Mould design and manufacturing considerations of honeycomb biocomposites with transverse fibre direction for aerospace application

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Abstract. Sandwich structures with honeycomb core are known to significantly improve stiffness at lower weight and possess high flexural rigidity. They have found wide applications in aerospace as part of the primary structures, as well as the interior paneling and floors. High performance aluminum and aramid are the typical materials used for the purpose of honeycomb core whereas in other industries, materials such as fibre glass, carbon fibre, Nomex and also Kevlar reinforced with polymer are used. Recently, growing interest in developing composite structures with natural fibre reinforcement has also spurred research in natural fibre honeycomb material. The majority of the researches done, however, have generally emphasized on the usage of random chopped fibre and only a few are reported on development of honeycomb structure using unidirectional fibre as the reinforcement. This is mainly due to its processing difficulties, which often involve several stages to account for the arrangement of fibres and curing. Since the use of unidirectional fibre supports greater strength compared to random chopped fibre, a single-stage process in conjunction with vacuum infusion is suggested with a mould design that supports fibre arrangement in the direction of honeycomb loading.

1. Introduction
Over the years, a large amount of researches has been conducted on the green and eco-friendly materials. However, fundamental researches in regards to natural fibre have deepened only in the recent years due to increasing demands for better environmental protection. The natural fibre reinforced polymer composites become high valuable materials due to their low cost and satisfactory mechanical properties, which make them attractive due to availability and renewability of raw materials. Normally, natural fibres are used as reinforcing material or else known as fillers for polymer based matrices [1]. They are renewable, cheap, completely or partially recyclable and biodegradable. Natural fibres have been proven to be the alternative to synthetic fibre in transportation including aerospace industry [2]. They have advantages of low density, high strength-to-weight ratio and most importantly, they are abundantly available and low cost compared to synthetic fibres. However, the primary disadvantage of natural fibre composites is their relatively high
One of many applications in using natural fibres is in the form of honeycomb structures. Honeycomb structures are man-made structures that resemble beehives, which consist of hexagonal cells. Applications of the honeycomb structures in aircraft parts include doors, wing flap, floors, wing-body fairings, rudders, overhead stowage bin, ceiling or sidewall panels, engine cowl, spoilers, nacelles and radomes [4]. The main function of using this structure is to reduce the sum of materials used, and to reach minimum weight and materials' cost in the manufacturing process. Honeycomb core with reinforced polymer composites offer greater specific stiffness and strength properties in flexure compared to their monolithic counterparts [5]. The most common materials used in manufacturing the honeycomb core include aluminum, fiberglass, carbon fibre, Nomex and also Kevlar reinforced with polymer. As the research goes on, the materials of honeycomb structures had been varied from time to time and there is an increasing demand to use natural fibre as the reinforcement to produce honeycomb biocomposites.

Natural fibre composite that is transformed into honeycomb cores improves weight saving, mechanical properties and also functional capabilities as heat dissipation, vibration control and energy dissipation characteristics. This has extended their application from predominantly non-structural components to load bearing structures. Recent researches explored the potential application of honeycomb structures from natural fibres and several techniques were proposed to develop the honeycomb from natural fibres. These techniques include fabrication of corrugated sandwich structures and single core structure. In both techniques, the type of resin dictates the design of the mould. For example, closed mould is needed for thermosetting resins whereas thermoplastics resin needs a mould that is made up of material that can withstand high temperature.

2. Existing fabrication process of honeycomb biocomposites

There are two types of process that can be done to fabricate honeycomb core depending on which type of resin used. They are corrugation process and single core process. Based on the literature review, normally single core process used thermosetting resin in a closed mould. On the other hand, corrugation process used thermoplastics resin in a compression mould. This is due to the characteristic of resin itself, either it is in solid or liquid form. However, in corrugation process, several processing steps are necessary such as compression, bonding, heating and cutting before it can be formed into a honeycomb core. The following are reviews on the development of natural fibre honeycomb core at the present time.

2.1. Corrugation process

Figure 1 shows the setup used for corrugation process by G. Petrone et al. (2013). Two types of fibres, which are unidirectional flax fibre mat and also random fibre mat, are used to make the core. They are fabricated using film stacking process where dry flax max and Low Density PolyEthylene (LLDPE) films are interleaved and laid between half hexagonal matched-dies that have the ability of heating and cooling process. The matched-die is heated up to 165°C after closing the mould at 500mm/s. A constant forming pressure of 0.5 MPa is maintained throughout the heating cycle for consolidation and the formed part is cooled within the die to avoid spring-back. A few other processes involved in producing the core are the laser cutting process of the corrugations to desired core thickness, and their assembly and bonding process using ultrasonic methods [6]. In addition, Rao et al. fabricated honeycomb core of sheet sisal fibre and polypropylene composites using the thermoforming process and assembling process, including ultrasonic bonding [7]. The sheets are thermoformed into half hexagonal and sinusoidal profiles using the matched-die thermoforming technique with forming rate of 500mm/min and 165°C die temperature. The formed corrugations are then extracted after they are left to cool to room temperature in the die. The corrugated sheets are cut to desired height and bonded using ultrasonic welder.
From both works, it is concluded that using corrugation process has a main disadvantage of involving too many processes, which increases manufacturing costs.

**Figure 1.** Matched dies for forming and ultrasonic bonding of flax-PE honeycomb core [5]

2.2. Single core process

From Ariel S. et al. (2014), a single core of jute fabric reinforced with vinylester composites is fabricated using two methods [5]. The first method is using a mould with fixed inserts as shown in Figure 2. The jute fabrics were placed between the inserts in zigzag pattern in ribbon direction and the vinylester were then poured into the mould at 20°C. The ensemble was molded under 50MPa pressure in hydraulic press for an hour at 80°C. The core was later post cured for 2 hour at 140°C in an oven. This method however results in different average fibre volume contents for the longitudinal and diagonal walls.

Meanwhile, the second method is by lateral compression method that allows for the lateral compression of the ensemble as shown in Figure 3. The resin wetted jute fabrics were intercalated between combs in ribbon direction, and the ensemble was then laterally pressed and clamped to remove excess resin and to drag entrapped air bubbles. Similar to the method for mould with fixed inserts, there is no longitudinal force applied to the fibre while disposing it into the mould. Both methods were completed with thermal treatments to cure and post-cure the resin. Using the mould with lateral compression requires the user to manually insert the fiber in between the hexagonal insert, which usually results in the lack of consistency of fiber volume throughout the honeycomb core structure.

**Figure 2.** Mould with fixed inserts

**Figure 3:** Mould with lateral compression
2.3. Comparison of corrugation process and single core process

The corrugation process contains several procedures such as cutting and ultrasonic bonding as mentioned before. Corrugation process is mainly about producing honeycomb core layer by layer, and then assembles them into a sandwich structure. It involves the use of many machines and labor works, thus increases the manufacturing cost. Many precaution steps need to be taken while fabricating honeycomb core structure with corrugation process such as the distribution of fiber volume in every layer and consistent length of the corrugation core (or otherwise, another cutting process has to be done to maintain the core length). Corrugated sandwich may have defects where the layer of sandwich does not perfectly bond to each other, or the cutting size of the layer is not the same, which results in inconsistent length of honeycomb core.

In contrast, single core process does not involve any other processes and it is easier to be used. Single process will readily produce a honeycomb core without the process of cutting, bonding and assemble. It is obvious that single core process is more reliable compared to corrugation process. This method can save a lot of time because it involves only one process for each core.

3. Methodology

Figure 4 shows a flowchart of this work. After the research requirement is identified, the next step taken in order to achieve the objective of this research work is by conducting a literature review. Before proceeding with CAD design using Solidwork software, the literature review is done to gather the information through research of associated fields that comprise of the manufacturing of honeycomb structure, type of mould used, suitable materials for the mould and the dimensions involved in designing the mould in accordance with ASTM standard, including all the detail size of honeycomb core structure such as wall thickness, core thickness and cell size. In this project, epoxy will be used as the resin. From preliminary work, it is found that epoxy and aluminum does not bond well. This is the reason aluminum is chosen as the material of the mould. The kenaf/epoxy composites can be easily taken out as it will not stick to the aluminum mould.

The process parameters highlighted in this work are pressure of vacuum infusion, weight ratio of kenaf to epoxy composite, temperature and number of inlet and outlet of the mould. The flow rate of resin into the mould depends on the pressure used. For example, in this work, the initial pressure should be around 60 psi. Initially, the vacuum process is run without the usage of resin in order to remove trapped air inside the mould. Once the reading of pressure is stable, the vacuum pressure will be increased to 80-100 psi and resin is infused into the mould. The epoxy has three types of curing rate which are slow, medium and fast curing. The one used in this experiment is a type of slow curing epoxy. Therefore, the pressure set must be suitable for the curing rate. If a higher pressure is used, the flow rate of resin will increase but air bubbles are most likely to form in between the fibres. However, if the pressure is too low, the resin will cure before it completely spread out into the mould. The weight ratio of kenaf fiber to epoxy is 10:90.

The next parameter is the position of inlet and outlet at the mould. Resin will be infused through the inlet while the outlet is to remove excess air and resin during infusion process. The position of inlet is important to make sure that the resin is spread evenly throughout the mould. For this research, the mould is designed to have five inlets and one outlet as shown in Figure 6. Vacuum infusion and curing process will take place under room temperature. The curing process usually takes 24 hours before epoxy hardened.
Start

Identify research requirement
- Problem Statements
- Project Objectives
- Project Scopes

Literature Review

Design Consideration
- Material – aluminum & polymer
- Fibre arrangement – chopped fiber & unidirectional fibre
- Standard dimension – Tencate Composite, Amber, Showa aircraft & Hexcel.

Final Design Selection
- Material- Aluminum (based on previous work)
- Fibre arrangement (Unidirectional fibre)
- Process (Vacuum Infusion)

Fabricate mould

Fabricate Honeycomb

Tensile test using ASTM 3039

Analyze data & observe damage mechanism

YES

Conclusion

Figure 4. Project flowchart
4. Initial design concept
A preliminary work has been done on a single core process using open mould with manual fixed insert. The work was focused on fabrication of mould to produce honeycomb core of rice husk reinforced with polypropylene composite. The mould was fabricated using aluminum and the hexagonal inserts are made from Allen key of harden mild steel. The mould is shown in Figure 5. The mould is fabricated using the processes of CNC Milling, EDM wire cut and EDM Die Sinker. The functionality of the mould has been demonstrated with composites powder blend that was manually compressed between gaps of inserts in the mould and cured in the furnace with temperature up to 250°C. However, it was found that this method is not suitable for thermoplastic resin as it comes in pallet form and difficult to compress them into the gap of hexagonal inserts. Furthermore, heat transfer to the mould was uneven at the surface and at the centre of the mould, causing the thermoplastic's failure to melt completely as shown in Figure 5b. The difference between this initial design concept and previous work by Ariel S. et al. (2014) is the type of resin used. The resin used previously was thermoset while in the initial design was thermoplastic.

Figure 5. (a) Drawing of open mould of inserts, (b) composites failed to melt completely

5. Proposed single core process with vacuum infusion
In this work, a honeycomb core of kenaf fibre/epoxy with transverse fibre direction is introduced by using the vacuum infusion using single core process. Single core is proposed because it uses less manufacturing process and using vacuum infusion method will increase the consistency of resin flow into the mould, thus ensure the resin spread evenly throughout the mould. Unidirectional fibre arrangement provides a greater load bearing as compared to random chopped fibre. In this work, transverse fibre orientation is suggested since honeycomb core mainly supports transverse compression. The preparation is started by fabricating the mould using aluminum to prevent the composites from stick to the mould. The mould is designed to support the use of continuous unidirectional kenaf fibre in honeycomb structure. All the dimensions of the mould are referred to the standard size of honeycomb structure used in aircraft. A single core mould with fixed inserts is designed based on the aerospace specifications for honeycomb core structures from four companies: Tencate Advance Composites, Amber Composites, Showa Aircraft Industry and Hexcel [8–13]. It is found that the cell size ranges from 3.2 mm to 19 mm and the core wall thickness is in the range of 2 mm to 100 mm with a tolerance of ±0.125 mm. The material for honeycomb core is kenaf fibre reinforced with epoxy. The epoxy is chosen due to the fact that it is more suitable to be used in vacuum infusion process compared to the thermoplastic polymer. Furthermore, as compared to other resins, epoxy composites exhibit higher strength values, thus contribute a higher ultimate tensile strength in the structure [14].

The honeycomb core will be fabricated using vacuum infusion process, thus a closed mould as shown in Figure 6 will be used. The black arrows indicate the inlet where resin will be infused and the red arrow indicates the outlet to the vacuum pump. A gasket rubber is mounted at the surrounding of top cover and base to prevent air from entering the mould. The height of the hexagonal inserts is depending on the core thickness. In this research, a honeycomb core thickness of 10 mm and wall thickness is 2 mm is suggested. Kenaf fibre is arranged in transverse direction in the mould before infusing the resin. Vacuum infusion has the advantages of consistent flow of resin and not depending on the workers’ concentration and skills [15].
The vacuum pressure is maintained at 80 psi while infusing the resin into the mould to maintain medium flow rate of the resin in order to prevent air bubble trapped between the hexagonal inserts. Furthermore, the mould is designed with five injector pins at the bottom of the base as shown in Figure 7 (as indicated by the arrows) to ease the dismantle process of honeycomb structure from the mould. In addition, more injector pins can be added in the event that the honeycomb core is still difficult to be dismantled from the mould.

6. Conclusion
A single mould has been designed properly such that it can be used to produce honeycomb core structure with transverse fibre direction using vacuum infusion method. This method can reduce manufacturing cost besides having a major advantage of consistent flow of resin into the mould. The presence of injector pin will ease the dismantling process compared to the first design concept. Furthermore, the mould is easy for maintenance as the inserts are not mounted permanently to the base.

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References
[1] Al-oqla F M and Sapuan S M 2014 J. Clean. Prod. 66 347–54
[2] Riedel U and Nickel J 2005 Biopolym. Online 272 34–40
[3] Bongarde U S and Shinde V 2014 Int. J. Eng. Sci. Innov. Technol. 3 431–6
[4] Liu L, Meng P, Wang H and Guan Z 2015 Compos. Part B Eng. 76 122–32
[5] Stocchi A, Colabella L, Cisilino A and Álvarez V 2014 J. Mater. 55 394–403
[6] Petrone G, Rao S, De Rosa S, Mace B R, Franco F and Bhattacharyya D 2013 Compos. Part B 55 400–6
[7] Rao S, Yadama V and Bhattacharyya D 18th Int. Conf. Compos. Mater. p1–6
[8] Tencate Advance Composites TenCate Advanced Composites
[9] Antibody C D 2011 Product Datasheet 2011–2014
[10] Amber Composites 2005 Aac amber aluminium commercial honeycomb
[11] Showa Aircraft Industry Co. Ltd. 2012 PAA-SHH
[12] Cell H and Specifications S 2012 Aramid Fiber/Phenolic Resin Honeycomb 1–2
[13] Hexcel Composites 1999 Honeycomb Data Sheets 1–40
[14] Mahjoub R, Mohamad J, Rahman A, Sam M and Raftari M 2014 J. Mater. 64 640–9
[15] Gaetzi R 2008 Why vacuum infusion benefits your quality, budget and environment