Manufacturing of a Sandwich Structure Engineered Wood with a Rice Husk Flake Core and Teak Veneer Reinforced with Glass/Carbon Fiber Skin

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The manufacturing of a sandwich structure engineered wood, constructed from a rice husk flake core and teak veneer as outside skins, was studied in this work. Epoxy adhesive was employed, while glass and carbon fiber, both short discontinuous and woven forms, were used as reinforcement. The impact strength, flexural properties, and dimensional stability of the samples after prolonged water immersion were measured. At the assigned reinforcement loadings, the rice husk flake/woven woods showed mechanical superiority over the rice husk flake/short discontinuous materials, regardless of the fiber type. The reason for the greater rice husk flake/woven interfacial adhesion and laminated woven strength, compared to the rice husk flake/short discontinuous composite was investigated. The samples constructed from teak veneer laminated with woven glass or carbon fiber skin and rice husk flake or rice husk flake/30% woven glass cores had greater mechanical properties. The high shear and tensile/compression stresses of woven glass or carbon fiber laminated onto teak veneer skins were confirmed. The sandwich structure engineered wood using woven glass and carbon fiber reinforcement exhibited good dimensional stability under prolonged water immersion. Carbon fiber was the better material candidate compared to woven glass in terms of manufacturing the sandwich engineered wood presented in this work.

Keywords: Sandwich structure engineered woods; Rice husk flake, Glass and carbon fibers reinforcement; Mechanical properties

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INTRODUCTION

Engineered woods manufactured from the by-products from cellulosic agro industries, *e.g.*, bagasse, rice husk flakes, and palm oil fibers, are important in terms of both environmental and circular economy aspects. In addition, the innovation trends for the next century are pushing for the manufacturing of lighter and higher mechanical strength engineered woods. These substituted wood products are in high demand, especially in the construction industry. Medium density fiberboard (MDF) is a traditional engineered wood, which is produced made from lignocellulose fiber incorporated with adhesive and/or reinforced materials *via* hot-pressed processing. Medium density fiberboards are typically manufactured with a density between 450 and 800 kg/m^3 (Li *et al*. 2009; Yousefi 2009; Ali *et al.* 2014). The properties of MDF depend on its fibers and type of adhesive bonding. The adhesives are necessary to ensure that effective bonding occurs between the fibers. The most commonly used resins for MDF products are based on formaldehyde. These resins include urea-formaldehyde (UF), phenol-formaldehyde (PF), melamine-formaldehyde (MF), and melamine-urea-formaldehyde (MUF). The major drawbacks of using common formaldehyde-based adhesives are as follows: (*i*) they contain harmful volatile organic compounds (VOC); (*ii*) there is a limited supply of petroleum feedstock needed for producing formaldehyde; and (*iii*) they have low resistance to moisture and insects (Li *et al.* 2009; Nasir *et al.* 2013). Concerning VOCs, Europe, North America, and some Asian countries have imposed banning regulations. Alternative adhesives, *e.g.*, epoxy-based or bio-based adhesives, have been investigated. Not only are epoxy adhesives considerably less toxic and form strong mechanical bonds, but the use of epoxy adhesive would also be beneficial for their resistance to moisture and insects (Meekum and Wangkheeree 2016; Meekum and Wangkheeree 2017a). Thermoset epoxy resin is not yet popularly used as an adhesive in engineered wood. However, it is used in high performance composite manufacturing. It has excellent properties, which include good adhesion to many substances, high mechanical properties, and good resistance to moisture and chemical attacks.

Rice husk flakes (RHF) has not yet been wildly used as a raw material for manufacturing engineered woods. Conventionally, they have been consumed as a household energy biomass feedstock, as it is an abundant byproduct of rice milling. It represents 22 wt% of total rice production (Ciannamea *et al.* 2017) and is vastly abundant in Asian countries. The unique characteristics of RHF, in comparison with other agricultural waste products, are its high silica (SiO_2) content (87 wt% to 97 wt%), high porosity, light weight, and extremely high external surface area with relatively low hydrophilicity (Soltani *et al.* 2015).

The mechanical properties of RHF reinforced polyester composites have been reported by Surata *et al.* (2014). The mechanical properties of RHF composites are improved by increasing the fiber fraction as well as *via* performing a fiber alkalization treatment. Rice husk/polyurethane foam material shows interesting sound absorption and thermal insulation applications (Buratti *et al.* 2018). Stronger natural fibers, *e.g.*, jute and wheat husk, have been used with RH to fabricate hybrid composite panel boards (Mavani *et al.* 2007). However, the suitable tensile strength is only found in the jute composite. Rice husk mixed with wood flour has been used for producing particleboard; of which the best mechanical and physical properties were found with 25% RH content and 9% adhesive content (César *et al.* 2017). Engineered fibers such as glass fibers (GF) and carbon (CF) fibers improve the mechanical properties of engineered woods (Gujjala *et al.* 2014). There are marginal improvements in the mechanical properties of jute/GF/epoxy boards, compared to boards without GF. To achieve superior properties in a composite, the interfacial adhesion of the fiber/matrix must be improved, as measured by the mean interfacial shear strength (IFSS). Chemical and/or physical surface treatments of natural fibers can improve the IFSS, but they are costly. Omitting these processing steps without diminishing the mechanical properties would be preferred, especially in engineered woods.

A previous work (Meekum and Wangkheeree 2019), manufacturing of engineered wood panels from untreated RHF, epoxy adhesive, and reinforced with short CF or GF, concluded that the optimal compression molding pressure for the manufacturing of 1.1 g/cm^3 engineered wood panel was 120 kg$_f$/cm^2. The mechanical performances were also significantly enhanced by reinforcing the wood with short CF and GF. By employing a hybridized CF/GF, the study also found that the mechanical performances of the engineered wood were reduced as the GF portion was increased. The inferior mechanical capability of this GF to CF ratio was explained by the theoretical composite "*rule of hybrid mixture*" (RoHM) (Meekum and Wangkheeree 2019).

In this present publication, the manufacturing process of sandwich structure teak laminated engineered woods was investigated. The sandwich structures were comprised of RHF with and without randomized short GF and CF reinforcement cores, and teak veneer skins. The beneath teak veneers were laminated with woven GF and CF. The mechanical and durability properties of these structures were evaluated and reported. Their usage as a high-performance interior and exterior construction material was the primary industrial application interest of this work.

EXPERIMENTAL

Materials

The materials used for manufacturing the sandwich structure engineered wood samples were categorized into three categories: (*i*) an in-house epoxy-based adhesive; (*ii*) untreated rice husk flakes (RHF); and (*iii*) glass and carbon fiber used for reinforcement. The in-house and room temperature cure epoxy resins were prepared *via* blending commercially available DGEBA, Novolac, and aliphatic epoxy resins, *i.e.*, YD 127, YD 515, YDPN 631, and RD 108, respectively (Aditya Birla Chemicals (Thailand) Ltd., Rayong, Thailand.). The amine-based hardener was formulated from triethylenetetramine (TETA) and isophorone diamine (IPDA), purchased from Vista Co., Ltd. (Bangkok, Thailand) and BASF (Thai) Ltd. (Bangkok, Thailand), respectively. The calculated parts per hundred (PHR) between the epoxy resin and amine-based hardener for the in-house epoxy formulation adhesive was 13 (Meekum and Wangkheeree 2019). The rice husk flake was obtained from a local rice mill (Nakhon Ratchasima, Thailand). The solid and dust impurities of the RHF were removed *via* sieving with a mesh size 4 sieve, and then the RHF was gently air dried. This method was used for the original form of RHF, *i.e.*, untreated RHF. It was vacuum dried at 105 °C for 4 h before its use in the manufacturing of sandwich structure engineered wood. Glass fibers (GF) and carbon fibers (CF), in both short randomized and plain weave forms, were employed as reinforcing materials for the manufacturing of sandwich structure engineered wood.

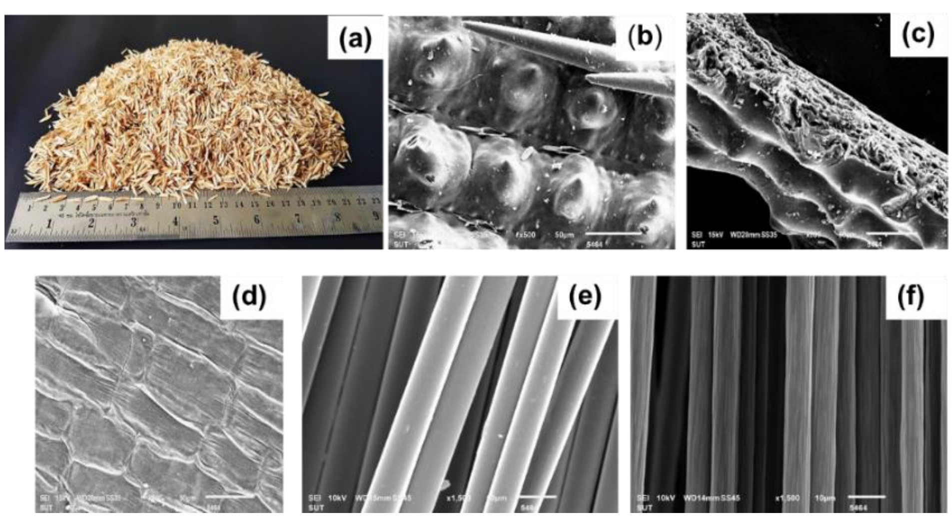

Fig. 1. (a) Optical photo of the original form of RHF; (b) SEM images of the outer husk or lemma; (c) SEM images of the husk cross section; (d) SEM images of inside the husk or palea; (e) SEM images of the glass fibers (GF); and (f) SEM images of the carbon fibers (CF)

The short randomized GF (sGF) and CF (sCF) were obtained from the woven waste available at a windsurfer manufacturer (Cobra International Co., Ltd, Chonburi, Thailand). The waste was chopped into its short fiber form *via* a high-speed cutting machine (FBC-20, Chareon Tut Co., Ltd., Samutprakarn, Thailand), to an approximate fiber length of 2 to 8 mm. Figure 1 shows the optical and SEM photos of the original rice husk flakes, as well as the GF and CF reinforcing materials. The chopped sGF and sCF had average diameters, measured *via* a SEM image metering system, of 8.80 and 6.50 µm, respectively (Meekum and Wangkheeree 2016). The plain weave GF (wGF) and CF (wCF) fabrics with an areal density of 160 and 100 g/m^2, respectively, were employed (supplied by Cobra International Co., Ltd). The reinforcement fabric (with dimension of 20 cm^2 x 20 cm^2) was cut with scissors prior to use for lamination. All of the reinforcement fibers, regardless to forms and types, were used without surface treatment and sizing removal.

Manufacturing of the Engineered Woods Samples

The typical engineered wood structures based on RHF manufactured and tested in this work are schematically presented in Fig. 2. The RHF/short fiber (sF) was a RHF core reinforced with either sGF or sCF at various loads. The X2 and X3 samples referred to RHF wood were reinforced with either wGF or wCF at 2 or 3 stacked piles, respectively. For the sandwich structure engineered wood, there were two types of skins; teak veneer and teak veneer reinforced with either wGF or wCF, Figs. 2(e) and 2(f), respectively. The woven reinforcements were placed beneath the teak veneer skins. The manufacturing procedures of these wood samples are described in the following section.

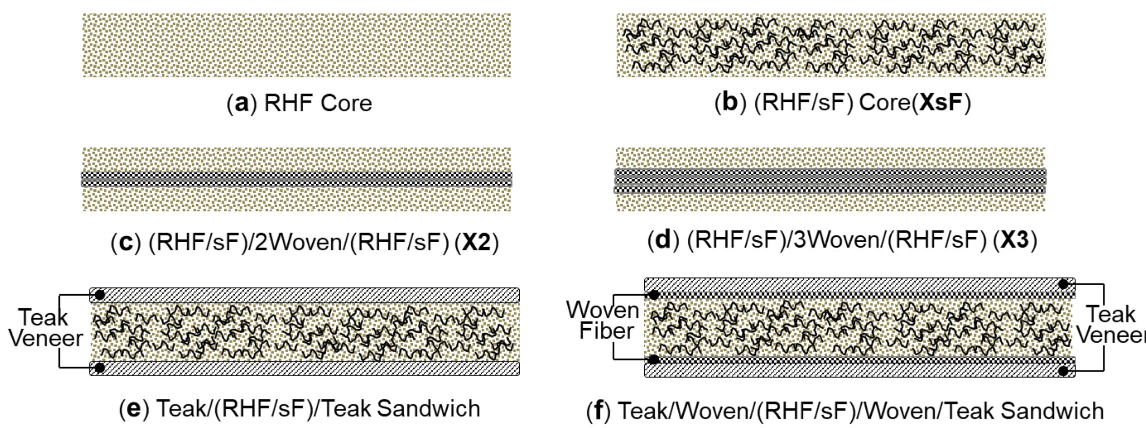

Fig. 2. Schematic drawing of (a) RHF Core; (b) RHF/sF Core (XsF); (c) (RHF/sF)/2woven/(RFH/sF) (X2); (d) (RHF/sF)/3woven/(RFH/sF) (X3); (e) Teak/(RHF/sUD)/Teak; and (f) Teak/Woven/(RHF/sF)/Woven/Teak sandwich structures

Manufacturing of the rice husk flakes (RHF) and reinforced RHF samples

The RHF and RHF/sF core samples, illustrated in Figs. 2a and 2b, were manufactured *via* compression molding with a mold dimension of 20 cm^2 x 20 cm^2, with a depth of 0.50 cm. Accordingly, the wood sample at an assigned density of 1.10 g/cm^3 was carefully obtained by loading 220 g of the molding ingredients. Next, 163 g of RHF or RHF/sF fibers and 57 g of epoxy adhesive were weighed and mixed in a high-speed mixer. This assigned core ingredient was equivalent to 35 parts of epoxy adhesive to 100 parts of fibers, *i.e.*, 35 phr. In addition, 10 wt% of either sGF or sCF were loaded into the mold for the manufacturing of the RHF/sF wood cores. The optimal consolidated molding parameters were as follows: 120 kg_f/cm^2 of pressure, a temperature of 120 °C, and 180s/30s/120s of press/decompress/press molding cycle time (Meekum and Wangkheeree 2019).

In the production of the (RHF)/Xwoven/(RHF) specimens, as shown in Figs. 2c and 2d, the wCF or wGF fabric cut with scissors (with dimensions of 20 cm^2 x 20 cm^2) was wetted with the epoxy adhesive *via* hand lay-up. The fiber to epoxy weight ratio was carefully controlled at 100 to 35. The 220 g of RHF and epoxy mixture were prepared as described above and was equally divided into two portions. The first half was uniformly transferred into the mold cavity and gently compacted. The epoxy wetted wCF or wGF were carefully laid on top of the compacted RHF in 2 or 3 stacked piles. The remaining RHF mixture was gently and evenly spread over the laminated fabric. The compression molding was performed at a temperature of 120 °C, a pressure of 120 kg_f/cm^2 and at the molding cycle times as previously described. The hardened X2 or X3 wood samples were allowed to cool down and then demolded. After annealing at room temperature for 24 h, the standard test specimens were obtained via cutting with a saw, polishing the edges, and finally post-curing the samples at a temperature of 60 °C for 12 h. Based on the areal density of wGF and wCF (160 g/m^2 and 100 g/m^2, respectively), using 2 or 3 layers of the woven reinforcement material yielded approximately 7 wt% and 10 wt% in terms of the woven reinforcement material in the respective RHF cores. These percentage ratios were adopted for the purpose of rationalizing the isotropic RHF core reinforced with 10 wt% short fiber.

Manufacturing of the sandwich structure engineered wood samples

Similar procedures to those described above were adopted for manufacturing the teak/(RHF/sF)/teak and teak/woven/(RHF/30sF)/woven/teak sandwich structures, as shown in Figs. 2e and 2f. Woven glass fiber or woven carbon fiber fabric and 20 cm x 20 cm x 0.08 cm teak veneers were utilized as faces for manufacturing the sandwich samples. Either RHF or RHF loaded with 30 wt% of short fibers were employed as the core component. For the structure using unreinforced teak veneer faces, the veneer was thoroughly wetted with epoxy adhesive *via* the hand lay-up process. Then, it was carefully placed onto the compression mold cavity. Next, 220 g of RHF or RHF/30sF mixture, prepared exactly as described above, was evenly loaded into the mold, and topped with the freshly prepared teak/epoxy skin. Finally, the molding elements underwent the compression molding process in the exact same manner as previously described. For the production of the sandwich engineered wood using teak reinforced with wGF or wCF faces, the teak/woven laminated materials were freshly prepared *via* the hand lay-up process. Eventually, the whole compression molding procedures, as mentioned above, was replicated; the sandwich engineered woods test specimens were obtained *via* cutting with a saw, polishing the edges, and finally post curing the samples at a temperature of 60 °C for 12 h. Due to the difference in the material constituents used in the manufacturing of sandwich structures, slight thickness variation of the sandwich samples was obtained. The typical thickness was approx. 5 mm.

Standard Testing

The mechanical properties, including the three-point flexural bending and Izod impact strengths (both notched and unnotched modes), were measured in accordance with ASTM standard D790-10 (2010) and ASTM standard D256-10e1 (2010), respectively. A universal testing machine (Instron Model 5565, Norwood, MA) with a load cell of 5 kN, a flexural span length of 80 mm, and crosshead speed of 15 mm/min was employed. A pendulum impact testing machine (Instron Ceast Model 9050, Norwood, MA) equipped with a striking impactor was employed. The impactor used a striking energy of 2.16 J and 11.0 J, which were assigned for the notched and unnotched impact strength measurements, respectively.

The durability of the RHF based wood samples, determined by means of the water absorption percentage ($\%WA_i$), the thickness swelling percentage ($\%TS_i$), and the dimension stability after removing the moisture, *i.e.*, the thickness swelling percentage after vacuum drying ($\%TS_{dried,i}$) samples subjected to 1 d and 7 d water submersion periods, were measured in accordance with ASTM standard D570-98(2010)el (2010).

RESULTS AND DISCUSSION

Rationalization Between the Usage of Short sUD or Continuous Woven Fibers as Reinforcement Materials

From a previous report by Meekum and Wangkheeree (2019), single and hybrid composite sGF and sCF were successfully employed as reinforcement materials for the manufacturing of RHF engineered wood panels. It has been also well established that the continuous form of engineering fibers demonstrates greater superiority in terms of reinforcing capability when compared to discontinuous/randomized short fibers. So, for the sake of engineering interest as well as for the material selection and design, the rationalization between usage of discontinuous sF or continuous woven wGF and wCF as the reinforcement material for the manufacturing of RHF engineered wood was one of the primary objectives of this work. The wGF and wCF were represented as continuous reinforcement materials. The RHF wood reinforced with sGF and sCF were obtained for comparison. Due to the constraints of the lack of wCF and wGF availability as well as compression mold volume, the exact loading wt% of the woven and short fibers included in the RHF wood samples could not be acquired. Simply, by employing 2 or 3 plies of wGF and wCF, the approximate calculated wt% fractions of the woven reinforcement materials included in the RHF wood samples were 7.9 and 11.8 for wGF and 7.5 and 11.2 for wCF, respectively. Accordingly, the RHF/sGF and RHF/sCF samples with a fiber content of 10 wt% were assigned and produced. However, an additional engineering aspect must be rationalized, *i.e.*, considering the solid mechanics of the material. By employing short fibers as the reinforcement material, an isotropic reinforced RHF wood sample was obtained. In contrast, the RHF/woven fiber reinforced wood samples, especially when using a sandwich type structure, is the orthotropic solid state material by nature. In fact, these two types of materials cannot truly, both theoretically and mechanically, be compared. However, the effectiveness of these two fiber types as a reinforcement material for RHF wood must be initially clarified for this study. The schematic structures of the RHF wood samples with and without 10 wt% of short fibers, as well as 2 or 3 piles of epoxy laminate were demonstrated in Figs. 2a to 2d, respectively. Those structures were notated as XsGF, XsCF, RHF, X2, and X3, correspondingly.

Table 1 presents the impact strength and heat deflection temperature (HDT) results of the manufactured wood samples. The Izod notched impact strength of the XsCF sample was noticeably higher than the XsGF sample. In addition, at identical reinforcement conditions, the notched impact values of the X2 and X3 structures were expectedly increased due to the increasing number of laminated piles. In comparison, at approximately equal fiber contents, the degree the impact strength was enhanced was more obvious in the wCF samples than the wGF samples. In general, GF is more brittle and notch-sensitive than CF. Consequently, the RHF/GF woods exhibited lower energy dissipation resistance under the impact crack failure propagation than the CF-reinforced RHF samples. A similar trend for the impact strength of the RHF wood samples reinforced with both forms and types of fibers was observed in the unnotched impact strength. The strength was superior when woven reinforcement was employed. Moreover, a high degree of unnotched impact strength enhancement was obviously observed, particularly for the XwCF-reinforced samples. For example, the unnotched impact strength of the X3wCF structure increased approximately four fold from the XsCF structure. In general, RHF and XsF are closely related to isotropic materials. However, the X2 and X3 structures are considered orthotropic in nature. The impact testing was performed in the edgewise direction, *i.e.*, perpendicular to the fabric reinforcement and consolidated compression force. Under isotropic material testing, the results do not depend on the test directions. In contrast, for orthotropic materials testing, the outcome does greatly depend on the constituent components of the specimen. In regard to the impact strength results in this study, it was suggested that the laminated layer plays an important role in resisting energy dissipation during impact crack failure propagation. Thus, the impact energy must be intensified *via* employing high toughness and crack resistance material. Carbon fiber/epoxy laminates typically demonstrate superior toughness and lower notch-sensitivity in comparison to GF/epoxy reinforced materials. Accordingly, at an identical material structure, the impact strength of the RHF samples reinforced with laminated wCF should be superior to the wGF reinforced RHF wood samples.

For the HDT results in Table 1, it was shown that the X2 samples, regardless of the fiber type, had a lower HDT than the XsF and X3 specimens. The HDT of the RHF sample reinforced with 2 laminated piles (X2), was marginally higher than the RHF wood sample. In addition, the HDT was improved, particular for the wCF, as the pile number increased from X2 to X3. Again, the dissimilarity in the composite structures, *i.e.*, isotropic *vs* orthotropic, must be considered in the discussion. For instance, for the isotropic XsF materials, the deformation of the sample, due to the thermal stress under the assigned standard bending force, was uniformly and simultaneously loaded across the specimen bar. The resistance to the bending load is executed by all RHF/fiber/adhesive constituents. Therefore, the HDT was immediately recorded, when the whole specimen was deformed at 0.25 mm or 0.01 inch. Thus, the incorporated short reinforcement material was homogeneous and directly enhanced the HDT of the wood sample. In contrast, testing the orthotropic RHF/woven/RHF sandwich-like structures (X2 and X3), the specimen deformation largely depends on each of the RHF faces. In the X2 and X3 structures, the thickness of the RHF skins were half the thickness of the unreinforced sample. Thus, there was only a thin core of the laminated wCF or wGF to support those thick skins. When subjecting the samples to the standard bending forces and thermal stress, the RHF skin would be deformed to the critical gauge, *i.e.*, 0.25 mm or 0.01 inch, at a lower HDT than the full thickness XsF sample. With the support of an ultra-thin wCF/epoxy or wGF/epoxy laminated core, it likely has no substantial strength/capability to resist the dimensional distortion due to the mechanical and thermal stress loads. Consequently, the HDT enhancement *via* sample reinforcement with wCF/epoxy or wGF/epoxy laminates would be minor. The strength of the laminated skin would be noticeably amplified by increasing the number of laminated piles from 2 to 3. Consequently, the HDT of the X3wCF and X3wGF samples was higher than the X2wCF and X2wGF samples, respectively.

Table 1. Impact Strength and HDT of the Unreinforced and Reinforced RHF Wood Samples

Fiber	Wood Structure Type	Fiber Content (wt%)	Impact Strength (kJ/m^2)		HDT (°C)
			Notched	Unnotched	
RHF	RHF	0.0	2.34 ± 0.09	2.19 ± 0.06	56.1 ± 0.1
CF	X10(sCF)	10.0	4.91 ± 0.56	6.19 ± 0.84	62.7 ± 0.7
	X2wCF	7.5	8.52 ± 0.80	14.86 ± 0.45	56.7 ± 0.1
	X3wCF	11.2	12.68 ± 0.78	24.87 ± 0.87	64.8 ± 0.6
GF	X10(sGF)	10.0	3.90 ± 0.26	4.12 ± 0.75	62.5 ± 0.6
	X2wGF	7.9	3.99 ± 0.36	6.62 ± 0.62	58.8 ± 0.8
	X3wGF	11.8	4.58 ± 0.27	7.78 ± 0.71	59.5 ± 0.1

For the flexural analysis, the typical loads against the displacement profiles of the unreinforced RHF, XsUD, X2, and X3 wood samples are demonstrated in Fig. 3. A sharp flexure failure at the maximum load was observed for the isotropic samples, RHF and XsF. Consequently, the ultimate strength and maximum deformation at break (Def_{max}) values were recorded at this point. However, there were three modes of the failure observed for the X2 and X3 sandwich wood samples. They initially failed at the thick RHF skin layer (1), followed by failure of the RHF/laminated woven interfacial delamination (2), and finally complete failure of the laminated core debonding (3), as demonstrated in Fig. 3.

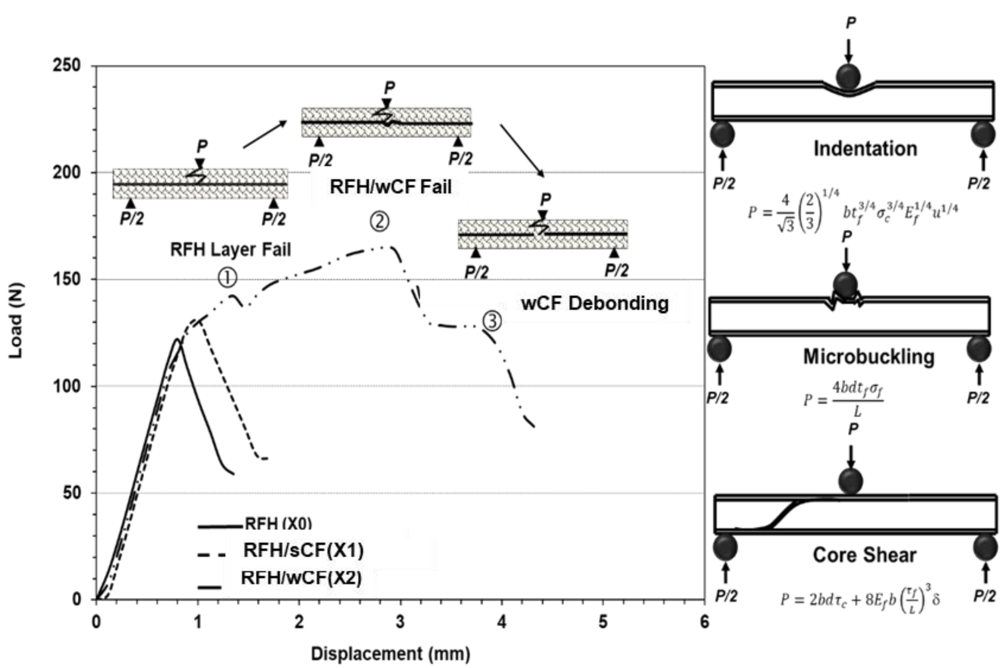

Fig. 3. The load and displacement profile of the flexural testing of the RHF wood samples

By adopting the failure mechanism of the sandwich structures (Meekum and Wangkheeree 2017a), these failure modes were referred to as skin indentation (1), microbuckling (2), and core shearing (3). The RHF/woven reinforced wood samples manufactured in this work had an orthotropic sandwich structure with thick skins and an ultra-thin epoxy/fiber laminated rigid core. Then, the ultimate flexural strength was recorded, calculated, and reported at the RHF/laminated interfacial delamination failure point (2). The Def_{max} was assigned at the complete laminated debonding failure point (3).

Table 2. Flexural Properties of the Unreinforced and Reinforced RHF Wood Samples

Fiber	Wood Structure Type	Fiber Content (wt%)	Flexural Properties		
			Ultimate Strength (MPa)	Modulus (GPa)	Def_{max}.[a] (mm)
RHF	RHF	0.0	28.57 ± 0.95	3.082 ± 0.098	1.91 ± 0.14
CF	X10(sCF)	10.0	44.71 ± 1.09	3.831 ± 0.173	2.81 ± 0.21
	X2wCF	7.5	44.75 ± 1.75	4.902 ± 0.151	8.10 ± 0.91
	X3wCF	11.2	47.72 ± 2.43	5.690 ± 0.156	10.81 ± 0.81
GF	X10(sGF)	10.0	30.66 ± 1.42	3.185 ± 0.207	2.68 ± 0.15
	X2wGF	7.9	38.05 ± 1.06	4.442 ± 0.073	11.98 ± 0.59
	X3wGF	11.8	40.37 ± 0.68	4.463 ± 0.189	14.68 ± 0.94
Note: [a]Maximum deformation at break					

Table 2 summarizes the flexural properties of the RHF, XsF, X2, and X3 wood samples. The flexural strength, modulus, and Def_{max} were higher in the woven reinforced RHF woods compared to the unreinforced samples for both type of fibers. The woven reinforced wood samples were superior in terms of their flexural properties in comparison to the short sUD reinforced samples. For the woven reinforced samples, particularly the wCF samples, the flexural characteristics were improved as the number of woven stacks increased. When comparing the RHF and XsF wood samples, the flexural properties were clearly enhanced by utilizing short sUD fibers (10 wt%) as reinforcement, regardless of the fiber type. Moreover, the sCF samples showed a greater degree of enhancement compared to the sGF samples. The flexural performance rationalization between the isotropic XsF wood and the orthotropic woven reinforced RHF sandwich structures (X2 and X3) were deliberated. Regardless of the fiber content and type, the flexural superiorities of the woven reinforced samples in comparison to the short fiber reinforced samples were obviously perceived. This was explained by their microbuckling failure mode (2), as illustrated in Fig. 3. The flexural failure strength of this mode was complementary to the RHF/woven interfacial adhesion and the laminated debonding strengths. Normally, RHF/woven interfacial adhesion strength is greater than the micro interfacial adhesion strength in RHF/sF fibers. Additionally, the woven laminated debonding strength was much higher than the strength of the short fiber composite material. Accordingly, the outstanding flexural properties of the sandwich structure, RHF/woven, over the short fiber reinforced sample were explained. Furthermore, due to the increased debonding strength of the laminated woven samples, *via* either increasing the number of stacking piles or alternating the woven fiber type to a higher performance fiber, the flexural properties of the RHF/woven were further enhanced. Thus, the flexural performance of the X3 sample was greater than the X2 sample, and the flexural performance of the X2wCF sample was higher than the X2wGF sample.

Referring to the mechanical performance results, regardless of the fiber type and content, the sandwich type RHF/woven wood samples showed mechanical superiority to the isotropic RHF/sF materials. The enhanced RHF/woven interfacial adhesion and laminated woven debonding strength in comparison to the short fibers could theoretically explain their superior mechanical performance.

Table 3. Summary of the Results of the Durability Properties Obtained from the Unreinforced and Reinforced RHF Wood Samples

Fiber	Wood Structure Type	Durability Properties					
		1 Day			7 Days		
		WA (%)	TS (%)	TS_{dried} (%)	WA (%)	TS (%)	TS_{dried} (%)
RHF	RHF	18.14 ± 2.57	6.83 ± 0.79	-0.74 ± 0.37	26.31 ± 0.65	8.68 ± 0.12	0.77 ± 0.32
CF	X10(sCF)	12.97 ± 0.63	5.18 ± 0.24	-1.35 ± 0.18	21.68 ± 0.68	7.04 ± 0.45	0.80 ± 0.54
	X2wCF	16.22 ± 0.69	8.04 ± 0.67	1.14 ± 0.73	20.55 ± 0.94	8.58 ± 0.18	1.21 ± 0.54
	X3wCF	18.53 ± 0.54	7.73 ± 0.86	-0.50 ± 0.02	22.52 ± 0.51	7.81 ± 0.44	0.71 ± 0.10
GF	X10(sGF)	12.72 ± 0.08	6.21 ± 0.46	-0.90 ± 0.02	27.69 ± 1.13	7.40 ± 0.59	1.27 ± 0.27
	X2wGF	20.53 ± 0.34	7.71 ± 0.79	-0.03 ± 0.01	25.08 ± 0.34	8.06 ± 0.45	-0.03 ± 0.09
	X3wGF	13.71 ± 0.84	7.10 ± 0.65	0.78 ± 0.21	21.92 ± 1.16	11.37 ± 0.87	2.54 ± 0.53

For the durability performance evaluation, Table 3 summarizes the water absorption percentages ($\%WA_i$) and the thickness swelling percentage ($\%TS_i$) of the RHF, XsF, X2, and X3 wood samples after consecutive 1 d and 7 d submersion tests. In comparison, the $\%WA_i$ and $\%TS_i$ values of the RHF, X2, and X3 wood samples were typically higher than the XsF samples, for both fiber types. For the RHF, X2, and X3 wood samples, the results were justified by the fact that the primary water infusion process upon prolonged submersion occurred at unreinforced RHF wood skins. Hence, there was no importance in terms of the $\%WA_i$ for the samples that underwent prolonged immersion. In contrast, there must be the differences in the hydrophilicity between the unreinforced RHF and XsF wood samples. Typically, rice husk flakes have a higher porosity and hydrophilicity than short sCF and sGF. Consequently, at the same specific surface area of the tested samples, the XsF wood samples must have a lower $\%WA_i$ than the unreinforced RHF samples. The thickness swelling after immersion for 1 d and 7 d ($\%TS_1$ and $\%TS_7$) are also reported in Table 3. A correlation between the $\%WA_i$ and $\%TS_i$ was observed. The $\%TS_1$ and $\%TS_7$ values of the RFH, X2, and X3 samples were higher than values for the XsF samples, regardless of the fiber type. The experimental outcomes indicated that a higher $\%WA_i$ resulted in an increased internal hydrostatic pressure. Accordingly, the greater thickness swelling values were caused by this internal expansion pressure. After removing the infused water *via* vacuum drying of the samples, the $\%TS_{dried}$ values were measured and reported in Table 3. The minimal $\%TS_{dried}$ values were revealed, regardless of immersion time and the fiber type. The results indicated that all the swelled samples returned to their original dimensions after removing the residual infused water. These results showed that the manufactured wood samples had relatively good dimensional stability when subjected to extraordinary high humidity, which is commonly found in tropical regions. Good compactness, strength, and elastic bonding occurring in the RHF-epoxy-RHF, fiber-epoxy-fiber, and RHF-epoxy-fiber samples should be considered for the justification of this study.

Manufacturing the Teak/GF/RHF Sandwich Structure Engineered Wood Samples

The orthotropic sandwich RHF/woven/RHF wood samples had mechanical superiority when compared to the isotropic RHF wood samples reinforced with short fibers. The exceptional interfacial adhesion between the RHF and woven fibers as well as the greater laminated woven fiber debonding strength compared to the short fiber reinforcement materials were the primary explanation. In this section, an actual sandwich structure engineered wood sample constructed from teak veneer reinforced with wGF skins and RHF reinforced with a 30 wt% sGF core was manufactured and analyzed. A sandwich structures fabricated from unreinforced teak skins and a RHF core was also constructed as the benchmarking product. A well-known stacking lamina design nomenclature for the composite sandwich structure was adopted to identify the engineered wood samples made in this work. For instance, T/wGF/RHF30sGF/wGF/T was notated for the sandwich engineered wood sample manufactured from teak (T) laminated with plain weave glass fiber (wGF) skins and rice husk flakes (RHF) reinforced with 30 wt% short glass fiber (sGF).

Table 4. Impact Strength and Flexural Properties of the RHF/GF Sandwich Structure Engineered Wood Samples

Sample	Sample Thickness (mm)	Impact Strengths (kJ/m^2)		Flexural Properties		
		Notched	Unnotched	Ultimate Strength (MPa)	Modulus (GPa)	Def.$_{max}$ (mm)
RHF Core	5.96 ± 0.11	2.54 ± 0.33	2.19 ± 0.06	28.04 ± 1.08	3.195 ± 0.199	1.87 ± 0.19
T/RHF/T	5.24 ± 0.08	4.73 ± 1.07	7.66 ± 0.98	73.86 ± 5.30	7.019 ± 0.383	2.69 ± 0.38
T/wGF/RHF/wGF/T	5.23 ± 0.06	12.35 ± 1.06	18.31 ± 1.07	86.32 ± 1.16	7.399 ± 0.250	4.43 ± 0.32
RHF30sGF Core	5.30 ± 0.08	7.83 ± 0.26	8.50 ± 0.71	47.54 ± 2.11	4.586 ± 0.540	2.67 ± 0.28
T/RHF30GF/T	5.04 ± 0.06	7.89 ± 1.28	10.21 ± 1.53	90.58 ± 2.26	7.552 ± 0.066	3.79 ± 0.67
T/wGF/RHF30sGF/wGF/T	5.00 ± 0.05	14.55 ± 0.93	26.14 ± 1.91	113.96 ± 0.87	8.221 ± 0.192	4.79 ± 0.15

Table 4 summarizes the impact strength and flexural properties of the engineered wood samples reinforced with GF. For both the notched and unnotched impact strength, the results showed that the strength of the T/wGF/RHF/wGF/T sandwich engineered wood sample was dramatically increased from the RHF core only sample. An unnotched impact strength approximately eight times higher than the RHR core only was achieved using teak/wGF faces in the manufacturing of the T/wGF/RHF/wGF/T engineered wood samples. In addition, by reinforcing the RHF with 30 wt% of sGF, the impact strength of the RHF30sGF core was approximately three times greater than the unreinforced RHF sample. However, marginal improvements in the impact strength was observed when the RHF30sGF core was sandwiched with teak veneer skins (T/RHF30sGF/T). However, a drastically higher impact strength was obtained *via* the addition of laminated teak veneer skins with 160 g/m^2 of plain weave glass fiber (T/wGF/RHF30sGF/wGF/T). When comparing the T/wGF/RHF/wGF/T and T/wGF/RHF30sGF/wGF/T wood samples, the structure including a RHF30sGF core undoubtedly demonstrated greater impact strength values than the unreinforced core samples. According to the impact results, the orthotropic continuous engineering fibers had superior mechanical reinforcing capability in comparison to the randomized discontinuous form fibers. Nevertheless, due to the brittleness of the teak veneer skins, a relatively small increase in impact strength was achieved when only the teak veneer skins were used for manufacturing the sandwich RHF or RHF30sGF engineered wood samples.

Figure 4 shows the typical load/displacement profile obtained from the flexural testing of the RHF/GF sandwich engineered wood samples. Figure 4 visualized the fact that the samples generally failed at their maximum loads and displacement points. Only the core shear (τ_c) failure mode was observed in the teak veneer skins sandwich structures. However, microbuckling of the face (σ_f) or skin, which immediately underwent wGF laminated debonding due to the flexural bending force, was revealed for the sandwich engineered wood samples with teak/wGF reinforced skins. Accordingly, the ultimate flexural strength values of the T/RHF/T and T/RHF30sGF/T samples were primarily due to their core shearing resistance. *Vice versa*, the ultimate strength values for the T/wGF/RHF/wGF/T and T/wGF/RHF30sGF/wGF/T samples were primarily due to the flexural strength of the teak/wGF laminated skins.

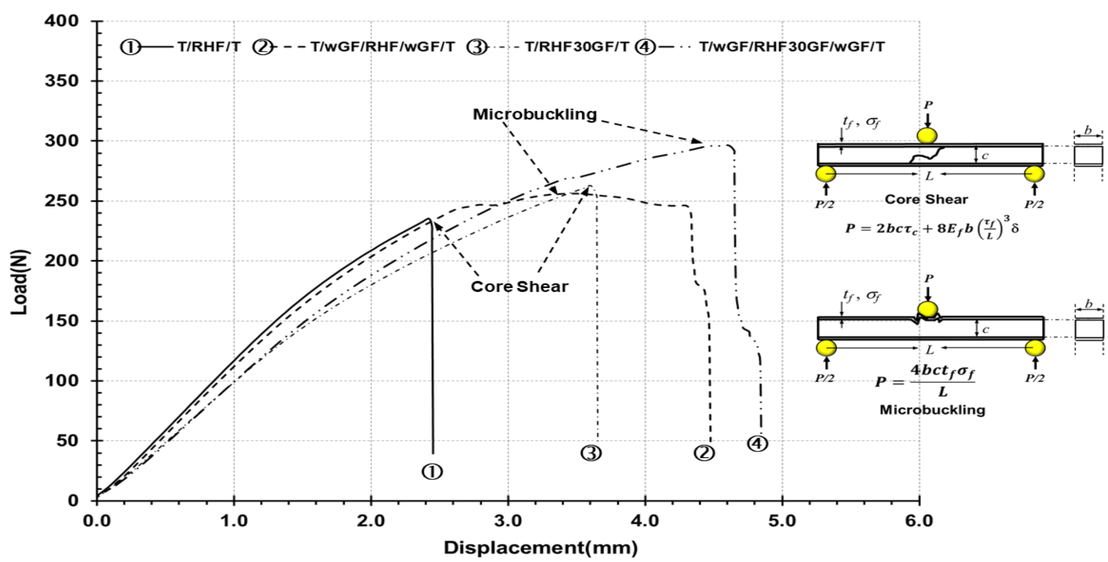

Fig. 4. Flexural load and displacement profile of the RHF/GF sandwich structure engineered wood samples

The flexural properties, *i.e.*, the ultimate strength, modulus, and Def_{max}, of the RHF/GF sandwich structure engineered wood samples are presented in Table 4. As expected, the results revealed that the flexural characteristics of the sandwich engineered wood samples constructed with a unreinforced RHF core were obviously increased after applying teak veneer and teak/wGF skins as faces. The ultimate strength, modulus, and Def_{max} increased approximately three-fold when teak/wGF laminated skins were applied to a RHF core. Similar trends were also found for the sandwich structures using RHF/30sGF as a core. Due to the superiority of the RHF/30sGF core over the unreinforced RHF core, under identical structure conditions, it is worth noting that the RHF/30sGF sandwich structures conclusively showed flexural superiority in comparison to the unreinforced RHF samples. As mentioned earlier, the sandwich structures with only teak veneer faces were deformed under flexure bending *via* a core shear failure mode. With sufficient face/core interfacial adhesion, the bending strength of the sandwich structure was principally contributed from the shear stresses of both the core (τ_c) and the faces (τ_f). Accordingly, the flexural strength of the sandwich wood structures with brittle unreinforced teak veneer faces were not drastically improved. However, the microbuckling failure mode was found to occur in the sandwich engineered wood structures constructed from teak/wGF skins.

Hence, the flexural properties were solely controlled by the ability of the skins to resist the shear (τ_f) and tensile/compression (σ_f) stresses applied to the faces. Subsequently, a major improvement in the flexural strength was achieved when the laminated teak/wGF skins were applied, due to their high shear and tensile stress resistibility, as the faces for the engineered wood structure. Similar rationalization was adopted to justify the enhancement of the flexural modulus of the unreinforced teak veneer in comparison to the teak/wGF laminated skins sandwich engineered wood samples. It was found that not only the strength and modulus of the teak/wGF skins were improved, but due to the higher elongation capability of the wGF skins compared to the brittle teak veneer, the Def_{max}, of the teak/wGF sandwich wood samples was also considerably increased.

After the durability performance examination, Table 5 summarizes the values for the water absorption percentages (%WA_i), the thickness swelling percentages (%TS_i), and the thickness swelling percentages after vacuum drying (%TS_{dried}) of the RHF cores and RHF/GF sandwich structure engineered wood samples after consecutive 1 d and 7 d submersion tests. The %WA_i values were drastically reduced by loading 30 wt% of sGF into the RHF core. As previously mentioned, the reduction in %WA_i could be due to the low hydrophilicity and non-porosity of the sGF. In comparison, for both core types, a minimal difference in the %WA_i values was observed between the teak veneer and teak/wGF skin sandwich wood samples. The results described above could be due to the fact that the water infusion process after prolonged water submersion primarily occurred at the core constituent. Hence, there was no major difference in the %WA_i values between the sandwich structures with only teak veneer and those with teak/wGF cores. The thickness swelling within the compression force direction after immersion for 1 d and 7 d (%TS_1 and %TS_7, respectively), were also reported in Table 5. The %TS_1 and %TS_7 were clearly reduced when the sandwich structures were constructed with either core type. Once again, both the RHF and RHF30sGF sandwich structures yielded a marginal declining tendency in terms of the %TS when comparing the teak veneer faces to the teak/wGF faces. The lowest thickness percentage buildups, by means of %TS_1 and %TS_7, were found in both teak/wGF skins sandwich samples. In addition, a slight increase in %TS was detected when the immersion time was increased from 1 d to 7 d. The results indicated that the faces, especially the strong teak/wGF laminated skins, could be used as a weather shield for sandwich engineered woods. Thus, the dimensional stability of the designed wood, upon water uptake, could be improved. In order to simulate the season changes from high humidity to dry conditions, the absorbed water was removed *via* vacuum drying, in order to evaluate the dimensional stability of engineered wood samples. The capability of the manufactured woods to return to their original dimensions was measured *via* the %TS_{dried} values. The obtained results were presented in Table 5. It can be seen that a value of nearly 0 was recorded for the %TS_{dried} results, regardless of the immersion time and core type. This number demonstrated that the engineered wood structures demonstrate exceptional dimensional stability. They had excellent dimensional resistance to the vast humidity deviations, which are commonly experienced in a tropical climate. Good strong bonding between RHF-epoxy-RHF, GF-epoxy-GF and RHF-epoxy-GF were suggested for this weather resistance benefit.

Table 5. Durability Properties Results of the RHF/GF Sandwich Structure Engineered Wood Samples

Sample	Durability Properties					
	1 Day			7 Day		
	WA(%)	TS(%)	TS_{dried}(%)	WA(%)	TS(%)	TS_{dried}(%)
RHF Core	18.14 ± 2.57	6.83 ± 0.49	-0.74 ± 0.37	26.31 ±0 .65	8.68 ± 0.12	0.77 ± 0.32
T/RHF/T	22.48 ± 0.89	6.62 ± 1.61	1.04 ± 0.14	34.56 ± 1.20	6.33 ± 0.82	0.85 ± 0.13
T/wGF/RHF/wGF/T	22.20 ± 0.77	4.06 ± 0.13	0.49 ± 0.13	35.48 ± 1.48	4.90 ± 0.40	0.87 ± 0.09
RHF30sGF Core	11.80 ± 0.68	5.12 ± 0.30	-1.68 ± 0.05	23.12 ± 1.70	5.82 ± 0.13	0.69 ± 0.21
T/RHF30sGF/T	15.54 ± 2.32	3.30 ± 0.07	-0.81 ± 0.24	27.14 ± 2.76	5.24 ± 0.85	0.05 ± 0.01
T/wGF/RHF30sGF/wGF/T	15.62 ± 1.34	3.84 ± 0.63	-1.30 ± 0.27	22.92 ± 1.33	4.71 ± 0.89	0.53 ± 0.16

In summary, for the manufacturing of sandwich structure engineered woods with either a RHF or RHF/30sGF core, a considerable improvement in their mechanical properties was achieved by applying either teak veneer or teak/wGF laminated skins to the engineered wood. In terms of material selection and design engineering consideration, teak/wGF was the better choice in comparison to unreinforced teak veneer skins. The high shear and tensile/compression stress resistance of the laminated teak/wGF skins were the primary reason for their selection. The sandwich engineered wood structure reinforced with GF had reasonably high dimensional stability under aggressive humidity variation.

Manufacturing the Teak/CF/RHF Sandwich Structure Engineered Wood Samples

The sandwich structure engineered wood samples constructed from teak veneer reinforced with woven CF skins and a RFH core reinforced with 30 wt% sCF were also manufactured and analyzed in this work. Table 6 summarizes the impact strength and the flexural characteristics of the CF reinforced engineered woods, which were measured in accordance with ASTM standards. For both the notched and unnotched impact strengths, the RHF30CF core yielded higher values than the unreinforced RHF core. In addition, the results show that the impact strength was commonly enhanced by using either teak veneer or teak/wCF laminated skins in the sandwich structures. Their inclusion yielded impact strength values three times greater than the samples without teak skins, especially for the unreinforced RHF structures. Furthermore, the results also showed that the 100 g/m^2 wCF skins provided excellent reinforcement in comparison to the brittle teak veneer faces, when both applied to unreinforced RHF cores. As shown in Table 6, the impact strength of the T/wCF/RHF/wCF/T sandwich wood samples was almost doubled in comparison to T/RHF/T. In contrast with the excellence reinforcing capabilities of the sCF when applied to the RHF core, the strength contribution of the unreinforced teak veneer skins was minor. Typically, the mechanical enhancement of the orthotropic woven CF is much higher than the anisotropic short sCF. Accordingly, improvements in the impact strength were still observed in the samples constructed with teak/wCF faces. Also, the impact strengths (both notched and unnotched) of the T/wCF/RHF30sCF/wCF/T sample were higher than for the T/RHF30sCF/T sample. Within all the constructed engineered woods, the T/wCF/RHF30sCF/wCF/T structure demonstrated the highest impact strength. As explained earlier, it was suggested that laminated layers play an important role in resisting energy dissipation during impact crack failure propagation. Thus, with the superior toughness of the wCF, the impact energy must be intensified by employing the T/wCF as the skins of the sandwich engineered woods.

Table 6. Impact Strength and Flexural Properties of the RHF/CF Sandwich Structure Engineered Wood Samples

Sample	Sample Thickness (mm)	Impact Strengths (kJ/m^2)		Flexural Properties		
		Notched	Unnotched	Ultimate Strength (MPa)	Modulus (GPa)	$Def._{max}$ (mm)
RHF Core	5.96 ± 0.11	2.54 ± 0.33	2.19 ± 0.06	28.04 ± 1.08	3.195 ± 0.199	1.87 ± 0.19
T/RHF/T	5.24 ± 0.08	4.73 ± 1.07	7.66 ± 0.98	73.86 ± 5.30	7.019 ± 0.383	2.69 ± 0.38
T/wCF/RHF/wCF/T	5.23 ± 0.07	8.27 ± 0.70	13.45 ± 1.08	123.94 ± 1.46	12.923 ± 0.250	5.23 ± 0.40
RHF30sCF Core	5.51 ± 0.11	12.34 ± 0.56	17.34 ± 0.56	63.43 ± 4.45	6.106 ± 0.722	2.46 ± 0.21
T/RHF30sCF/T	5.18 ± 0.09	12.00 ± 1.34	17.42 ± 2.12	114.83 ± 3.49	8.862 ± 0.175	3.38 ± 0.35
T/wCF/RHF30sCF/wCF/T	5.19 ± 0.06	15.53 ± 1.13	26.56 ± 0.71	145.61 ± 3.12	14.149 ± 0.292	4.12 ± 0.35

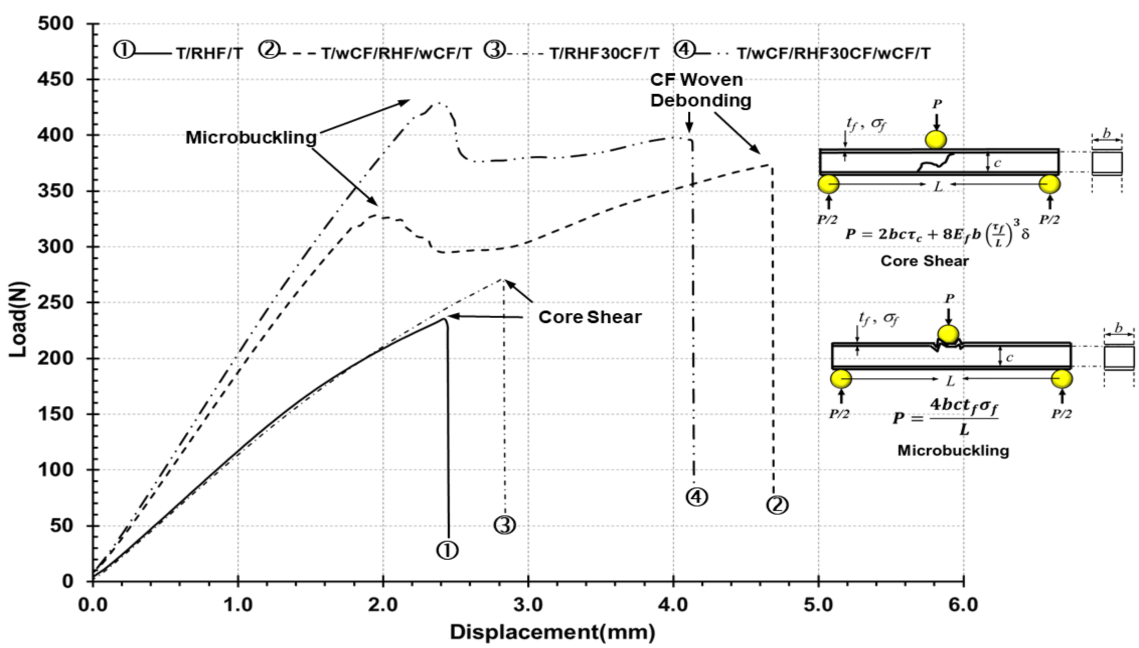

Fig. 5. Load and displacement profile obtained from flexural testing of the RHF/CF sandwich structure Engineered wood samples

The profile of the bending force and specimen displacement at 15 mm/min, which was obtained from the RHF/CF sandwich engineered woods flexural testing, is shown in Fig. 5. Only a core shear failure mode was visualized for the T/RFH/T and T/RHF30sCF/T sandwich structures. In contrast, the preliminary microbuckling of the upper teak veneer layer, the prolonged plastic deformation of the wCF, and finally wCF debonding/broken failure phenomenon were visualized for the sandwich structures constructed from teak/wCF laminated skins, as can be seen in Fig. 5. Consequently, the ultimate flexural strength was recorded at the core shear and microbuckling points for the sandwich samples with teak veneer faces and teak/wCF laminated faces, respectively. However, the $Def._{max}$ value was marked at the sample failure point. This meant that the $Def._{max}$ value of the T/RHF/T and T/RHF30sCF/T structures was the same as point at which the entire sample collapsed. The $Def._{max}$ values of the T/wCF/RFH/wCF/T and T/wCF/RFH30sCF/wCF/T samples were at the plastic deformation broken point of the laminated wCF. Considering the integrated area under the load/displacement profile curves, the teak/wCF laminated sandwich engineered wood samples demonstrated that they show greater in the area than the teak veneer skin samples. The greater integrated area means higher in material toughness. Accordingly, better toughness of the teak/wCF sandwich engineered wood must be interpreted. The flexural properties, *i.e.*, the ultimate strength, modulus, and $Def._{max}$, of all the RHF/CF samples are summarized in Table 6. As expected for the given core materials, especially for the unreinforced RHF core, the ultimate strength, modulus, and $Def._{max}$ increased when the teak and teak/wCF faces were integrated into the sandwich structures. Up to five times the reinforcing capability in terms of their flexural characteristics was found for the T/wCF/RHF/wCF/T engineered wood samples. Once again, the unreinforced teak veneer skins had lower flexural property values than the teak/wCF flexural property values. Due to the mechanical strength contribution of the core constituent, the degree of enhancement in terms of the bending strength of the sandwich engineered woods with a RHF/30sCF core was less pronounced than the sandwich engineered woods with a RHF core. Nevertheless, there is no doubt that the inclusion of sCF at a 30 wt% load provided excellent reinforcement for the RHF core. Additionally, laminating high strength continuous wCF into the teak veneer skins when manufacturing the sandwich structure engineered wood samples with a RHF30sCF core provided additional strengthening in terms of bending toughness. Once again, the exceptional resistance of the laminated teak/wCF in terms of high shear and tensile/compression stresses were the primary contributing factor for the enhancement of the flexural properties of the teak/wCF sandwich engineered wood samples.

In terms of the material design and selection considerations, it is worth rationalizing the mechanical reinforcing effectiveness of glass fibers *versus* carbon fibers. From a previous publication by Meekum and Wangkheeree (2019), it was found that randomized sCF yielded much better mechanical enhancement when used in manufacturing reinforced RHF cores compared to GF. In order to further enhance the short fiber reinforced RHF cores used in the manufacturing of the sandwich engineered wood samples, it was determined that wCF was the best reinforcement candidate in terms of a mechanical enhancement material.

Finding new alternative wood substitutes for interior and exterior construction materials was one of the industrial applications that generated interest for manufacturing novel sandwich structure engineered woods in this study. In a tropical climate, the dimension stability of the material, due to high rainfall and humidity, is one of the primary issues for wooden construction materials. Therefore, determining the durability properties *via* simulating these conditions using prolonged water immersion testing is mandatory. Table 7 shows the $\%WA_i$ and $\%TS_i$ of the RHF/CF sandwich structure engineered wood samples after consecutive 1 d and 7 d prolonged immersion. When a 30 wt% load of short sCF was included in the RHF core, the $\%WA_i$ was decreased in comparison with the non-reinforced RHF core. The low hydrophilicity and non-porosity of the short sCF could explain this decrease, as previously noted in the GF cores. Noticeably, regardless of the core type, the $\%WA_i$ (for both 1 d and 7 d of immersion) of the sandwich structure samples generally increased. As teak veneer is relatively hydrophilic in nature, an increase in the

%WA_i was detected after introducing teak veneer as the skins of the sandwich engineered wood. The values reported in Table 7 reveal that the declining tendency of the %TS (%TS_1 and %TS_7) was observed when teak and teak/wCF were applied as skins on both the RHF and RHF30sCF cores. The lowest thickness expansion was noticed in the samples with teak/wCF skins. In addition, only a slight increase in %TS_i was detected when the immersion time was increased from 1 d to 7 d. The results indicated that the faces, especially a teak/wCF laminated skin, could be used as environmental protective layers for the sandwich engineered woods. Thus, the dimensional stability of the materials upon water uptake should be increased. After removing the absorbed water *via* vacuum drying, which simulated the drying phenomena due to the seasonal change from rainy to dry, the elastic contraction to the original dimension was evaluated using the %TS_{dried} (as shown in Table 7). It is shown that small %TS_{dried} values, regardless of immersion time and core type, were recorded. These near zero expansion results showed that the constructed sandwich engineered woods had relatively high dimensional stability under aggressive humidity variation, which was demonstrated by simulated tropical seasonal changes. Strong bonding occurring between the RHF-epoxy-RHF, CF-epoxy-CF, and RHF-epoxy-CF as well as the high elasticity of the CF are responsible for the improved dimensional stability.

Table 7. Durability Properties Results of the RHF/CF of the Sandwich Structure Wood Samples

Sample	Durability Properties					
	1 Day			7 Day		
	WA (%)	TS (%)	TS_{dried} (%)	WA (%)	TS (%)	TS_{dried} (%)
RHF Core	18.14 ± 2.57	6.83 ± 0.49	-0.74 ± 0.37	26.31 ±0 .65	8.68 ± 0.12	0.77 ± 0.32
T/RHF/T	22.48 ± 0.89	6.62 ± 1.61	1.04 ± 0.14	34.56 ± 1.20	6.33 ± 0.82	0.85 ± 0.13
T/wCF/RHF/wCF/T	15.90 ± 1.24	3.95 ± 0.42	0.04 ± 0.02	28.43 ± 1.32	4.09 ± 0.41	-0.06 ± 0.00
RHF30sCF Core	11.30 ± 2.35	4.19 ± 0.78	-1.52 ± 0.55	20.37 ± 1.36	5.85 ± 0.12	0.37 ± 0.04
T/RHF30sCF/T	15.54 ± 2.32	3.30 ± 0.07	-0.81 ± 0.24	21.99 ± 1.97	5.24 ± 0.85	0.05 ± 0.01
T/wCF/RHF30sCF/wCF/T	15.18 ± 0.51	2.56 ± 0.79	-1.73 ± 0.07	21.68 ± 0.98	6.17 ± 0.57	1.01 ± 0.38

While manufacturing sandwich structure engineered woods with a RHF core and teak veneer faces, it was found that the mechanical and durability properties were drastically enhanced with the inclusion of a 30 wt%. load of sCF in the core, as well as laminating 100 g/m^2 of plain weave CF onto the teak veneer faces. The high shear and tensile/compression stress resistance of the laminated teak/wCF were judged to be responsible for the enhancement, based on both theoretical grounds. In addition, it was determined that CF was superior to GF in terms of mechanical performance. Hence, it was found that the T/wCF/RHF30sCF/wCF/T engineered wood sample had greater mechanical performance in comparison to the T/wGF/RHF30sGF/wGF/T sample. In terms of material selection for mechanical design consideration, carbon fiber is the best candidate for manufacturing sandwich structure engineered woods with rice husk flake/epoxy adhesive as the core.

CONCLUSIONS

1. At the given fiber loads, regardless of the fiber type, orthotropic sandwich structure woods constructed from rice husk fiber (RHF)/woven fabrics showed mechanical superiority compared to the isotropic RHF/short fiber (sF) sandwich structure woods. The superior RHF/woven interfacial adhesion and the laminated woven debonding strengths to short fiber reinforcement was theoretically explained. Good dimensional stability, due to strong bonding between the RHF-epoxy-RHF, fiber-epoxy-fiber, and RHF-epoxy-fiber were also taken for explanation.
2. The sandwich structure engineered wood samples manufactured with a RHF/30 short glass fiber (sGF) core and laminated teak/woven glass fiber (wGF) skins had remarkable mechanical properties. The contributions of the high shear and tensile/compression stress resistance of the laminated teak/wGF skins were explained. The obtained sandwich structure wood samples also showed reasonably good dimensional stability under prolonged water immersion.
3. Remarkable mechanical and durability properties were achieved *via* the inclusion of a 30 wt% load of short carbon fiber (sCF) in the RHF core as well as from using laminated teak/woven carbon fiber (wCF) as skins, *i.e.*, the T/wCF/RHF30sCF/wCF/T configuration. The high shear and tensile/ compression stress resistance of the laminated teak/wCF faces judged, based on theoretical and practical grounds, to be responsible for its superiority. Good dimensional stability of the samples subjected to prolonged water immersion was also accomplished.
4. When manufacturing sandwich structure engineered wood with a rice husk flake core, teak veneer skins, and epoxy adhesive, carbon fiber, both randomized discontinuous and woven continuous forms, were the better material in terms of mechanical design compared to glass fiber.

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