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Experimental Investigation on Impact Resistance and Energy Absorption of Multicell Thin Walled Glass Fibre Reinforced Polymer Composite

Nanjundaswamy H.S.[1,*], Srikanth H.V.[2], Sambhaji Lore[3]

Abstract

The objective of this study is to explore the behaviour of different types GFRP cell structures under dynamic load testing. In this study we have designed, fabricated, tested and analyzed specimens of different configurations (Cylindrical structure – 1 cell, 2 cell and 4 cell) using Glass Fibre Reinforced Polymer (GFRP). GFRP constituents are Glass fibre of 200 GSM with L-12 epoxy and K-6 hardener. Test specimens were manufactured by conventional manufacturing techniques. These test specimens were subjected to Drop weight Impact Test. The Limiting crushing force, displacement and strain energy absorption were investigated experimentally on all the test samples. In the testing, the crushing behaviour of all the configurations of multi-cell were determined. Considering free mass/load of 30 kg and free fall height of 1 metre, for same height of single/two/four cell composite structures results showed that crush depth in Single Cell is about 16.038%, Two Cell is about 13.44% and Four Cell structure is about 9.384%, This proves that the 4 cell composite structure is stronger to 2 cell and to single cell composite structures.

Keywords: Glass Fibre Reinforced Polymer, Multi cell, Drop weight impact test, Limiting load, Strain energy,

INTRODUCTION

During the recent times, we find exponential usage of vehicles for transportation by the society. Dependence on the transportation system has become the most essential. Because of the increase in the number of vehicles on the roads, the number of crashes and fatality rate is also greater than before. In view of this, greater demand has been promoted to ensure the higher standards of safety in vehicles. This has encouraged the researcher to design the efficient energy absorber to dissipate the energy during impact whereas protecting the passenger in the vehicle.

Bumpers and crash boxes are fitted in transport vehicles for absorbing crash energy. This absorbs energy in the event of collision or crash. The metallic structures are not preferred since they transfer the energy to the chassis whereas composite structures are preferred since they absorb the kinetic energy. In view of this, composite structures have become very popular in crashworthiness applications. Composite multi-cell thin-walled structures are found good at absorbing energy when subjected to crash load or compressive load. The energy absorbing capability of multicell is important for aerospace applications where in aircraft is subjected to dynamic loads due to impact with foreign objects like bird hits. Another example is the deceleration pulse

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generated at the passenger seats in the aircraft during landing. In view of the foregoing, using multicell composites is beneficial because of various advantages of lightweight, high flexural modulus, high impact strength, high chemical resistance, ease of manufacturing. For the study of current project, multi-cell components are fabricated using E-glass Epoxy composites (Glass Fibre Reinforced Polymer -GFRP).

M. A. Mansor et al. [1] carried out investigations on crushing behaviour of fibre metal laminates at low speed axial impact load. The failure was observed in bare composite tubes and not in fibre metal laminate tubes due to the combinations of two different materials. Kui Wang et al. [2] studied crashworthiness behaviours of Multicell filled thin-walled structure made from carbon-fibre reinforced polyamide in dynamic impact and quasi-static compression tests. Results indicated that Specific Energy Absorption of all the structures at dynamic impact condition were significantly lower as compared to quasi-static compression condition. Quiang Gao and Wei-Hsin Liao [3] investigated energy absorption characteristics of thin-walled structure containing double arrowed auxetic structure. A theoretical model was developed for predicting energy absorption crushing force. Tengfei Kuai et al. [4] studied the failure behaviour of composite thin-walled multicellular structures and also aimed to study sensitivity of cell numbers. It was observed that energy absorption of inner rib and tube were better than that of cross shaped multicellular tubes and it was observed that the specific energy absorption and compression force increase with cell numbers. Wu Hong et al. [5] analysed the axial crushing behaviour of multicell tubes with triangular lattices made out of mild steel and observed that multicell tubes have MCF about 62 to 102 percent greater than single cell tubes. This indicates higher energy absorbing characteristics of multicell lattice tube compared to a single cell tube. A Alvavi Nia and M Parsapour [6] analysed the multicell thin-walled tubes of octagonal, square, triangular, and hexagonal sections subjected to quasistatic load with a Santam 5 kN setup. The specimens were loaded axially at a speed of 10 Nmm/min. The results showed that SEA of multicell tubes were found higher than single celled tubes. Heung Soo-kim [7] carried out the simulation of extruded Aluminium shape for weight efficiency and maximum crash energy absorption suing triggers for both simple and complex collapses. It was observed that in complex collapse, the deformation took place at the centre for the first fold and this was then followed by regular crushing mode for successive foldings. Jianguang Fang et al [8] carried out the dynamic crushing behaviour of extrudable multicell tubes and found out that functionally graded thickness multicell tubes have higher SEA, EA and CFE and similar value of PCF when compared to multicell tubes with uniform thickness.

Alexander J M [9] carried out failure analysis of thin cylindrical shells in axial loading, and developed an analytical model for given material. It was found that good agreement exists between this model and experimental results. Hsu S S and Jones NJianguang Fang et al [10] have explored the behaviour of thin-walled circular tubes of aluminium alloy, mild steel and stainless steel by subjecting them to Quasi-static and dynamic axial crushing load and observed that the critical length increases with more impact velocity. S.R. Reid [11] in his paper on Plastic deformation in axially compressed metal tubes used as impact energy absorbers, pin pointed modes of deformation originating from the axial compression of tubes. S.R. Guillow et al. [12] brought out study on axial compressive test on circular AA6060 aluminium tubes in the T5 condition, considering D/t in the range of 10–450. It was observed that collapse modes for L/D is $\leqslant$10. A mode classification chart and an relationship between average force, D/t ratio and FAV has been developed. Wlodzimierz Abramowicz et al. [13] predicted the mean dynamic crushing loads with an axisymmetric mode of deformation as per Alexander's theoretical solution and non symmetric mode of deformation as per Wierzbicki, agreed with corresponding experimental results. Weigang Chen et al. [14], derived closed-form solutions for foam-filled double cell and triple cell columns to calculate the mean crushing strength based on numerical results and found that the gain of SEA is approximately 30% for single cell and approximately 40% for double cell and triple cell. T.Wierzbicki and W.Abramowicz [15] developed a foundational folding mechanism by assuming the material's rigidity and applying the principle of kinematic continuity at the interfaces between rigid and deformable regions. Through this approach, they achieved a strong alignment with existing experimental data in terms of the mean crushing force and the specific geometry associated with the local collapse mode. A.G.Pugsley [16] observed that the average crushing loads align with experimental findings and also offered an explanation for the transition, as tubes increase in thickness (R/t<50), shifting from the diamond pattern to the crinkling mode, a phenomenon previously discussed by Alexander. T. Wierzbicki and W. Abramowicz [17] developed a fundamental folding mechanism, assuming the material's rigidity and applying kinematic continuity conditions at the interfaces between rigid and deformable regions. This approach yielded a strong correlation with existing experimental data concerning the average crushing force and the specific geometry associated with local collapse modes. T. Wierzbicki, et al. [18] introduced a progressive crushing model for circular tubes. This model encompasses an active zone characterized by plastic deformations featuring two folds or buckles. The developed model is capable of accurately representing finite load peaks, varying peak heights, uneven peak spacing, reduced crushing distances, realistic final shapes of crushed tubes, and an increased distance between the initial two peaks. A.G Mamalis, et al [19] experimentally analysed the crushing and crashworthiness characteristics of carbon fibre reinforced plastic tubes, by subjecting them to static compressive loads. A. G. Mamalis et al [20], impact tested FRP tubes to get high strain rate and analysed the influence of the tube geometry, material properties and compressive strain rate, collapse modes, amount of the peak load and energy absorbing capacities of the thin-walled tubes. K.N. Shivakumar, et al [21] conducted a study that investigated the crushing characteristics, collapse modes, and crashworthiness behaviour of carbon fibre-reinforced plastic tubes under static axial compressive loading. It was also examined, how the energy-absorbing capacity of these thin-wall tubes is influenced by laminate material properties, including the fibre volume content and stacking sequence. N. Rajesh Mathivanan, et al [22], studied experimentally the low speed impact characteristics of woven glass fibre epoxy matrix composites of EP3 grade and found that two different types of damages i.e., a crack from the centre to the edge, or damage consisting of a dent localized in the region of impact are occurred. W.J. Cantwell and J. Morton [23] subjected woven glass fibre epoxy matrix composites at impact energy levels from 3 to 15 J to investigate the low-velocity impact response and it was found that at impact velocity of 4.429 m/sec there was a catastrophic failure. C. Meola and G.M. Carlomagno [24] used single stage gas gun for conducting ballistic impact test to study the effect on temperature. The test showed that temperatures exceeded respective glass transition temperatures for the polymer constituents. R.D. Hussein et al. [25], developed an analytical model to predict mean crushing force by subjecting square CFRP tubes to axial compression. It was found that the difference between analytical and experimental results is less than 7 %. L. Pickett and V. Dayal [26] presented the investigation on the effect of tube dimensions and ply orientation angles on the energy absorption and compared numerical results with that of experiments performed. Z. Zhang et al [27] studied the specific energy absorption characteristics of metallic, composite and hybrid tubes subjected to axial compressive load, using LS-DYNA. G. Sun et al. [28] subjected circular aluminium and CFRP tubes to quasi-static and oblique compression for studying the crashworthiness characterization. It was found that the energy absorption of the CFRP tubes decreased significantly from $\theta = 10°$ to 30°, while in aluminium tubes the declination was steady.

From the literature it was found that no significant works on drop weight impact tests were found to determine strain energy absorbed and displacement of the structures before failure. In the present wok, drop weight impact test of single cell, two cell and four cell multicell structures were tested with drop weight impact test machine (Make-Instron, Model-CEAST 9350) with a drop height of 1000 mm and drop weight of 30 kg.

METHODOLOGY

Preparation of Multicell Structures

The methodology involves design of single cell, 2-cell and 4-celled multi-cell structures, hand lay-up process was adopted to manufacture Multi cell thin-walled structure out of E-Glass Reinforced Epoxy Composite, bi- directional glass fibre as the reinforcement and epoxy resin as the matrix. The cells were manufactured with 47 mm inside diameter with 2 mm wall thickness i.e., 51 mm outside diameter and height of 102 mm. A seasoned Teak wood was selected considering the stability of dimensions irrespective of climatic conditions. The mandrel for one cell, two cells and 4 cells were designed, considering the ease of manufacturing like wrapping the GFRP, removal of finished sample without damaging the sample and the mandrel. In case of 4 cell mandrel, a small taper was introduced from top to bottom (1 mm to a distance of 150 mm), in all the four approximately 90º segments. This taper was introduced in the test mandrel (Figure 1) deliberately for ease of removing the test sample. The fabricated multicell structures/test samples are shown in Figure 2.

Drop Weight Impact Test

The Drop Weight Impact Testing Machine (Make-Instron, Model-CEAST 9350) was used for the study with the following specification; Energy range of 0.59–757 J; Impact Speed 0.77–4.65 m/s; Drop Height 0.03–1.10 m; Drop Weight 2–70.0 kg. Four numbers of each of samples from single cell, two cell and four cell structure were tested and average of all the values are considered for the analysis. The drop weight impact testing machine performs the impact of a guided striker (Tup) perpendicular and centred on the specimen. The tup or striker insert has striking insert with suitable diameter (55 mm in our case) and tup holder can be equipped with additional weights. The test specimen is placed at the striker central axis with external indirect clamping. Split ring of 20 mm thickness (shown as yellow colour in experimental setup) provides the location and butting to the test samples. Additionally, two sides clamping about 180 degrees apart is done in view of safety. The clamping height was 30 mm, with an assumption that crushing will be more than 50% of the height of the cylindrical structure/cell (Figure 3).

The fabricated test specimens were subjected to dynamic impact load test. Force vs displacement plots were used to study the crashworthiness behaviour. During the testing process, the impactor is released as free fall from a height of 1 meter. The impactor stops at a point when all the energy gets transferred to the test specimen. The crushing of the tube begins at the bottom end, where the tube deforms plastically and folds. The conditions at which test were carried out are shown in Table 1. The test specimens after the tests are shown in Figure 4.

Figure 1. Multicell structure with mandrels.

Figure 2. Test samples.

Table 1. Conditions at which test were carried out.

Drop Height	1000 mm
Mass	30 Kg
Impact Energy	293.3 J
Impact Velocity	4.43 m/s

Figure 3. Impact Testing Machine, Test specimen on the base plate and with Tup.

After test - Single Cell Structure (1C1;1C2;1C3;1C4) | After Test - Two Cell Structure (2C1;2C2;2C3;2C4) | After Test - Four Cell Structure (4C1;4C2;4C3;4C4)

Figure 4. Test specimens after the impact test.

Table 2. Test Results of 1 C Batch

Test Specimen ID	Height/Thickness in mm	Displacement Thickness in mm	Limiting Force in Newtons
1C1	104.59	14.131	23150.958
1C2	105.15	16.864	23257.493
1C3	105.91	15.682	23178.382
1C4	102.58	14.978	23223.637

RESULTS AND DISCUSSIONS

Dynamic Crush Test and Force Displacement Curves:

Single Cell Structure

Table 2 gives tabulation of crush test values in respect of single cell structure (1C1;1C2;1C3;1C4). It is seen that crush depth/displacement are 13.51%, 16.038%, 14.807% and 14.601% respectively. On an average the Crush depth/displacement is 14.739%. Maximum Limiting crushing force of 23257.382 N was observed in 1C2 sample. Average Limiting crushing force works out to 23202.62 N (Figure 5)

It is observed from the experimental test results of Single Cell Structure that average crush depth or displacement thickness is 15.41375 mm for an average height of 104.5575 mm.

Two Cell Structure

Table 3 gives tabulation of Crush Test values in respect of Two Cell Structure (2C1;2C2;2C3;2C4). It is seen that Crush depth/displacement is 13.5705%, 13.386%, 14.1337% and 13.441% respectively. On an average the Crush depth/displacement is 13.633%. Maximum Limiting crushing force of 23130.757 N was observed in 2C1 sample. Average Limiting crushing force works out to 23102.47 N (Figure 6).

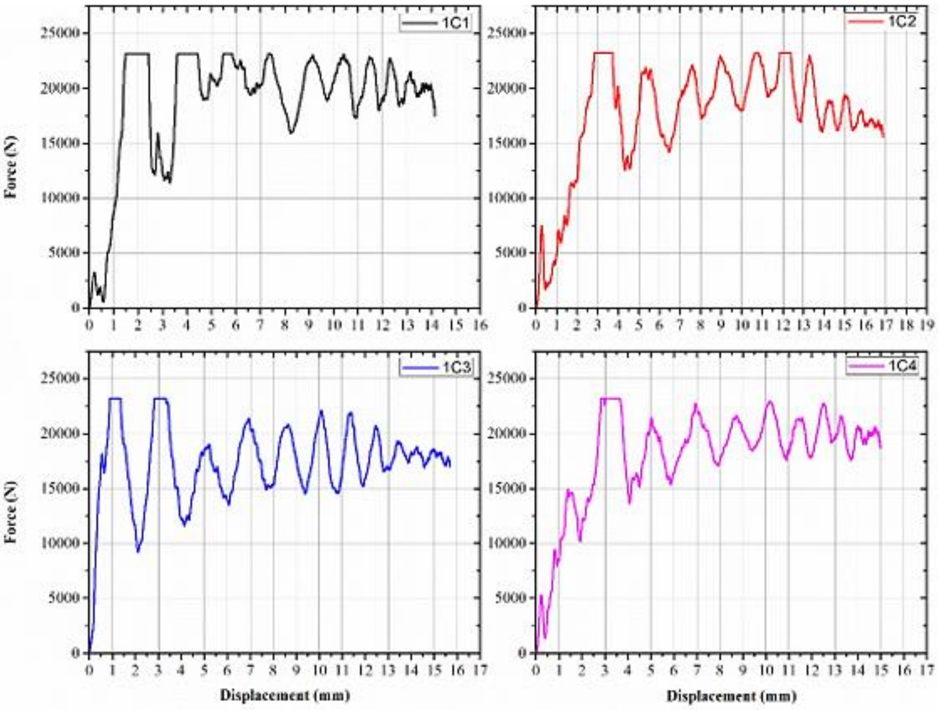

Figure 5. Force Vs Displacement individually (1C1;1C2;1C3;1C4) for each test sample.

Table 3. Test Results of 2 C Batch.

Test Specimen ID	Height/Thickness in mm	Displacement Thickness in mm	Limiting Force in Newtons
2C1	104.69	14.207	23130.757
2C2	104.37	13.971	23094.87
2C3	104.09	14.712	23087.139
2C4	105.66	14.202	23097.127

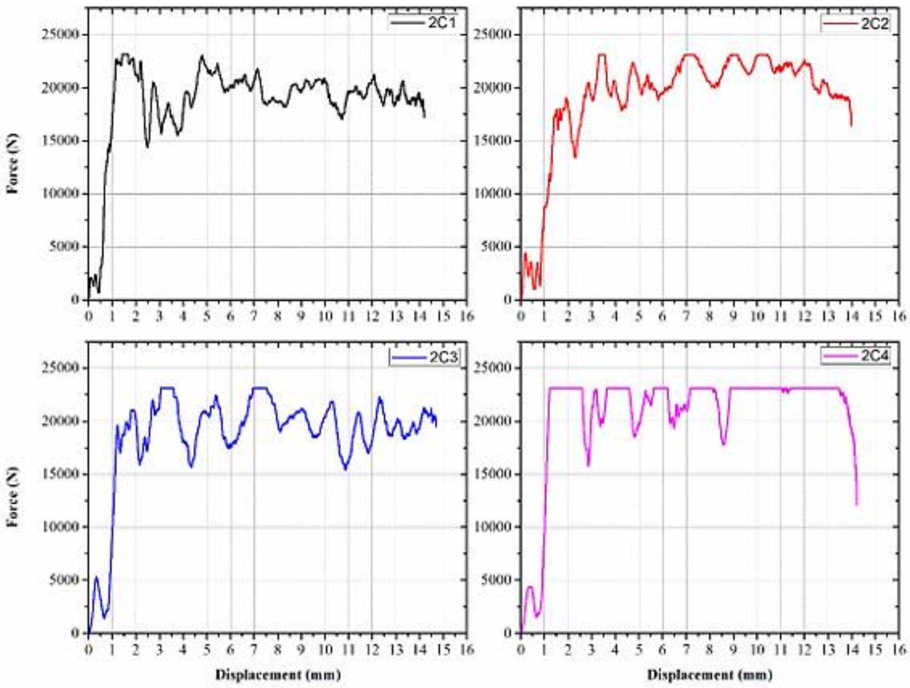

Figure 6. Force Vs Displacement individually (2C1;2C2;2C3;2C4) for each test sample.

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Table 4. Test Results of 4 C Batch

Test Specimen ID	Height/Thickness in mm	Displacement Thickness in mm	Limiting Force in Newtons
4C1	105.76	12.088	23064.625
4C2	102.98	11.546	23055.935
4C3	100.85	9.129	23041.038
4C4	105.54	9.904	23069.985

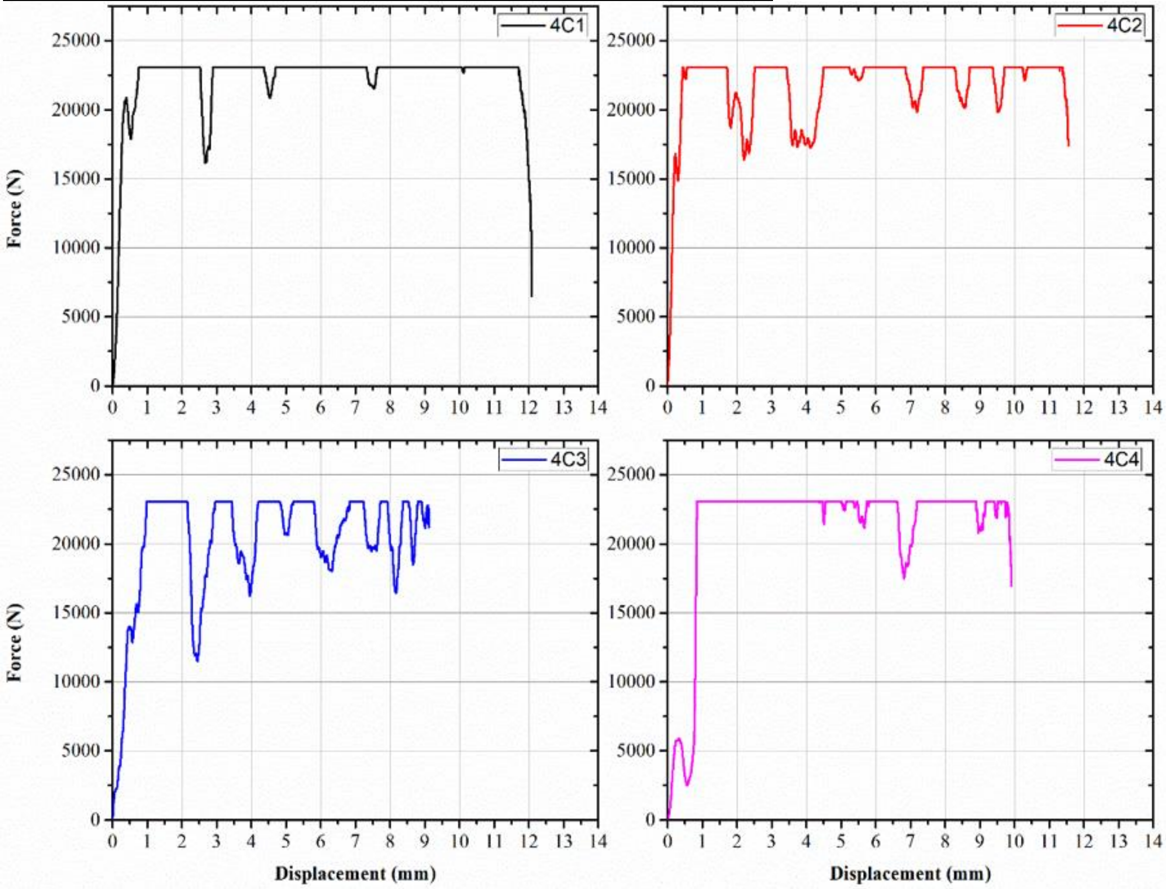

Figure 7. Force Vs Displacement individually (4C1;4C2;4C3;4C4) for each test sample.

It is observed from the experimental test results of Two Cell Structure that average crush depth or displacement thickness is 14.273 mm for an average height of 104.7025 mm.

Four Cell Structure (4C1;4C2;4C3;4C4)

Table 4 gives tabulation of crush test values in respect of Four Cell Structure (4C1;4C2;4C3;4C4). It is seen that crush depth/displacement is 11.429%, 11.211%, 9.052% and 9.3841% respectively. On an average the crush depth/displacement is 10.269%. Maximum Limiting crushing force of 23069.99 N was observed in 4C4 sample. Average Limiting crushing force works out to 23057.90 N (Figure 7).

It is observed from the experimental test results of Four Cell Structure that average crush depth or displacement thickness is 10.66675 mm for an average height of 103.7825 mm.

Comparison of Displacement Vs Limiting Force across Single Cell, Two Cell and Four Cell Test Samples/Structures of Comparable/Same Height

Displacement and Limiting Force of comparable height Single Cell, Two Cell and Four Cell Structures are tabulated in Table 5 and Table 6.

Table 5. Comparison of Test Results of all 3 types of cells of same height (1C3;2C4;4C1).

Sample Specimen ID	Height/Thickness in mm	Displacement Thickness in mm	Limiting Force in Newtons
1C3	105.91	15.682	23178.382
2C4	105.66	14.202	23097.127
4C1	105.76	12.088	23064.625

Table 6. Comparison of Test Results of all 3 types of cells of same height (1C1;2C2;4C4).

Sample Specimen ID	Height/Thickness in mm	Displacement Thickness in mm	Limiting Force in Newtons
1C1	104.59	14.131	23150.958
2C2	104.37	13.971	23094.87
4C4	105.54	9.904	23069.985

Table 7. Strain Energy in respect of Single Cell Structure (1C1;1C2;1C3;1C4).

Test Specimen ID	Height/Thickness in mm	Displacement Thickness in mm	Strain Energy in Joules
1C1	104.59	14.131	266.713
1C2	105.15	16.864	295.822
1C3	105.91	15.682	272.215
1C4	102.58	14.978	269.484

Table 8. Strain Energy in respect of Two Cell Structure (2C1;2C2;2C3;2C4).

Test Specimen ID	Height/Thickness in mm	Displacement Thickness in mm	Strain Energy in Joules
2C1	104.69	14.207	265.493
2C2	104.37	13.971	266.676
2C3	104.09	14.712	274.467
2C4	105.66	14.202	295.042

Table 9. Strain Energy in respect of Four Cell Structure (4C1;4C2;4C3;4C4).

Test Specimen ID	Height/Thickness in mm	Displacement Thickness in mm	Strain Energy in Joules
4C1	105.76	12.088	268.636
4C2	102.98	11.546	251.140
4C3	100.85	9.129	183.807
4C4	105.54	9.904	209.879

From the Table 5 and Table 6, it can be seen that with the increase of number of cells the Displacement/Crush depth is less, proving that with the increase in number of cells, strength increases.

Strain Energy Absorbed across Single Cell, Two Cell and Four Cell Test Samples/Structures

Displacement and Strain Energy Absorbed of comparable height Single Cell, Two Cell and Four Cell Structures are tabulated in Table 7, 8 and 9.

From the Table 7, 8 and 9, it can be seen that the Average Strain Energy Absorption in case of Single Cell is 276.058 Joules, Two Cell is 275.419 Joules and Four Cell is 228.365 Joules.

Comparison of Strain Energy Absorbed across Single Cell, Two Cell and Four Cell Test Samples/Structures of Comparable/Same Height

Displacement and Strain Energy Absorbed of comparable height Single Cell, Two Cell and Four Cell Structures are tabulated in Table 10 and 11.

Table 10. Comparison of Strain Energy Absorbed in all 3 variety of cells of same height

(1C3;2C4;4C1).

Sample Specimen ID	Height/Thickness in mm	Displacement Thickness in mm	Strain Energy in Joules
1C3	105.91	15.682	272.215
2C4	105.66	14.202	295.042
4C1	105.76	12.088	268.636

Table 11. Comparison of Strain Energy Absorbed in all 3 variety of cells of same height (1C1;2C2;4C4).

Sample Specimen ID	Height/Thickness in mm	Displacement Thickness in mm	Strain Energy in Joules
1C1	104.59	14.131	266.713
2C2	104.37	13.971	266.676
4C4	105.54	9.904	209.879

Table 12. Comparison of Strain Energy Absorbed Vs Peak Force of all 3 variety of cells of same height (1C3;2C4;4C1).

Sample Specimen ID	Height/Thickness in mm	Displacement Thickness in mm	Limiting Force in Newtons	Strain Energy in Joules
1C3	105.91	15.682	23178.382	272.215
2C4	105.66	14.202	23097.127	295.042
4C1	105.76	12.088	23064.625	268.636

Table 13. Comparison of Strain Energy Absorbed Vs Peak Force of all 3 variety of cells of same height (1C1;2C2;4C4).

Sample Specimen ID	Height/Thickness in mm	Displacement Thickness in mm	Limiting Force in Newtons	Strain Energy in Joules
1C1	104.59	14.131	23150.958	266.713
2C2	104.37	13.971	23094.87	266.676
4C4	105.54	9.904	23069.985	209.879

From the Table 10 and 11, it can be seen that Strain Energy Absorbed values are decreasing with the increase of number of cells.

Comparison of Strain Energy Absorbed, Limiting Force and Displacement across Single Cell, Two Cell and Four Cell Test Samples/Structures

Displacement, Peak Force and Strain Energy Absorbed of comparable/same height Single Cell, Two Cell and Four Cell Structures are tabulated in Table 12 and 13.

From the Table 12 and 13, it can be seen that crush depth is decreasing with the increase of number of cells. In terms of Strain Energy Absorbed, values are decreasing with the increase of number of cells. Because of software constraint in the Impact Testing Machine, we have apprehensions on the values of Limiting/Maximum Peak Force and Strain Energy Absorbed.

CONCLUSIONS

1. From the study, the displacement i.e., crush depth in Single Cell is about 16.038%, Two Cell is about 13.44% and Four Cell structure is about 9.384%. This is considering free mass/load of 30 kg and free fall height of 1 metre, for same height of single/two cell/four cell composite structures. This proves that the 4 cell composite structure is stronger to 2 cell and to single cell composite structures. More the number of cells, more the strength it would be.
2. It can be concluded that 4 cell structures absorb more strain energy as compared to single cell

and two cell structures, and this can be used for applications where more load is acting in a structure. In our studies, due to the limiting load, the stain energy values for four cell structure are less than the single cell and two cell structure, because of lesser displacement.

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