# PHYSICAL AND MECHANICAL BEHAVIORS OF THERMALLY MODIFIED RUBBERWOOD GLULAM BEAM UNDER SUSTAINED AND CYCLIC LOADING

*T. Pulngern**
Associate Professor
E-mail: tawich.pul@kmutt.ac.th

*T. Udtaranakron*
Researcher
E-mail: thippakorn.udt@mail.kmutt.ac.th

*K. Chanto*
PhD Student
Department of Civil Engineering
Faculty of Engineering
King Mongkut's University of Technology Thonburi
Bangkok 10140, Thailand
E-mail: kasan.cha@kmutt.ac.th

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**Abstract.** This study evaluated the effect of thermal modification on the physical and mechanical properties of rubberwood glued laminated (glulam) timber. The flexural creep property and cyclic loading behavior were also investigated. The obtained results indicated that the MC and specific gravity of thermally modified rubberwood decreased with an increase in modification temperature. Moreover, the flexural strength of the rubberwood glulam timber at modification temperatures of 180 and 220°C was 8.57% and 46.72%, respectively, which was less than that of the control rubberwood dried at 90°C. However, the MOE between the thermally modified rubberwood glulam timber and control specimens was not significantly changed. The flexural creep test indicated that the maximum relative creep of the thermally modified rubberwood timber equaled 0.31, which was lower than that of other natural timber and tended to decrease when increasing the stress level. Various mathematical models were also proposed, and the best-fitted model was found to be the Bailey–Norton power law model. Nevertheless, the cyclic loading results also proved that thermal modification temperature had a direct effect on the ductility index and energy dissipation of rubberwood glulam timber, but it had no significant effect on the impairment of strength.

***Keywords:*** Creep, cyclic loading, glulam, thermally modified rubberwood.

## INTRODUCTION

Wood is a naturally renewable material that has been used in construction for many centuries. The obvious advantages of wood are simplicity in fabrication, high strength-to-weight ratio, sustainability, and high thermal and sound insulation properties (Ansell 2015; Issa and Kmeid 2005). The embodied energy of timber construction and its carbon dioxide emissions are extremely low compared with those of other materials such as concrete and steel (Anshari et al 2017; Uzel et al 2018). The demand for timber for building constructions has increased continuously because of the realization of sustainability and environmental impacts (Issa and Kmeid 2005). Currently, wood is important to many professionals including engineers, architects, and contractors.

Rubberwood (*Hevea brasiliensis*) is one of the economic plants in Thailand and also in Southeast Asia. Thailand's rubber production was ranked first in the world in 2017 at approximately 4.56 million tons. Nowadays, most of

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* Corresponding author

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the export products from rubberwood are in the form of raw material and rubberwood lumber (Chetpattananondha et al 2017). However, the exportation of rubberwood lumber in Thailand is gradually decreasing, which directly affects the lumber and related industries. Moreover, most rubberwood lumber is produced by using a constant drying temperature between 80 and 90°C together with chemical treatment for termite resistance. Typically, the drying time for wood treatment is very long and depends on the thickness of the wood. Therefore, thermally modified technology, which is one of the environmentally friendly technologies, is applied as an alternative method for wood treatment. The purpose of this thermally modified technique is to improve the dimensional stability and decay resistance of wood (Sandberg and Kutnar 2016). Nevertheless, the glued laminated timber (glulam) technique is also applied for structural beam fabrication for the addition of value in lumber products. The process of glulam manufacturing involves joining laminate wood or small lumber, which is typically used for producing beams and columns or other structural members for building (Li et al 2018a). The glulam technique could also reduce the poor properties of timber and some defects including twisting, bowing, and splitting due to drying and sensitivity to insect infestations after cutting down. This technique is typically applied for complex structural members, including for straight or curved forms of building constructions (Nadir and Nagarajan 2014).

Considering the thermal modification process (Gonza´ lez-Peña et al 2009; Bakar et al 2013; Cademartori et al 2013; Todaro et al 2015), MC and temperature can modify the structure of wood in relation to its chemical component. It can then permanently change the structure of wood that is obtained. Cellulose and hemicellulose are polysaccharides that function as cell walls, while lignin has an aromatic structure. The transformation of the lignin–polysaccharide complex is directly affected by treatment with a high temperature of 180 to 200°C, and organic acid is released during decomposition of hemicelluloses in the cell wall. Finally, the chemical structure of wood is changed. The change in the chemical function on the surface during treatment directly affects the color of thermally modified wood (Li et al 2018b). Previous research (Tomak et al 2018) also suggested that the advantages of thermally modified wood included weathering resistance, wettability, homogeneous color, fungal decay resistance, and increment in dimensional stability. Furthermore, thermally modified wood could be used in $CO_2$ lasers for evaluating the wettability of modified wood compared with unmodified wood (Li et al 2019). This process could effectively reduce the hygroscopicity of wood by the degradation of hemicellulose and cellulose (Herrera et al 2018). Other research work also mentioned that this method is an environmentally friendly technology that does not use hazardous substances with a reduction in the environmental impact (Li et al 2017). However, previous studies (Zahn and Rammer 1995; Mohamad et al 2011; Nadir and Nagarajan 2014) have mainly applied the glulam technique on local wood utilization in each area such as Douglas-fir (*Pseudotsuga menziesii*) in Europe. Also, hardwood in Malaysia is called kapur (*Dryobalanops* spp.), merpauh (*Swintonia* spp.), resak (*Vatica* spp. and *Cotylelobium* spp.), and bintangor (*Calophyllum* spp.). Meanwhile, a previous study (Yue et al 2020) evaluated the flexural properties of glulam beam with thermally treated poplar in a high RH environment. Thermally modified rubberwood integrated with the glulam technique has yet to be found.

The objective of this study was to evaluate the effect of thermal modification with various modification temperatures on the physical, mechanical, and time-dependent properties of rubberwood glulam timber under static loads, sustained loads, and cyclic loads. Creep models are also determined, which can be used to predict long-term deformation. In addition, the ductility, impairment of strength, and energy dissipation of the thermally modified rubberwood glulam are also obtained from the cyclic loading test. The results of this study can be beneficial for the future product improvement of thermally modified rubberwood glulam members.

## MATERIALS AND METHODS

### Specimen Preparation

***Thermally modified rubberwood.*** The thermally modified rubberwood with high temperature used in this study was supplied by JK Innovation Wood Products Co., Ltd. (Rayong, Thailand). In the first phase, rubberwood was treated by using heat and steam until the modification temperature of 100°C was reached. Thereafter, the temperature was increased again up to 130°C, while the MC in the rubberwood was decreased to nearly zero. The first phase of heating was 18 to 24 h. Then, the rubberwood was modified again by the treatment process at heating temperatures of 180°C and 220°C for 2-3 h. Finally, the treated specimens were cooled down and moisture conditioning was applied by water-spraying systems to decrease the temperature. The MC of the treated wood was approximately 4-7%. The last procedure lasted 24 h for thermal modification.

***Preparation of glued laminated timber using rubberwood.*** Polyurethane with a commercial brand COSMO PU-160.110 (Weiss Chemie + Technik GmbH & Co. KG, Haiger, Germany) was used as an adhesive in glulam manufacturing. This adhesive was imported from Weiss Chemie + Technik, Germany (Weiss Chemie + Technik 2018) and provided by Deco Enterprises Co., Ltd. (Chachoengsao, Thailand). The viscosity, density, skinning time (dry), and tensile shear strength of adhesive were 4500 mPa-s, 1.14 g/cm$^3$, 35 min, and 13 MPa, respectively. Specimen preparation processes were commenced by 1) cleaning the wood specimens to remove moisture, oil, and dust before gluing; 2) spraying adhesive on the specimens at 250 g/m$^2$; 3) arranging wood by four layers and pressing with a pressure of 0.015 N/mm$^2$ for a duration of 90 min; and 4) uncompressing the specimens and cleaning off the excess adhesive. Finally, the obtained dimension of the glulam beam was 80 mm × 80 mm × 1280 mm (1:1:16) for the static flexural, creep, and cyclic loading tests.

### Experimental Methods

***Physical and mechanical property test.*** The MC, specific gravity, and four-point bending tests of rubberwood specimens were examined. The specimens that were prepared at high temperatures of 180°C and 220°C were denoted as specimens RW180 and RW220, respectively. The control rubberwood dried at 90°C with chemical treatment was denoted as specimen RW90. The MC test of rubberwood specimens was evaluated according to ASTM D4442 (American Society for Testing Materials ASTM D4442-16). The specific gravity test was carried out according to ASTM D2395 (American Society for Testing Materials ASTM D2395-14), where the specimens had dimensions of 23 mm × 75 mm × 120 mm with three specimens for both tests. The four-point bending test for glulam beam using rubberwood was evaluated in accordance with ASTM D198 (American Society for Testing Materials ASTM D198-14). The span-to-depth ratio (*L/d*) of the specimen equaled 15, while the overhang at each support was set at 40 mm. The glulam beam specimen was installed on two-end supports with span length *L*. The load was applied at a third point location with 1/3 of a load span, as presented in Fig 1. The loading rate for this test was 2 mm/min. The average values of flexural properties were obtained from three individual specimens in each group. From the flexural properties test, the MOE, MOR, ultimate load, deflection at ultimate load, and failure behavior were obtained.

***Flexural creep test.*** The flexural creep test for rubberwood glulam specimens was performed in accordance with ASTM D198 and ASTM D6815 (American Society for Testing Materials ASTM D198-14, ASTM D6815-09). The glulam beam specimens were installed on the steel frame for creep testing, which was designed to bend the specimen vertically similar to a four-point bending test setup, as illustrated in Fig 2 (Pulngern et al 2010). The loading was performed using a solid steel weight hung from pulleys, which were applied with various stress levels including 25%, 40%, and 55% of the ultimate load obtained from

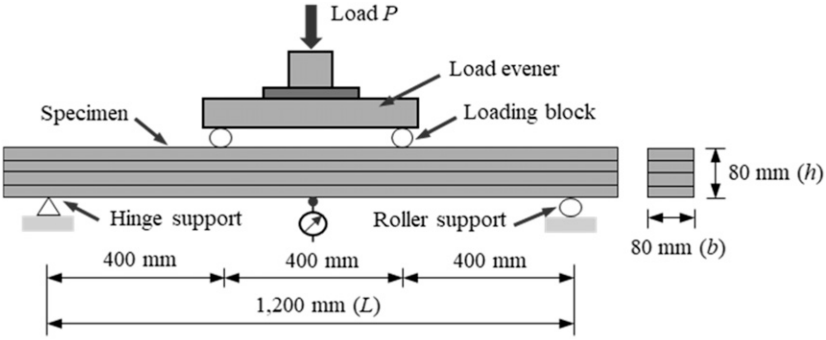


Figure 1. Four-point bending test setup of glulam beam.

the flexural test. Deflections of specimens were measured at the midspan of the beam specimen and initially recorded in minutes (1, 2, 5, 15, and 30 min) and subsequently in hours (1, 2, 5, 20, 50, 70, 120, 250, 350, 500, 700, and 1000 h). Flexural creep tests were carried out in a controlled room with an average temperature and RH of 28.7°C and 85%, respectively, and SDs of 0.54 and 2.11, respectively. Creep test information including initial displacement, final displacement, and creep displacement was obtained from the individual test specimens.

***Cyclic loading test.*** The cyclic test for beam specimens was carried out in accordance with EN 12512 (European Standard EN 12512 2005). The setup for tested specimens was similar to the four-point bending method, while the end support and loading block were clamped by studs and bolts, as shown in Fig 3. The cyclic loading

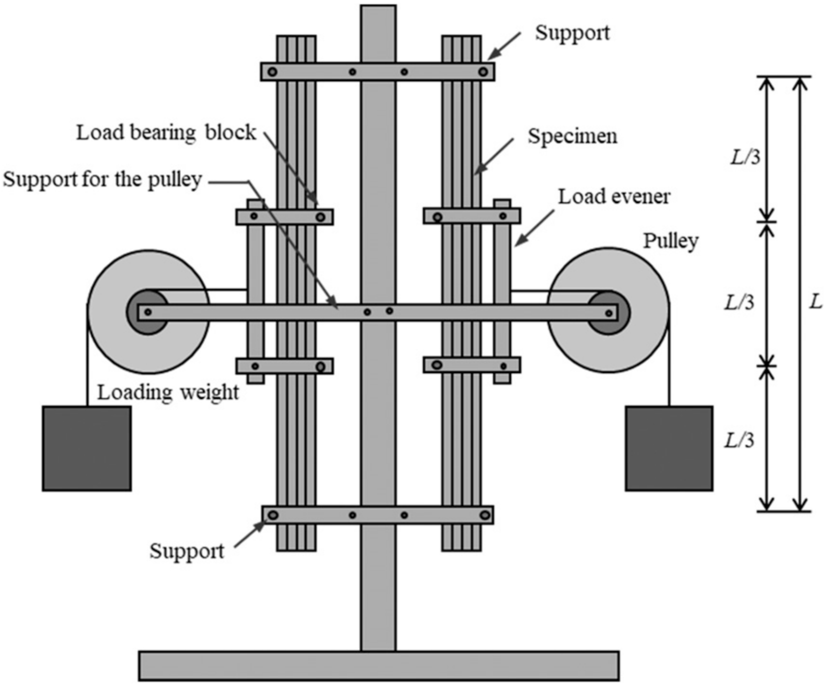


Figure 2. Experimental setup for the flexural creep test.

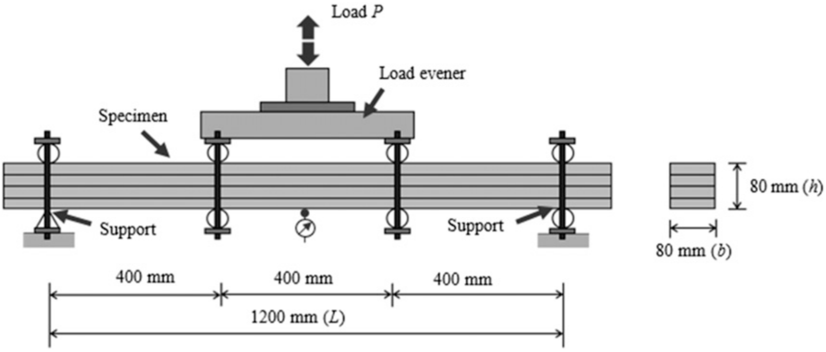


Figure 3. Cyclic loading test setup of glulam specimens.

test of the glulam beam was conducted in three individual specimens, focusing on impairment of strength, ductility, and energy dissipation in each group. In the initial stage, the load in compression was applied to the specimen in the first cycle until the displacement at the midspan was raised up to 25% of an estimated yield displacement ($0.25\Delta_y$). Afterward, the beam specimen was unloaded to zero displacement and then reloaded by increasing the displacement to 25% of the estimated yield displacement ($-0.25\Delta_y$) on the tension side. Then, testing was repeated with an increment yield displacement at $0.5\Delta_y$ step by step until the specimen failed or the displacement reached 30 mm. The applied displacement on the specimen for other cycles was repeated three times. The cycle of applied displacement corresponding to the test procedure of the cyclic loading test is shown in Fig 4 (European Standard EN 12512 2005).

## Creep Model

The flexural creep experimental results were used to evaluate the time–stress–dependent empirical creep models (Holzer et al 1989; Boresi and Schmidt 2002). Creep models were proposed by various mathematical models including power, exponential, and hyperbolic functions. The power function given by Bailey and Norton (Norton 1929; Bailey 1935) can be expressed as follows:

$$\delta_c = a\sigma^b t^m. \quad (1)$$

The Dorn model (Dorn 1962) was written in the form of the exponential function, as shown in the following equation:

$$\delta_c = ae^{b\sigma} t^m, \quad (2)$$

where $\delta_c$ is the displacement value (mm), $\sigma$ is the maximum stress at extreme fiber (MPa), $t$ is time

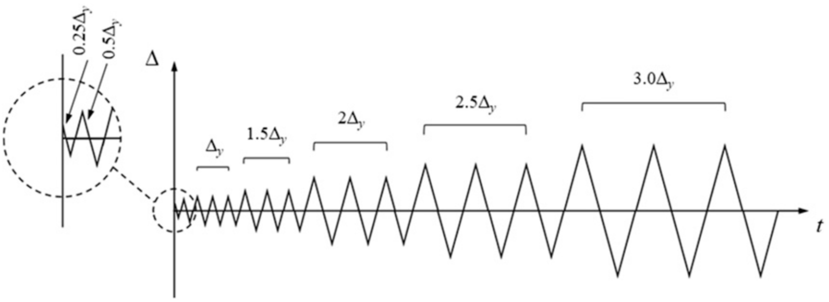


Figure 4. Cycles of applied displacement.

after loading (h), and $a$, $b$, and $m$ are creep parameters that were obtained from fitting curve technique. The hyperbolic function (Pickel et al 1971) given by Pickel could be used to predict the long-term creep behavior shown as

$$\delta_c = ae^{(-A/T)} \sin h(b\sigma)t^m \text{ and} \tag{3}$$

$$\delta_c = ae^{(-A/T)} [\sin h(b\sigma)]^n \, t^m, \tag{4}$$

where $T$ is the temperature (°C), and $a$, $b$, $n$, $m$, and $A$ are the creep parameters. Because the temperature at the control room is constant, the exponential term on the general form Pickel model becomes constant. Therefore, Eqs 3 and 4 could be rearranged as the following equations and are also called the simplified Pickel model and adjusted Pickel model, respectively,

$$\delta_c = a \sin h(b\sigma)t^m \text{ and} \tag{5}$$

$$\delta_c = a[\sin h(b\sigma)]^n \, t^m. \tag{6}$$

## RESULTS AND DISCUSSION

### Physical and Mechanical Properties

***Specific gravity and MC.*** The results from the specific gravity test revealed that specific gravity for the control rubberwood (RW90) and thermally modified rubberwood at 180°C and 220°C (RW180 and RW220) were 0.76, 0.64, and 0.60, respectively. The increment in modification temperature for property modification processes resulted in a decrement in specific gravity. The resulting value of RW90 had a MC of 9.66%, while RW180 and RW220 were 7.73% and 6.26%, respectively. The MC of all specimens satisfied the dry condition criterion of the American Wood Council (AWC), which defines that the MC of lumber must be equal to or less than 19% (America Wood Council 2018 ANSI/AWC NDS-2018). In comparison with recent research (Qiaofang et al 2019), the obtained results showed that the MC of rubberwood specimens modified by various high temperatures (170°C, 185°C, and 220°C) for 1.5 and 3 h have also decreased by increasing temperature and drying durations. Hence, the high modification temperature was related to the MC, which was decreased by increasing the modification temperature.

### Flexural Test

The load–displacement curves of the control glulam (GRW90) and thermally modified rubberwood glulam (GRW180 and GRW220) are illustrated in Fig 5. The relations between load and displacement of glulam specimens were obtained until the linear proportional limit. The obtained results showed that the rubberwood glulam specimens behaved as a brittle material.

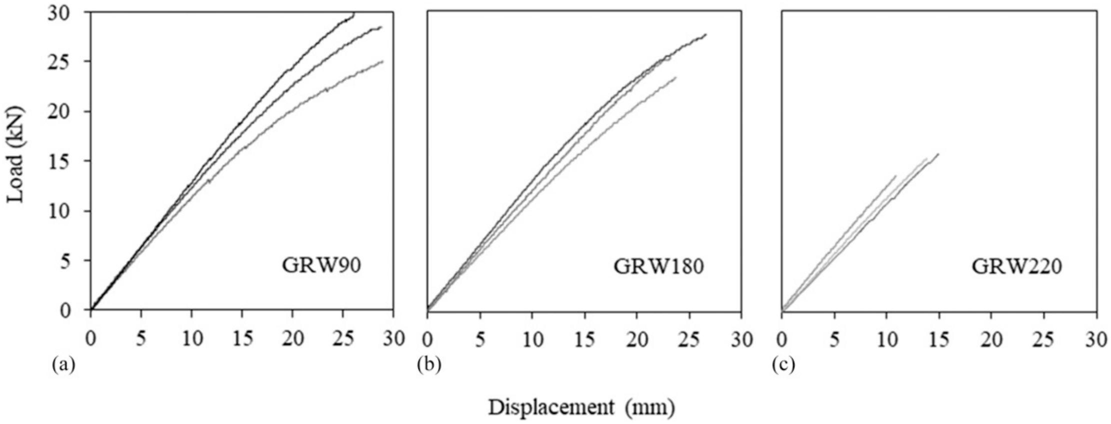


Figure 5. Load–displacement curves of rubberwood glulam specimens.

Table 1. Flexural properties of thermally modified rubberwood glulam specimens.

| Specimen | Ultimate load (kN) | Maximum displacement (mm) | MOR (MPa) | MOE (MPa) |
|---|---|---|---|---|
| GRW90 | 27.86 (2.50) | 27.88 (1.62) | 65.00 (5.88) | 10,529.80 (827.33) |
| GRW180 | 25.44 (2.61) | 24.52 (1.81) | 59.43 (5.04) | 10,711.62 (799.18) |
| GRW220 | 14.83 (1.13) | 13.20 (2.08) | 34.63 (2.69) | 10,463.15 (1,061.93) |

The values in parentheses are the SD from three independent determinations.

The results of the flexural properties are summarized in Table 1. The MOR for GRW180 and GRW220 was 59.43 MPa and 34.63 MPa, respectively, which decreased by 8.57% and 46.72% in comparison with the control rubberwood glulam (GRW90), which had a MOR of 65.00 MPa. The results also showed that higher modification temperature resulted in the lower flexural strength of rubberwood.

Scanning electron microscope (SEM) analysis was also conducted to illustrate the change in the cell wall structure of the rubberwood specimens. Figure 6 shows micrographs of thermally modified rubberwood with high temperature and the control rubberwood, which were taken from a parallel-to-grain cross-section of the specimens. The obtained results indicated that the cell structure of RW220 modified at a drying temperature of 220°C was clearly changed and collapsed because of the high temperature. Previous research (Herrera et al 2018) also studied the properties of some thermally modified wood species treated at 190°C for 8 h. The results showed that high temperature directly affected the cell wall, softening the cell and causing a loss in strength.

## Creep Behavior

Table 2 shows the ultimate loads evaluated from the four-point bending test of the control rubberwood glulam and thermally modified rubberwood glulam for the flexural creep test, while the time–displacement relations of glulam specimens applied with various stress levels are shown in Fig 7. During the testing time of 1000 h, the obtained results revealed that the creep response of all glulam specimens remained in the secondary creep behavior and delamination between layers of the glulam specimen was not found. Then, creep displacement, which is the difference between the final displacement and initial displacement, was considered and used to determine the relative creep, which is defined as the ratio between the creep displacement and initial displacement at 1 min. A summary of creep results consisting of the initial and final displacement, creep displacement, and relative creep of rubberwood glulam specimens is provided in Table 3. In comparison with previous research studies (Gowda et al 1996; Shen and Gupta 1997; Gerhards 2000; Epmeier et al 2007; Chanto 2017), the relative creep of Douglas-fir glulam timber (Chanto 2017) ranged from 0.14 to 0.66

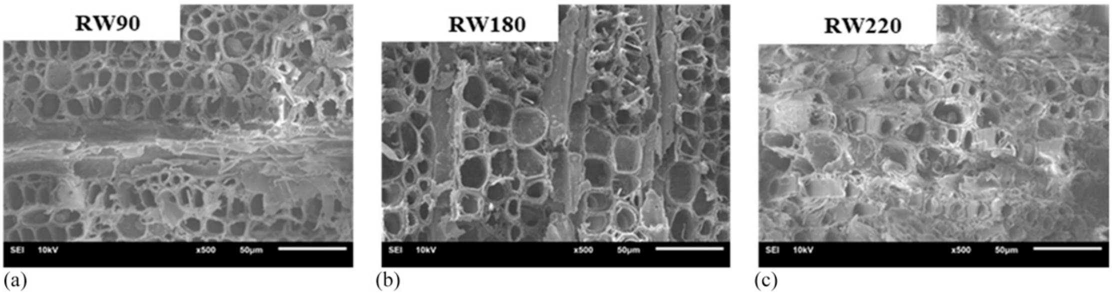


Figure 6. Micrograph taken from the cross-section by using SEM; (a) control rubberwood specimen, (b) thermally modified rubberwood specimen at 180°C drying temperature, and (c) thermally modified rubberwood at 220°C drying temperature.

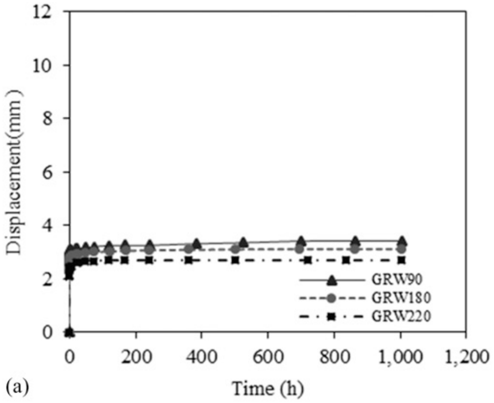
Table 2. Stress levels and loading weight for flexural creep test.

| Specimen | Stress level (%) | Loading weight (kN) |
|---|---|---|
| GRW90 | 25 | 0.70 |
| | 40 | 1.11 |
| | 55 | 1.53 |
| GRW180 | 25 | 0.64 |
| | 40 | 1.02 |
| | 55 | 4.63 |
| GRW220 | 25 | 0.37 |
| | 40 | 0.59 |
| | 55 | 0.82 |

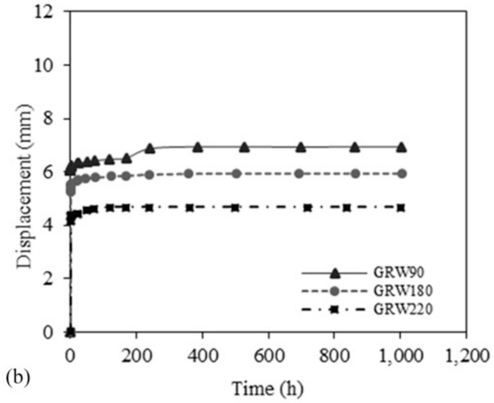
and other solid woods (Gowda et al 1996; Shen and Gupta 1997; Gerhards 2000; Epmeier et al 2007) ranged from 0.80 to 1.40, whereas the modification of rubberwood glulam timber in this work gave relative creep in the range of 0.11-0.31 depending on temperature modification, as shown in Table 4. It could be seen that the relative creep of rubberwood glulam with thermal modification obtained in this study was slightly lower than that of Douglas-fir glulam but was significantly lower in comparison with solid woods (Douglas-fir lumber, Scots pine sapwood, pine, and spruce). Thermal modification had a slight effect on the relative creep of rubberwood glulam. By considering the applied stress effect on the creep response, all stress levels gave low relative creep and a slight change was obtained by increasing the applied stress. It seems that the creep response of thermally modified wood tends to be reduced if it is used with the glulam technique.

## Creep Model

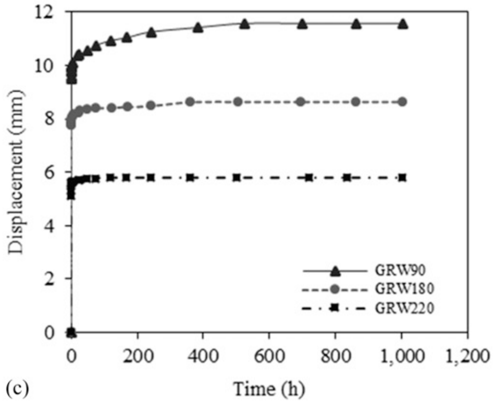
Figures 8-10 represent various creep models including power law, Dorn, simplified Pickel, and adjusted Pickel models comparing the experimental results of the rubber glulam specimens. The creep parameters were evaluated from the experimental results, as shown in Table 5. The results demonstrated that the empirical creep models are related to the experimental results with a coefficient of determination, $R^2$, ranged from 0.957 to 0.998. The power law model by Bailey and Norton was the best model in



Level of stress 25%



Level of stress 40%



Level of stress 55%

Figure 7. Creep curve of thermally modified rubberwood glulam specimens by various stress levels.

Table 3. Relative creep and creep displacement of tested specimens.

| Specimen | Stress level (%) | Displacement (mm) | | Creep displacement (mm) | Relative creep |
|---|---|---|---|---|---|
| | | 1 min | 1,000 h | | |
| GRW90 | 25 | 2.92 | 0.51 | 0.51 | 0.18 |
| | 40 | 6.05 | 0.89 | 0.89 | 0.15 |
| | 55 | 9.49 | 2.09 | 2.09 | 0.22 |
| GRW180 | 25 | 2.39 | 0.74 | 0.74 | 0.31 |
| | 40 | 5.24 | 0.70 | 0.70 | 0.13 |
| | 55 | 7.77 | 0.89 | 0.89 | 0.11 |
| GRW220 | 25 | 2.11 | 0.59 | 0.59 | 0.28 |
| | 40 | 4.15 | 0.52 | 0.52 | 0.13 |
| | 55 | 5.13 | 0.65 | 0.65 | 0.13 |

comparison with other models. Eqs 7-9 describe the power law model of GRW90, GRW180, and GRW220, respectively. Each equation presented the creep parameters for the glulam timber which were modified at temperatures of 90, 180, and 220°C, respectively. The constant term for each equation was a creep parameter that was mentioned in the previous creep model of the power law model that appeared in Eq 1. By considering the creep parameters related to the stress level, the exponent term of creep parameters ($b$ and $m$) decreased with increasing modification temperature, while the factoring coefficient ($a$) increased. This means that the increment in modification temperature also directly affects the creep response. These creep models can be used to predict the long-term deformation of rubberwood glulam with thermal modification.

$$\delta_{c,90} = 0.041\sigma^{1.538}t^{0.018}, \qquad (7)$$

$$\delta_{c,180} = 0.090\sigma^{1.291}t^{0.012}, \qquad (8)$$

$$\delta_{c,220} = 0.321\sigma^{0.970}t^{0.011}. \qquad (9)$$

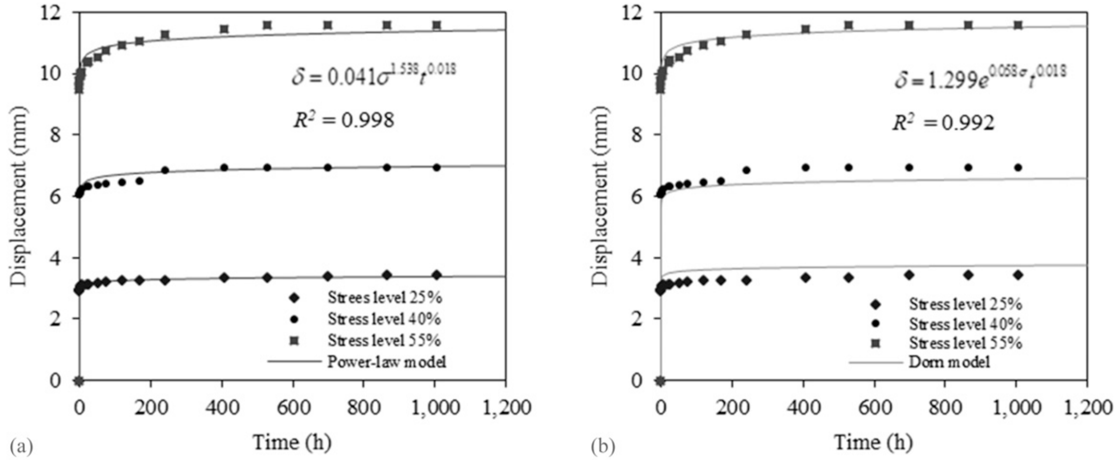
## Cyclic Test

***Comparison between flexural and cyclic loading tests.*** The load–displacement relations of rubberwood glulam specimens between the flexural test and the cyclic loading test are presented in Fig 11. The backbone curves were considered from hysteresis on the cyclic loading of the glulam specimens. At the beginning of the backbone curves, linear behavior was obtained and represented a good correlation with the flexural test. In the case of MOE, the glulam specimens in both tests showed no significant differences. Furthermore, the ultimate loads obtained from the cyclic loading test decreased by about 10-20% in comparison with the static flexural tests. These are because of the fact that the accumulation of damage under several loading–unloading–reloading cycles also affected the strength impairment of the material. Generally, most failure mechanisms in the glulam specimens under cyclic loading occurred because of tension failure and then spread up the crack in the midspan zone of the beam. The crack typically initiated from the bottom of the specimen to the top layer. However, the delamination failure or the

Table 4. Relative creep results of rubberwood glulam in comparison with solid woods.

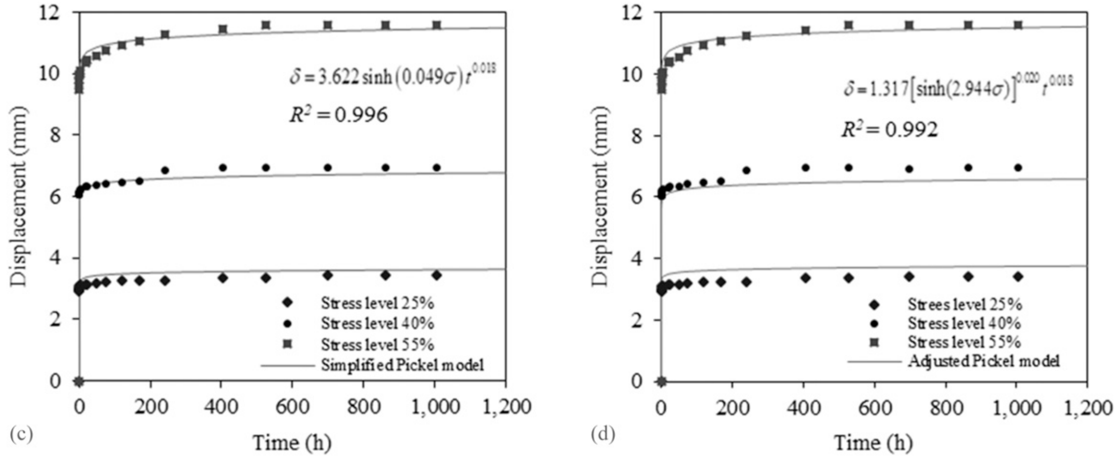
| Specimen | Relative creep |
|---|---|
| Thermally modified rubberwood glulam | 0.11-0.31* |
| Douglas-fir glulam | 0.14-0.66 (Chanto K 2017) |
| Douglas-fir lumber (10% MC) | <1.0 (Gowda S et al 1996) |
| Scots pine sapwood (14-6% MC) | 1.0-1.3 (Gerhards CC 2000) |
| Pine and spruce (8-14% MC) | 0.8 (Epmeier h et al 2007) |
| Douglas-fir lumber (11% MC) | 1.0-1.4 (Shen Y and Gupta R 1997) |

*This study.



Power-law model

Dorn model



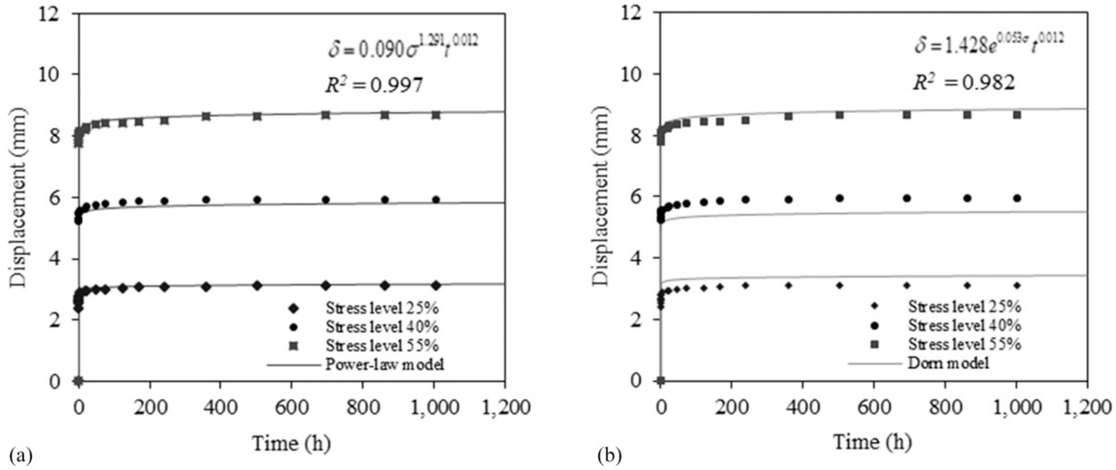
Simplified Pickel model

Adjusted Pickel model

Figure 8. Predicted flexural creep model of GRW90 specimens.

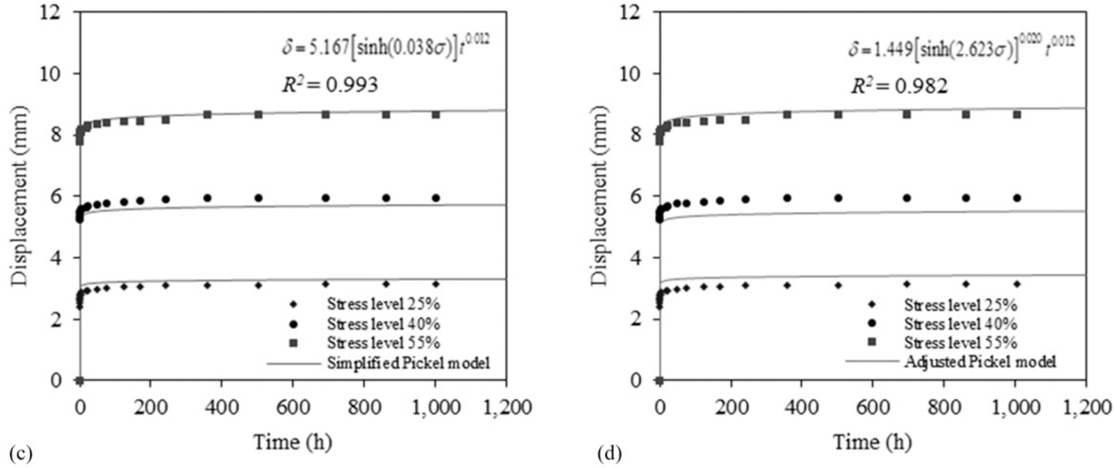
sliding failure mode also occurred in some specimens, combined with other failure modes such as the simple tension, horizontal shear, and bras tension. Similar behaviors were found for all backbone curves, meaning that thermal modification did not affect the static cyclic ratio and failure behavior.

***Impairment of strength.*** The impairment of strength is defined as a reduction in the load that is applied to a specimen from the first to the third cycle of the same amplitude (European Standard EN 12512). Table 6 shows the impairment of strength for GRW90, GRW180, and GRW220, which were calculated by using the percentage of the load on the third cycle to the first cycle. The test results showed that the impairment of strength depends on the increment in displacement. The failure of all specimens occurred when the cyclic loading test was reached two times the yield displacement, $2\Delta_y$. The modification temperature did not have a significant effect on



Power-law model

Dorn model



Simplified Pickel model

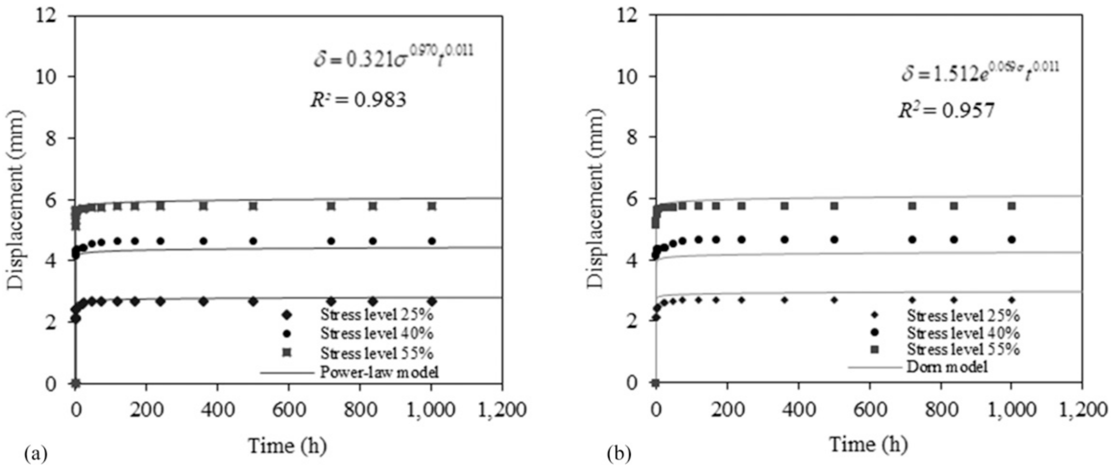
Adjusted Pickel model

Figure 9. Predicted flexural creep model of GRW180 specimens.

the impairment of strength in the case of rubberwood glulam.

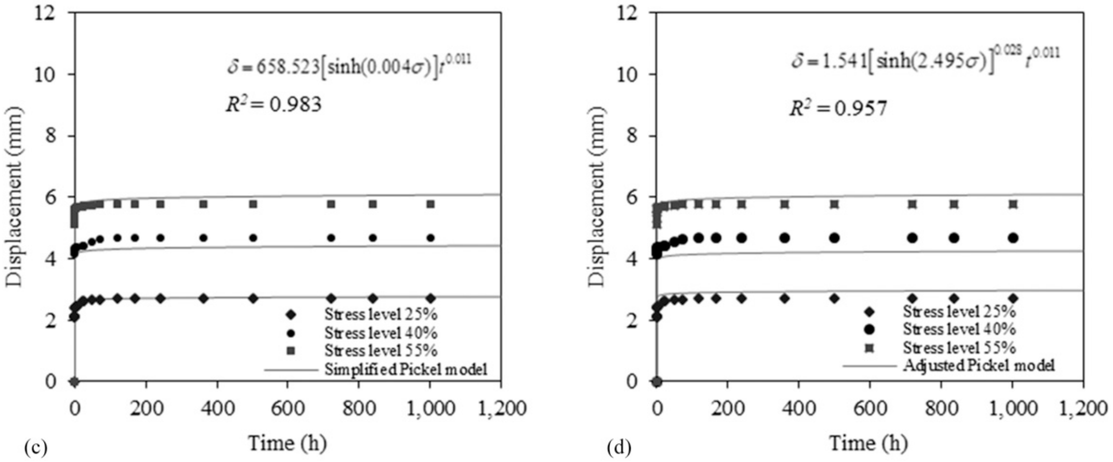
***Ductility.*** To evaluate the performance of structural members under applied load, ductility can be reflected as the abilities of the material under an increment in amplitude displacement for a plastic range (European Standard EN 12512). The ductility index is defined as a ratio between the ultimate displacement, $\Delta_u$, and the yield displacement, $\Delta_y$. The ductility index of the control rubberwood glulam (GRW90) and thermally modified glulam (GRW180 and GRW 220) were 1.58, 1.47, and 1.45, respectively. It can be seen that the increment in modification temperature reduced the ductility index. This is because the internal structure of wood was changed at high temperatures.

***Energy dissipation.*** Figure 12 shows the results of the hysteresis energy dissipation for GRW90, GRW180, and GRW220. The energy



Power-law model

Dorn model



Simplified Pickel model

Adjusted Pickel model

Figure 10. Predicted flexural creep model of GRW220 specimens.

dissipation or hysteresis energy absorbed was calculated by the area of the force–displacement loops under the cyclic loading test. It was found that the increment in energy dissipation depended on the increment in displacement. Moreover, the thermally modified rubberwood specimens with 220°C drying temperature (GRW220) resulted in lower energy dissipation than GRW90 and GRW180, respectively. This can further confirm that higher modification temperature reduced the energy dissipation of rubberwood.

## CONCLUSIONS

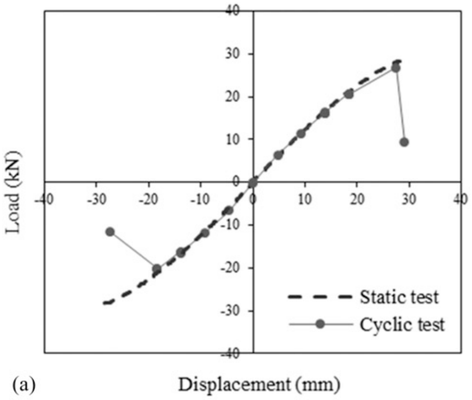
This study investigated the influence of the thermal modification temperature on the physical and mechanical properties, including the time-dependent and cyclic properties of rubberwood glulam. The following conclusions

Table 5. Creep parameters and coefficient of determination for creep models.

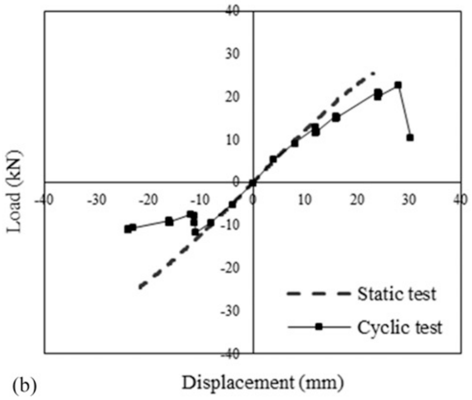
| Proposed model | Value of parameter | Specimen | | |
|---|---|---|---|---|
| | | GRW90 | GRW180 | GRW220 |
| Power law | $A$ | 0.041 | 0.090 | 0.321 |
| | $B$ | 1.538 | 1.291 | 0.970 |
| | $M$ | 0.018 | 0.012 | 0.011 |
| | $R^2$ | 0.998 | 0.997 | 0.982 |
| Dorn | $A$ | 1.299 | 1.428 | 1.512 |
| | $B$ | 0.058 | 0.053 | 0.069 |
| | $M$ | 0.018 | 0.012 | 0.011 |
| | $R^2$ | 0.992 | 0.982 | 0.957 |
| Adjusted Pickel | $A$ | 3.622 | 5.167 | 658.523 |
| | $B$ | 0.049 | 0.038 | 0.004 |
| | $M$ | 0.018 | 0.012 | 0.011 |
| | $R^2$ | 0.996 | 0.993 | 0.983 |
| Simplified Pickel | $A$ | 1.317 | 1.449 | 1.541 |
| | $B$ | 2.944 | 2.623 | 2.495 |
| | $M$ | 0.018 | 0.012 | 0.01 |
| | $N$ | 0.020 | 0.020 | 0.028 |
| | $R^2$ | 0.992 | 0.982 | 0.987 |

were noted from the experimental and empirical models:

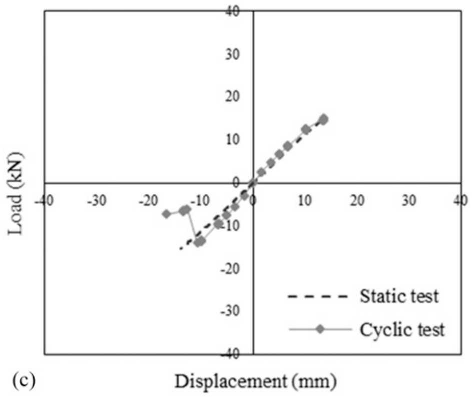
1. Thermal modification at high temperature exhibited lower MC and specific gravity at 15.79% and 26.67%, respectively. The MC of rubberwood ranged from 6.20% to 9.70%, which could be used as construction material without the strength reduction factor because of excessive MC during the structural calculation.
2. The flexural properties of rubberwood glulam with 180°C and 220°C treatment temperatures for modification were decreased to 8.57% and 46.72%, respectively, although a significant change in the MOE was not found. The failure mechanism under the flexural test occurred because of simple tension.
3. Relative creeps of thermally modified rubberwood glulam with high temperatures are lower than those of unmodified timber. Various mathematical creep models were proposed, and it was found that the power law model given by Bailey and Norton was the best-fitted model that could be used to predict the long-term deformation of rubberwood



GRW90



GRW180



GRW220

Figure 11. Comparison between flexural static and cyclic loading test results.

Table 6. Strength impairment of specimens under cyclic loading.

|  | $0.75\Delta_y$ |  | $\Delta_y$ |  | $1.5\Delta_y$ |  |
|---|---|---|---|---|---|---|
| Specimen | Tension | Compression | Tension | Compression | Tension | Compression |
| GRW90 | 98.77 | 99.39 | 98.51 | 98.03 | 88.75 | 83.62 |
| GRW180 | 98.30 | 65.82 | 96.20 | 96.77 | 94.86 | 96.40 |
| GRW220 | 98.75 | 98.72 | 98.15 | 97.30 | 96.59 | 58.02 |

$\Delta_y$ is the yield displacement.

glulam. Also, the modification temperature influences the creep behavior, especially the power law model, in which the $R^2$ value was reduced with the increment in drying temperature.

4. In the case of cyclic loading, the behavior of rubberwood glulam specimens showed impairment of strength. Strength deterioration occurred because of the accumulation of damage over several loading–unloading–reloading cycles. The temperature for property modification had no significant effect on the impairment of strength and also the ductility index. The energy dissipation of the specimen modified at 220°C decreased in comparison with the control specimen. The failure mechanism under low amplitude of displacement occurred mainly because of simple tension, whereas high amplitude resulted in delamination failure.

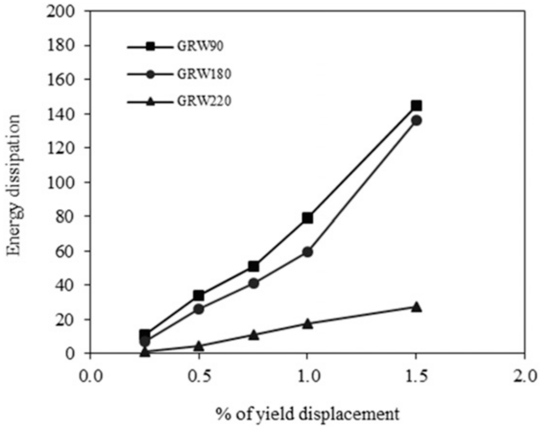


Figure 12. Energy dissipation of thermally modified rubberwood glulam specimens.

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