Mechanical behavior of Kenaf/Epoxy corrugated sandwich structures

S Bakhorì, M Z Hassan, Y Daud, S Sarip, N Rahman, Z Ismail, and S A Aziz
1UTM Razak School of Engineering and Advanced Technology, Universiti Teknologi Malaysia Kuala Lumpur, Jalan Sultan Yahya Petra, 54100 Kuala Lumpur, Malaysia
2FPSK, Tower B, Persiaran MPAJ, Jalan Pandan Utama, 55100, Kuala Lumpur

Email: mzaki.kl@utm.my
Phone: +60326154629

Abstract. This study presents the response of kenaf/epoxy corrugated sandwich structure during quasi-static test. Force-displacements curves have been deducted to determine the deformation pattern and collapse behavior of the structure. Kenaf/epoxy sandwich structures skins fabricated by using hand layup technique and the corrugated core were moulded by using steel mould. Different thicknesses of corrugated core web with two sizes of kenaf fibers were used. The corrugated core is then bonded with the skins by using poly-epoxy resin and has been cut into different number of cells. The specimens then tested under tensile and compression at different constant speeds until the specimens fully crushed. Tensile tests data showed the structure can be considered brittle when it breaking point strain, \( \varepsilon \) less than 0.025. In compression test, the specimens fail due to dominated by stress concentration that initiated by prior cracks. Also, the specimens with more number of cells and thicker core web have higher strength and the ability to absorb higher energy.

1. Introduction

Application of composite sandwich structure in industries is getting expanded. The characteristics of this structure can be considered good performance in specific modulus and specific strength also known as stiffness-to-weight ratio [1, 2] and strength-to-weight ratio respectively [3-5]. Sandwich structure has also shown best properties in shear strength and good ability to absorb energy [4-6]. In various types of applied load condition, bonding between the core and the skins exhibits different mechanical response. This is due to the optimisation of the energy absorption of the sandwich structure [7]. Also, geometrical composition of the core members has important features that influenced the deformation pattern and the strength of the structure [8]. As the structure reached the peak stress in a compression test, the micro-buckling appeared and the failure load of the sandwich structure can be expressed as,

\[
\frac{1}{P_{cr}} = \frac{1}{P_E} + \frac{1}{P_S}
\]

where, \( P_{cr} \) is the critical buckling load, \( P_E \) is the Euler buckling load and \( P_S \) is the core shear buckling load. A previous study [9] suggested that the corrugated core failure was caused by short strut, subsequently decreased the stability of the core that caused micro-buckling during compression test.
The study also suggested that by increasing the thickness of the core, the stiffness of the structure also increased, then the deflection had decreased. Another study by Zhang [10] reported that the sandwich structure capable of absorbing high energy also demonstrated good mechanical properties. Another investigation of composite rod reinforced PVC foam panels using easy rules of mixtures also showed a good capability to absorb energy during compression test [7].

Kenaf is a natural material that has potential to replace conventional fibre in composite structure. It offers competitive cost and easily grow in tropical country. This study aims to investigate quasi-static response, energy absorbing and failure modes of kenaf/epoxy sandwich structures. The overall deformation pattern and collapse behaviour will be characterised by force-displacement data.

2. Experiment Set Up

2.1. Manufacturing process

Kenaf/epoxy sandwich structure consists of skin layer and corrugated core have been prepared using kenaf natural fibre and poly-epoxy resin. The epoxy resin used as binder to bind the skin and core. Both the skin and core were layup by hand. The skins were initially prepared using 300mm × 300 mm flat metal mould. The corrugated core structures were prepared using corrugated mould. The mould consists of uniform corrugation with trapezoidal profile. The mould was made by steel with the dimension of 510 mm × 300 mm using computer-controlled machine (CNC). The top and bottom cavity plate of the mould illustrated as in figure 1.

![Figure 1. Schematic diagram of top and bottom cavity plate of corrugated steel mould.](image)

| Material      | Specimen ID | No. of unit cell | Kenaf thickness (mm) | Corrugated core thickness (mm) | Skin thickness (mm) | Mass (g) |
|---------------|-------------|------------------|----------------------|-------------------------------|---------------------|----------|
| Kenaf/epoxy   | 2A, 2B, 2C  | 2                | 4                    | 3.5                           | 5                   | 30       |
|               | 3A, 3B, 3C  | 3                | 4                    | 3.5                           | 5                   | 40       |
|               | 4A, 4B, 4C  | 4                | 4                    | 3.5                           | 5                   | 51       |
|               | 4C, 4D, 4E  | 4                | 8                    | 6.1                           | 5                   | 59       |

Table 1. Specimen properties of kenaf/epoxy sandwich panels.

Both the flat metal sheet and corrugated mould surface were layered by wax before poly-epoxy resins were applied. Then, the kenaf fibre was laid on the surface with poly-epoxy resin. Two different thicknesses of corrugated core, 4 mm and 8 mm kenaf fibre were used. To reduce voids, roller or brush was used to remove air bubbles that trapped within the layers. Then, the top plate and upper metal sheet were placed on the laid kenaf fibre with poly-epoxy resin and being clamped together with
the lower plates, and left for 24 hours to cure. Finally, the sandwich structures cut into various sizes as shown in Figure 1 for subsequent tests.

2.2. Experimental procedure

Tensile and compression tests were carried out using Shimadzu AG-X Universal Testing Machine. For tensile test, each material was tested in tension according to ASTM D638 Standards. Three specimens were tested for each different tensile speed (1 mm/min, 150 mm/min and 300 mm/min). For the compression test, the sandwich panels were tested in different number of cells (2 cells; 3 cells; 4 cells) and different thickness of the core web (4mm and 8mm). Cell is the void produced by repetitive trapezoidal corrugated core. In this test, the sandwich panel placed between the compression plates of the testing machine and uniform lateral load applied by giving a constant speed of the machine. The experiment stops when the sandwich panels are fully crushed. Data was recorded in the force-displacement traces through the machine recording system.

3. Results and Discussion

3.1. Tensile strength of kenaf/epoxy structure

![Stress-strain curve for kenaf/epoxy tensile test.](image)

Figure 2 show the stress-strain curve for kenaf/epoxy specimen in tensile test at the speed of 1 mm/min. Based on the graph, the specimen initially shows elastic behaviour and followed by plastic behaviour. In the elastic region, the proportional limit stress, $\sigma_{pl}$ is recorded at 2.05 MPa and the proportional limit strain, $\epsilon_{pl}$ is 0.0006 mm/mm. The upper yield point, $(\sigma_Y)_u$ of 2.88 MPa and the lower yield point $(\sigma_Y)_l$ of 2.85 MPa also recorded. The strain value where the yield ends is at 0.006 that is 10 times greater than the strain of the proportional limit of 0.0006 MPa. The specimen seem to be hardened until it reaches the ultimate stress, $\sigma_u$ at 27.58 MPa and the stress total failure, $\sigma_f$ at 27.33 MPa. The strain failure value is 0.019 mm/mm which is 31 times greater compared to strain of the proportional limit. During the tensile test, the matrix already brooks at the end of second region but the data keep to continue as the strain increases. This could be explained by strain hardening of the fibre due to pulling out condition, detachment and debonding. Therefore, large amount of overall force needed to break the kenaf fibres.
Figure 3. Stress-strain curve for kenaf/epoxy tensile test with different loading rate.

Figure 3 shows the failure modes of the specimens when three different loading rates applied under tensile test. It is observed that specimens undergo uniform deformation and localise necking. A uniform deformation starts when loading rate applied the stress reached a maximum value. Then, the stress is reduced as the cross-sectional area of the specimen reduced. At this point, kenaf natural fibre achieved the maximum force. Elastic modulus for these specimens is 3.50 GPa (for the loading rate of 1 mm/min), 1.85 GPa (for the loading rate of 150 mm/min) and 1.75 GPa (for the loading rate of 300 mm/min). The figure, shows that an increase of loading rate is resulted an increase in elastic modulus of elastic for the kenaf/epoxy laminates. As we can be seen from the figure, all the specimen break at strain that are less than 0.025mm/mm and the stress required to break all specimens are less that 30 N/mm². From the observation it could be suggested that the kenaf/epoxy specimens are considerably brittle.

3.2. Quasi-static response of kenaf/epoxy sandwich structure

The force-displacement relationship of quasi-static compression test of kenaf/epoxy is shown in figure 4. The compression test data have determined three comparable phases; they are elastic deformation, compression shear-coupled progressive buckling and densification [11]. Firstly, the curve shows non-linear trend. This happened because the load is not applied yet and the compression plate does not touch the upper skin of the sandwich structures. Therefore, a large displacement is recorded because the thickness of the sandwich panel is not lateral to each other [4]. Non-linear trend of the stress is kept to increase during the compression until the peak stress achieved which indicates that the specimens are having elastic deformation as shown in Figure 5(a) and stops at the peak load. At this point, the structure is having compressive shear-coupled progressive buckling upon the failure of the corrugated-cell structure as in figure 5(b). This could decrease its stability and the core wall starts to buckle up as in figure 5(c). Subsequently the applied force at this phase has been reduced. At the densification stages, the core is break off and the shape of structure is changed as the load increases as in figure 5(d).
The compression tests results of kenaf/epoxy sandwich structure have also been carried out with different number of cells. Force-displacement data have been recorded and plotted in one graph as shown figure 6. This experimental data showed that the specimen that has more number of cells indicate higher peak load compared to other specimen that has less number of cells. The highest peak load of 6.75 kN for four cells specimen, followed by 4.65 kN and 2.9 kN for three cells and two cells specimen. During the compression test, the load slightly decreases before reaching the peak stress. It can be explained by edge debonding between the core and the skins that reduce the contact area as showed in figure 5(b). The major load reduction after the peak stress is due to instability of the core where the structure begins to fracture. At the end, the normal force regain until the compression stopped. At this point, the delamination of the sandwich structure occurred. The failure modes of the specimens were dominated by stress concentration and cracks were initiated.
Figure 6. Force-displacement curve of kenaf/epoxy sandwich panel with different number of cells.

Figure 7 shows the comparison of kenaf/epoxy force-displacement curves with different core-web thickness. The peak load for 8 mm and 4 mm core-web sandwich panel are 17.55 kN and 6.76 kN respectively. This means 8mm corrugated core panel needs higher stress to make it lose core stability and to initially buckle [4]. This result is clearly shown that by increasing the thickness of the corrugated core is giving significantly increased the peak strength of the sandwich panel during the quasi-static compression test [11].

Figure 7. Force-displacement curve of kenaf/epoxy sandwich structure with different core web thickness during compression test.
Figure 8: Total energy absorption for corrugated kenaf/epoxy sandwich structures.

Total energy absorption was calculated by measuring area under force-displacement curve. The total energy absorption for this study is shown as in figure 8. Sandwich panel that have 2 cells have total energy absorbed of 94.51 kJ/kg whereas for panel with 3 cells is 134.59 kJ/kg and panel with 4 cells have the total energy absorbed of 161.63 kJ/kg. Kenaf/epoxy sandwich panels with more number of cells have absorbed more energy. The panel that has highest energy absorption, 365.07 kJ/kg is the panel that consists of 4 cells with doubled core thickness of 8 mm. By comparing the panel that have 4 cells with 4mm core thickness, the total energy absorption of this panel has 2.25 times higher. This data suggest that by increasing the core thickness could increase the stiffness and strength of the panel structure.

4. Conclusions
Series of tensile and compression tests have been carried out to investigate the response of kenaf/epoxy corrugated sandwich structure. Follow are the conclusions that can be deducted from the current study.

(a) The tensile test showed that the kenaf/epoxy specimen can be considered as brittle material.
(b) Failure mode of the sandwich panels have been nominated by stress concentration that begins with initial cracks.
(c) Sandwich structure with more number of cells and have thicker corrugated core have the higher strength.
(d) Panels that have more number of cells and have thicker core web showed good ability to absorb more energy.

Acknowledgements
The authors would like to acknowledge Universiti Teknologi Malaysia Kuala Lumpur for providing laboratory facilities and aids under project no. PY/2014/03023.

References
[1] Castanié B, Bouvet C, Aminanda Y, Barrau J-J, Thévenet P 2008 International Journal of Impact Engineering 35 620-34
[2] Bartolozzi G, Baldanzini N, Pierini M 2014 Composite Structures 108 736-46
[3] Yahaya M, Ruan D, Lu G, Dargusch M 2015 International Journal of Impact Engineering 75 100-9
[4] Rejab M, Cantwell W 2013 *Composites Part B: Engineering* **47** 267-77
[5] Kazemahvazi S, Zenkert D 2009 *Composites Science and Technology* **69** 913-9
[6] Jin F, Chen H, Zhao L, Fan H, Cai C, Kuang N 2013 *Composite Structures* **98** 53-8
[7] Zhou J, Hassan M Z, Guan Z, Cantwell W J 2012 *Composites science and Technology* **72** 1781-90
[8] Kazemahvazi S, Tanner D, Zenkert D 2009 *Composites Science and Technology* **69** 920-5
[9] Russell B, Malcom A, Wadley H, Deshpande V 2010 *Journal of Mechanics of Materials and Structures* **5** 477-93
[10] Zhang P, Liu J, Cheng Y, Hou H, Wang C, Li Y 2015 *Materials & Design* **65** 221-30
[11] Hou S, Zhao S, Ren L, Han X, Li Q 2013 *Materials & Design* **51** 1071-84