness of hierarchical honeycomb structures is function of sub-structure geometry. In the present investigation, crushing of vertex based hierarchical honeycomb with regular polygonal (n=3, 6, 9, 12, 15) and circular sub-structures is analysed using nonlinear explicit finite element code LS-dyna in both in-plane and out of plane directions. Effect of different sub-structure geometry on crashworthiness of vertex based hierarchical honeycomb is studied. Further a parametric analysis is performed to investigate the size effect of sub-structure on crashworthiness of hierarchical honeycombs, for every considered sub-structure geometry. To investigate the effect of crushing velocity on energy absorption similar analyses are performed at higher crushing velocity. In case of in-plane crushing, vertex based hierarchical honeycomb with large sized triangular sub-structure is found to have best energy absorption compared to other hierarchical honeycombs. While in case of out of plane crushing, vertex based hierarchical honeycomb with small sized hexagonal sub-structure is found to have better energy absorption among compared to other hierarchical honeycombs. An improvement in energy absorption of hierarchical honeycombs is found in both in-plane and out of plane crushing at higher crushing velocity.

Keywords: Hierarchical honeycomb, LS-dyna, in-plane crushing, out of plane crushing, crashworthiness

INTRODUCTION

Thin-walled cellular structures are widely used in different kinds of industrial fields, such as aerospace, transportation and packaging etc. due to their excellent mechanical properties and outstanding performance in energy absorption [1–3]. Honeycomb, which is one of the most common cellular structure, have been explored by many authors considering triangular, square, hexagonal and circular unit cells numerically, experimentally and analytically [4–7]. In the last two decades topic of honeycombs are analysed for its mechanical behavior such as compression [8], fatigue [9], impact loading [10–12] crashworthiness etc. Since honeycomb structure has good energy absorption ability but there is a requirement of further improvement. In order to improve the crashworthiness and energy absorption capacity of honeycombs some new cell configurations were developed. These configurations are bio inspired or hierarchical

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honeycomb [13], graded honeycomb [14], hybrid honeycomb, tandem honeycomb [15], reinforced honeycombs [16] etc. The energy absorption of honeycomb structure is found be increased under axial crushing with introduction of non-convex corners in unit cells of honeycomb [17]. Among these, hierarchical honeycombs gradually obtain researchers' attention for hierarchy effect and their hierarchy orders. Over the last few years, a variety of hierarchical structures such as tubes [18], composites [19] and honeycombs [20, 21] are developed and analysed for exploring their mechanical properties. Two methods are widely adopted in obtaining a hierarchical honeycomb structure better can be visualized from Figure 1.

REPLACEMENT OF MONOLITHIC CELL WALLS IN A HONEYCOMB BY SMALLER SUB-STRUCTURES

Replacement of Each Three Edge Vertices in a Honeycomb by Smaller Sub-structures

If the sub-structure geometry and honeycomb cell geometry have the same topology, the resultant structure can be regarded as a self-similar hierarchical structure. The honeycombs which generated by second method is called vertex based hierarchical honeycomb. These types of honeycombs are generated by replacing every three-edge vertex of honeycomb by sub-structures like triangle, hexagon, circle etc. In the last few years, vertex based hierarchical honeycombs with triangular [22], hexagonal [21], circular [23] sub-structures are investigated for in-plane, out of plane compression and impact loading for crashworthiness analysis. The crushing properties like energy absorption, mean load, and initial peak load etc. of the above-mentioned vertex based hierarchical honeycombs are compared with regular honeycomb's crushing properties but crushing properties are not compared with other vertex based hierarchical honeycombs like triangular based is not compared with hexagonal sub-structure based and other hierarchical honeycombs. So, in the present analysis author modelled different vertex based hierarchical honeycombs with following sub-structure geometries: triangle, hexagon, nonagon, dodecagon, pent-decagon, and circle. These models are crushed at similar crushing conditions in both in-plane and out of plane direction. Their performance parameters are calculated and compared with each other. The effect of sub-structure size on performance parameters is observed also. The above-mentioned analysis has not been done till now as per the author knowledge.

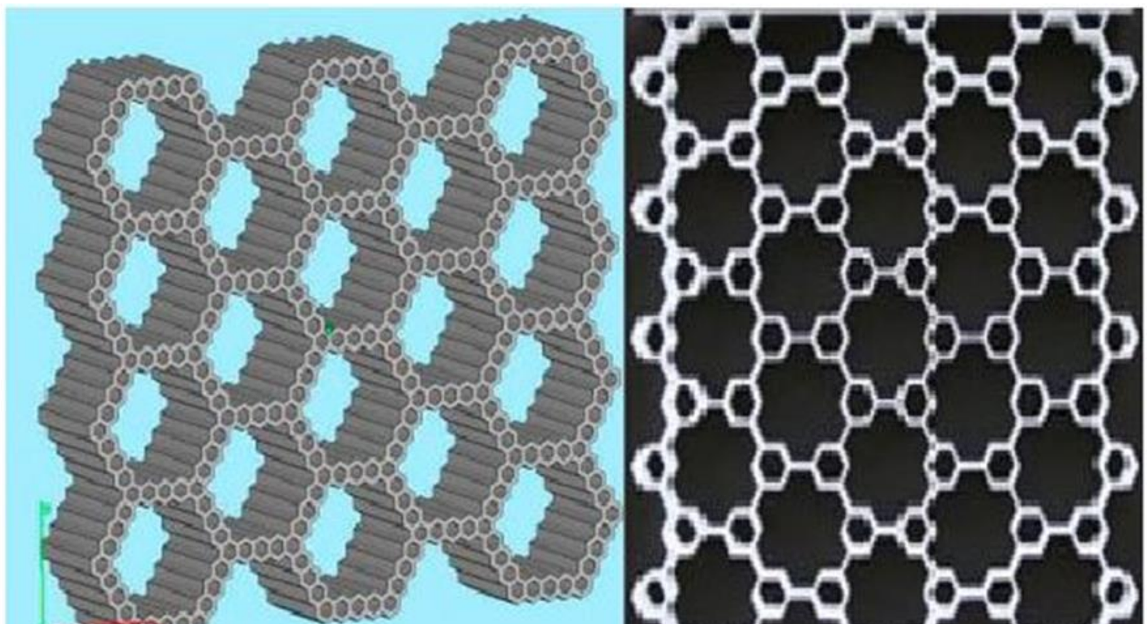

Figure 1. Hierarchical honeycomb generated (a) by first method (b) by second method.

In the upcoming section, in Section 2 hierarchical configurations of the hierarchical honeycombs and a size factor are introduced. In Section 3, the finite element (FE) models are established and validated as well as convergence test is performed for obtaining suitable mesh size. In Section 4, the numerical results, deformation mode, crushing response and energy absorption of the hierarchical honeycombs are analyzed and discussed. Comparisons with the regular honeycomb and other vertex based hierarchical honeycombs with different sub-structures are also carried out. In last section, some remarkable conclusions are made on the basis of numerical results.

HIERARCHICAL CONFIGURATIONS

Based on the concept of hierarchical design of materials, smaller regular sub-structures like triangle, hexagon, nonagon, dodecagon, pent-decagon are hierarchically introduced to replace each three-edge vertex of a base regular hexagonal honeycomb. For determination of sub-structure size, a size factor is introduced. This factor would help during comparison of results in upcoming section. This factor is defined as the ratio of circum-radius of regular sub-structure to the circumference radius of base regular hexagonal honeycomb. This can be better visualized by Figure 2.

$$\alpha = \frac{\text{Circumradius of regular sub−structure geometry (r)}}{\text{Circumradius of base hexagonal honey comb (R)}}$$

The value of α will ranges between minimum zero (0) to maximum 0.5. Zero value of sub-structure size factor will represent regular honeycomb without any hierarchy. A set of hierarchical honeycombs can be obtained by changing α. For α>0.5, the sub-structures will overlap that is why sub-structure size factor ranges from 0 to 0.5.

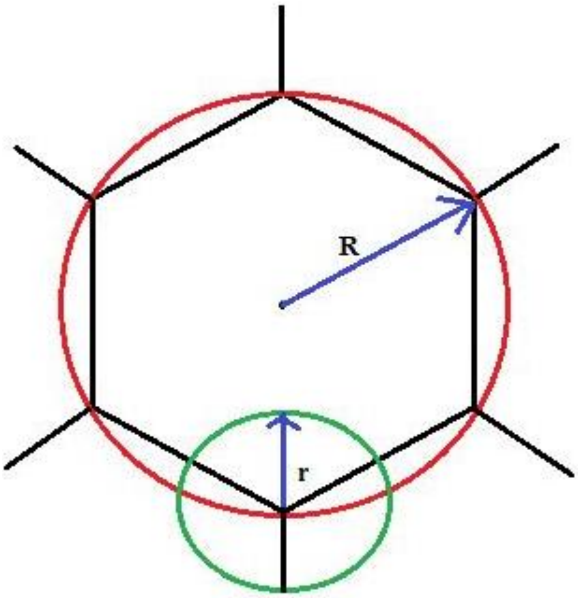

Figure 2. Circum-circle of base hexagonal honeycomb and sub-structure.

NUMERICAL MODELS

Finite Element Modeling

To explore of sub-structure geometry effect on energy absorption of the hierarchical honeycomb structures, numerical analyses are conducted. The explicit FE code LS-dyna is employed to simulate the crushing processes of the hierarchical honeycombs with various geometrical parameters. As honeycombs are anisotropic structures, it has three orthotropic directions: two in-plane and one out-of-plane. Mechanical properties are same in-plane directions for regular celled honeycomb. Therefore, simulations of crushing along the two directions are carried out respectively.

FE Model for In-plane Crushing

As shown in Figure 3, the FE model for in-plane crushing consists of two rigid crushers and a honeycomb core sandwiched between the rigid crushers. One of these crushers is fixed and other one moving with the speed of 10 m/sec towards fixed crusher. The honeycomb cores are modeled with designing software Catia using wireframe and surface modeling tool. Every three-edge vertex of regular hexagonal is replaced with regular polygonal sub-structures to generate vertex based hierarchical honeycombs. For every hierarchical honeycomb, the side length of base regular hexagon is used 20 mm and width in out of plane direction is used 10 mm. The length in x-direction for complete structure is used 180 mm and in y-direction 190.56 mm. These models are directly imported in LS-dyna for simulation. Belytschko-tsay 4-node shell element [24] is used for meshing honeycomb core. Belytschko-tsay 4-node shell element has five integration points through the thickness and one integration point in the element plane. The mesh size is used 1.5× 1.5, after performing convergence test as shown in Figure 3. The contact between the rigid crusher and honeycomb core are simulated using node to surface contact while for honeycomb core is simulated surface to surface contact. The relative motion between honeycomb core and fixed crusher is fixed using the bonded contact. The friction coefficient for surface-to-surface contact of honeycomb core is used 0.3 for static and 0.2 for dynamic. The cell wall material is assumed to be elastic, perfectly plastic. Typical aluminium alloy AA 6061-O Sheet with Young's modulus of elasticity E= 68:2GPa, the yield stress $\sigma_y = 37.66$ MPa Poisson's ratioν=0.3 and density $\rho = 2712 \ \frac{kg}{m^3}$ is assigned.

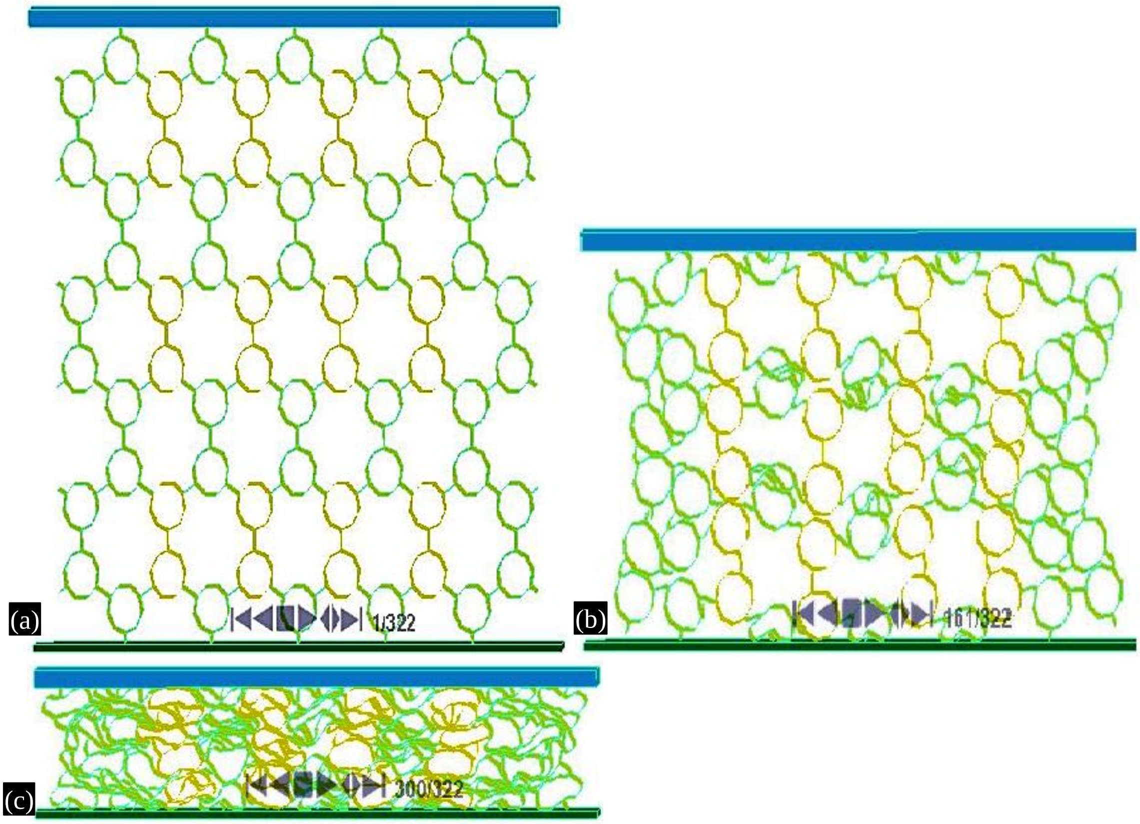

Figure 3. (a–c) In-plane crushing arrangement and crushing.

FE Model for Out of Plane Crushing

Core and crushers arrangement in out of plane loading is shown in Figure 4. Crushing of core for arbitrary sub-structure is shown in Figure 5. The construction for out of plane crushing is similar to in plane crushing. But for this case, out of plane width of honeycomb core is considered 40 mm and mesh size is considered 2×2. Remaining conditions like material, contact, friction coefficients etc. are same as in plane crushing.

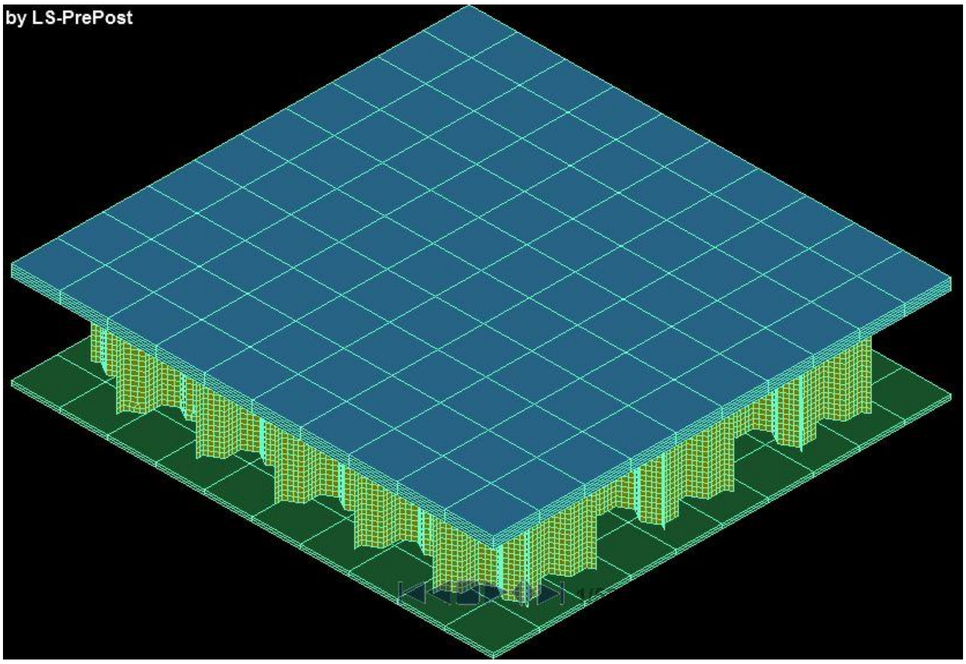

Figure 4. Out of plane crushing arrangement.

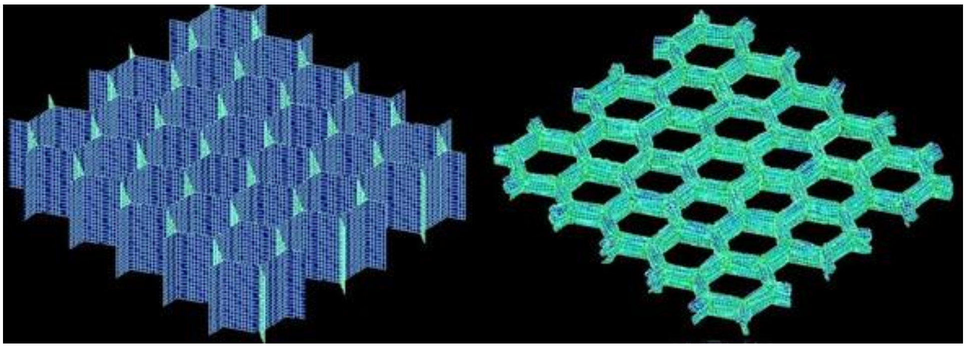

Figure 5. Out of plane crushing of core.

Performance Parameters

The performance of honeycomb under crushing can be determined from following parameters. These parameters help in comparison of crashworthiness performance of one honeycomb with other. These parameters quantify the crashworthiness performance.

Energy Absorbed

In case of numerical crashworthiness analysis energy absorbed by cellular structure is represented by area under the load displacement curve. It can be calculated by

$$\text{EA}=\int_0^{\delta} Pd\delta$$

Where, P and δ are the crushing force and displacement respectively. But the main key performance indicator is specific energy absorption (SEA).

$$\text{SEA}=\frac{\text{Energy absorbed by cellular structure (EA)}}{\text{Mass of cellular structure(m)}}$$

Mean Load

Mean load during crushing can be defined as energy absorbed per unit deformation. It can be obtained by dividing energy absorbed (EA) by deformation (δ).

Mean load $P_m = \frac{\int_0^\delta P d\delta}{\delta}$

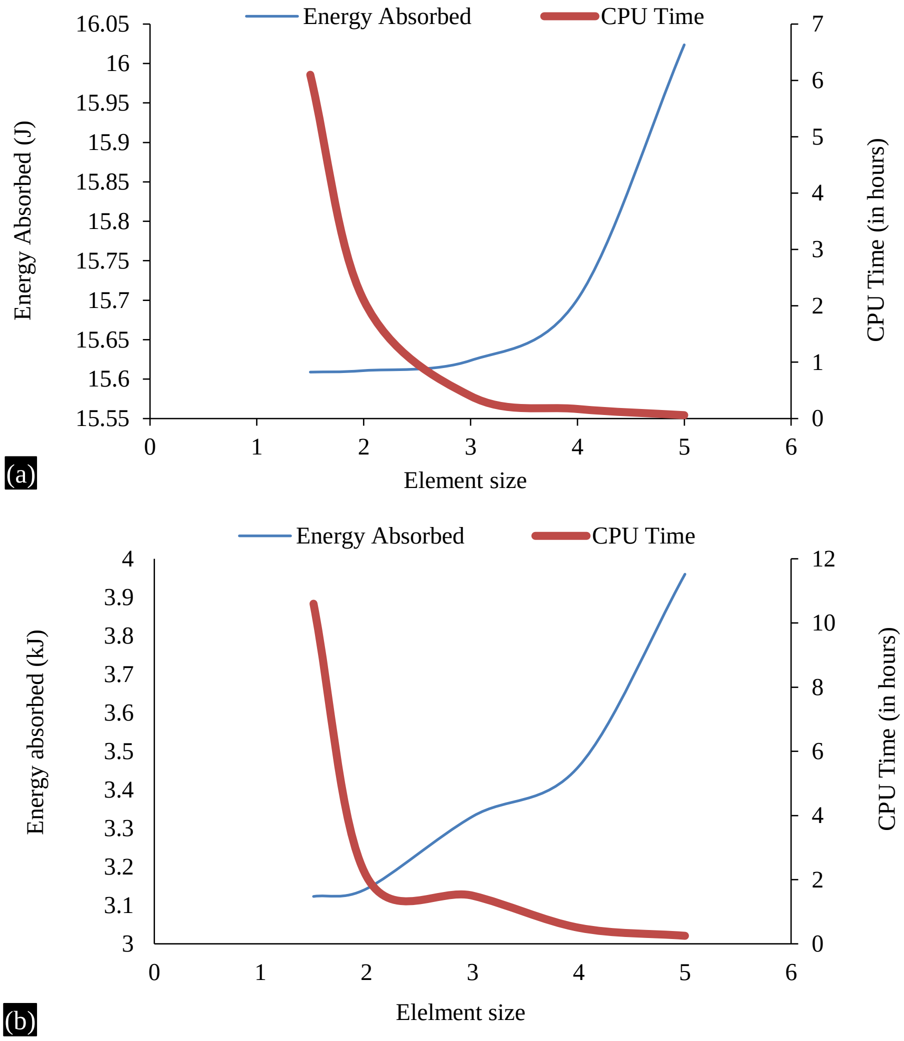

Figure 6. Convergence test for mesh size. (a) In-plane Convergence. (b) Out of plane convergence.

Validation of Finite Element Model

Convergence test on element size is performed firstly. Figure 6 shows the effect of element size on calculated energy absorbed and analysis time for the base regular honeycomb under crushing in both in-plane and out of plane direction. It is seen that simulated energy absorbed stabilizes and converges when element size reduces to 1.0 mm in in-plane direction and 1.5 mm in out of plane direction. At the same time, computing time increases with smaller mesh size. For better compromise between computing size and results convergence, mesh size 1.5 mm for in-plane loading and 2 mm for out of plane loading is used.

For validation of the accuracy of numerical models' validation analyses are performed subsequently. As, little test data about the dynamic responses of hierarchical honeycomb is available. However, a simulation result of single-stage honeycomb is a special case for hierarchical honeycomb structure with α= 0 may be verified against those reported in literature. Gibson and Ashby (1997) [25] studied the quasi-static plateau stress of regular hexagonal honeycomb under in-plane and out of plane compression and derived theoretical formula for calculating the plateau stress, which is in-plane direction

$$\sigma_p = \frac{2}{3}\left(\frac{t}{l}\right)^2 \sigma_{ys}$$

Out of plane direction, $\sigma_p = 6.6\left(\frac{t}{l}\right)^{\frac{5}{3}}\sigma_{ys}$

Where,
σ_p= Plateau stress, σ_{ys}= Yield Stress,
t = Wall thickness, *l*= Wall length of regular honeycomb.

The plateau stress σ_p is defined as the average nominal stress between the initial peak and the compressive stress corresponding to the densification strain.

$$\sigma_p = \frac{\int_{\varepsilon_p}^{\varepsilon_d} \sigma d\varepsilon}{\varepsilon_d - \varepsilon_p}$$

Nominal stress is calculated as, $\sigma = \frac{Load}{Area}$

Where, ε_d is densification strain, ε_p is strain corresponding to first peak stress. Load is the force between top crusher and honeycomb core, area is the original cross-section area of the honeycomb normal to crushing direction.

In the validation, another aluminium alloy is used whose young modulus (E) is 68 GPa and yield stress (σ_{ys}) is 120.95 MPa. In the process of model validation, '*l*' varies from 15 mm to 20 mm with the increment of 2.5 mm and '*t*' varies from 0.8 mm to 1.2 mm in the steps of 0.2 mm in case of in-plane while for out of plane is validated for only thickness of 0.8 mm. In Tables 1 and 2 theoretical results and numerical results are presented for in-plane and out of plane crushing respectively. Numerical results show good agreement with theoretical results in both in-plane and out of plane crushing.

Table 1. Validation results for in-plane loading.

S.N.	Regular hexagon side length (*l*) (mm)	Wall thickness (*t*) (mm)	Theoretical plastic collapse stress (MPa)	Numerical plastic collapse stress (MPa)	% discrepancy
1.	15	0.8	0.229	0.233	-1.75
		1.0	0.358	0.354	1.22
		1.2	0.516	0.502	2.72
2.	17.5	0.8	0.169	0.174	-2.96
		1.0	0.263	0.276	-5.75
		1.2	0.379	0.386	-1.80
3.	20	0.8	0.129	0.132	-2.32
		1.0	0.202	0.213	-5.45
		1.2	0.290	0.306	-5.52

Table 2. Validation results for out of plane loading.

S.N.	Regular hexagon side length (*l*) (mm)	Wall thickness (*t*)(mm)	Theoretical plastic collapse stress (MPa)	Numerical plastic collapse stress (MPa)	% discrepancy
1.	15	0.8	6.030	5.620	6.80
2.	17.5	0.8	4.665	4.389	5.91
3.	20	0.8	3.734	3.465	7.2

In another validation experimental work of Lee et al. (2008) [26] is compared with the finite element model. Lee et al. (2008) [26] performed impact crushing of thin-walled square tube under impact loading. The experimental load displacement curve and numerical load displacement curve are showing in good agreement (Figure 7). Thus, the finite element modelling approach is effectively validated. So, it can be concluded that our modelling approach is reasonable and reliable.

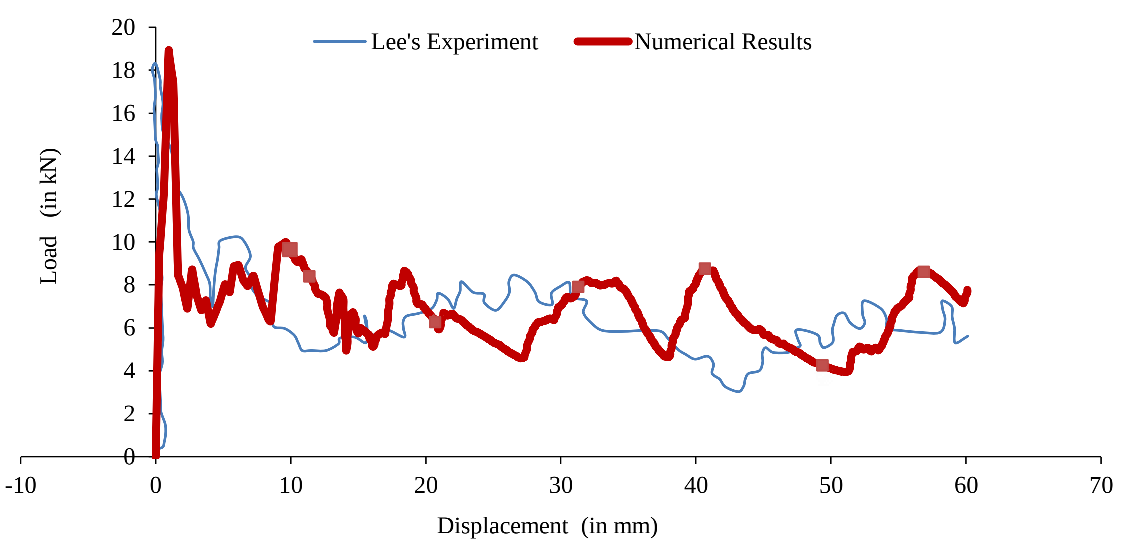

Figure 7. Comparison of numerical results with that of lee et al. (2008) experiment.

RESULTS AND DISCUSSION

In-plane Crushing of Hierarchical Honeycombs

Crushing of hierarchical honeycomb along the in-plane direction (x-direction) is simulated and studied. Various hierarchical honeycombs with α (sub-structure size factor) ranged from 0.25 to 0.5 are considered. All the hierarchical honeycombs are developed based on the same base honeycomb with cell length of L_o= 20 mm, wall thickness of t_o= 0.5 mm and the height of the honeycomb (Z direction) to be 10 mm. To make reference for comparison, the base honeycomb is also studied, which can be seen as a special hierarchical honeycomb with α = 0.

All the performance parameters of different hierarchical honeycombs with different sub-structures geometry and sizes under in-plane crushing are detailed in Table 3. The in-plane crushing behaviours of hierarchical honeycombs with different sub-structures are shown in Figures 8–14. The load-displacement plot is showing the in-plane crushing behavior of hierarchical honeycombs. The crushing response of honeycomb can be divided into three zones elastic zone, plateau zone and densification zone. The crushing response is found to be depending upon the sub-structure geometry and size. Few hierarchical honeycombs are showing negative Poisson's ratio (NPR) effect for smaller sub-structure. Based on the performance parameters, it is found that hierarchical honeycombs with triangular sub-structure with large size is showing best energy absorption in comparison to other hierarchical honeycomb under in-plane crushing. The reason behind this is that triangular sub-structure geometry provides more stiffness against crushing in comparison to other sub-structure geometry.

To check the effect of crushing velocity on energy absorption the same analysis is performed at higher velocity. It is found that energy absorption is increasing with increasing crushing velocity because more kinetic energy available for honeycomb core to absorb.

Out of Plane Crushing of Hierarchical Honeycombs

Crushing of hierarchical honeycomb along the out of plane direction (z-direction) is simulated and studied. Various hierarchical honeycombs with α varied from 0.25 to 0.5 are considered. All the hierarchical honeycombs are developed based on the same base honeycomb with cell length of L_o= 20 mm, wall thickness of t_o= 0.5 mm and the height of the honeycomb (z-direction) is used 40 mm. For comparison, the base honeycomb is also studied, which can be seen as a special case of hierarchical honeycomb with α = 0.

Table 3. Performance parameters for in-plane crushing.

S.N.	Sub-structure	α	For 10 m/sec crushing velocity			For 15 m/sec crushing velocity		
			EA (J)	*SEA (J/kg)*	*Mean load (N)*	*EA (J)*	*SEA (J/kg)*	*Mean load (N)*
1.	None (regular honeycomb)	0.00	20.606	767.45	171.716	24.4020	908.82	203.350
2.	Triangle (n=3)	0.25	32.099	875.0	267.307	36.5205	995.54	304.337
		0.30	40.359	1044.23	336.290	45.3597	1173.60	377.996
		0.35	49.779	1225.50	414.372	53.6211	1320.06	446.842
		0.40	45.248	1062.68	376.685	58.3031	1369.26	485.859
		0.45	59.559	1336.91	496.105	68.5319	1538.31	571.099
		0.50	64.143	1379.14	534.401	65.7164	1412.95	547.636
3.	Hexagon (n=3)	0.25	31.8121	789.77	264.948	40.2436	999.09	335.360
		0.30	41.2136	959.12	343.446	44.0938	1026.15	367.448
		0.35	48.5359	1063.27	404.088	50.5621	1107.60	421.351
		0.40	56.8924	1176.92	473.954	58.5318	1210.83	487.765
		0.45	62.8788	1232.43	523.366	68.8961	1350.37	574.134
		0.50	59.0942	1100.25	492.230	65.3316	1216.37	544.430
4.	Nonagon (n=9)	0.25	36.6707	894.84	305.55	42.8761	1046.26	357.301
		0.30	42.2396	964.15	351.65	43.7383	998.36	364.485
		0.35	48.9304	1049.33	407.51	50.5663	1084.41	421.385
		0.40	53.3409	1078.46	444.31	55.3211	1118.50	461.009
		0.45	57.8891	1107.23	481.83	59.7738	1143.34	498.115
		0.50	50.4777	915.94	420.65	51.8062	940.05	431.718
5.	Dodecagon (n=12)	0.25	36.4801	884.29	303.822	42.0772	1020.54	350.643
		0.30	42.8899	972.56	357.124	44.7936	1015.73	373.280
		0.35	51.5311	1096.87	428.915	51.6700	1099.83	430.583
		0.40	54.6365	1096.02	455.304	57.6962	1157.39	480.801
		0.45	58.2461	1104.61	485.191	60.3291	1144.11	502.742
		0.50	51.0267	917.75	425.174	53.0966	954.97	442.472
6.	Pent-decagon (n=15)	0.25	35.7828	865.57	297.82	45.1484	1092.12	376.236
		0.30	42.0513	950.52	350.11	44.2221	999.59	368.517
		0.35	49.9832	1060.31	416.44	50.9292	1080.38	424.410
		0.40	55.2918	1104.95	460.67	58.3960	1166.98	486.633
		0.45	54.7865	1035.07	456.40	56.8514	1074.08	473.761
		0.50	50.5003	904.53	420.66	52.8301	946.26	440.250
7.	Circle	0.25	37.7118	907.62	314.26	42.3294	1018.61	352.695
		0.30	41.5114	933.05	345.77	43.9567	973.91	361.078
		0.35	49.0748	1034.68	408.61	49.9886	1053.94	461.571
		0.40	53.1866	1055.92	422.80	55.6145	1104.12	463.454
		0.45	53.2027	998.174	443.20	55.4838	1040.97	462.365
		0.50	33.0730	588.07	275.60	36.4904	648.83	304.867

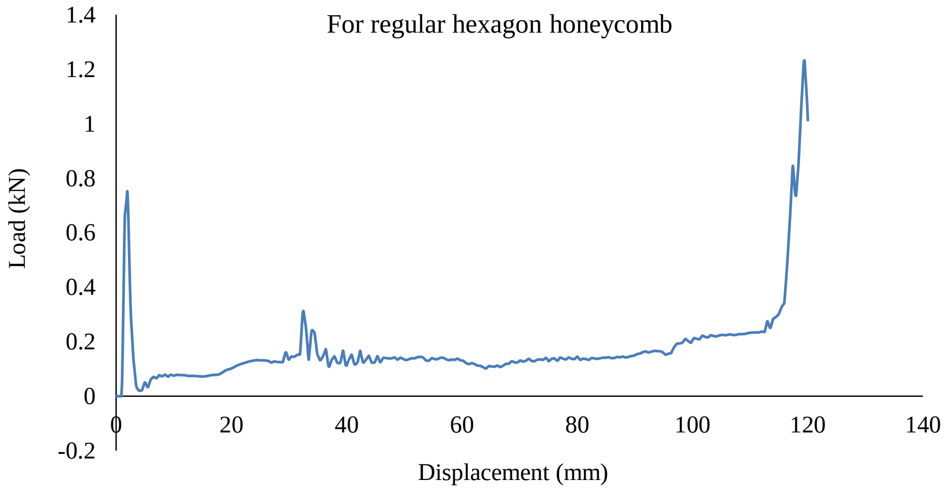

Figure 8. Load-displacement curve under in-plane crushing for hexagonal honeycomb.

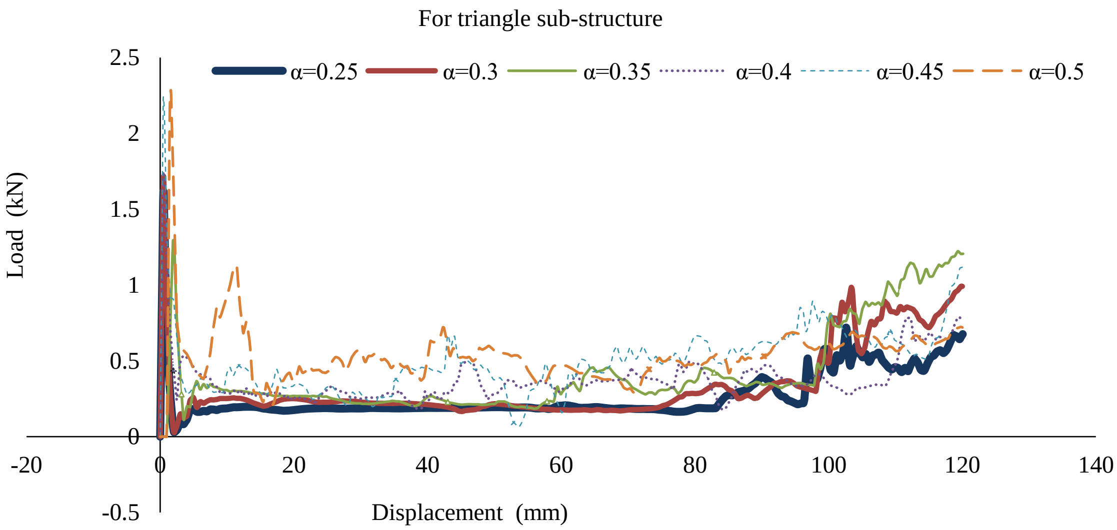

Figure 9. Load-displacement curve under in-plane crushing for hierarchical honeycomb (n=3).

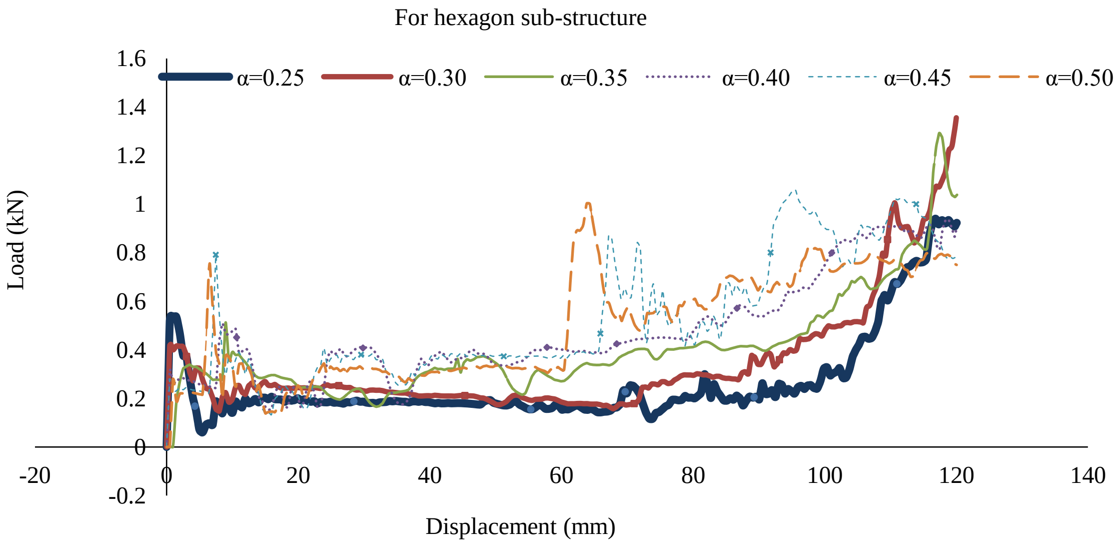

Figure 10. Load-displacement curve under in-plane crushing for hierarchical honeycomb (n=6).

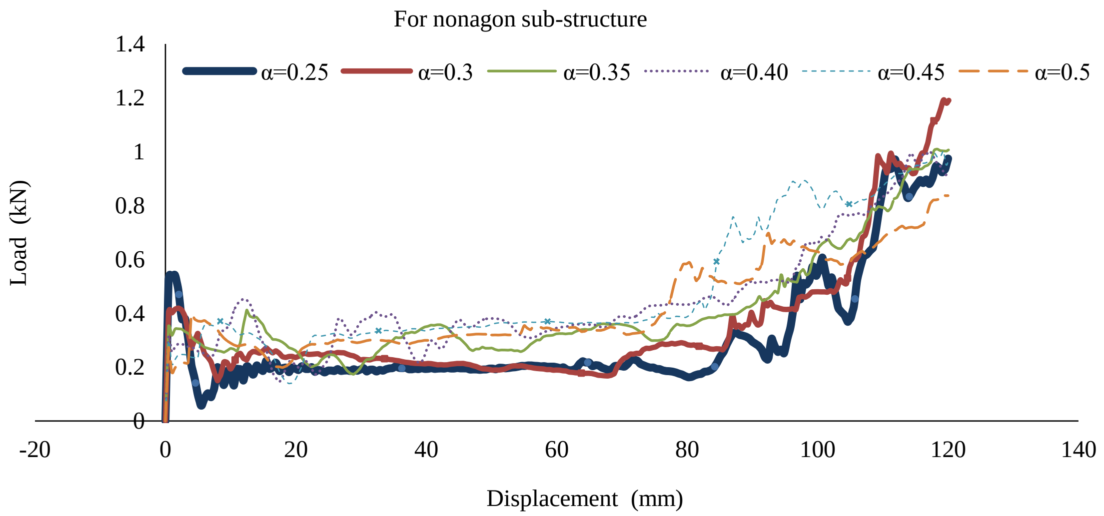

Figure 11. Load-displacement curve under in-plane crushing for hierarchical honeycomb (n=9).

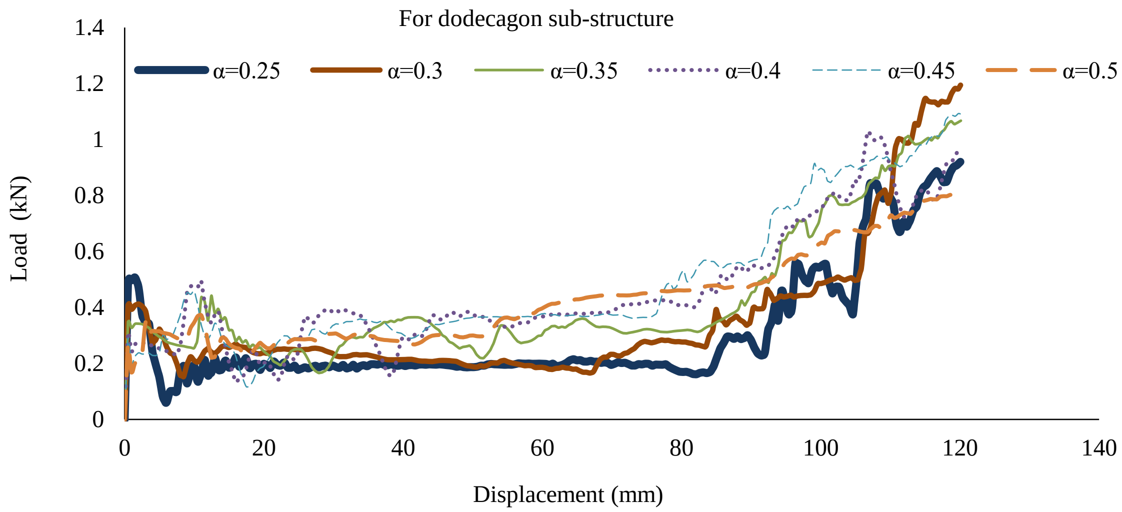

Figure 12. Load-displacement curve under in-plane crushing for hierarchical honeycomb (n=12).

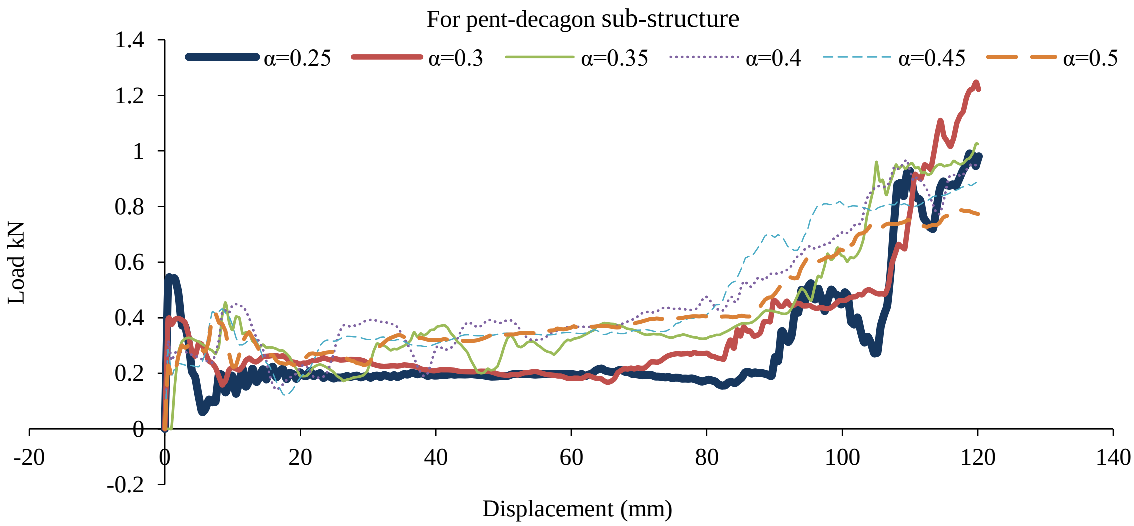

Figure 13. Load-displacement curve under in-plane crushing for hierarchical honeycomb (n=15).

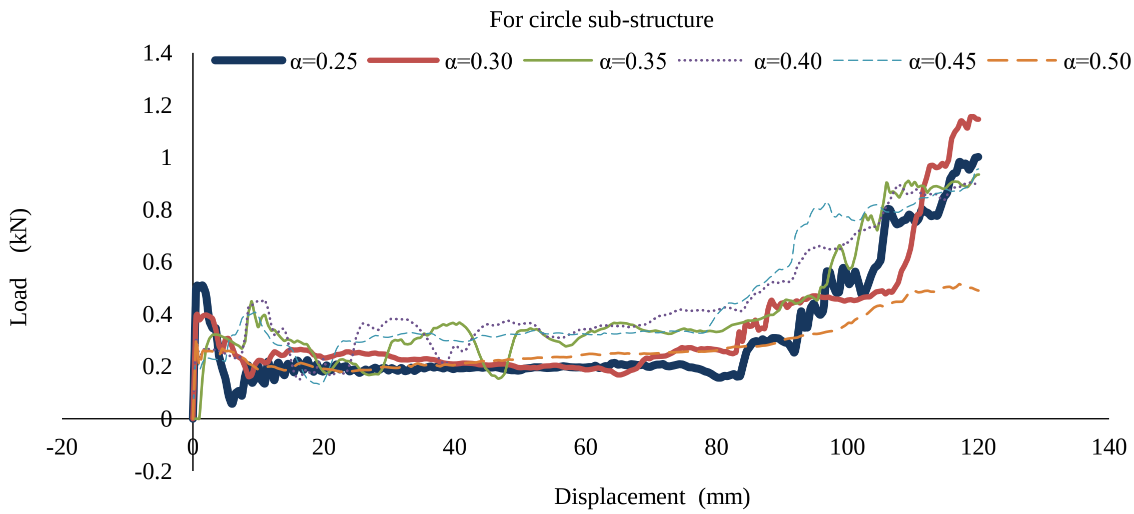

Figure 14. Load-displacement curve under in-plane crushing of hierarchical honeycomb (for circular sub-structure).

All the performance parameters of different hierarchical honeycombs with different sub-structures geometry and sizes under out of plane crushing are detailed in Table 4. The out of plane crushing behaviours of hierarchical honeycombs with different sub-structures are shown in Figures 15–21. The load-displacement plot is showing the out of plane crushing behavior of hierarchical honeycombs. Similar to in-plane crushing, the out of plane crushing response of honeycomb can be divided into three zones elastic zone, plateau zone and densification zone. The number of folds generated and folding pattern in crushed structure is found to be depending upon the sub-structure geometry. The crushing response is found to be depending upon the sub-structure geometry and size.

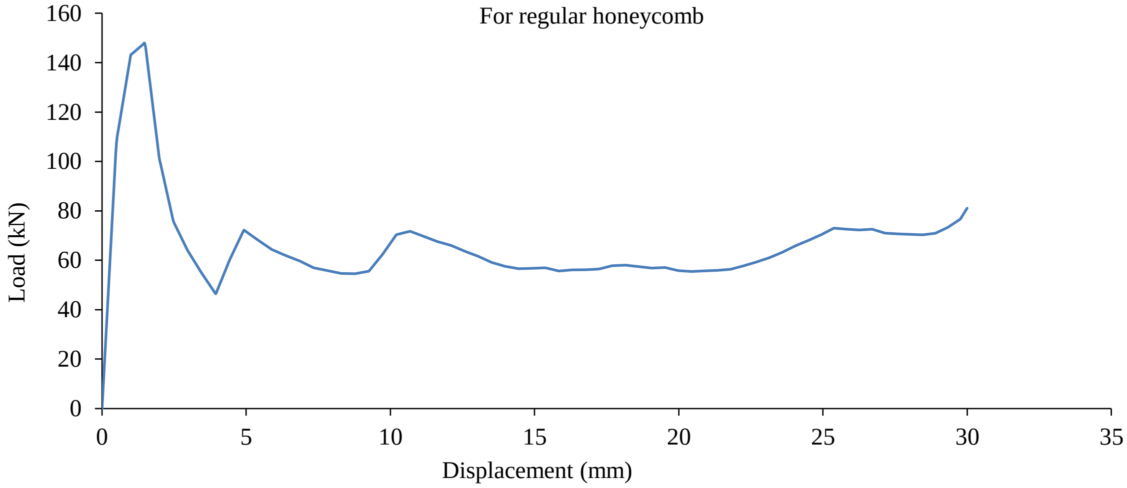

Figure 15. Load-displacement curve under out of plane crushing for hexagon honeycomb.

Hierarchical honeycombs are showing better energy absorption than regular honeycomb in both crushing directions. With the increasing the number of sides in sub-structure geometry, the mass and stiffness against deformation both are increasing. A good compromise between mass and stiffness is shown by hierarchical honeycomb with smaller sized hexagonal sub-structure. Actually, all hierarchical honeycombs except with triangular sub-structure are showing overall good energy absorption in out of plane crushing. The check effect of crushing velocity, same analysis is performed at high velocity. It is found that energy absorption is increasing with increasing crushing velocity because more energy is available for absorption.

Table 4. Key performance parameters for out of plane crushing.

S.N.	Sub-structure	α	For 10 m/sec crushing velocity			For 15 m/sec crushing velocity		
			EA(J)	*SEA (kJ/kg)*	*Mean load (kN)*	*EA(J)*	*SEA (kJ/kg)*	*Mean load (kN)*
1.	None	0.25	1984.31	18.476	66.144	2148.50	20.004	71.617
2.	Triangle (n=3)	0.25	3667.70	24.995	122.256	3870.77	26.379	129.025
		0.30	3677.11	23.784	122.463	3896.61	25.204	129.887
		0.35	3618.26	22.269	120.608	3819.43	23.507	127.314
		0.40	3557.38	20.886	118.579	3791.28	22.259	126.376
		0.45	3524.57	19.779	117.485	3780.01	21.212	126.000
		0.50	3493.41	18.778	116.447	3849.89	20.693	128.329
3.	Hexagon (n=6)	0.25	4770.82	29.610	158.904	4927.74	30.584	164.258
		0.30	5051.52	29.390	168.260	5171.49	30.088	172.383
		0.35	5268.97	28.855	175.615	5359.37	29.350	178.645
		0.40	5247.96	27.141	174.932	5297.00	27.394	176.567
		0.45	5108.31	25.031	170.932	5198.59	25.473	173.286
		0.50	5238.89	24.385	174.629	5497.43	25.588	183.247
4.	Nonagon (n=9)	0.25	4736.08	28.892	157.764	4954.59	30.225	165.153
		0.30	5113.22	29.178	170.327	5185.76	29.592	172.858
		0.35	5308.47	28.460	176.949	5370.99	28.796	179.033

		0.40	5307.75	26.828	176.925	5455.91	27.577	181.863
		0.45	5301.88	25.353	177.024	5328.38	25.480	177.612
		0.50	5177.11	23.485	172.570	5243.69	23.787	174.789
5.	Dodecagon (n=12)	0.25	5055.36	30.653	168.512	5162.62	31.303	172.087
		0.30	4975.93	28.208	165.864	5048.69	28.620	168.289
		0.35	5016.99	26.697	167.233	5151.32	27.412	171.710
		0.40	5151.29	25.834	171.709	5250.51	26.331	175.017
		0.45	5189.68	24.604	172.989	5514.27	26.143	183.809
		0.50	4718.03	21.214	157.267	4918.82	22.117	163.960
6.	Pent-decagon (n=15)	0.25	4917.25	29.736	163.908	4915.91	29.728	163.863
		0.30	5183.40	29.291	172.782	5249.25	29.663	174.975
		0.35	5236.75	27.772	174.558	5316.12	28.193	177.204
		0.40	5128.73	25.623	170.957	5224.74	26.102	174.158
		0.45	5217.05	24.641	173.901	5142.23	24.287	171.407
		0.50	4685.93	20.983	156.197	4854.65	21.738	161.821
7.	Circle	0.25	4456.98	26.817	148.566	4572.13	27.509	152.404
		0.30	5242.84	29.461	174.761	5319.39	29.891	177.313
		0.35	5471.34	28.839	182.378	5491.58	28.945	183.052
		0.40	5209.48	25.856	173.649	5229.12	25.953	174.304
		0.45	5648.90	26.496	188.297	5723.15	26.844	190.771
		0.50	3676.87	16.344	122.562	3713.68	16.508	123.789

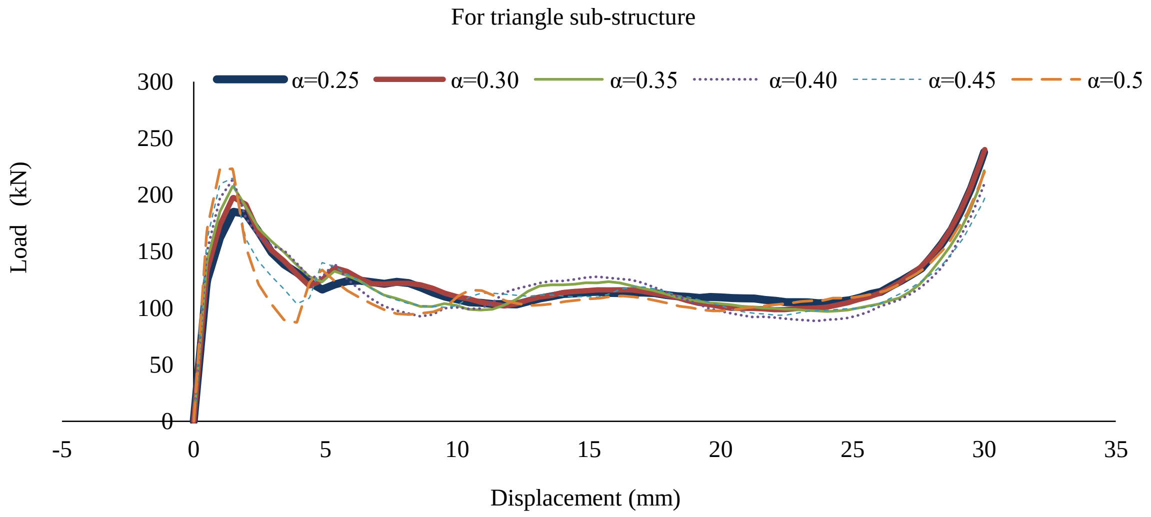

Figure 16. Load-displacement curve under out of plane crushing of hierarchical honeycomb (n=3).

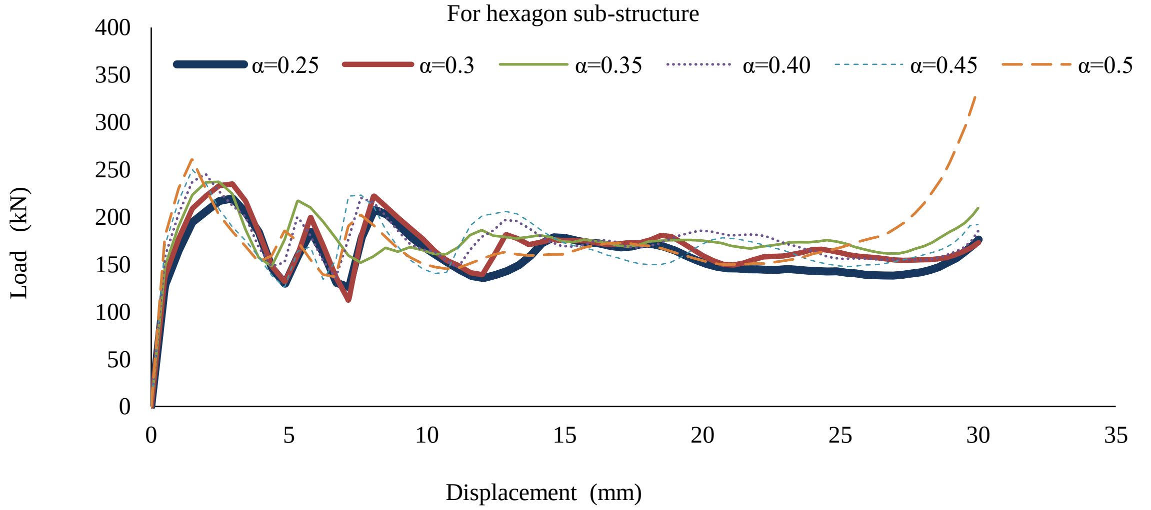

Figure 17. Load-displacement curve under out of plane crushing of hierarchical honeycomb (n=6).

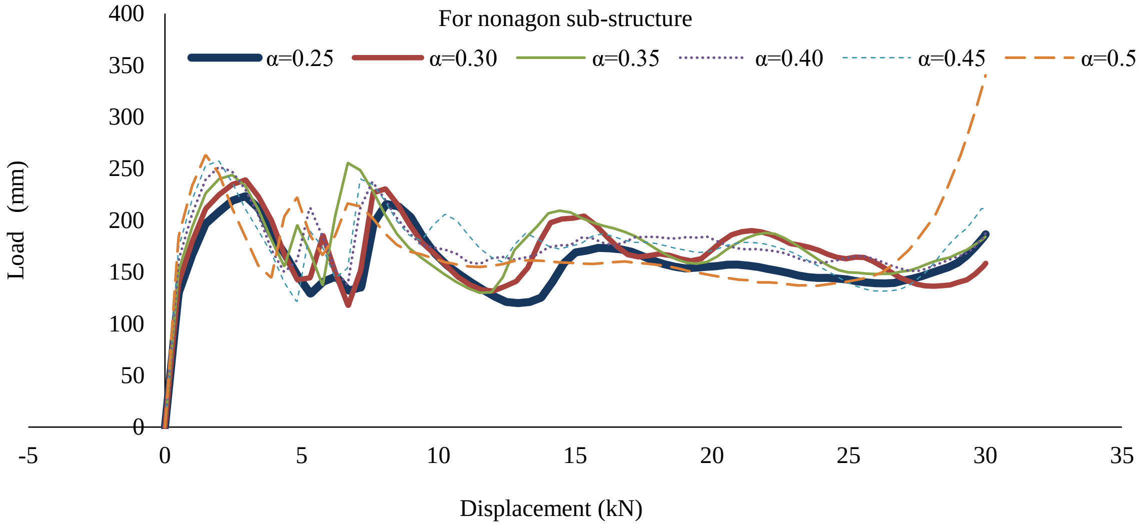

Figure 18. Load-displacement curve under out of plane crushing of hierarchical honeycomb (n=9).

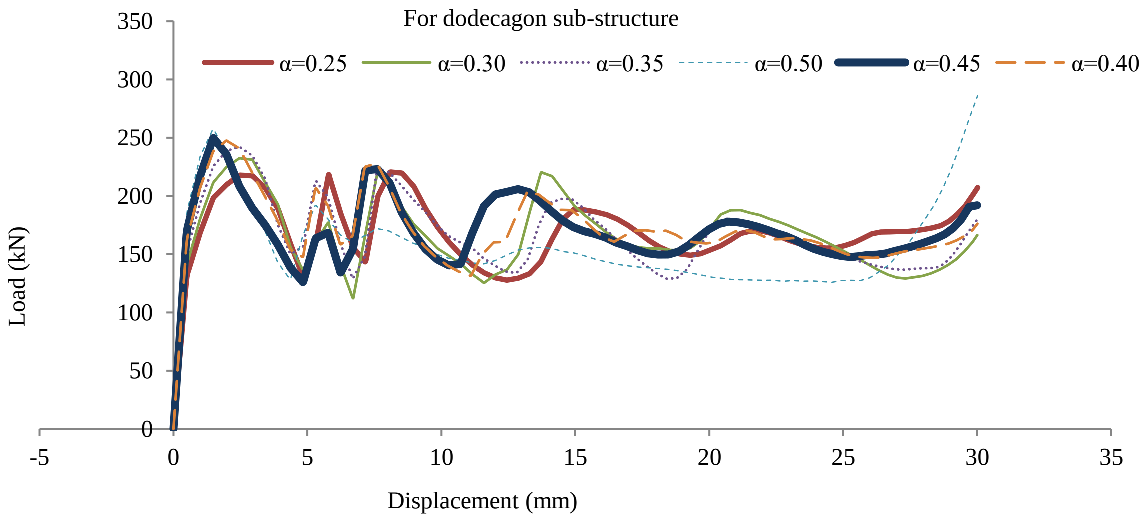

Figure 19. Load-displacement curve under out of plane crushing of hierarchical honeycomb (n=12).

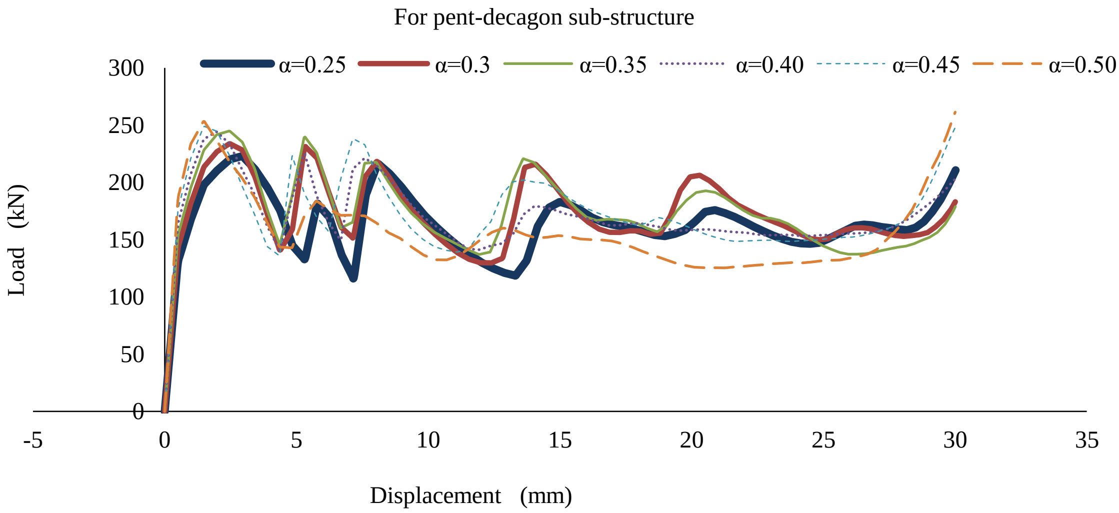

Figure 20. Load-displacement curve under out of plane crushing of hierarchical honeycomb (n=12).

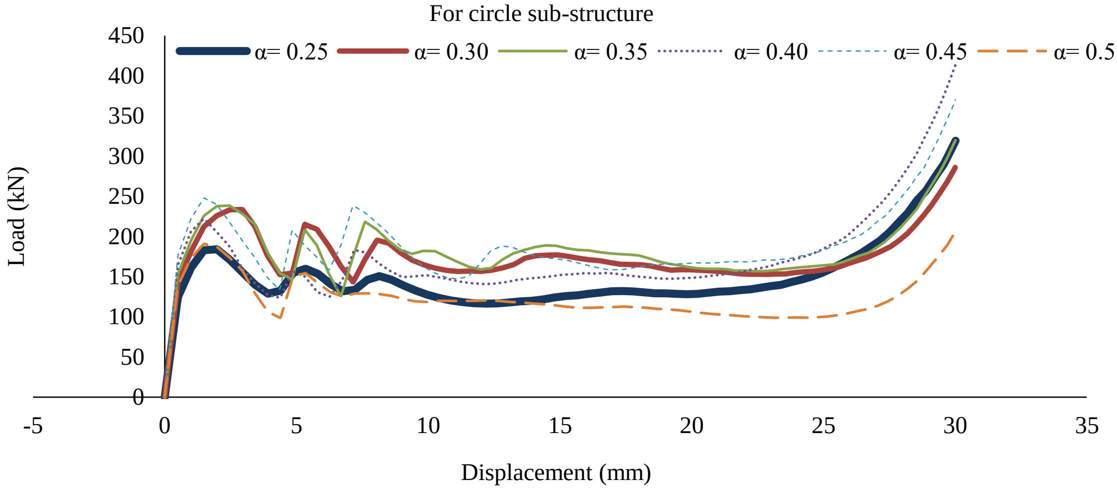

Figure 21. Load-displacement curve under out of plane crushing of hierarchical honeycomb (for circular sub-structure) [26].

CONCLUSION

In the present work crashworthiness analysis of vertex based hierarchical honeycombs with polygonal (n = 0, 3, 6, 9, 12, 15) and circular sub-structure both out of plane and in-plane directions is performed. The effect of sub-structure geometry on energy absorption is analysed. A parametric study on size of sub-structure is performed to analyze the effect of sub-structure size on crashworthiness of hierarchical honeycombs. The effect of crushing velocity on energy absorption is investigated.

In plane crushing results are:

- All sub-structure geometries show improvement in energy absorption of hierarchical honeycomb as compared to regular hexagonal honeycomb.
- Large sized triangular sub-structure geometry based hierarchical honeycombs shows overall best energy absorption ability in in-plane crushing.
- The smaller sized sub-structures show maximum initial peak load.
- Smaller sized hexagonal and circular sub-structures based hierarchical honeycombs are showing negative Poisson's ratio effect during crushing.
- Specific energy absorption ability of honeycombs increases with increase of velocity.

Out of plane crushing results are:

- All sub-structure geometries show improvement in energy absorption of hierarchical honeycomb as compared to regular hexagonal honeycomb.
- Normally all sub-structures except triangular shows approximately same crushing behavior. But the overall good crashworthiness behaviour is observed for hexagonal sub-structure.
- Specific energy absorption and mean load of crushing increases with decrease the size of sub-structure of hierarchical honeycomb.
- The larger sized sub-structures show maximum initial peak load.

Based on above results it can be concluded that introduction of hierarchy in honeycomb is a good way for improving crashworthiness of honeycomb. Vertex based hierarchical honeycomb with triangular sub-structure with sub-structure size factor α ranges from 0.45 to 0.50 is more suitable for energy absorption for in-plane crushing. While that vertex based hierarchical honeycomb with hexagonal sub-structure with smaller sub-structure is more suitable for energy absorption for out of plane crushing. The research area in this field is not limited yet. Hierarchical honeycombs with different combinations such as reinforced, tandem or hybrid form can be researched in future for improving crashworthiness behaviour. Manufacturing of hierarchical honeycomb is still costly so new manufacturing method can be researched for cheap manufacturing of hierarchical honeycombs.

REFERENCES

1. Energy Absorption of Structures and Materials. G. Lu, T. Yu. S.L. Woodhead Publishing, 2003.
2. On design optimization for structural crashworthiness and its state of the art. J. Fang, G. Sun, N. Qiu, N.H. Kim, Q. Li. S.L. Struct. Multidiscip. Optim., 2013, Vol. 55(3), pp. 1091–1119.
3. Hierarchical honeycombs with tailorable properties. Ajdari A., Jahromi B. H., Papadopoulos J., Hashemi H. N., Vaziri A. 2012, International Journal of Solids and Structures, Vol. 49, pp. 1413–1419.
4. Experimental study of the out-of-plane dynamic compression of hexagonal honeycombs. Xu S., Beynon J.H., Ruan D., Lu G. 2012, Composite Structure, Vol. 94(8), pp. 2326–2336.
5. Crushing analysis of metal honeycombs. T., Wierzbicki. 1983, International Journal of Impact Engineering, Vol. 1, pp. 157–174.
6. The out-of-plane properties of honeycombs. Zhang J., Ashby M.F. 1992, International journal of Mechanical science, Vol. 34(6), pp. 474–489.
7. Crushing analysis of polygonal columns and angle elements. Zhang X., Huh H. 2010, International Journal of Impact Engineering, Vol. 37, pp. 441–451.
8. Optimum honeycomb filled crash absorber design. Zarei H., Kroger M. 2008, Materials and Design, Vol. 29, pp. 193–204.
9. Modelling the fatigue behaviour of composites honeycomb materials (aluminium/aramide fibre core) using four-point bending tests. Abbadi A., Azari Z., Belouettar S., Gilgert G., Freres P. 2010, International Journal of Fatigue, Vol. 32, pp. 1739–1747.
10. Dynamic crushing strength of hexagonal honeycombs. Hu L. L, Yu T. X. 2010, International Journal of Impact Engineering, Vol. 37, pp. 467–474.
11. Inertia effects on the progressive crushing of aluminium honeycombs under impact loading. Hao B., Zhao H., Pattofatto S., Liu J. G., Li Y. L. 2012, International Journal of Solids and Structures, Vol. 49, pp. 2754–2762.
12. Energy absorption characteristics of bio-inspired honeycomb column thin-walled structure under impact loading. Hao P., Du J. 2013, J. Mech. Behav. Biomed. Mater., Vol. 79, pp. 301–308.
13. How does bio-inspired graded honeycomb filler affect energy absorption characteristics? Niana Y., Wana S., Lia X., Sua Q., Lib M. 2019, honeycomb filler affects energy absorption characteristics, Vol. 144.
14. Bitzer, Tom. Honeycomb technology: material, design, manufacturing, applications and testing. S.L. Springer: Science+Business Media Dordrecht, 1997. 1.
15. Mechanical behavior of composited structure filled with tandem honeycombs. Wang Z., Liu J., Lu Z., David H. 2017, Composites Part B: Engineering, Vol. 114, pp. 128–138.
16. Energy absorption properties of non-convex multi- corner thin-walled columns. Tang Z., Liu S., Zhang Z. 2012, Thin-Walled Structures, Vol. 51, pp. 112–120.
17. Investigation of lateral crushing behaviors of hierarchical quadrangular thin-walled tubular structures. Luo Y., Fan H. 2018, Thin-walled structure, Vol. 125, pp. 100–106.
18. Hierarchical composite honeycombs. Zhao L., Zheng Q., Fan H., Jin F. 2012, Material Design, Vol. 40, pp. 124–129.
19. Numerical and analytical investigation on crushing of fractal-like honeycombs with self-similar hierarchy. Zhang D., Fei Q., Jiang D., Li Y. 2018, Composite structure, Vol. 192, pp. 289-299.
20. Crashworthiness of vertex based hierarchical honeycombs in out-of-plane impact. Sun G., Jiang H., Fang J., Li G., Li Q. 2010, Material Design, Vol. 110, pp. 705–719.
21. A numerical study on the in-plane dynamic crushing of self-similar hierarchical honeycombs. He Q., Feng J., Honggen Z. 2019, Mechanics of Materials, Vol. 138.
22. Crushing of vertex-based hierarchical honeycombs with triangular substructures. Zhang D., Fie Q., Liu J., Li Y. 2020, Thin-Walled structure, Vol. 126.

23. Plastic collapse of cylindrical shell-plate assembled periodic honeycombs under uniaxial compression: experimental and numerical analyses. Chen Q., Shi Q., Signetti S., Sun F., Li Z., Zhu F., He S., Nicola, Pugno M. 2016, International Journal of Mechanical Sciences.
24. O., Hallquist J.LS-DYNA: user's manual. Vol. 1. S.L. Livermore California. Livermore Software Technology Corporation, 2018.
25. Gibson L.J., Ashby M.F. Cellular Solids: Structures and Properties. S.L. Cambridge University Press, 1997.
26. Energy absorption control characteristics of al thin-walled tubes under impact load. Lee K.S, Yang Y J, Kim S K, Yang I Y. August 2008, Acta Mechanica Solida Sinica, Vol. 21(4), pp. 383–388.