STRUCTURAL MECHANICS OF 3D WOVEN HONEYCOMB COMPOSITES

Abstract

Honeycomb is considered an excellent structural material because of its high strength and shear rigidity, excellent energy absorbing property, high impact strength, lower weight, high crushing stress, and almost constant crushing force. Honeycomb being a cellular solid is a well-known core used to build sandwich structures while making structural composites. Because of this excellent mechanical performance, honeycombs are frequently used in the aircraft industry as a core of sandwich panels and in the automotive industry as efficient impact attenuators. The hollow spaces in the honeycomb structure reduce weight but also ensure the required strength, provided they are designed correctly. 3D woven honeycomb composite has a promising future in the lightweight application areas and can be the real substitute for aluminum and other metal alloys as these structures provide structural integrity. This thesis focuses on the manufacturing of lightweight 3D woven honeycomb composite structures of different cell geometry, the number of layers, face thickening sheet, honeycomb with different fibers, cell cross-sectional shape, different directions of hexagonal channels during weaving of honeycomb, and investigation of the effect of these parameters on the mechanical performance of their respective composites. Additionally, a comparison is made between the 3D woven honeycomb composite with metallic and 3D printed polymeric honeycomb composite structures of similar cell geometry with respect to their mechanical properties.

The textile fiber-based 3D woven honeycomb structure is engineered by using fabric geometrical parameters and mathematical expressions have been developed to calculate the repeat unit weight, fiber volume fraction (FVF), and specific weight of 3D woven honeycomb structures. Five 3D woven honeycomb fabric samples with different cell sizes of E-glass fiber were produced using model-based construction parameters on a customized rapier weaving machine. Fabric dimensional parameters were determined experimentally to validate the model value with actual results. A reasonably high agreement was observed between experimental and theoretical values. This model can be used as a tool to engineer woven honeycomb reinforcement architecture to produce lightweight structural composite materials. The main objective of this section is to predict the weight of the repeat unit, FVF, and specific weight of the honeycomb structure with different cell geometrical parameters and different materials well before its production on the weaving machine.

In the next chapter, 3D woven honeycomb structures were developed with different cell geometry by varying the cell size, free wall length, bonded wall length, opening angle, and the number of honeycomb layers keeping overall composite thickness and cell shape constant. The variation of cell geometry was carried out by changing the number of picks in the honeycomb wall. Composite samples were prepared from the honeycomb preforms with epoxy resin (matrix) using VARIM (vacuum-assisted resin infusion method) process and characterized for their flatwise compression behavior. The results revealed that the structural parameters of the 3D woven honeycomb composite influenced flatwise compression energy significantly. The regular cell shape, smaller cell size, and higher number of layers of honeycomb composites exhibited higher specific energy absorption in flatwise compression. In edgewise compression and three-point bending analysis, the specific ultimate load is higher for a honeycomb composite structure with an opening angle of

60°, smaller cell sizes, small wall length, and for a higher number of layers keeping constant thickness or constant cell shape. In the low-velocity impact test, structural changes in honeycomb composite significantly affect the specific impact energy absorption. The specific impact energy absorption increases with large cell size, less opening angle, higher wall length, and a greater number of layers. The thickened face sheet was expected not to contribute to the compressive load of the honeycomb structure; however, the bending load was improved consistently with the addition of each face sheet to the honeycomb core. 2LFC (Two-layer face sheet) has higher strength while with the increase in layer and also with 3D solid structure face sheet, specific compression energy decreased. An increase in face sheet thickness did not help to increase specific compression energy absorption but had a negative effect because of the increased weight and volume. The specific bending load was observed to be higher for 3D solid structure face sheet honeycomb composite as compared to 2D face sheet honeycomb composite of similar thickness.

3D woven honeycomb composites were prepared using three different fibers including natural and high-performance fibers to study the effect of fiber type on the mechanical properties of the honeycomb structure. The honeycomb fabric samples of similar areal density and cell size were produced from glass, sisal, and Kevlar fibers. The fabric samples were woven with similar free wall and bonded wall lengths by using a pre-decided number of picks. Other honeycomb cells parameters such as the height of the cell and the opening angle were kept constant by fabricating the moulds of the required dimension as per honeycomb cell size. Specific flatwise compression energy and specific ultimate load in edgewise compression was observed to be higher for Kevlar fiber composite as compared to glass, and sisal fiber composite. In the three-point bending and in-plane impact test, the Glass fiber honeycomb composite gives a higher specific bending load and impact energy compared to Kevlar and sisal honeycomb composites.

Numerical simulation along with experimental validation was used to investigate the flatwise compression behavior in the out-of-plane direction of 3D woven honeycomb composites with varied cell cross-sectional shapes such as hexagonal, triangular, and rectangular cell shapes. The total and unit cell perimeter of all three honeycomb cell shapes were kept constant to enable comparison of mechanical behavior. Edgewise compression, three-point bending behavior, and impact energy were compared experimentally for all three configurations. The effect of cell cross-sectional shape on the mechanical properties of honeycomb composites was investigated. Among three honeycomb composites, hexagonal honeycomb gives superior mechanical performance. The flatwise compression behavior of honeycomb structures has been predicted using FEM on the LS-DYNA platform, and the results have been validated using experimental data. The predicted values were in good agreement with the experimental results. Hexagonal honeycomb gives better flatwise compression energy as compared to other cell cross-sectional shapes as revealed by both experimental and numerical analysis.

The design and manufacturing of 3D woven honeycomb fabrics and their composites in both warp and weft directions were carried out to examine the effect of the direction of the hexagonal channel on the mechanical properties of the composites. Both the preforms were converted to their respective composites and mechanical analysis was carried out to understand the comparative advantage of the warp and weft way honeycomb weaving systems. The mechanical characteristics such as compression, three-point bending, and in-plane impact of composite samples were investigated keeping cell parameters constant. The comparison of mechanical properties of these two honeycomb composite samples revealed that warp-way honeycomb composites give better performance in edgewise compression and three-point bending test while weft-way honeycomb composite gives higher energy absorption under flatwise compression and high in-plane impact resistance. The direction of cell channels decides the direction of loading to the honeycomb cell. Since the crimps in the warp and weft directions are different, the deformation of honeycomb composite cells ought to be different in the warp and weft directions.

In the last chapter, the mechanical characteristics of 3D woven honeycomb composites were compared with the honeycomb of the existing technology of metallic honeycomb and polymeric 3D printed honeycomb. Mechanical characterization of aluminum honeycomb and 3D woven Kevlar honeycomb composite sandwich panels concerning their flatwise, edgewise compression, and three-point bending tests were carried out. 3D woven Kevlar honeycomb composite gives better results than the aluminum honeycomb for flatwise and three-point bending behavior. In the case of edgewise compression, aluminum honeycomb gives significant results as compared to 3D woven Kevlar honeycomb composite. The investigation of the mechanical behavior (i.e., compression, flexural, and impact) of FDM (fused deposition modelling)-built honeycomb structures and their comparison with 3D woven honeycomb composite structures were carried out. E-glass tow of 600 Tex was used to produce woven honeycomb samples. ABS (acrylonitrile butadiene styrene) was used as basic material to produce 3D printed honeycomb composite samples of identical cell geometry by the FDM process. The mechanical characterization revealed that the woven honeycomb structure gives better mechanical properties than the FDM-built honeycomb specimen. In flatwise compression, the FDM specimens give significant results as compared to woven honeycomb composites. However, other mechanical characteristics such as edgewise compression, three-point bending, and low-velocity impact behavior of woven honeycomb composites are superior to those of FDM specimens.

This research confirmed that the mechanical performance of 3D woven honeycomb composite structures is influenced by different parameters such as cell geometry, number of layers, face sheet thickening, fiber type, cell cross-sectional shape, and directions of hexagonal channels of honeycomb preform during weaving. The finding of this study can help to design and manufacture the honeycomb structures according to the end-use applications as it encompasses the detailed investigation of the mechanical performance of 3D woven honeycomb composites of different structural parameters. A comprehensive analysis of the relative advantage of honeycombs of different manufacturing methods can be used as a suggestive guideline to select the appropriate technique based on mechanical performance, end-use applications, and cost of manufacturing.