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REGULAR PAPER

Investigating the crumpling effect in honeycomb sandwich panels under bending loads using FEA technique

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Abstract
In this study a representative sandwich panel is investigated statically in two different configurations under similar bending loads. In one configuration serrations are introduced in the honeycomb core while the other one has unmodified core. Three-point bend test (TPBT) has been performed on both configurations through Finite Element Analysis (FEA) technique using ANSYS Workbench considering American Society for Testing and Materials (ASTM) standards. In both configurations the same aluminium honeycomb core is modelled having an adhesive layer in between adjacent foils to simulate actual scenario instead of relying on the block properties. Honeycomb core offers highest strength in its thickness (T) direction or the *z*-direction by virtue of its shape. Any distortion in the shape of the honeycomb adversely affects its strength. During bending the honeycomb core witnesses multidirectional forces consequently leading to distortion or crumpling. The serrations in the structure allow bending of the honeycomb core with minimal loss of strength by limiting the deformation to a specific region consequently preserving the shape as well as the strength of the honeycomb core. The results of both samples are compared with respect to deflection, strain and reaction force. It proves that serrated core is more favourable to be used in bent or curved sandwich panels.

Abbreviations

ASTM	American Society for Testing and Materials
CFRP	Carbon fibre reinforced polymer
FEA	Finite element analysis
HVAC	Heat ventilation and air conditioning
LED	Light-emitting diodes
TPBT	Three-point bend test

Symbols

ρ	Density
σ	Tensile stress
τ	Shear stress
υ	Poisson ratio
E	Young’s modulus
G	Shear modulus

Subscripts

U	Properties at ultimate strength
Y	Properties at yield strength

1.0 Introduction

The highest strength offered by the honeycomb material is in its thickness (T) direction or the Cell height that is because of its shape [1] as shown in Fig. 1(b). If any distortion occurs in the shape of the honeycomb, it will adversely affect the strength of that honeycomb. This phenomenon is even more prominent when the cell walls are affected. So, the efforts need to be made in a way that the least distortion is witnessed by the honeycomb while making curved or bent structures. Modern aerospace vehicles are sleeker, agile and light in weight. Consequently, we see different innovative shapes of aerospace vehicles. Owing to these requirements honeycomb sandwich structures have evolved a great deal but with corresponding complexity in manufacturing and preservation of structural properties. Many times, the designers reach a crossroad where innovative manufacturing technique is to be adopted in order to form honeycomb structures into complex geometries.

In past, many attempts have been made to quantify the amount of deformation, buckling and stress developed due to loads applied on honeycomb sandwich panels [2–4]. However, the FEA models or numerical analysis of the sandwich panels in light of global and local deformation is to date an incomplete subject. This is due to primitive modelling of the specimen. The FE methods are considered reliable [5] to analyse honeycomb core for stiffness and energy absorption characteristics [6–10]. Improvement in stiffness of honeycomb sandwich structure due to carbon fibre reinforced polymer (CFRP) tubes was numerically validated in a study [11]. The effects of in-plane and out-plane loadings were analysed on honeycomb w.r.t wall thickness, cell size, and node length [12].

Honeycomb structures are the most sought-after material for structure design engineers particularly in the fields of aerospace, aeronautics and automobiles industry. Honeycombs offer a unique and profound set of properties like high strength-to-weight ratio, thermal as well as acoustic insulation, impact load absorption, etc. High flexural stiffness makes it able to withstand tensile and bending loads. Stiffness enhancement efforts often lead to the use of various fillers like foam, sand, potting material, etc. [13–16].

In some research, instead of filling the honeycomb core with any filler, the face sheet and core were modified in a peculiar way to establish anti-impact characteristics of the sandwich structure. The study [17–19] mentions the effects of a braided face sheet on structural endurance of the sandwich structure while the other one highlights conical core and its effects in strength enhancement. The bending in corrugated truss core sandwich structure was investigated with the conclusion that distributions of truss cores have a significant impact on bending behaviour [20].

In order to perform linear and nonlinear analyses on honeycomb sandwich panels, the model is often simplified using symmetries to reduce the computation time and resources. It is however imperative that the region of focus shall not be undermined while simplifying the model. In a research study [21] honeycomb was modelled and analysed with solid element however modelling the honeycomb as a shell element produces equally good results [22–24]. Equivalent volume geometries have been used quite often to optimise solution resources [25, 26] hence optimising the solution spectrum to a particular area to have focused results. The effects of temperature on material properties have also been highlighted [27–30].

Studies are not unbridled to static loads; rather dynamic loads are also discussed on damage prediction as well as crack monitoring [31, 32]. However, it is pertinent to mention here that in this research, the effects of temperature on the honeycomb sandwich panel have not been discussed. FE techniques have evolved a great deal with time [33–38] consequently FEA on honeycomb have gained more prominence.

All the studies discussed above had only one objective that is to enhance the structural strength of the honeycomb sandwich panels. This research aims at identifying and controlling the amount of

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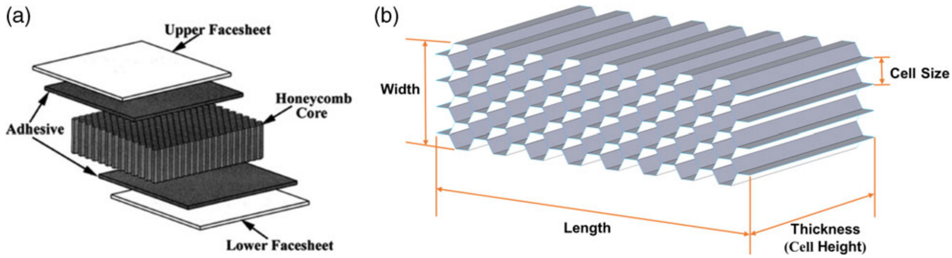

Figure 1. *(a) Main components of sandwich panel (b) honeycomb core nomenclature.*

wrinkling/crumpling in the adhesive-bonded aluminium honeycomb core sandwich panel having a carbon fibre face sheet. In this research the adhesive layer between the foils of aluminium core has been modelled to make it as rational as possible. Consequently, there are a huge number of bonded contacts in FEA model. Previously the adhesive had never been modelled between the foils of honeycomb core; however, we do see examples where the adhesive has been modelled between core and the face sheets [39–42] to simulate linear as well as a nonlinear solution on honeycomb core sandwich panels [43, 44]. The main components of a sandwich structure are expressed in Fig. 1(a) [45].

Soon after the inception of honeycomb structures in the early 1900s, they have gained popularity in the structures industry around the globe. Honeycomb materials are mostly used where flat or slightly curved surfaces are needed and their high Specific strength is valuable. With the advancements in manufacturing machines, it is getting easy to prepare honeycomb structures of various types and sizes therefore we see an increasing trend of its utility. Chief consumers are found in the following areas: wind turbine blades, wind tunnel, jet aircraft and helicopters, substructure of rockets, boats, marine industry components, gliders, automobile structures, train doors, HVAC applications, telescope mirror structure, racing shells, fluid direction guides, loudspeakers, LEDs and snowboards, to name a few.

This research entails the essence of introducing serrations in the honeycomb core at specific locations to allow for easy bending. Furthermore, the influence of adhesive layer between adjacent corrugated foils of the core have been introduced to simulate true deformations of honeycomb core during the study. Details of material and sample are shared in Section 3. Description of FEA model and analysis is expressed in Section 4 while adopted methodology for analysis is depicted in Section 5. The results are discussed in Sections 6 and 7.

2.0 Research significance

This research lays special emphasis on the serrations introduced in the core which greatly affect the bending behaviour of the core. An adhesive layer has been modelled that bonds the aluminium foils of the honeycomb core together. Having the adhesive modelled in the core gives a true depiction of the actual honeycomb sandwich and hence the results are expected to be more realistic. Most of the past studies leave this aspect; however, in few studies adhesive is present as a layer between the core and face sheet.

It is worth mentioning that the technique adopted in this study is not just applicable on metallic cores rather it can be used for non-metallic cores as well, like Nomex and Kevlar. Serrations and notches are very helpful in manufacturing curved and bent structures out of non-metallic honeycomb cores. It further relieves us from developing/using complex shaped cores. By developing a deliberate but controlled deformation we can achieve overall strength of the honeycomb sandwich structure.

This methodology does not require any filler material to be filled in the core in order to control its deformation. Cutting serrations also provide ease in manufacturing of the honeycomb sandwich structures. Precisely located serrations can be conducive to bend the core and curve it in desired diameters and make joints at desired angles. This gets even more practical with the increase of core thickness.

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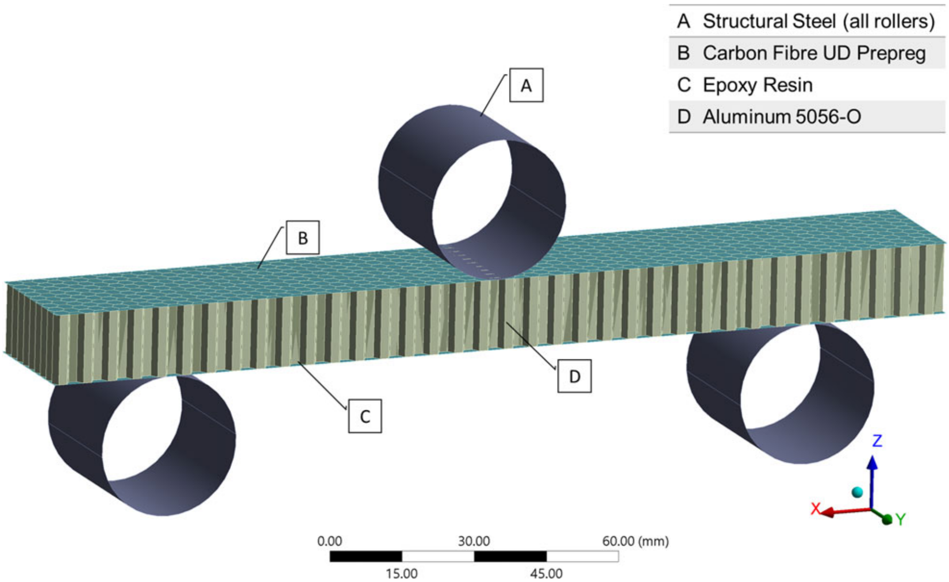

Figure 2. *Material distribution in the model (ANSYS).*

3.0 Simulation approach

3.1 Materials

The main components of a sandwich panel are the face sheets, the core and the adhesive that bonds them together. Aluminium and carbon fibre prepreg are the most used materials for the face sheets of sandwich panels. The core material is selected depending upon the desired set of mechanical properties. Commonly used face sheets are made from fibreglass, aluminium, carbon fibre and Kevlar. The core is typically made of aluminium, thermoplastic honeycomb, Nomex and stainless steel. Among these materials, aluminium offers the highest strength-to-weight ratio. Manufacturing of honeycomb core is by corrugation, expansion and molding; however, the popular manufacturing method is expansion and corrugation.

The honeycomb sandwich panel selected for this study is made from four materials as depicted in Fig. 2. Honeycomb core is modelled with Al-5056-O foils. The thickness of foils is 0.04 mm while cell size of the honeycomb core is 3.2 mm and cell height is 15 mm. Epoxy carbon UD prepreg constitutes the face sheets each of thickness 2 mm. Carbon fibre face sheets augment the honeycomb core in strength as well as in toughness. The resin represents the adhesive layer placed between the honeycomb core foils. It is this adhesive layer that joins the foils together to give it a shape of honeycomb core the thickness of each layer is 0.01 mm. The adhesive material that bonds the face sheet and the core is also epoxy resin. The pusher and supports are modelled with structural steel. The objective of using steel cylinders is to obtain complete deformation only in the sandwich structure and not in the pushers and supports so that focus remains on the crumpling of honeycomb cells. The properties are mentioned in Table 1.

3.2 CAD model of test specimen

The CAD (computer-aided design) model is prepared using *SolidWorks (Dassault Systems, USA)* and then it was analysed in *ANSYS Workbench (Version 19.2, Ansys Inc. USA)*. The model is prepared as surface as per cell width and height. The generated model was converted to step files and sent to finite element analysis software i.e., ANSYS Workbench. Honeycomb sandwich samples are prepared in two configurations and then a comparative study is performed. In these samples the only thing different is

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Table 1. Material properties

Properties	Aluminium 5056	Resin	Structural steel	Carbon fibre prepreg
ρ (g/cm³)	2.64	1.35	7.85	1.49
σ_Y (MPa)	152	33	250	2,231
σ_U (MPa)	290	33.1	460	–
E (GPa)	71	35.2	200	121
υ	0.33	0.39	0.33	0.4
G (GPa)	25.9	12.6	–	4.7
τ (MPa)	179	–	–	60

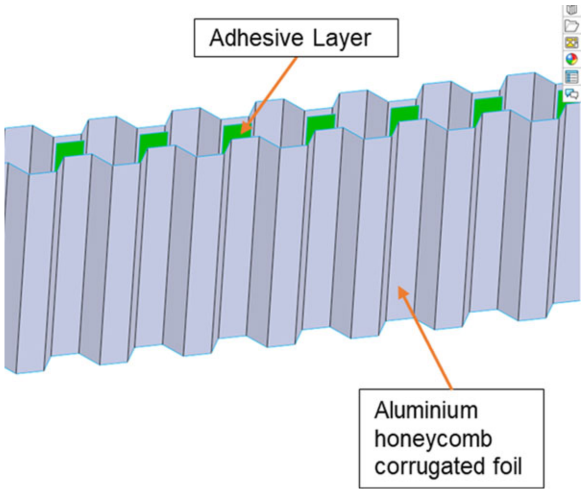

Figure 3. *Detailed view of CAD model with adhesive layer.*

the core. The two configurations of the core are *un-serrated* and *serrated*. The geometry and location of serration is expressed in subsequent sections. Apart from the core, every other component is same in both samples (see Figs. 3– 7). Linear analysis is performed on both samples.

3.2.1 Un-serrated (normal) core

In this case the core is modelled as per its manufacturing procedure i.e., corrugated aluminium foils are modelled separately and then joined together with the help of adhesive layer to form the honeycomb core. Refer to Fig. 3 for details.

By modelling the adhesive layer between the adjacent corrugated foils simulates the true picture of how the honeycomb core is manufactured. This core is then used to model complete the sandwich panel so that analyses can be performed. The honeycomb core modelled in this way gives a rational depiction of the core consequently true deformations and stress values can be expected. Details of complete CAD model are shown in Fig. 4.

The adhesive layer has been modelled as a bonded contact type on its both sides with the foils. This is phenomenon spreads in the whole core. Consequently, the simulation time is unusually high as compared to ordinary cores represented through block properties.

3.2.2 Modified (serrated) core

The second model or the modified model which is under discussion has a serrated core. The serrations are the V-shaped sections cut through the honeycomb core under the pusher region. The dimensions and

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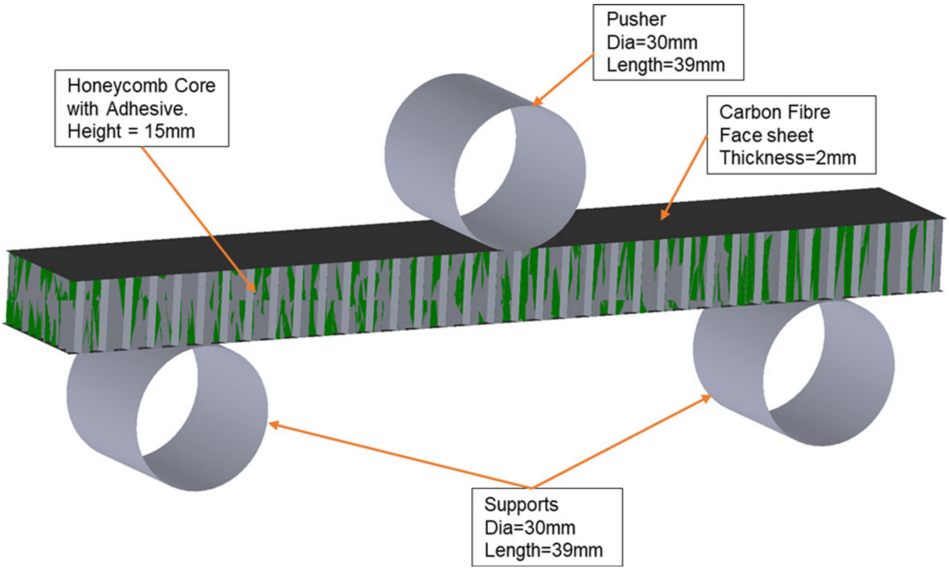

Figure 4. *CAD model of sandwich panel showing dimensions of various components.*

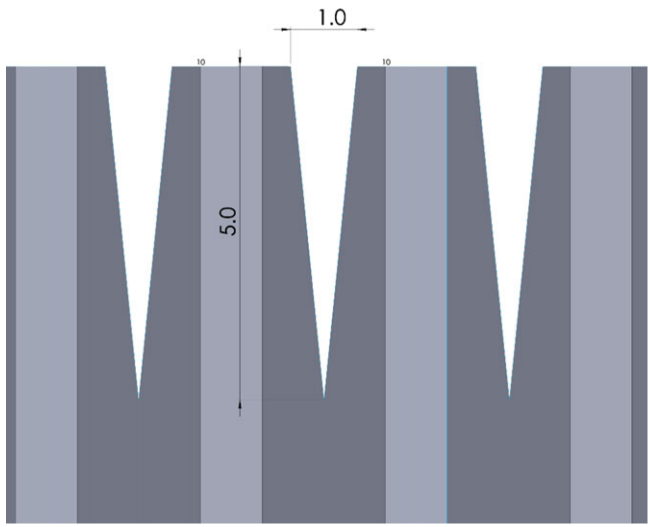

Figure 5. *Geometry of serration (dimensions in mm).*

geometry of serrations is shown in Fig. 5. The V-notch has a width of 1 mm and a depth of 5 mm. These serrations have significantly changed the results, which are elaborated in Section 7. The serrated core was modelled by modifying the aluminium foils. A total of 10 V-shapes notches were cut on the top surface of each foil so that the region under the Pusher faces the serrations. Then these modified foils were joined with adhesive layer to form the honeycomb core just like previous section. The thickness, cell size and height of the core are same.

As a result of cutting the serrations, the adhesive layer modelled between the foils have to be modified as well;, Fig. 6 shows the modified foils and the adhesive layer. This was necessary to ensure proper contacts and also to avoid the effects of extra adhesive material on the analyses.

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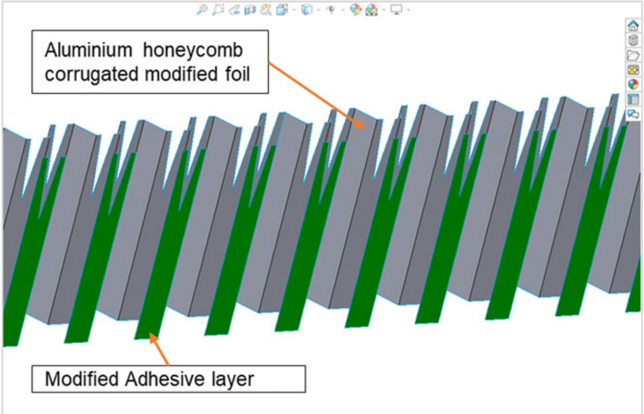

Figure 6. *Modification of adhesive layer w.r.t serrations.*

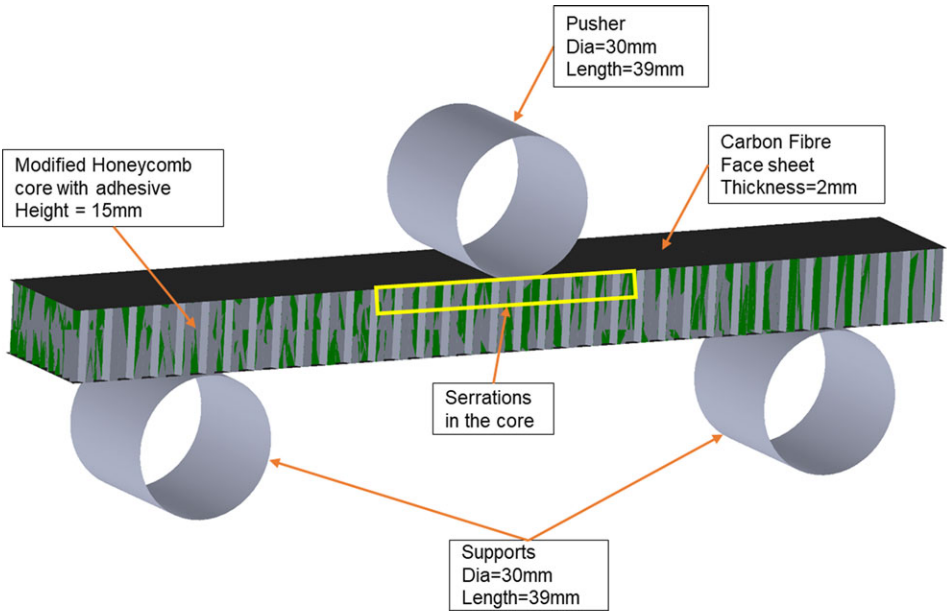

Figure 7. *Modified sandwich panel having serrated core.*

Figure 7 shows the complete sandwich having a serrated core. The only difference in this model is that of the serrated core being used instead of normal core. The rest of the components have the same specs as discussed in Section 3.2.1.

4.0 Finite element analysis (FEA)

FEA is a technique to divide the subject structure into sub-divisions called elements, the method is called meshing. The number of elements to be made is in the hands of researcher. It can be controlled by controlling the element size, element edge length, etc. The mesh can be coarse or fine depending upon the desired details of result. In this study shell elements have been used to model the components. Salient features of the mesh of the model are expressed in Fig. 8 and Table 2. FEA is used to verify the precision of the theoretical predictions so that comparison with the experimental outcomes can be

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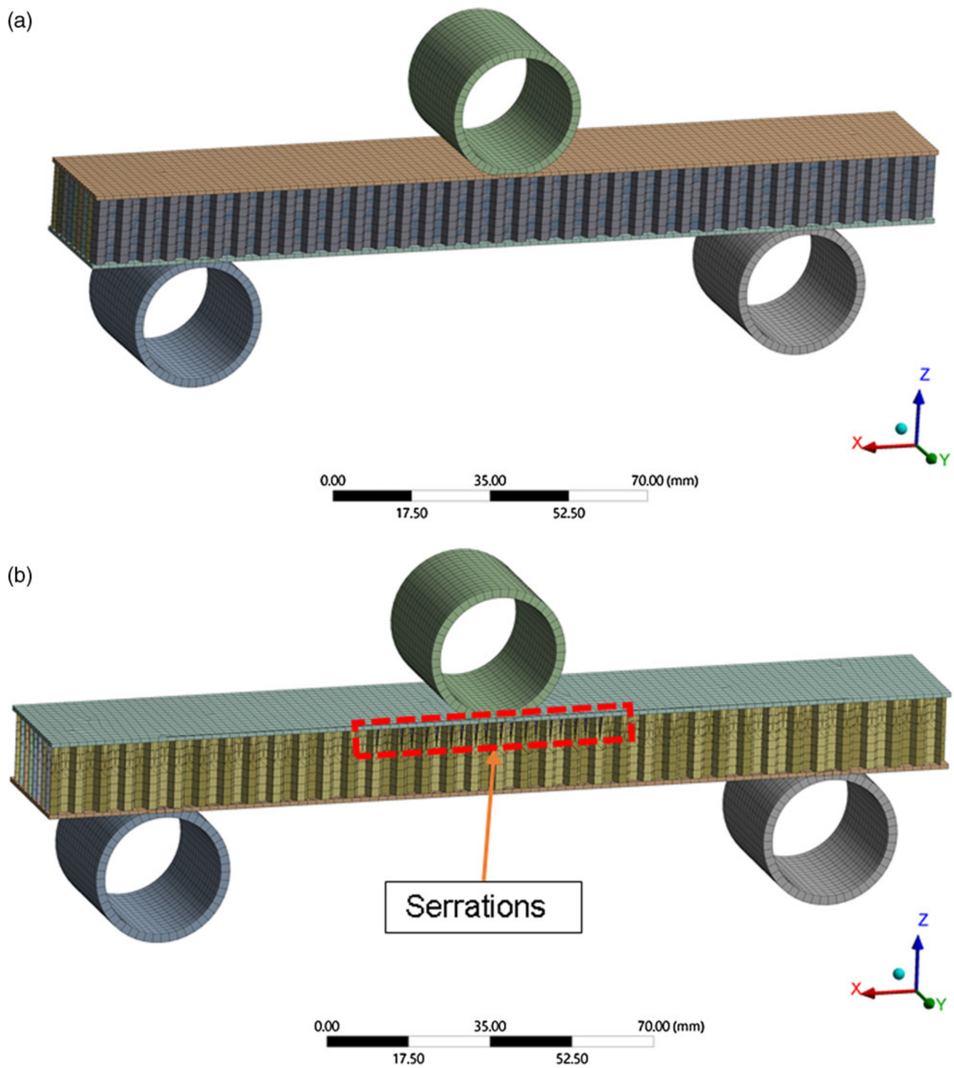

Figure 8. *Meshed model: un-serrated core (a) and serrated core (b).*

established. Experimentation can be costly; therefore, FEA is the best choice to envisage the deformations and identify remedies. FEA is an economical, highly effective and time-saving method. It is a computational technique to predict how the structure will behave against applied forces, moments, thermal loads, fluid movement, vibrations and other physical influences in the real world. FEA is helpful in solving problems in a variety of fields, including material strength, vibrations, acoustics and many more. It quantifies the results at element level and then gives a cumulative effect on the complete structure. It allows to fine tune the results in a region of concern by using a fine mesh in that area. This further enhances its capability to predict desired results at a particular point of the structure. In this way FEA facilitates the design engineer regarding structural integrity and topology optimisation.

5.0 Methodology

The main scheme of TPBT considering ASTM standard C-393 has been adopted. It suggests the sample size of 200 mm × 70 mm. But in order to simplify the solution a symmetric model is used that has a

Table 2. *Mechanical entities of model shown in Fig. 8*

Sr. No.	Entity(element size = 2.0 mm)	Un-serrated model	Serrated model
1	Elements	31,089	35,150
2	Nodes	40,704	47,724

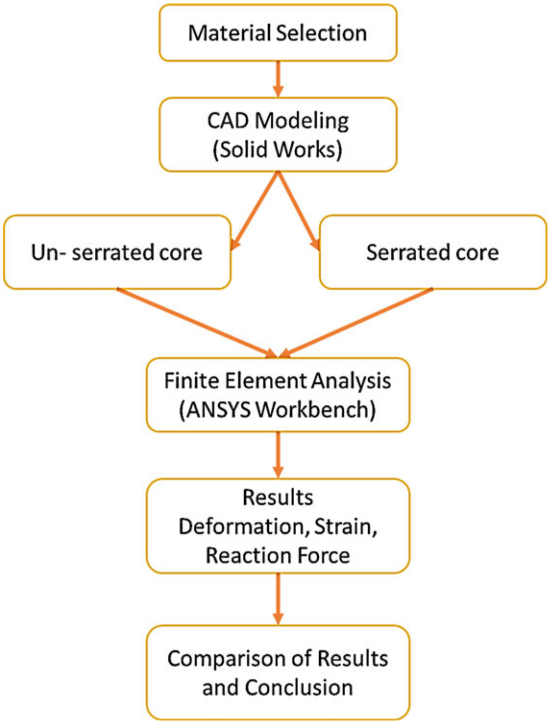

Figure 9. *Methodology adopted in this research.*

length of 200 mm and width of 35 mm while the overall thickness of both samples is 19 mm as depicted in Figs. 4 and 7. Two configurations of honeycomb sandwich panel, as discussed in previous sections, have been subjected to linear structural analysis in ANSYS Workbench. Shell model of the sandwich panel configurations is taken to perform analysis instead of solid. A brief description of methodology is illustrated in Fig. 9.

Honeycomb structure is mainly affected in four different ways i.e. layer breakage, splitting, core tearing and core crushing. It is imperative that load and constraints be applied on the model in such a way that true picture of the core crumpling can be estimated. In Fig. 10, the load is applied at point P1 on the top face sheet, also referred to as *facing* in ASTM 393 standard. The length of support span, denoted by S, is 150 mm. The sample is constrained at the supports.

Boundary conditions at the pusher and support are:

- Pusher: displacement (0, −20, 0) [x, y, z]
- Supports: remote displacement
  - Translations: Tx = Ty = 0 while Tz = allowed
  - Rotations: Rx = Rz = 0 and Ry = allowed.

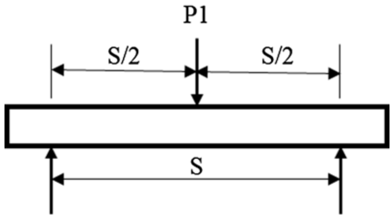

Figure 10. *Scheme of three-point bend test.*

Where, **Tx**, **Ty** and **Tz** are translation displacements along X, Y and Z-axis while **Rx**, **Ry** and **Rz** are rotational displacements about X, Y and Z-axis. Refer Fig. 8 for axis connotation.

Bonded contact has been defined between pusher and face sheet. It will transfer all the load on the top face sheet and consequently the same is applied on the honeycomb core and subsequently on the lower face sheet. The two supports having a bonded contact with lower face sheet forbid the model from translating downwards as well as side wards on the application of load as a result deformation is witnessed in the sample. To obtain uniformity in tests, the magnitude of deformation is kept same for both serrated and un-serrated samples linear static analysis is performed. This generates different deformation pattern and different reaction force is obtained at the supports. These patterns are recorded for comparison and are discussed in Section 6.

6.0 Result and discussion

Honeycomb structures provide high out-of-plane compressive and shear strength with minimal density and weight. During the forming process excessive bending and/or impact load cause considerable local deformation leading to crushing or wrinkling of sandwich structure, which is often referred to as crumpling. Both configurations are subjected to bending loads under the same boundary conditions. The results are discussed on the basis of three parameters i.e. *strain, deformation pattern and reaction forces*. The comparison between un-serrated and serrated sandwich panels is discussed based on the linear solution performed on both samples.

6.1 Strain comparison

Strain values in un-serrated and serrated sandwich panels are 27% and 32%, respectively, as shown in Fig. 11. It's important to see that the latter value is just a localised value in a single element; however, if we compare the probe values we don't see much of a difference in the whole sample. The un-serrated model has a distributed value of strain of about 3% while the distributed strain of the serrated model is 1.5% as shown in Fig. 11. We can see through Fig. 11(a) and (c) that the maximum strain is at the bottom face sheet in un-serrated core while Fig. 11(b) and (d) shows that maximum strain is at the tip of V-shaped serrations.

6.2 Buckling (bulging) effect in the core (visual comparison)

Results of linear analysis on un-serrated and serrated models clearly show the difference of bending pattern between the two cores and the magic done by the serrations. Deformation of same magnitude was applied through the pusher i.e. 20 mm. We can see that the apparent bulging is present in the cell walls of the un-serrated sandwich core under the pusher as well as above the supports. It is highlighted with red dotted shapes, see Fig. 12. However, in serrated core we do not see cell walls being buckled/bulged at the same locations. This is because the serrations cut in the core have confined the deformation to very

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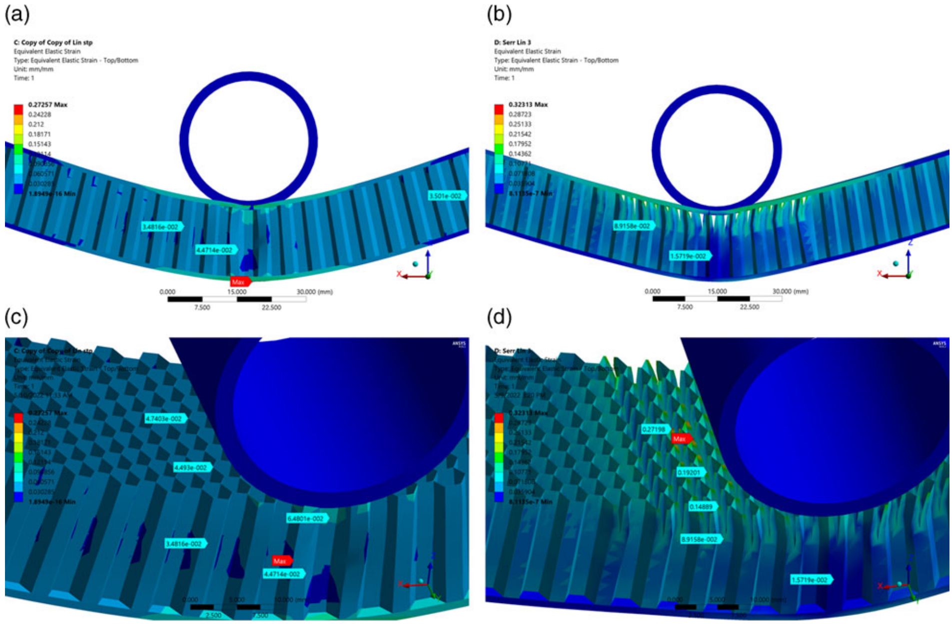

Figure 11. *(a) Strain in un-serrate model (b) Strain in serrated model (c) Strain distribution in honeycomb core of un-serrated model (d) Strain distribution in honeycomb core in serrated model.*

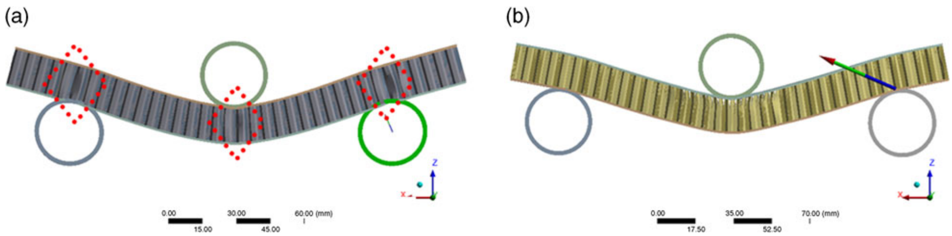

Figure 12. *Apparent buckling (bulging) effects in un-serrated core (a) and serrated core (b).*

small region consequently preserving health and strength of rest of the honeycomb core. This ensures a higher structural endurance of serrated core sandwich panels.

6.3 Reaction force

Another comparative study that facilitates in understanding the impact of serrations in the model is learning the reaction force. The same magnitude of pusher displacement i.e. 20 mm was applied to both models, but we observe that magnitude of reaction forces is different see Fig. 14, which is chiefly due to the presence of serrations in the core. The z-component of reaction force in serrated core is lesser than the un-serrated sandwich. This infers that serration led to absorption of energy in the core consequently lesser reaction force is developed at the supports.

The total reaction force is also contributed by x and y components that are neutralised by the same magnitude of reaction on the other support. The main difference is seen in Z-component as evident from Figs. 13 and 14. It tells that having the serrations offers the better performance of the honeycomb as we see no deflection in the cell walls despite giving the same deflection.

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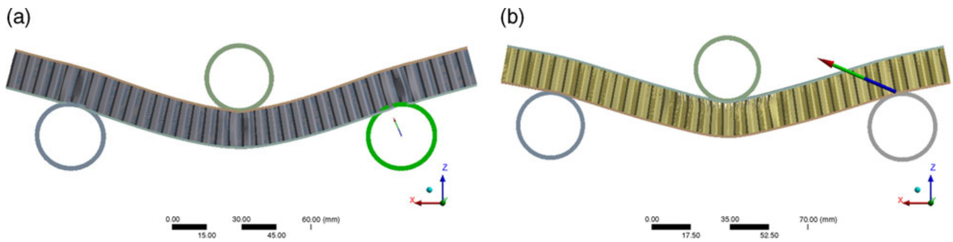

Figure 13. *Reaction force un-serrated core (a) and serrated core (b).*

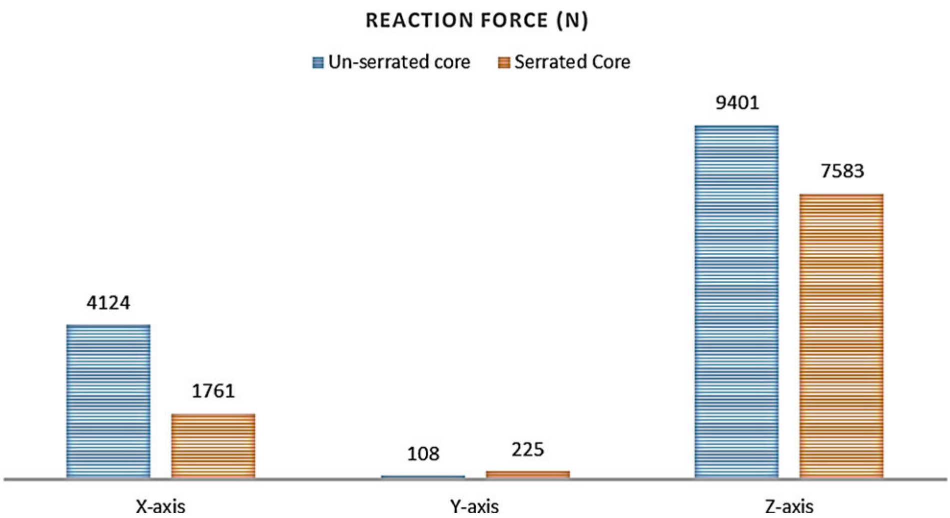

Figure 14. *Comparison of reaction force between un-serrated and serrated core.*

We know that honeycombs have the highest modulus in the z-axis while it's negligible in the x and y direction, and that is because of its cellular structure. So, any arrangement that preserves the shape of the honeycomb cell certainly enhances the strength of the honeycomb.

Serrations provide ease in bending by allowing localised deformation and limiting the deformation to a specific region. In such a way it preserves the shape of adjacent cells hence contributing to the strength of the honeycomb. This proves that cutting serrations has limited the material deformities to the upper end and is supporting the subject of curtailing the crumpling in the honeycomb core.

7.0 Conclusion

Two configurations of honeycomb sandwich panels have been studied under same boundary conditions. It is concluded that cutting serrations in the honeycomb core have proved to be a fruitful improvisation as it preserves the strength in whole core. We see a reduction in z-component of reaction force by almost 24% in serrated core as compared to un-serrated one. There are buckling/bulging effects in the cell walls of un-serrated core, which adversely affect the strength of honeycomb. On the contrary, the serrated core shows no buckling/bulging in cell walls; therefore, the serrations facilitate to restrict the deformation/crumpling to a limited region and contribute to enhance the strength of the sandwich panel. Although the values of deformation and stress are higher in serrated core, but it is localised; therefore it is tolerable as compared to un-serrated model where crumpling effects spread throughout the core.

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8.0 Future work

1. Further refinement can be brought in this study by changing the geometry and number of serrations.
2. Current study consists of linear static analysis on the cores. Non-linear study may also be performed using same configuration to see the behaviour of the core in plastic region.
3. This study is conducted on aluminium-based core. Non-metallic cores can also be analysed in the same manner. So that those structures may also be covered in which non-metallic cores are used. This will mark the effectiveness of the methodology adopted in this research.
4. Experiments could be conducted based on same footings laid down in this study so that comparison could be established between FEA and experimental results.

Declaration. The author(s) declare that they have no conflict of interest regarding the research, authorship and/or publication of this article.

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