Mechanical properties of bamboo fiber-polyester composites

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ABSTRACT: Experimental investigations were performed to characterize the mechanical properties of bamboo fiber-polyester composites. The composite laminates were fabricated by infusing different forms of untreated bamboo fibers (randomly oriented, bamboo textiles and bamboo foam cores) with polyester resin. The results showed that the engineered bamboo fiber composites have strength and stiffness properties suitable for structural applications. Among the tested composites, the laminates with randomly oriented bamboo fibers exhibited the highest strength properties. Its strength in flexure, tension, compression, and shear are 58, 35, 48, and 32 MPa, respectively and its Modulus of Elasticity (MOE) is 3.2GPa. However, only the tensile strength and MOE showed better properties to that of neat polyester resin which are 15% and 4 % higher, respectively possibly due to relatively poor load transfer between the fibers and the matrix. Importantly, the flexural strength of the bamboo fiber-polyester composites is 200% and 30% higher than the standard particleboard and medium density fiberboard, respectively, used in the construction industry. It is expected that the results of this preliminary study will provide information to support the development and application of this new generation composites in housing and construction.

1 INTRODUCTION

Glass and carbon fibers have been used for several years in many applications varying from aerospace components to civil engineering infrastructures. However, the high production and material costs of these synthetic fibers limit their wider use for the development of fiber reinforced composite materials. Consequently, there is an increasing interest in research and development to utilize the less expensive natural fibers as reinforcement in making composites. Natural fibers are gaining wide acceptance because of their added advantages such as lightweight, renewability and biodegradability. In addition to this, studies conducted by Joshi et al. (2004) reveal that natural fiber composites are environmentally superior to glass fibers making them an emerging and realistic alternative to synthetic fibers in some engineering applications. It is anticipated therefore that the use of sustainable natural resources in the development of new generation composites will be a necessity and will play a crucial role in the near future.

Bamboo is a widely available material in many parts in the world and has been used extensively as a substitute to wood in making furniture and low-cost housing. It has been estimated that more than 2.5 billion people depend on the use of bamboo (Hogart 2006). In Australia, bamboo has been in small-scale cultivation in several areas of Queensland for only more than 20 years (Zhu et al. 2009). The current market for bamboo products is for shoots and culm production. However, the Australian market has long been importing bamboo products such as flooring, laminates, composite board, and chipboard for its housing and construction. Thus, a study t that supports the development and adaptation of cleaner, greener and more renewable materials while providing the construction and building industry with an alternative and environmentally sustainable materials such as bamboo fibers is warranted.

Among the well-known natural fibers, bamboo has one of the most favorable combinations of low-density and high mechanical stiffness and strength (Osorio et al. 2011). Nugroho & Ando (2001) indicated that these properties of bamboo make it a promising material for the manufacture of various engineered composite products. Despite its high mechanical properties, biodegradability and low cost, bamboo is not fully utilized in modern construction due to its cylindrical shape requiring special joints and connections. Consequently, bamboo fibers are extracted and used as reinforcement of polymer composites to practically apply the benefit of bamboo in various engineering systems.

It is technically difficult and expensive to extract long and straight bamboo fibers (Rao & Rao 2007). Only in recent years that the interest to study the potential of bamboo fibers as reinforcing materials for composites is increasing because of the limited availability of fibers (Osorio et al. 2011). The high mechanical properties, biodegradability and low cost consideration make bamboo an attractive fiber for reinforcement (Rao & Rao 2007). This project aims at introducing bamboo fiber composites in the Australian housing and building industry through an evaluation and understanding of their basic mechanical characteristics. Comparison of the mechanical properties with the standard particleboard and medium density fiberboard used in the construction industry was also conducted.

2 EXPERIMENTAL PROGRAM

2.1 *Materials*

Different forms of untreated bamboo fibers (textile, foam core and randomly oriented) as shown in Figure 1 were used in the preparation of composite laminates. The bamboo fibers were provided by an industry partner in Hongkong, China. The nonwoven textile consists of 50% short bamboo and 50% cotton fibers. The foam core has a thickness of 20 mm which consists of 50% short bamboo fibers and 50% polyester. These materials are currently being used for thermal and noise insulation, vibration filling for building products or cavity filling for cars. The randomly oriented fibers consist of raw bamboo fibers with lengths ranging from 30 to 100 mm. According to the industry partner, the raw bamboo fibers were obtained by steam explosion process.

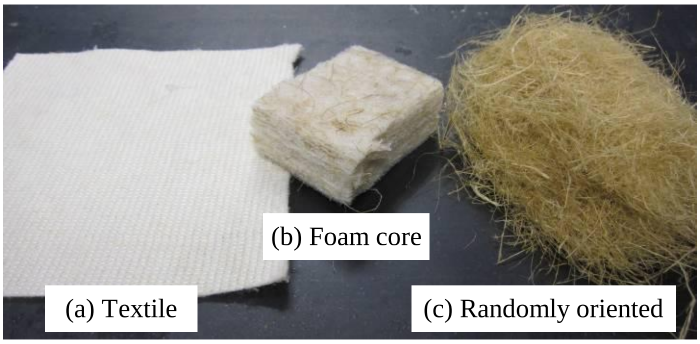


Figure 1. Different forms of bamboo fibers

Polyester resin (AROPOL 1472/25P Infusion) was used as the matrix component in the production of composites with properties listed in Table 1. The quantity of catalyst added to the resin for curing was 1% by volume of the polyester resin.

Table 1. Properties of polyester resin.

Property	Value
Modulus of elasticity, GPa	3.1
Flexural strength, MPa	80.3
Tensile strength, MPa	30.9
Compressive strength, MPa	107.7
Shear strength, MPa	34.3
Shear modulus, GPa	1.1

2.2 *Specimen preparation*

The composite laminates were prepared in 400 mm x 400 mm dimensions. All the specimens were prepared with a fiber volume fraction of approximately 50% by weight. The composite laminates were produced using the vacuum bagging process as shown in Figure 2. In this process, a vacuum of 92 bars is applied to the fibers through a vacuum bag which is properly sealed along its perimeter. In the production of composites with randomly oriented fibers, bamboo fibers were randomly oriented and placed on the infusion table. A transparent glass was applied on top to check if the fibers are evenly distributed, to ensure a smooth surface and to maintain the thickness of the specimen. The samples were cured for 24 hours at room temperature and then taken off the mould. The bamboo composite laminates were then pre-cured at 80^{o}C for 5 hours before cutting into required specimen dimensions.

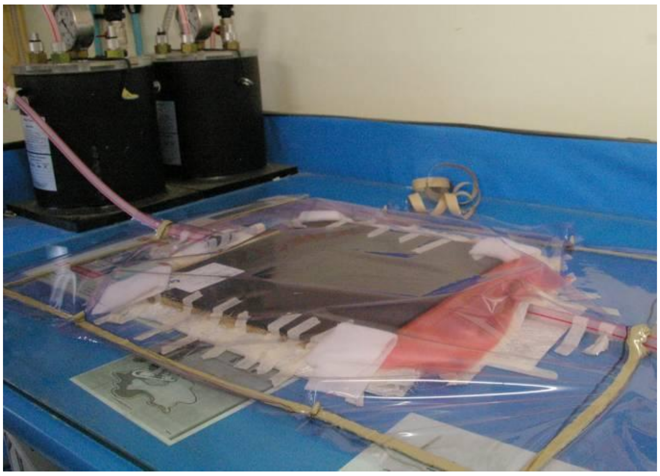


Figure 2. The vacuum bagging process.

2.3 *Test set-up and procedure*

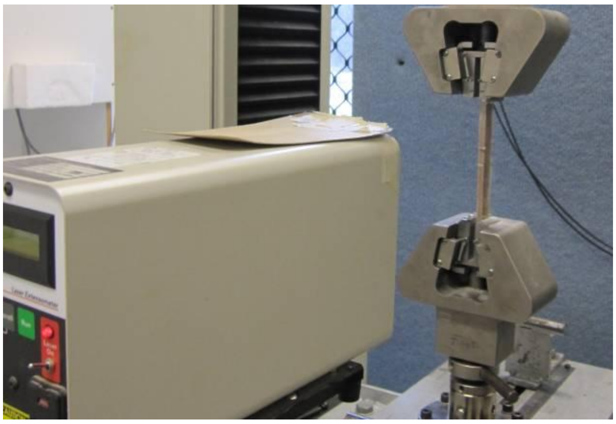
The experimental investigation using coupon specimens following the ISO and ASTM test standards were performed to characterise the flexural, tensile, compressive, and shear properties of the different bamboo fiber composites laminates. Six replicates for each specimen type were prepared and tested. The dimensions of the specimen and the standards followed for the different test of coupon specimens are listed in Table 2. The average thicknesses, *t* of the bamboo composite laminates made from textile (BCT), foam core (BCF) and randomly oriented fibers (BCR) are 0.9, 7.9 and 4.8 mm, respectively.

Table 2. Details of specimens for coupon tests.

Type of test	Test standard	Dimensions (mm)		
		thickness	length	width
Flexural	ISO 14125:1998(E)	actual	16t	15
Tensile	ISO 527-1:1995	actual	300	25
Compressive	ISO 14126:1999	actual	140	12.75
Shear	ASTM D5379:1993	actual	76	20

Figure 3 shows the different test set-up for bamboo fiber-polyester composites. The flexural behaviour of the bamboo fiber composites was determined under a three point static bending test shown in Figure 3a. The tensile test was conducted using a 100 kN testing machine with the load applied at a rate of 1.3 mm/min. Laser displacement transducer was also used to measure the elongation of the specimen as shown in Figure 3b. For specimen BCT, glass fiber composite tabs were glued at both ends of the tensile specimen to prevent damage introduction at the grip. On the other hand, the compressive test of specimen BCR was conducted using the Wyoming Modified Celanese Compression test fixture (Fig. 3c) while the compressive test of specimen BCF was performed using a rectangular specimen directly loaded under the testing machine. The shear test was then conducted using a rectangular beam shape specimen with symmetrically located V-notch at the centre as shown in Figure 3d.

(a) Flexural test



(b) Tensile test

(c) Compressive test (d) Shear test

Figure 3. Test set-up for bamboo fiber-polyester composites

3 RESULTS AND DISCUSSION

The mechanical behaviour of bamboo fiber-polyester composites in flexure, tension, compression, and shear is presented in the following section.

3.1 *Flexural behavior*

Figure 4 shows the typical stress-strain curve for bamboo composites under bending. In this figure, BCF-F, BCR-F and NR-F represent the bamboo composites made from foam core, composites from randomly oriented bamboo fibers and the neat polyester resin tested in bending, respectively. It is observed that both the flexural stress-strain curves of BCF-F and NR-F show a linear increasing trend and suddenly drops due to failure of specimen suggesting a brittle behavior. The specimen BCF-F failed at a maximum stress of around 42 MPa and strain of 1.4% while the specimen NR-F failed at a stress of 80 MPa and strain of 2.6%. On the other hand, the specimen BCR-F shows a linear elastic behavior up to stress of around 60 MPa and strain of 2% then becomes nonlinear before final failure. Interestingly, Osorio et al. (2011) reported that the failure strain of bamboo fiber composites in flexure is around 2%. This result shows that the bamboo fibres started to break at this level of strain and progressively until failure failure. As can also be seen from the figure, the flexural stiffness of specimens BCF-F and BCR-F is very similar to that of NR-F with the flexural strength and strain lower than that of the NR-F. The strength of specimens BCF-F and BCR-F is only 54% and 75%, respectively compared to the neat resin. This shows that the bamboo fibers do not act effectively as reinforcement to the polyester resin which results in the flexural stiffness dominated by the matrix properties. As expected, the results indicated that the composites with a higher amount of bamboo fibers will exhibit a higher flexural strength. It was discussed in Section 2.1 that specimen BCF-F contains only 25% of bamboo fibers while the specimen BCF-F contains 50% bamboo fibers.

One advantage of the addition of bamboo fibers is the ductile failure behaviour of specimens BCF-F and BCR-F compared to the brittle behavior of NR-F. In contrary to neat polyester, the load drop does not propagate until the total specimen failure. Figure 5 shows the failure of specimens BCF-F and BCR-F. As can be seen from the figure, both the specimens did not fail abruptly even after the maximum load. It is believed that the crack growth at the tensile side of the specimen is retarded by the fiber which prevents immediate failure as also observed in the stress-strain relationship in Figure 4. The bamboo fibers immediately carried the load once crack propagation is initiated in the specimen. Complete failure of the specimen occurred when all the fibers along the cracks failed.

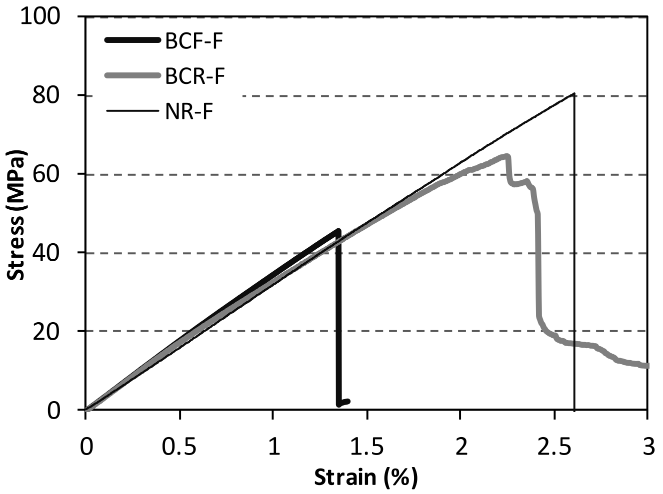
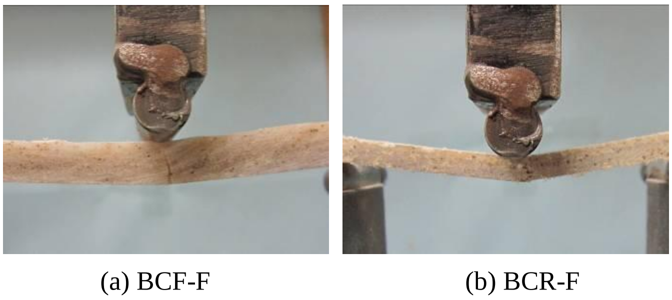


Figure 4. Flexural stress-strain behavior of bamboo composites



(a) BCF-F (b) BCR-F

Figure 5. Failure of bamboo composites under bending

3.2 *Tensile behavior*

Figure 6 shows the typical stress-strain curve for bamboo composites under tensile load. In the graph, the composites laminate from bamboo textile is designated as BCT-T. Under tensile loading, an almost linear elastic behavior up to fracture of the fibers was observed for all specimens. Based on the test results, the specimen BCF-T, BCR-T, BCT-T, and NR-T failed at an average tensile strength of 21.6, 35.3, 18.5, and 30.9 MPa, respectively. This shows that only the specimen BCR-T has a higher tensile strength (14% higher) than the neat polyester resin. Moreover, this specimen also exhibited a slightly higher MOE (4% higher) than the neat polyester.

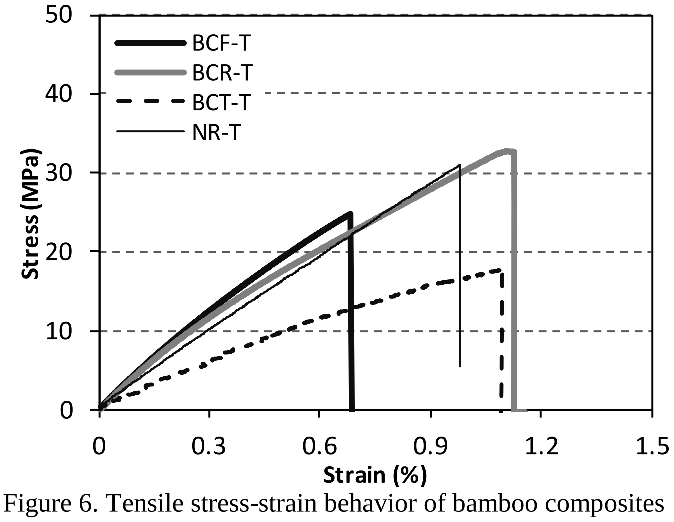
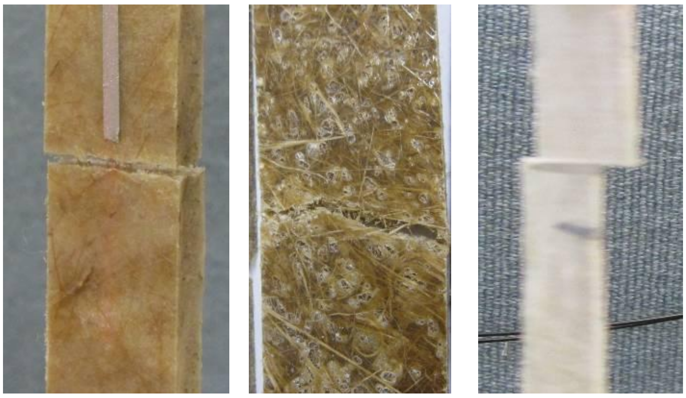


Figure 6. Tensile stress-strain behavior of bamboo composites

Mylsamy & Rajendran (2011) indicated that the tensile properties in a composite depend mainly on the fiber orientation and adhesion between the fiber and the matrix. Also, the fibers should be long along the direction of the load to effectively utilize its high tensile strength (Nugroho & Ando 2001). As the bamboo fibers are randomly oriented in the composite laminates, it is believed that only the fibers which are oriented perpendicular to the load provided reinforcement to the composites. This is similar to the observation of Wong et al. (2010) where they noted that only the longitudinal fibers contributes in the energy dissipation and in crack retardation in short bamboo fiber reinforced polyester composites. In the same study, the authors could only get a maximum of 25% increase in the tensile strength of polyester composites reinforced with 10 mm unidirectional bamboo fibers. They mentioned that this minimal strength gain in composites even by reinforcing with bamboo could be due to the relatively short bamboo fibers. The marginal strength gain for specimen BCR-T compared to the NR-T can also be due to the gathering of the fibers which made it difficult to wet them with polyester resin resulting in poor adhesion. The results also show that the strain at failure is only around 1.1% which is low compared to the tensile failure strain of bamboo fiber which is normally in the range 1.4 to 1.7% as reported by Rao & Rao (2007). However, it is interesting to note that it is only the tensile properties that showed an enhanced property among the investigated mechanical properties. This is due to the nature of the bamboo fibre itself where it exhibited the highest strength in tension compared to other properties as suggested by Nugroho & Ando (2001).

All specimens failed in the gauge length as shown in Figure 7. For specimens BCF-T and BCR-T, a clean fracture is observed. This result suggests that the tensile behavior of these composites is governed by the more brittle polyester resin. However, the specimen BCR-T failed due to matrix cracking with some fiber breakage showing that the fibers contributed to some extent on the overall tensile strength. It was also noticed that the fiber failed by tearing with some interfacial failure observed. There are also some traces of polyester resin still adhere to the fiber. This type of failure is an indication that the adhesion between the fiber and the matrix was not lost and the failure process was dominated by the matrix material properties. In general, the lower tensile strength of this bamboo composite than what is expected can be due to the premature fracture occurring in the specimen due to material defects and voids as shown in Figure 7b. These voids caused a weakening of the bonding strength between the fibers and the resin. Also, these defects are due to the presence of waxy materials and impurities on the surface of the bamboo fibres as no treatment was done before the production of the laminates.



(a) BCF-T (b) BCR-T (c) BCR-T

Figure 7. Failure of bamboo composites in tension

3.3 *Compressive behavior*

Figure 8 shows the stress and strain relationship of the bamboo composites under compression. In compression, a nonlinear behavior was observed at higher stress and strain especially for specimens BCF-C and NR-C. Under compressive load, the specimens BCF-C, BCR-C and NR-C failed at an average stress of 78.5, 48.9 and 107.7 MPa, respectively with the failure strain for specimens BCF-C and NR-C is more than 10% while the specimen BCR-C failed at a strain of only 2%.

In compression, a higher load is observed in all composites specimens as well as the neat polyester resin compared to other mechanical properties investigated. This is expected as Sigley et al. (1991) indicated that thermosetting polymers like polyester are usually brittle in flexure, tension and shear but show considerable ductility in compression. In addition, Mylsamy & Rajendran (2011) suggested that the most important parameter controlling the compression properties of fiber composites is the interfacial adhesion between the fiber and matrix. Thus, higher compressive properties are expected for composites with low fiber content ratio as the resin can easily wet and impregnate the fibers. In the study, the composites with 25% bamboo fibers (specimen BCF-C) exhibited a compressive strength of 73% that of the neat resin while the strength of specimen with 50% bamboo fibers (BCR-C) is only 45% of NR-C.

Figure 9 shows the failure behavior of bamboo composites in compression. It can be seen in Figure 9b that the weak fiber-matrix interface resulted in the shear crimping failure of specimen BCR-C leading to a lower failure strength than NR-C. This type of failure is due to the low fracture strain of bamboo fibers and the poor adhesion between the matrix and the fibers. In contrast, the better transfer of stress from the matrix to the fibers in specimen BCF-C resulted in this specimen behaving in compression similar to that of NR-C. Although some level of wrinkling was observed as shown in Figure 9a, the relatively low amount of fibers made the resin easily wet the fibers.

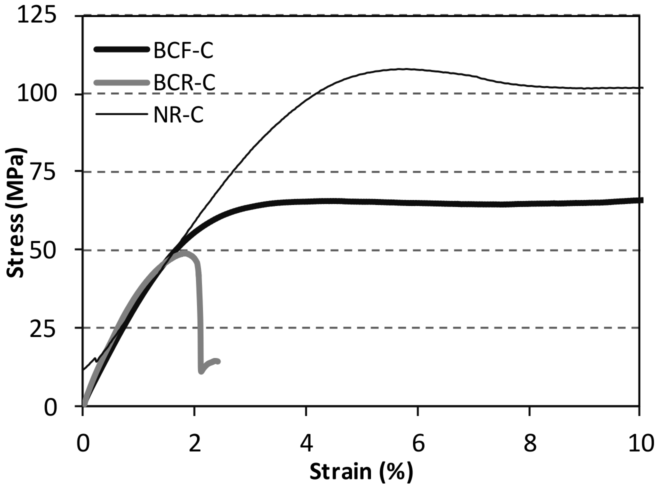
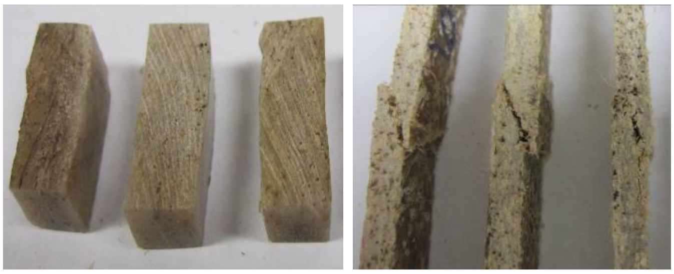


Figure 8. Compressive stress-strain behavior of bamboo composites



(a) BCF-C (b) BCR-C

Figure 9. Failure of bamboo composites in compression

3.4 *Shear behavior*

Figure 10 shows the shear stress and strain behavior of the bamboo fibre composites and the neat polyester resin. As can be seen from the figure, the specimen NR-S exhibited linear elastic behavior up to failure in shear. Also, the shear stiffness of the neat polyester is similar to that of specimens BCF-S and BCR-S. It is obvious from the figure that the specimen NR-S has a higher shear strength compared to specimens BCF-S and BCR-S. The shear strength of NR-S is 34.3 MPa while the specimens BCF-S and BCR-S are 32.8 and 25.9, respectively. On the other hand, both specimens BCF-S and BCR-S showed some ductility before failure. These specimens failed at a shear strain higher than 3% while the neat polyester resin failed at a shear strain of only 2.2%.

The failure mechanism in shear of specimens BCF-S and BCR-S is shown in Figure 11. As can be seen from the figure, the failure of both specimens is mainly due to shear failure originating from the V-notch root. After the first initiation of failure, the load gradually decreased. With the continuous application of the load, the shear cracks propagated in two opposite sides along the fiber direction. This crack propagation can also be observed in Figure 10 by the nonlinear portion of shear stress-strain curve. Visible large cracks were observed between the two notches across the specimen width suggesting the complete failure of the specimen.

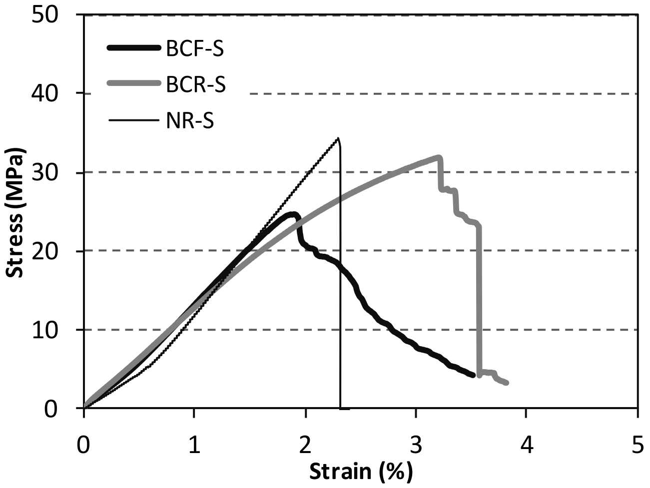


Figure 10. Shear stress-strain behavior of bamboo composites

(a) BCR-S (b) BCF-S

Figure 11. Failure in shear of bamboo composites

4 COMPARISON WITH OTHER PANELS

The properties of bamboo fibre-polyester composites were compared to the typical property values for standard particle board (PB) and medium density fiberboard (MDF) used in the Australian building industry. The average value for the strength and elastic properties of bamboo fibre composites determined from the different mechanical tests are summarized in Table 3. The typical property values for a 12 mm thick particleboard and a 5 mm thick MDF as recommended by the Engineered Wood Products Association of Australasia are also listed in the table.

The comparison showed that the specimens BCF and BCR have higher stiffness than PB and MDF. However, only specimen BCR has flexural strength better than a standard particleboard and MDF. The strength of this composites is 200% and 30% higher than the standard particleboard and MDF suggesting that bamboo fiber-polyester composites with randomly oriented fibers has high potential to be used as a building material in the construction industry.

Table 3. Mechanical properties of composite panels.

Property	BCF	BCR	BCT	PB	MDF
Young’s Modulus, GPa	3.2	3.2	1.7	2.8	1.8
Bending strength, MPa	42.6	58.8	--	18.0	55.0
Tensile strength, MPa	21.6	35.4	18.6	--	--
Compression, MPa	78.5	48.9	--	--	--
Shear strength, MPa	25.9	32.8	--	--	--

5 CONCLUSIONS

The mechanical properties of bamboo fiber with polyester matrix were determined. Based on the results, the following conclusions can be drawn:

- The laminates with randomly oriented fibers exhibited the highest strength and stiffness among the investigated bamboo fibre-polyester composites.
- The strength of bamboo composites in flexure, tension, compression, and shear are 58, 35, 48, and 32MPa, respectively and its MOE is 3.2GPa.
- Only the tensile strength and stiffness properties of bamboo composites are better than neat resin, which are 15% and 4 % higher, respectively.
- The reinforcement of bamboo fibres in composites resulted in a ductile failure as the fibers are preventing the immediate failure of the specimen.
- The good mechanical properties of bamboo composites in this study can certainly have an edge over conventional panel products used in the housing and construction industry.

6 REFERENCES

Engineered Wood Products Association of Australasia. Facts about particleboard and MDF. *EPWAA*, Australia.

Joshi, S.V., Drzal, L.T., Mohanty, A.K., and Arora, S. 2004. Are natural fiber composites environmentally superior to glass fiber reinforced composites? *Composites Part A* 35: 371-376.

Hogart, N.J. 2006. Demography and management of top end bamboo, bambusa arnhemica. *McS thesis*, Charles Darwin University, Australia.

Mylsamy, K. & Rajendran, I. 2011. Influence of alkali treatment and fiber length on mechanical properties of short Agave fiber reinforced epoxy composites. *Journal of Materials Science* 26(15): 3985-3990.

Nugroho, N. & Ando, N. 2001. Development of structural composite products made from bamboo II: fundamental properties of laminated bamboo lumber. *Journal of Wood Science* 47: 237-242.

Osorio, L., Trujillo, E., Van Vuure, A.W. & Verpoest, I. 2011. Morphological aspects and mechanical properties of single bamboo fibers and flexural characterization of bamboo/epoxy composites. *Journal of Reinforced Plastics and Composites* 30(5): 396-408.

Rao, K.M.M. & Rao, K.M. 2007. Extraction and tensile properties of natural fibers: Vakka, date and bamboo. *Composite Structures* 77: 288-295.

Ratna Prasad, A.V. & Mohana Rao, K. 2011. Mechanical properties of natural fiber reinforced polyester composites: Jowar, sisal and bamboo. *Materials and Design* 32: 4658-4663.

Sigley, R.H., Wronski, A.S. & Parry, T.V. 1991. Three-parameter yield criterion for a brittle polyester resin. *Journal of Materials Science* 26(15): 3985-3990.

Wong, K.J., Zahi, S., Low, K.O. & Lim, C.C. 2010. Fracture characterization of short bamboo fiber reinforced polyester composites. *Materials and Design* 31: 4147-4154.

Zhu, G.X., Ockerby, S., White, D.T. & Midmore, D.J. 2009. Identifying agricultural practices to sustain bamboo production in Queensland, Australia. *ACIAR Proceedings* 129: 124-130.