The Bending Stress on GFRP Honeycomb Sandwich Panel Structure for a Chassis Lightweight Vehicle

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Abstract. This paper discusses the bending stresses of the hexagonal honeycomb sandwich panel structure made of glass fiber reinforced polymer (GFRP) composite. The 1D axial hexagonal honeycomb sandwich panel structure consists of a honeycomb core and thin wallsheets. The plastic steel epoxy resin, polyaminoamide-bisphenol-A resin, and thermosetting resin were used as adhesive in every layer of the sandwich panel structure. The initial design is based on specific requirements that the panel will use as a chassis of the lightweight vehicle to achieve better fuel efficiency (Urban Concept with maximum vehicle weight is 300 kg). The axial load was dominantly on the chassis. The specimen is tested using the universal testing machine by three points bending method. The analysis is carried out through the response of adhesive between honeycomb core and wallsheets. The results show the bending stress of the honeycomb sandwich panel structure with three adhesives is more than enough for a lightweight chassis vehicle.

1. Introduction

Honeycomb construction has been used extensively in the automotive, marine and aviation industries, as a structure with high flexibility and lightweight [1-3]. In general, honeycomb construction is a sheet used as a cover panel. The panel consists of a honeycomb core, and two surface layers call facesheets. The panel is only allowed to accept bending and shearing load, in the other hand this honeycomb construction becomes weak against the impact and buckling loads that usually occur in axially loaded construction [4].

The need for lightweight materials for rigid construction is increasing. Examples of rigid construction are chassis and bumper vehicles on energy-efficient future vehicles [5]. One key to fuel savings is to reduce the weight of the vehicle. This research aims to investigate the lightweight construction (honeycomb structure) which accept axial loads like a rigid structure. Fiber reinforced polymer composite materials have been shown to have high strength and low weight. The weakness of this material needs a complicated manufacturing process and have high flexibility. Therefore, they required a method to increase the stiffness. There is still a limited amount of data about the axial load capability of a honeycomb sandwich panel structure. The construction alternative was needed to support the demand for lightweight materials that can be used in construction with axial and bending loads.
The results of this study can be used as a reference in using the honeycomb structure in general and especially on lightweight chassis vehicle. This research is important to get answers on how the ability of the honeycomb structure can be loaded with the axial and bend loads safely.

1.1. Honeycomb structure

The honeycomb is a structure formed from the arrangement of hexagonal patterns [6] at first (now can be made of rectangular [7-8], polygonal and curve [3] patterns). The honeycomb structure is generally used as a core of panel construction. The honeycomb core material has been produced with a variety of shapes and types of materials (metals, plastics, ceramics, and composites). The honeycomb structure is commonly used on sheet panels, where the structure is very strong and low weight. One disadvantage of using this honeycomb structure is susceptible to bending loads because the Poisson's ratio is positive, usually negative [9]. The simple form of the honeycomb structure as shown in figure 1 below.

![Figure 1. (a) Honeycomb core structure, (b) general view, (c) unit cell, (d) the unit cell parameters [10].](image1)

The process of making composites with glass fiber as a honeycomb core is almost the same as making composite sheets in general. The difference in the process of making this honeycomb is the hexagonal shape. Two of the hexagonal half-finished (corrugated) sheet is glued together with polymer adhesive and pressed into a honeycomb construction (hexagonal). The sequence of processes can be seen in figure 2 below:

![Figure 2. (a) Hexagonal half-finished sheet, (b) final honeycomb core](image2)

The honeycomb core provides out-of-plane stiffness to carry through-thickness compression and shear loads [9-10]. The overall in-plane stiffness of the structure also increases but ignored because less than the facesheets. The in-plane stiffness prevents the honeycomb core from bowing outwards as wrinkles form in the facings [10]. The core will behave like a spring in extension, without facesheets, and has no significant stiffness. The facesheets increases the effective in-plane stiffness [10]. The in-

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plane deformation of a cell is straightforward, without facesheets and the honeycomb cores cell walls will bend when they are loaded in-plane, giving linear elastic behaviour.

1.2. Bending stresses
Consider a simply supported beam with the total length \( L_f \), span length \( L \), thickness \( h \), and width \( b \) loaded in three-point bending, as shown in figure 3. The three-point bending used cylindrical loading head and supports.

\[
\sigma_x(y) = \frac{M_b(x)y}{I} 
\]

Where \( I \) is a moment of inertia about the z-axis of cross-section beam and \( y \) is vertical distance from the neutral axis. A composite beam has two or more elemental structural forms, that can be different or same materials, bonded or joined together. If the composite has two different property of the material, for instance \( E_f \) is Young’s modulus for the facesheet (note in subscript \( f \)), and \( E_c \) is Young’s modulus for the core (note in subscript \( c \)), then the normal stress of facesheet and core were written below:

\[
\sigma_{xf} = -E_f \cdot (y/\rho) \quad \text{and} \quad \sigma_{xc} = -E_c \cdot (y/\rho) 
\]

\[
M_b(x) = \frac{[E_f I_f + E_c I_c]}{\rho}
\]

1.3. Chassis of lightweight vehicle
The lightweight vehicle is a concept in the automotive industry to build vehicles that are less heavy as a way to achieve better fuel efficiency and handling without lessen overall safety for driver and passengers. Automotive manufacturers are constructing lightweight vehicles for two reasons, i.e., meeting vehicle emissions standards and meeting fuel efficiency standards [11]. The chassis is the mainframe in a vehicle that supports all the components and occupants. The chassis should be rigidity in bending and torsion. Most of the chassis has a 24% of total weight [12] and reducing the weight of chassis means less mass on the moving axle parts that give a better engine response of the vehicle to the road. The new fiberglass reinforced polymer composite material will reduce the weight of the chassis more than 30% compared to the steel [12].
The honeycomb sandwich panels have been used for structural applications and performance automotive industries. The honeycomb is one of lightweight core material types, which have been used in various combinations with skins of fiber reinforced polymer composite as well as aluminum [13]. Honeycomb is a part of a composite – a core material, most of them lightweight that maintains the distance between two facesheets, which are stiff concerning in-plane extension and contraction [10]. Table 1 shows the properties of aluminium (5052), aramid fiber/phenolic resin (HRH), and fiberglass/phenolic (HFT) honeycomb core.

### Table 1. The density, compressive and plate shear (W direction) strength of hexagonal honeycomb core (adopted from [14]).

| Type   | Cell size (inch) | Density (lb/ft²) | Compressive Strength (lb/in²) [MPa] | Plate shear Strength (lb/in²) [MPa] |
|--------|------------------|------------------|------------------------------------|------------------------------------|
| 5052   | 1/8              | 3.1              | 285 [1.96]                         | 130 [0.89]                         |
|        | 3/16             | 3.0              | 285 [1.96]                         |                                    |
|        | 3/8              | 3.0              | 285 [1.96]                         | 125 [0.86]                         |
| HRH    | 1/8              | 2.0              | 120 [0.83]                         | 60 [0.41]                          |
|        | 3/16             | 3.0              | 290 [2.00]                         |                                    |
|        | 3/8              | 3.0              | 290 [2.00]                         | 95 [0.65]                          |
| HFT    | 1/8              | 3.2              | 310 [2.14]                         | 95 [0.65]                          |
|        | 3/16             | 2.0              | 170 [1.17]                         | 60 [0.41]                          |
|        | 3/8              | 4.0              | 500                                | 195                                |

2. Materials

2.1. Glass Fiber Reinforced Polymer (GFRP)

GFRP is a composite material that uses a glass fiber as a fiber and a polymer as a matrix. GFRP composite was widely used in the manufacture of composite material as aircraft components, marine applications, piping, automotive components, and industrial constructions. Table 2 shows the most important of glass fiber types from a tensile strength perspective.

### Table 2. Common Glass Fiber Types Used in GFRP [13]

| Glass type | Description |
|------------|-------------|
| E          | Alumino-borosilicate family of glasses, use in most GFRP |
| E-CR       | Corrosion-resistant E-glass, better mechanical properties than E |
| R          | High-strength glass with performance intermediate to E and S |
| S          | S-glass was developed for high strength, modulus superior thermal and corrosion performance. A family of glasses composed primarily of the oxides of magnesium, aluminum, and silicon. |

The glass fibers were formed or fiberized by pulling fibers through tiny orifices in a precious metal bushing then rapidly cooled, gathered, coated with sizing, and in the case of continuous fibers, fed to a winder that configure to product roving fibers [13]. Woven roving (WR) structure firstly has used on composite armor type. Rovings were kept independent of each other until reached the loom to minimize interaction between rovings [13].

WR 200 is a glass fiber woven roving fabric that made of E-glass direct roving by bidirectional interweaving and has an area weight of 200 g/m² [15]. It was suitable for hand lay-up, mold pressing, pultrusion, filament winding and continuous laminating processes to manufacturing automotive, industrial, and marine components [15]. The features of WR 200 are compatible with multiple resin systems as a matrix, excellent corrosion resistance, moldability and laminate property, and easy operation with less resin consumption. WR 200 has a tensile strength of 820 N on Warp (machine direction) and 700 N on Weft (cross-machine direction) each 25 mm length [15].
2.2. Adhesive Bonding
The strength of adhesively bonded honeycomb sandwich panel structure is the key to mechanical behaviour and performance in-service of this structure. This bond must exist between the surface of a facesheet and the edge of a thin flexible cell wall of the honeycomb core. The joint is known as a tee or butt joint that can be effective in transmitting the shear and normal loads for sandwich panel structure [16]. The adhesive can be classified by the way they set or by chemical type. Some of the classes are Toughened Acrylics, Epoxies, and Polyurethanes [17]. The Toughened acrylics can be used in minimal surface preparation and bond well to a wide range of materials. They are fast curing and offer high strength and toughness [17].

Epoxy adhesive is common as plastic steel adhesive consists of an epoxy resin and the hardener. This adhesive can be used to join most material and have good strength, low shrinkage and do not produce volatiles during curing [17]. Polyurethane adhesive provides strong impact-resistant joints and has better low-temperature strength than any other adhesive [17]. The adhesives are useful for bonding glass fiber reinforced polymer because of their fast curing.

In this study, the type of adhesives are selected to be plastic steel epoxy resin (Devcon), polyaminoamide-bisphenol-A resin, and thermosetting resin to study the effect of the type of adhesive on the bending strength of the studied specimens, and the corresponding specimens were named types A, B, and C specimens, respectively.

2.3. Honeycomb Sandwich Panel
Generally, honeycomb sandwich panel structures consist of three layers: the high-modulus high-density facesheets, the low-density core, and the core-to-facesheet bonding adhesives. The facesheets, in the sandwich panel structures, are spaced to provide most of the in-plane tensile, compressive loads and bending rigidity, i.e., the applied edgewise loads and flatwise bending moments (figure 4(a) and 4(b)).

![Figure 4. Honeycomb sandwich section](image)

The core is designed to keep the facesheets (or wallsheets) a desired distance apart and transmits shear between them and provides most of the shear rigidity of the construction. The adhesive that bonding them together must be adequate to transfer the stresses from the facesheets (or wallsheets) to the core.
3. Experimental Setup
3.1. GFRP composite characterization
GFRP composite was made with WR 200 glass fiber and Eposchon Bisphenol A-epichlorohydrin epoxy resin mixed with Eposchon Polyaminoamide epoxy hardener matrix. Hand lay-up method was used during the composite molding with three-layer each composed. The hexagonal honeycomb core manufactured by slotting together woven glass fiber sheets reinforced polymer composite of thickness \( t_c = 3 \text{ mm} \) and density \( \rho = 1216 \text{ kg/m}^3 \). The wallsheet comprised glass fiber WR200 (of diameter 5.5–6.5 \( \mu \text{m} \)) made of E-glass direct roving by bidirectional interweaving. The fibers were embedded within an Eposchon polyaminoamide-bisphenol-A epoxy resin. The two wallsheets manufactured from the same material of the core, three plies were stacked to obtain wallsheet thickness about 3 mm, and the density \( \rho \) is 751 kg/m\(^3\). By bonding two thin wallsheets to a thicker core material, a layered 1D axial honeycomb sandwich panel structure is formed (figure 4(c)).

3.2. Three points bending test
The test specimens are made rectangular in cross-section. The width \( b \) of the specimen is taken as 45 mm, and the height \( h \) of the specimen is selected as 50, 90 and 180 mm, where the 180 mm height is the maximum height of the chassis of the lightweight vehicle. The length \( L_f \) of the specimen is taken as 240 mm where 60 mm is the total unsupported length, and span length \( L \) is 180 mm as seen in Figure 5. All the axial edgewise bending tests were carried out at a loading rate of 5 mm/min on a Hung Ta universal testing machine.

![Figure 5. Schematic drawing of three-point bending of edgewise honeycomb sandwich panel.](image)

The moment of inertia of hexagonal hollow is determined by:

\[
I_h = \frac{A}{12} \left[ \frac{d^2(1+2c) - z_30^\circ}{4c_230^\circ} \right]
\]

\[
A = \frac{3d^2\tan 30^\circ}{2}
\]

\[
Y = \frac{d}{2c_330^\circ}
\]

\[
Z = \frac{t}{y} = \frac{A}{69} \left[ \frac{d(1+2c) - z_30^\circ}{4c_230^\circ} \right]
\]

Where \( d \) is the distance from flat to the flat of hexagon shape (cell size), \( A \) is an area of hexagon and \( Z \) is section modulus. The distance cross-section of hexagon shape is 40 mm, then the result of \( I_h, A \) and
Z are 153,600, 1385.6 mm² and 6656, respectively. Equation (3) shows the bending moment theoretical when in practice, the applied bending moment is calculated with:

$$M_p(x) = \left(\frac{p}{2}\right) \left(\frac{l}{2}\right) \left(\frac{h}{2}\right)$$

(8)

$$\sigma_x(y) = \frac{M_p(x)}{Z} = \frac{p \cdot l \cdot h}{8 \cdot Z}$$

(9)

4. Results and Discussion

1D axial hexagonal bending load-displacement curves of (A) plastic steel epoxy resin (Devcon), (B) polyaminoamide-bisphenol-A resin, and (C) thermosetting resin are shown in Figure 6. There is three specific height of specimens, i.e., 50 mm, 90 mm, and 180 mm. Figure 6 indicates the load time the displacement plots for different adhesive bonding at a specific height of 180 mm. The bending results demonstrated similar load profiles for all adhesive bondings. The ultimate load for every profile has different displacement; the longer displacement indicates the higher the modulus. All of the specimens have yield point at above 1000 N.

Figure 6. The load-displacement curve of honeycomb sandwich panels subjected to the static three-point bending test with different adhesive bonding.

The curves of 1D axial hexagonal bending load can be divided into three stages: first, visco-elastic stage, load increase almost linearly with displacement until the critical yield point; second, elastic-plasticity stage, is indicates by fluctuating load with displacement increase; third, plasticity collapse stage, the load decreases as displacement increases. Burlayenko and Sadowski [18] mentioned the optimum strains as large as 10% in bending where the honeycomb core behaves like a spring, and only small strains happened in the beam, although the geometry allows large distortion of the structure. When the strain reached 10%, the core begins to exhibit non-linear behaviour, and then the deflection curve increasing rapidly [18].

There are three failure modes appear on the bending of the honeycomb sandwich panel in this study, i.e., wall crushing (WC), wall debonding (WD), and core crushing (CC). The adhesion strength between the hexagonal honeycomb cores and wallsheet appeared to be the limiting factor in several cases; debonding (figure 7(a)) is the dominant failure mode.
Table 3. Failure loads and collapse modes.

| Adhesive Type | height (h) (mm) | Displacement (max) (mm) | Fail Force (max) (N) | Fail Mode |
|---------------|----------------|-------------------------|----------------------|-----------|
| A 50          | 3.45           | 273.0 ± 6.96            | CC, WC               |
| A 90          | 3.68           | 596.2 ± 16.87           | CC, WD               |
| A 180         | 4.32           | 2114.8 ± 29.63          | CC, WD               |
| B 50          | 4.44           | 243.4 ± 3.05            | CC, WC               |
| B 90          | 5.16           | 458.2 ± 9.55            | WD                   |
| B 180         | 6.25           | 1682.6 ± 20.98          | CC, WD               |
| C 50          | 3.55           | 169.0 ± 4.47            | CC, WC               |
| C 90          | 4.24           | 378.2 ± 6.02            | CC, WD               |
| C 180         | 5.08           | 1391.6 ± 4.28           | CC, WD               |

*WC = wall crushing, WD = wall debonding, CC = core crushing, 1 at the bottom

Table 3 shows the failure loads and collapse modes that occur on 1D axial honeycomb sandwich panels. Almost all the beams failed by the core crushing mode, especially at the bottom panel (figure 7(b)), and some wall crushing mode (figure 7(c)) can occur at the same time. The strength of the hexagonal honeycomb cores is much greater than the adhesive and the thin wallsheet since there is less failure in the honeycomb core materials.

Debonding is the most dominant failure mode in the experiments for axial edgewise hexagonal honeycomb sandwich panels due to the higher shear strength of core materials compared to that of the adhesive. Figure 8 shows the applied bending stress on axial edgewise honeycomb sandwich panels with a different specific height of the specimens. The result shows that increase the height of the specimen will increase the bending stress, and the plastic steel epoxy adhesive (A) has higher strength than the others.
Kalisahak28 is ethanol urban concept car (city car) that developed by IST AKPRIND 1 team. The main goals to design and develop the Kalisahak28 are a part of fuel efficiency and use renewable energy, also a part of to fulfill the regulation of fuel efficiency world competition lightweight vehicle. The chassis Kalisahak28 and the illustration of full-frame chassis are shown in Figure 9.

Figure 10 shows the bending load case for Kalisahak28 structure. The loads that cause this bending load case scenario are body car weight (Wfb), driver weight (Wd), and engine weight (We). In this case, the bending and shear loads are calculated only on one frame, where loads of each part are assumed homogeneous and a half of their weight.

The experimental results indicate that all of the 90 mm and 180 mm height specimens can handle more than 378 N and 1391 N, respectively. The bending stress reached a minimum of 0.46 MPa and 1.71 MPa for 90 mm and 180 mm height specimens, respectively. It means all of the type adhesives can be used in this chassis. The best adhesive is A type (plastic steel epoxy).
Figure 10. Bending moment diagram (BMD) and Shear force diagram (SFD) of Kalisahak28 Chassis.

This result is compliance with Manalo et al. [19] and Zhang et al. [20], wherein beams and similar applications, structural components are used in the edgewise orientation for higher strength and stiffness, the composite sandwich beams tested in the edgewise position failed at a higher load with less deflection.

5. Conclusions
The 1D axial hexagonal honeycomb GFRP composite sandwich panels with hexagonal honeycomb cores have been designed and manufactured using adhesion method. Three-point bending test was carried out to study the bending stress of the composite sandwich panels. Failures and theoretical static loads were analysed and calculated to predict the bending stress response all of the specimens with different adhesive type. The bending stress of 1D axial hexagonal honeycomb sandwich panel with three adhesives (plastic steel epoxy, polyaminoamide-bisphenol-A resin, and thermosetting resin) is more than enough for Kalisahak28 lightweight chassis vehicle.

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