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Author names and affiliations:
Taiyo Okada: Faculty of Agriculture, Shizuoka University, 836-Ohya, Suruga-ku, Shizuoka 422-8529, Japan
Hikaru Kobori: Faculty of Agriculture, Shizuoka University, 836-Ohya, Suruga-ku, Shizuoka 422-8529, Japan
Yoichi Kojima: Faculty of Agriculture, Shizuoka University, 836-Ohya, Suruga-ku, Shizuoka 422-8529, Japan
Shigehiko Suzuki: Faculty of Agriculture, Shizuoka University, 836-Ohya, Suruga-ku, Shizuoka 422-8529, Japan
Kuniharu Nishikido: Sekisui House, Ltd., 1-1-88-Oyodonaka, Kita-ku, Osaka-shi, Osaka 531-0076, Japan
Akira Hirose: Sekisui House, Ltd., 1-1-88-Oyodonaka, Kita-ku, Osaka-shi, Osaka 531-0076, Japan
Kazuaki Takahashi: Sekisui House, Ltd., 1-1-88-Oyodonaka, Kita-ku, Osaka-shi, Osaka 531-0076, Japan

Corresponding author:
Corresponding author: Yoichi Kojima
E-mail address: kojima.yoichi@shizuoka.ac.jp
Telephone and fax numbers: 054-238-4856

Abstract

Glued laminated timber (glulam) is widely used in building construction and required to have high durability as a structural member. A decrease in adhesion properties induces the delamination of glulam and declines its mechanical properties. Aqueous polymer-isocyanate adhesive (API) is relatively new in terms of structural applications, and there is little available information regarding the durability of glulam laminated by the glue. In this study, two different cyclic accelerated aging treatments were used to assess the durability of API bonded glulam consisting of sugi, hinoki and spruce. Durability was estimated by a change in shear strength. In both accelerated aging treatments, the wood failure percentage of glulam did not decrease although the shear strength declined. Thus it was assumed that the decrease in shear strength was affected by wood cracks rather than deterioration of adhesives. Additionally the durability of API bonded glulam, resorcinol formaldehyde resin (RF) bonded glulam, and solid wood was compared using a deterioration model. Eventually it was presumed that API bonded glulam had high durability equal or greater than solid wood and RF bonded glulam when they were exposed to a cyclic wet-dry treatment.

Key words
glulam, durability, accelerated aging treatment, aqueous polymer-isocyanate

Text

1 Introduction

Glued laminated timber (glulam) is widely used as a structural material in buildings. The Japanese Agricultural Standard (JAS) for glulam was first established in 1966. Glulam was licensed for use in medium- and large-scale buildings through the establishment of a large dimension glulam on the JAS in 1986 and revision of the Building Standard Law in 1987. The use of glulam in public buildings has been promoted in recent years; thus an increase in its structural application in medium- or large-scale construction is expected.

When glulam is used as a structural beam in buildings, it is required to have high durability in order to retain the imperative strength to ensure that the structural skeleton of the construction is maintained. Therefore, to extend its use to medium- and large-scale buildings, its reliability as a structural member must be ensured through the evaluation of its durability.

The mechanical properties of glulam can decline due to the deterioration of the laminae, adhesive, and interface between the wood and bond. Since deterioration of the adhesive induces delamination of glulam (Teder and Wang 2013), a change in the adhesion property is useful for evaluating the durability of glulam (Raknes 1997; Milan et al. 2008). Thus, when a new adhesive for glulam is developed, it is important to evaluate the durability of glulam laminated by the adhesive.

Recently in Japan, resorcinol formaldehyde resin (RF), phenol RF (PRF) and aqueous polymer-isocyanate adhesive (API) have been used to bond laminae for manufacturing glulam. RF and PRF have been widely used in structural glulam since the 1940s, and both have shown high durability (Yanagawa and Masuda 2011a, 2011b).

On the other hand, API was developed as a solution to the problem of formaldehyde emissions from wood based materials in the 1970s (Yamada 2015). Many studies on the adhesion properties of API were previously carried out by Taki et al. (1978, 1979, 1980), API has mainly been applied to glulam used for interior fixtures, whereas its use for structural glulam has been limited because the achievements of using API for structural application such as fire resistance were insufficient (Tohmura 2016). Hence an evaluation of the fire resistance of API-bonded glulam (GA) was conducted by Uesugi et al. (1993, 1994), and a part of API has been accepted to be used in structural glulam for “Use Environment B” in accordance with JAS (2007) since the revision of JAS criteria in 2007. Recently the demand for API has increased because API does not contain formaldehyde, has a discreet color, etc.

However, the use of API in structural applications is relatively new compared to RF and PRF, and there have been few studies on the durability of GA. Although Yanagawa and Harata (2017, 2018) reported the durability of preservative-treated sugi GA following an outdoor exposure test, the study was specifically performed to clarify sugi glulam durability in the outdoor environment.

When glulam is used as a structural beam in residential, and medium- and large-scale buildings (e. g., public buildings), it is exposed to the indoor environment. The potential durability of GA in the indoor environment has not been assessed; thus, a quantitative evaluation of the durability of GA laminated with various wood species is required to ensure its reliability. In order to evaluate the durability performance quantitatively, it is necessary to determine the effects of cyclic water absorption and desorption on GA.

In this study, we evaluated durability of GA following water absorption and desorption to ensure its reliability. GA, RF-bonded glulam (GR), and solid wood (SW) were exposed to two kinds of cyclic accelerated aging treatments, and a block shear test was conducted to determine changes in shear strength. In addition, a deterioration model was used to evaluate the durability of GA.

2 Materials and methods

2.1 Glulam conditions

Three types of GA, composed of sugi (*Cryptomeria japonica*), hinoki (*Chemaecyparis obtusa*), and spruce (*Picea* sp.) and one type of GR laminated of same kind of spruce as GA were prepared. 7 Sugi glulam with 5 layers were manufactured from 35 laminae, with a thickness of approximately 24.5 mm, width of 120 mm, and length of 3000 mm. It was designed to have the same-grade composition as five L-80 grade laminae, as defined in the JAS for glulam (2007). Also 7 hinoki and total of 14 spruce (7 with API and 7 with RF) glulams with 4 layers were made from 28 and 56 laminae, respectively, with a thickness of approximately 30.5 mm, width of 120 mm, and length of 3000 mm. These glulams were designed to have a the mixed-grade symmetrical composition, with two L-110 grade laminae as external layers and two L-80 grade laminae as internal layers, as defined in the JAS for glulam (2007).

2.2 Adhesives and the manufacturing of glulam

In this study, laminae which surfaces were planed were used. The laminae were laminated with two-component API (main agent: KR-134SA, hardener: AX-200a; Koyo Sangyo Co., Ltd., Japan). The combination ratio between the main agent and the hardener was 100:15. To evaluate the tendency for deterioration with different adhesives, a spruce glulam laminated with RF (main agent: PRX-275AS, hardener: PRX-350BT; Aica Kogyo Company, Limited, Japan) was prepared. The combination ratio between the main agent and the hardener was 100:30. API with a spreading rate of 240 g/m^2 and RF with a spreading rate of 283 g/m^2 were applied on one of the bonded surfaces of the laminae by a bead type glue spreader. In the GA, the laminated member was exposed to a pressure of 0.98 MPa for 30 min by a cold press (at a surface temperature of 31°C). In the GR, the laminated member was exposed to a pressure of 1.27 MPa for 10 min by a high-frequency press at a temperature of 60 °C. Through the above-mentioned processes, a total of 28 glulam beams, which means seven glulam beams for each combinations, were manufactured with an approximate size of approximately 120 mm (height), 120 mm (width), and 3000 mm (length). The surface of these glulam beams were planed.

2.3 Specimens

A schematic diagram of the specimens composed of 4 layers is shown in Fig. 1. Specimens with dimensions of approximately 120 mm (height) by 29 mm (length) by 25 mm (width) were randomly cut from each glulam beam according to the JAS for glulam (2007). Additionally, a notch of 2 mm (width) by 3 mm (thickness) was placed in each layer to conduct the block shear test, as shown in Fig. 1. In all, 97 specimens were obtained for sugi GA, and 100 specimens were acquired for hinoki GA, spruce GA and GR, respectively. In addition, 40 SW specimens for each wood species with the same size as the four layered glulam specimens were also prepared to compare the durability with glulam specimens. The weight of all specimens was measured and specimens were divided into three groups with the same mean and range of weight in each group. Total of 52 specimens (10, 21 and 21 for control, boil-dry (BD) cyclic treatment and hot water-dry (HD) cyclic treatment) in each type of glulam and all 40 specimens (10, 15, and 15 for control, BD cyclic treatment and HD cyclic treatment) in each kind of SW were selected and tested in this study.

2.4 BD treatment conditions

One cycle of BD consisted of the following steps: boiling for 4 h, cooling in room temperature water for 1 h, and drying at 70 °C for 19 h. This protocol followed the boiling water delamination test used in the JAS criteria (2007). In the standard, the drying time depends on the specimen mass; 19 h was applied here to simplify the treatment procedure. For each material, 15 specimens were exposed to BD treatment and 3 specimens were selected to evaluate durability after 5, 10, 15, 30, and 60 cycles. In addition, the weight of several specimens was measured under wet and dry conditions.

2.5 HD treatment conditions

HD, which was a milder treatment than BD, was also conducted. One cycle of HD consisted of the following steps: soaking in hot water at 70 °C for 4 h, cooling in room temperature water for 1 h, and drying at 40 °C for 19 h. For each glulam, 18 specimens were exposed to the HD treatment; and 3 specimens were selected to evaluate durability after 1, 5, 10, 20, 55, and 75 cycles; and 15 specimens of each SW were subjected to the treatment of 1, 10, 20, 55, and 75 cycles. Additionally, the weight of several specimens was measured under wet and dry conditions.

2.6 Block shear test

After the accelerated aging treatments, each specimen was stored in a constant temperature and humidity room at 20 °C with 60%RH more than 2 weeks, and then a block shear test was performed using an amsler type universal testing machine (RS-2, T. V.; Shimadzu Co., Ltd., Japan), with a constant loading rate of 1 mm/min in accordance with the JAS (2007). The shear strength τ (N/mm^2) was determined for every shearing surface tested and calculated according to the following equation:

$$\tau = \frac{P_{max}}{S}, \qquad (1)$$

where P_{max} indicates the fracture load (N) in the block shear test and S is the sheared area (mm^2), which was 25 mm (width) by 25 mm (length) for all specimens in this study.

Since the specimens consisting of four or five layers were tested, the block shear test for one specimen of sugi glulam was performed four times, while the tests for the other materials were conducted three times. To ensure a consistent evaluation, shear strength values were removed in the following cases: the shearing surface of the specimen was broken during the accelerated aging treatment, the position of a fracture occurring as a result of the block shear test diverged from the shearing surface, or the breakage of a specimen in the shearing test was clearly affected by a weak point, such as a knot. The percentage of wood failure on the specimen surfaces was visually estimated in 5% increments.

2.7 Weight change rates

In several specimens, the weights in wet and dry conditions were measured at every five cycles of each treatment, and the weight change rates (WC (%)) were calculated as follows:

$$\mathrm{WC} = \frac{W_i - W_0}{W_0} \times 100, \qquad (2)$$

where W_{i} is the weight (g) in cycle i, and W_0 is the weight (g) before the accelerated aging treatment.

3 Results and discussion

3.1 Wood failure and shear strength

Table 1 shows the wood failure percentage and shear strength of glulam and SW after the two kinds of the accelerated aging treatments. In each glulam, wood failure percentage did not clearly decrease as the number of cycles increased for each treatment. It was reported that the adhesion property of API decreases in the wet state compared to the air-dried state because the glass transition point shifted towards a lower temperature, and, in contrary, the property recovered up to air-dried state due to evaporation as a result of the glass transition point shifted towards a higher temperature (Taki et al. 1979). Thus, the adhesion property of API in the air-dry state might not decrease even after 60 cycles of BD treatment or 75 cycles of HD treatment. In addition, the wood failure percentage of GR specimens after 5, 10, 15, and 60 cycles of BD treatment and all cycles of HD treatment did not differ from that of the control specimens according to the results of a t-test (a significance level of 5 %). However wood failure percentage was significantly higher after 30 cycles of BD treatment than in the control specimen, possibly due to the post curing, scattering of the adhesive amount, etc.

The shear strength of each specimen decreased in both BD and HD treatments. In the case of BD, there was a slight decrease in the shear strength of sugi GA after 15 cycles and a significant decrease after 30 cycles, whereas the difference in shear strength between 30 and 60 cycles was small. In contrast, there was a marked decrease in the shear strength sugi SW after 10, 30, and 60 cycles. Since the shear strength of sugi SW in the BD treatment was higher after 15 cycles than after 10 cycles, the results might have been affected by the fluctuation of wood. Consequently, the decline in strength was more significant in sugi SW than in sugi GA. That of hinoki GA and SW tended to drastically decline after five cycles. The main reason for this was the obvious influence of a weak shearing surface. Shear strength significantly decreased with an increase in BD treatment cycle number for spruce GA, GR, and SW. Spruce GA had a higher shear strength than GR and SW after 15 cycles, although the control value was lower.

In the HD treatment, sugi GA and SW had an almost equal or higher shear strength than control specimens for up to 10 cycles. Although GA had a lower strength than SW in the control specimen results, that of the glulam was almost equivalent to or higher than that of SW after 10 cycles. The decrease in the strength of hinoki GA was not remarkable until after 10 cycles. Then it declined with an increase in the number of cycle after 20 cycles. However that of hinoki SW decreased with an increase in cycle number.

In spruce, both glulam GA and GR tended to have decreasing shear strength with an increase in cycle number after 20 cycles, whereas that of SW significantly declined after 10 cycles. After 75 cycles of HD treatment, the difference in strength between the three materials for spruce was negligible although among the control specimens, GA was the weakest of the materials.

From these results, it can be concluded that the shear strength of each material in the BD treatment declined with an increase in cycle number up to 30 cycles, after which the rate of decrease dropped. Therefore, it can be assumed that the shear strength of glulam and SW tended to decrease nonlinearly and finally converge when they were exposed to the cyclic BD treatment. Conversely, in the HD treatment, each glulam displayed a slight decrease in shear strength with an increase in cycle number after 20 cycles, and the strength of SW tended to gradually decline with increase in cycle number after the initial cycles. It was presumed that the decrease in shear strength up to 75 cycles of HD treatment would be similar to that below 30 cycles of BD treatment, because conditions such as the water and drying temperatures in the HD treatment were milder than those in the BD treatment. As can be seen from the above results, although wood failure percentage of glulam did not decrease, its shear strength decreased.

The reason for this was determined by investigating the WC and external conditions in a specimen cross-section. Fig. 2 shows the WC in wet and dry conditions during the two accelerated aging treatments. As the result of both BD and HD treatments, the WC was higher than the initial value in the wet state and less than that in the dry state. The WC under the wet condition of the BD treatment was much larger than that in the HD treatment. Since the decrease in shear strength in the HD treatment was less than in the BD treatment, it was assumed that the difference in the amount of water between them affected the rate of decrease in the shear strength.

A cross-section of specimens before and after the accelerated aging treatments was observed. Fig. 3 shows cross-sections of example specimens before and after the accelerated aging treatments. In both the BD and HD treatments, the specimens color changed and cracks emerged along the radial direction of the laminae. There were more and larger cracks in the BD treatment than in the HD, as shown in Fig. 3. The number of cracks significantly increased as the cycle number increased. These results indicate that the amount and time of water movement during the accelerated aging treatments affected the size and number of cracks appearing along the radial direction in laminae. Additionally, internal cracks may arise and penetrate the shearing surface during these treatments. Moreover, it appeared that shear strength was affected by a decrease in the shear area because the strength was calculated using a fixed shearing area of 25 × 25 mm. Thus, it was that the decrease in shear strength was affected by deterioration and cracks in the wooden part of the glulam rather than those of adhesive.

3.2 Durability based on shear strength retention and the deterioration model

For a relative evaluation of the decrease in shear strength between GA, GR, and SW, shear strength retention (SSR) was calculated by the Eq. (3):

$$\mathrm{SSR} = \frac{\overline{\tau_i}}{\overline{\tau_0}}, \qquad (3)$$

where $\overline{\tau_0}$ is the mean shear strength (N/mm^2) of control specimens and $\overline{\tau_i}$ denotes the mean shear strength (N/mm^2) of specimens after i cycles of the accelerated aging treatments. When the mean shear strength of the specimens after the accelerated aging treatment was higher than the mean shear strength of the control specimens, the strength was defined as 1. It was confirmed that the shear strength of each material tended to decrease nonlinearly as the cycle number increased in the BD treatment. Thus, it was expected that glulam and SW maintained a certain shear strength without dropping to 0, unless delamination occurred on the bonding line. Hence, to compare the durability among GA, GR, and SW, the deterioration trends of each material were predicted as follows (Suzuki and Saito 1988):

$$\text{Predicted SSR} = A + (1 - A)\exp\left(\frac{-t}{B}\right), \qquad (4)$$

where the coefficient A indicates the saturation value of SSR, coefficient B denotes the decreasing rate, and t is the cycle number of the accelerated aging treatment. The values of A and B were calculated by the nonlinear least-square regression.

Fig. 4 shows the SSR and regression curves in GA, GR, and SW for BD treatment. When the SSRs of

GA and SW were compared, sugi GA had a higher SSR than SW in all cycles of BD treatment, with a difference of approximately 0.29 between SSR values after 60 cycles. In addition, the regression curve of sugi GA was less steep than that of sugi SW. Hinoki GA maintained a higher SSR than its SW, although the SW had a higher SSR than GA in the first 15 cycles. The regression curve of hinoki GA tended to fall dramatically to reach a saturation value after 1 cycle of BD treatment, after which this value was maintained. This occurred because the standard deviation of hinoki GA shear strength after five cycles was relatively high, and the SSR was higher after 30 cycles than after 5-15 cycles of BD treatment. For spruce, GA had a higher SSR than its SW in each cycle, and the trends were determined by regression curves. When comparing spruce GA and GR, although GR had a higher SSR than GA up to 10 cycles, this reversed after 15 cycles and finally GA maintained an approximately 0.15 higher SSR than GR. The regression curve for GA reached a saturation point faster than the curve for GR; however, the SSR of GA stabilized at a higher value than that of GR. Yanagawa et al. (2017) reported that sugi GA had a higher SSR than GR following outdoor exposure for 10 years. Thus, spruce GA maintained a higher SSR than its GR in both experimental and theoretical studies. On the other hand, it was found that the regression curves of GR and SW for spruce were similar.

When focusing on the different SSR tendencies among species in GA, measured sugi GA was found to have the highest SSR, while hinoki GA had the lowest at 60 cycles. It was assumed that the tendency for a decreasing SSR in hinoki GA was due to large sample fluctuation. Consequently the regression curves showed that hinoki GA maintained slightly higher SSR than spruce GA. As a result of the differences among the three species in the SW samples, SSR of sugi SW decreased gentler than that of hinoki and spruce up to 15 cycles. Since SSR of sugi SW decreased dramatically after 10 cycles and it was lower than SSR after 15 cycles and similar to SSR after 30 cycles, it could be conceivable that the SSR after 10 cycles was caused by fluctuation of wood. In hinoki SW, the SSR dramatically decreased to approximately 60% after 5 cycles, and then it remained ranging from approximately 60 to 65 % until 15 cycles. Additionally, in spruce SW, the SSR decreased to approximately 70%, which is noticeably lower than the SSR of sugi SW, and then declined to approximately 54% after 15 cycles. In other words, it can be presumed that the decrease in SSR of spruce SW with increasing the number of cycles was more drastic that that of sugi SW. However, although their SSR values displayed a clearly different trend up to 15cycles with above results, they showed a similar tendency after 30 cycles.

The SSR and regression curves of GA, SW, and GR for the HD treatment are shown in Fig. 5. For the HD treatment in sugi materials, GA had a higher SSR than SW at each cycle number, which was similar to the results for the BD treatment. Finally, the difference in SSR between sugi GA and its SW became smaller. The SSR for GA was lower after 75 cycles of HD treatment than after 60 cycles of BD treatment. Hence, the result at 75 cycles of HD treatment appeared to vary according to the fluctuation of wood. The regression curves of sugi GA and SW showed that the SSR tended to slowly decrease with an increase in cycle number of HD treatment compared to hinoki and spruce. Hinoki GA sustained a higher SSR than its SW at each cycle in the HD treatment. Although the SSR of GA for hinoki significantly decreased by more than 0.4 after 5 cycles of BD treatment, the decrease in SSR for both materials was more gradual in the HD treatment, and became more apparent as the cycle number increased. As described above, the domain in which the deterioration occurred in the HD treatment after 75 cycles might correspond to the domain below 30 cycles in the BD treatment. Spruce GA had a much higher SSR than its SW and the regression curve tended to decrease, while maintaining high value. In addition, according to the regression line, spruce GA sustained a higher SSR than GR in each cycle of HD treatment. However, after 75 cycles of HD treatment, the difference in SSR between GA and GR was not significant. Conversely, the regression curve of GA tended to indicate a higher SSR than the curve for GR, with the difference eventually reaching approximately 0.14. The regression curve of GR ran parallel with that of SW from 20 to 55 cycles, whereas GA showed higher SSR than SW.

When considering the decrease in SSR of GA among wood species, sugi maintained the highest value, followed by hinoki and spruce. At the same time, the regression curve of spruce was predicted to maintain a higher SSR than hinoki. Additionally, the differences in SSR among wood species in SW samples were similar to those for GA. It appeared that glulam could maintain a higher SSR than SW, and that spruce GA was able to maintain a higher SSR than GR when they were exposed to BD and HD treatments.

To quantitatively evaluate and compare the durability among GA, GR, and SW, the value of A was converted into the saturation shear strength (A') by multiplying the mean shear strength of each control specimen. Moreover, the cycle number required to decrease the shear strength to the standard shear strength was calculated, in order to quantitatively compare the durability among GA, GR and SW. The standard value used in the JAS criteria is the lower limit of shear strength after the delamination test

(2007). According to the JAS criteria, a 75 × 75 mm specimen is exposed to an immersion delamination test, boiling water delamination test, or vacuum and pressure delamination test. After the delamination tests, a specimen for use in a block shear test is cut from the edge of the delamination specimen and a block shear test is conducted for the evaluation of adhesion property. The standard values configured for each species of sugi, hinoki, and spruce are 5.4, 7.2, and 6.0 N/m^2, respectively (JAS 2007). The adhesion durability of engineered wood is satisfactory in the indoor environment if it satisfies the JAS criteria (Yanagawa 2012). Since BD treatment was designed in accordance with JAS criteria, the durability of engineered wood was expected to be high and its reliability as a construction material increased, when the specimens had a higher shear strength than the standard value after more than two cycles of the treatment.

Table 2 shows the determination coefficient (R^2) between SSR and predicted SSR and the values calculated by the deterioration model (Eq. (4)). The predicted SSR regression fit well with the actual SSR in each cycle. The predicted SSR of sugi GA for the HD treatment had a relatively lower R^2 than other materials because the R^2 was influenced by the SSR trend, in which the value at 55 cycles was higher than that at 20 cycles. The R^2 for the other materials exceeded 0.82, and it was determined that the model enabled the accurate prediction of the tendency for SSR to decrease.

In terms of a comparison of the *A'* between GA and SW in BD, the three types of GAs had higher *A'* values than the corresponding SWs. In particular, both *A'* and *B* values of sugi GA were higher than those of the SW. Hinoki GA had a lower *B* value than the SW. However, the *A'* value of hinoki GA was higher than that of SW and the standard value. This result could have been influenced by the fluctuation in shear strength after 5 cycles. Spruce GA had a higher *A'* value than its GR and SW, although the *B* value of spruce GA was lower than its GR and SW.

Based on the BD treatment, when setting the number of cycles required to meet the standard values defined by the JAS criteria for each material, although GA is commonly used in "Use Environment B", in this study there were more than two cycles, and all GA used satisfied the requirements in "Use Environment A" which is considered the most severe environment. For sugi materials, the cycle number was significantly greater for GA compared to SW. On the other hand, since the *A'* value of hinoki GA for BD treatment was higher than the standard value, the cycle number needed to reach the *A'* value could not be calculated, whereas the cycle number of hinoki SW could be estimated. It was predicted that the SW would reach the standard value faster than the other materials. In comparing the results among the spruce materials, although it was predicted that GA would drop to reach the standard value in an earlier cycle than GR and SW, the differences were not large.

In HD treatment, the *A'* values were 0, with the exception of hinoki and spruce SW and spruce GR. Because it was assumed that the shear strength of each material did not decrease to a saturation value, the other materials used in this study had *A'* values of 0. Hence, the *B* values and cycle number required to meet the standard criteria were used for evaluating durability in the results of HD treatment. Sugi GA had a higher *B* value and a larger the needed cycle number than the SW. However, the deterioration model predicted that the cycle number of sugi GA in the HD treatment was less than that in the BD treatment. A possible reason for this is that the shear strength of sugi GA in HD treatment after 75 cycles was lower than that in BD treatment after 60 cycles, and the saturation value estimated for the BD treatment was not 0. Moreover, hinoki and spruce GA had clearly higher *B* values than SW.

From the above-mentioned results, GA was predicted to maintain a higher shear strength than the standard value. Furthermore, the predicted cycle number for both treatments resulted in the GA requiring more cycles than GR and SW to reach the standard value with the exception of the result for hinoki and spruce in the BD treatment. Hence, GA may have a high durability performance comparable to or above that of SW and GR.

The decrease in shear strength may have occurred due to the cracks appearing along the radial direction of the laminae. Accordingly, the different decreasing rate of shear strength between glulam and SW was considered by differences in the materials. Glulam has a bonding line and is composed of a number of wood laminae, which have different annual ring angles. On the other hand, SW does not have a bonding line and the annual ring angles are consistent. Thus, the warp of specimens did not occur in a consistent direction in glulam, and it was assumed that the internal stress and the cracks that occur with warp were smaller than those appeared on SW. In addition, in the case of glulam, the bonding line might inhibit the development of cracks on shearing surface of the laminae. On the other hand, in the case of SW, cracks have the potential to intrude into the shearing surface. Furthermore, element of glulam specimens are smaller than SW specimens. Simply thickness of SW specimen is 4 or 5 times larger than glulam element. This indicates that the internal stress of SW is greater than glulam specimen. Hence, the crack size and amount in glulam might be smaller than and there may be less cracks than in SW, and the effects of cracks in glulam on shear strength are less significant than in SW. For these reasons, it was presumed that glulam could maintain a higher SSR than SW, even though the decrease in shear strength depended on the deterioration and presence of cracks in the wooden part rather than in the adhesive.

Spruce GA had a higher shear strength saturation value in the BD treatment and required a larger number of cycles in the HD treatment to reach the standard value than its GR. Ebewele et al. (1991) reported that the flexibility and toughness mostly affect the durability and stability of wood products joined by urea-formaldehyde resin. Mototani et al. (1996) reported that API is plasticized by water and can deform (i.e., swelling and shrinking of wood), whereas PRF cannot, and the amount of damage by wood deformation for API is smaller than for PRF. In a case when glulam was exposed to the outdoor environment for 10 years to evaluate its durability, Yanagawa et al. (2017) reported that GA had a higher SSR than GR and speculated that the reason for this was that the stresses in RF occurred due to wood swelling and shrinking because of the greater stiffness of RF compared to API.

In this study, there may have been differences in the durability between GA and GR because of the contrasting flexibility between these adhesives. The ability of API to deform could correspond to the swelling and shrinking of wood and restrict the penetration of cracks into the shearing surface, whereas because it did not deform, RF was fractured by the deformation of wood and allowed the infiltration of cracks into the shearing area. Consequently, the SSR of GR decreased more than that of GA. Therefore, GA would have durability equal to or higher than that of SW and GR when they were exposed to cyclic wet and dry treatments that were repeated 60 or 75 times. However, in this study, cracks on the bonding lines of API and RF were not observed. Thus, the relationship between cracks in the wood and adhesive should be considered sensitively when assessing the durability of glulam.

4 Conclusions

In this study, three types GA, SW and one GR were exposed to two kinds of cyclic accelerated aging treatments to evaluate the durability of the GA. In both treatments, the shear strength of each material decreased with an increase in cycle number whereas there was no change in wood failure percentage. It was assumed that the decrease in shear strength occurred due to the genesis and development of cracks on the wooden part of the material rather than deterioration of the adhesive. Moreover, to compare the deterioration in SSR among GA, SW, and GR, three parameters (the saturation value, the decreasing rate, and the cycle number needed to reach the standard value defined in the JAS) were calculated. Glulam maintained a higher SSR than SW, because the effects of cracks on shear strength for SW were larger than those for glulam. In addition, GA maintained a higher SSR than GR, possibly because the ability of API to deform with wood swelling and shrinking affected the durability of glulam. In conclusion, GA had durability equal to or higher than that of SW and GR when they were all exposed to cyclic wet and dry treatments that were repeated many times.

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Figure Captions:

Fig. 1 Schematic diagram of the test specimens composed of 4 layers

Fig. 2 Weight changes in the wet and dry states during the two kinds of the accelerated aging treatments. BD is a cyclic treatment of boiling for 4 h and drying at 70 °C for 19 h; HD is a cyclic treatment of soaking in hot water at 70 °C for 4 h and drying at 40 °C for 19 h; GA is API bonded glulam; SW is solid wood; GR is RF bonded glulam

Fig. 3 Cross-sections of spruce GA specimens before and after the accelerated aging treatments. (a) is the control specimen; (b) is the specimen after 75 cycles of the HD treatment (soaking in hot water at 70 °C for 4 h and drying at 40 °C for 19 h); (c) is the specimen after 60 cycles of the BD treatment (boiling for 4 h and drying at 70 °C for 19 h)

Fig. 4 Shear strength retention and regression curves of glulam and solid wood for the cyclic boiling-drying treatment. Regression curves were drawn by Predicted SSR = $A + (1-A) \exp(-t/B)$; GA is API bonded glulam; GR is RF bonded glulam; SW is solid wood

Fig. 5 Shear strength retention and regression curves of glulam and solid wood for the cyclic hot water-drying treatment. Regression curves were drawn by Predicted SSR = $A + (1-A) \exp(-t/B)$; GA is API bonded glulam; GR is RF bonded glulam; SW is solid wood

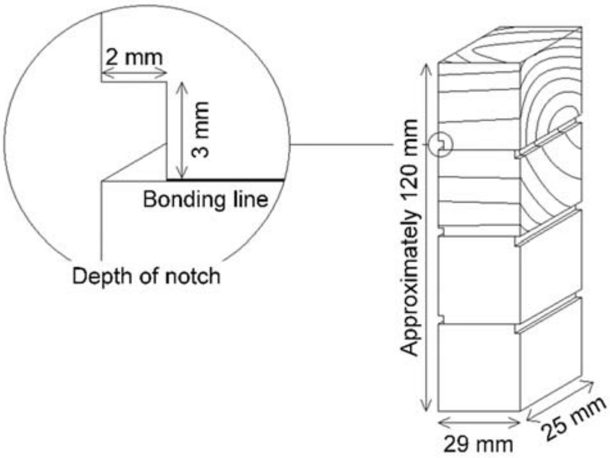
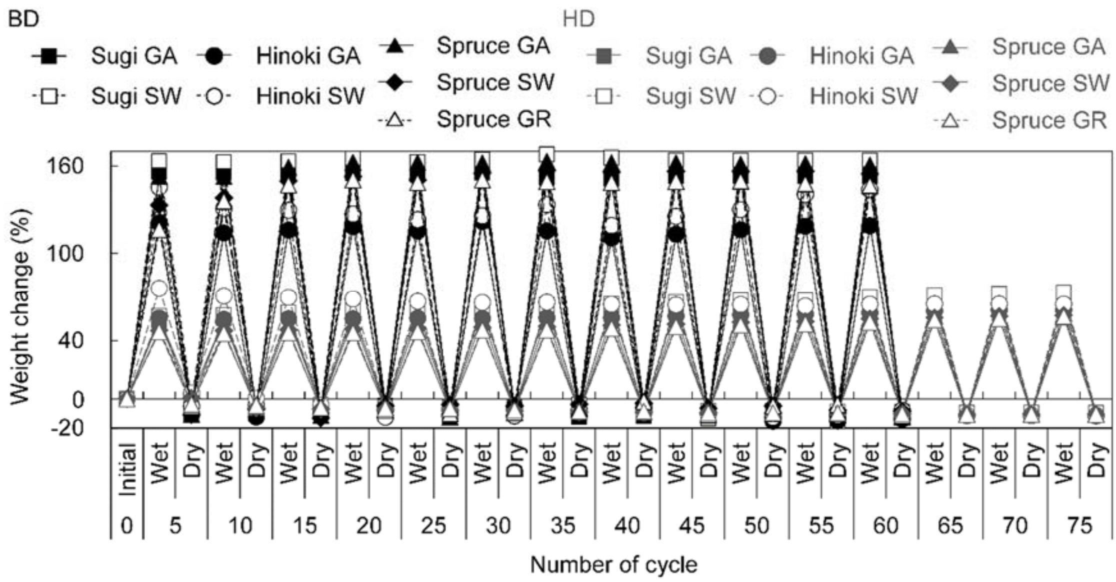


Fig. 1 Schematic diagram of the test specimens composed of 4 layers



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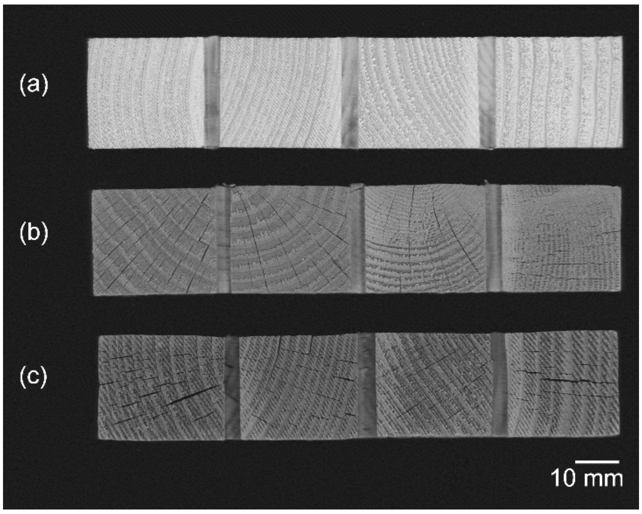

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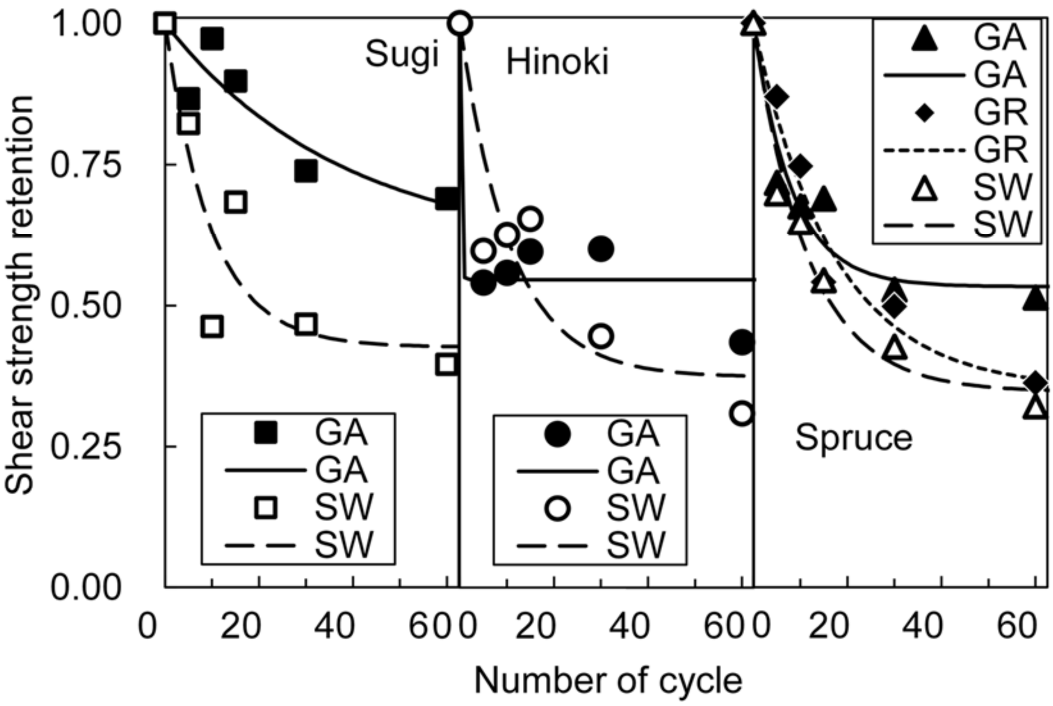

Fig. 4 Shear strength retention and regression curves of glulam and solid wood for the cyclic boiling-drying treatment. Regression curves were drawn by Predicted SSR = $A + (1–A) \exp(-t/B)$; GA is API bonded glulam; GR is RF bonded glulam; SW is solid wood

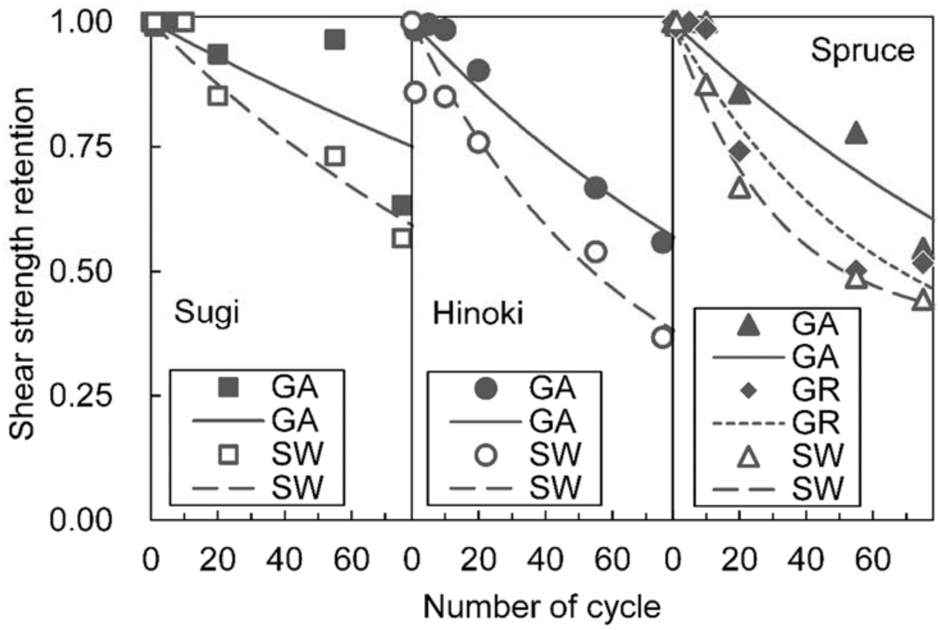

Fig. 5 Shear strength retention and regression curves of glulam and solid wood for the cyclic hot water-drying treatment. Regression curves were drawn by Predicted SSR = $A + (1–A) \exp (-t/B)$; GA is API bonded glulam; GR is RF bonded glulam; SW is solid wood

Table 1 Wood failure percentage and shear strength of glulam and solid wood after two different accelerated-aging treatments

Species	Material	Evaluation item	Value type	Control	Cycle number										
					BD					HD					
					5	10	15	30	60	1	5	10	20	55	75
Sugi	GA	Wood failure (%)	Mean	99	100	99	99	98	90	100	100	99	100	98	92
			SD	5	0	3	3	4	13	0	0	3	0	4	17
		Shear strength (N/m^2)	Mean	8.9	7.7	8.6	8.0	6.6	6.1	8.8	10.4	10.1	8.3	8.6	5.6
			SD	1.1	1.8	2.2	0.9	1.4	1.9	2.4	1.2	2.1	2.4	1.4	2.2
	SW	Shear strength (N/m^2)	Mean	9.8	8.1	4.5	6.7	4.6	3.9	10.1	-	10.3	8.3	7.2	5.5
			SD	2.2	3.0	2.4	2.5	1.6	1.5	2.3	-	2.2	3.0	2.9	2.7
Hinoki	GA	Wood failure (%)	Mean	98	100	95	100	96	91	91	99	99	94	94	94
			SD	4	0	14	0	5	20	14	3	3	8	10	11
		Shear strength (N/m^2)	Mean	13.5	7.3	7.5	8.0	8.1	5.9	13.3	13.4	13.3	12.2	9.0	7.5
			SD	2.6	4.9	2.5	3.2	2.3	2.6	3.7	3.7	3.9	4.4	3.8	2.9
	SW	Shear strength (N/m^2)	Mean	10.9	6.5	6.8	7.1	4.9	3.4	9.4	-	9.3	8.3	5.9	4.0
			SD	1.8	1.9	3.1	3.5	2.3	2.0	2.9	-	2.2	2.7	2.2	2.1
Spruce	GA	Wood failure (%)	Mean	99	100	100	100	100	100	99	100	99	99	95	99
			SD	3	0	0	0	0	0	3	0	3	4	5	3
		Shear strength (N/m^2)	Mean	9.4	6.8	6.4	6.5	5.0	4.8	9.3	10.0	9.4	8.1	7.3	5.1
			SD	1.8	1.5	1.1	1.6	1.6	1.5	1.8	1.7	1.1	1.6	1.9	2.3
	GR	Wood failure (%)	Mean	88	94	90	93	99	93	96	91	90	91	89	86
			SD	12	8	11	8	3	10	5	20	9	9	15	13
		Shear strength (N/m^2)	Mean	9.9	8.6	7.4	5.3	4.9	3.6	9.8	10.2	9.7	7.3	4.9	5.1
			SD	1.5	1.1	2.6	2.4	1.6	1.3	1.1	2.5	1.8	3.1	1.8	1.5
	SW	Shear strength (N/m^2)	Mean	11.3	7.9	7.3	6.1	4.8	3.6	11.8	-	9.9	7.5	5.5	5.0
			SD	2.3	5.0	3.7	3.2	0.8	1.2	3.8	-	3.3	2.9	2.7	2.1

BD is a cyclic treatment of boiling for 4 h and drying at 70 °C for 19 h; HD is a cyclic treatment of soaking in hot water at 70°C for 4 h and drying at 40 °C for 19 h; GA is API bonded glulam; SW is solid wood; GR is RF bonded glulam; SD indicates Standard deviation

Table 2 Determination coefficients (R^2) between shear strength retention (SSR) and predicted SSR, and calculated values by the deterioration model

Species	Material	Standard value (N/mm²)	BD				HD			
			R^2 *1	A'*2 (N/mm²)	B*3	Predicted cycle number*4	R^2 *1	A'*2 (N/mm²)	B*3	Predicted cycle number*4
Sugi	GA	5.4	0.82	5.3	38.1	137.0	0.65	0.0	271.8	135.5
	SW		0.82	4.2	9.8	14.8	0.96	0.0	149.1	88.6
Hinoki	GA	7.2	0.91	7.4	0.2	-*5	0.98	0.0	139.1	87.3
	SW		0.83	4.1	10.7	8.4	0.95	1.3	64.1	31.3
Spruce	GA	6.0	0.92	5.0	8.2	12.3	0.92	0.0	155.0	69.8
	GR		0.97	3.5	17.1	15.8	0.94	2.7	59.1	45.5
	SW		0.97	3.9	11.6	14.6	0.99	4.4	30.5	44.0

*1 Determination coefficient between shear strength retention and predicted shear strength by the deterioration model, Predicted SSR = $A + (1-A) \exp(-t/B)$.

*2 Saturation shear strength calculated by multiplying the mean shear strength of each control specimen and the saturation point of SSR predicted by the deterioration model.

*3 Rate of decrease.

*4 Predicted cycle number: Required number of cycles of the accelerated-aging treatment to reach the JAS standard value.

*5 The cycle number could not be calculated