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Mechanical properties of hybrid joints in timber structures

Kosuke Imakawa¹, Yo Ochiai², Kenji Aoki¹, Naruhito Hori¹, Akio Takemura¹ and Tetsuo Yamaguchi^{1*}

Abstract

Mechanical joints with screws or bolts are widely employed in timber structures and are known to provide high toughness. However, they result in low stiffness, which is a representative limitation of wood structural joints. In this study, we investigated the mechanical properties of hybrid joints comprising mechanical and adhesive joints, to prevent the decrease in stiffness while maintaining high toughness. Wood and steel plates were joined with screws and adhesives, and their stiffness, bearing capacity, and fracture energy were evaluated by lap-shear tests. We inferred that the stiffness and bearing capacity of the hybrid joints change with the type of adhesive used, while the fracture energy primarily depends on the diameter of the screws. Interestingly, when the adhesive strength was too large, a decrease in the fracture energy was observed because the precursory rupture of the adhesive joint triggered the wood failure in the fastened regions and lead to the early pull-out of the screws. To suppress such decrease and early pull-out, an adhesive fillet, i.e., the coating of the adhesive onto a larger area than that of the steel plate, was investigated. Accordingly, we successfully improved the toughness. Our results suggest the importance of optimal designs for the hybrid joint in timber structures.

Keywords: Timber structure, Hybrid joint, Adhesion, Mechanical joint, Adhesive fillet

Introduction

In timber structures, mechanical joints using fasteners, such as screws, bolts, or pins, are widely employed to connect one or more wood members to another, directly or indirectly using metallic parts [1–6]. Mechanical joints are required to be robust against strong seismic forces [7] and are well fitted to this purpose. However, it is well known that the mechanical joints often exhibit low stiffness because of the unavoidable clearance between a fastener and a hole and non-negligible bending deformation of the fastener [8]. To address these limitations while maintaining their advantages, hybrid joints, which are a combination of a mechanical joint with high toughness and an adhesive joint exhibiting high stiffness [9–11], are considered to be effective [8, 12, 13]. In fact, several

studies have been conducted on the relationship between structures and mechanical properties of hybrid joints [8, 14–16]. It was reported that the hybrid joint comprising a steel plate and laminated wood bonded with adhesives and bolts exhibits high load-bearing capacities [17]; in addition, hybrid joints made of adhesives, screws, and a rubber sheet inserted between a steel plate and laminated wood exhibits anti-creep performance over 20 years [18]. Other geometries, such as glued-in-steel rods [19–21], glued-in-FRP (fiber-reinforced plastics) rods [22, 23] and glued-in-steel plates [24–26], have been developed to improve the mechanical properties of timber joints.

However, most of the studies, conducted on the hybrid joints in timber structures, focused on the mechanical behavior of fasteners; the impact of adhesives on mechanical properties and the interaction between mechanical and adhesive joints have not always been elucidated. This implies that the optimum design principles for timber joints are yet to be established to date.

*Correspondence: yamaguchi-tetsuo@g.ecc.u-tokyo.ac.jp

¹ Department of Biomaterial Sciences, The University of Tokyo, 1-1-1 Yayoi, Bunkyo-ku, Tokyo 113-8657, Japan
Full list of author information is available at the end of the article

In this study, we systematically investigate the mechanical properties of hybrid joints. We prepare specimens with different screw sizes and various types of adhesives, and then evaluate three types of mechanical parameters: stiffness, bearing capacity, and fracture energy. Accordingly, we successfully elucidate the roles played by the mechanical joint and adhesive, and also determine optimum conditions exhibiting high stiffness, high bearing capacity, and large fracture energy.

Experiment

Hybrid joint specimen

The geometry of a hybrid joint specimen is illustrated in Fig. 1a. It comprises a wood, steel plates, adhesive, and screws. One of the two joints (the right side in Fig. 1a) was designed to be weaker by reducing the bonded area and the number of screws. Subsequently, the deformation and fracture behavior of the weaker joints were observed.

As wood materials, spruce–pine–fir (SPF) was cut into blocks with the dimensions of 150 mm (longitudinal direction) and 89 mm × 38 mm (cross section). The average density was 472 kg/m³. The wood materials were dried in an oven at 105 °C for 24 h, and moisture contents were calculated. The average moisture content was 9.6%.

As fasteners, self-tapping screws (SUS316L) with a length of 20 mm and a diameter of 2 mm, 4 mm, or 6 mm were employed.

Steel plates (SPCC) with the dimensions L (length along the tensile direction) = 150 mm, W (width) = 35 mm, and t (thickness) = 2.3 mm were also used in this study. Four holes with a diameter of 2.5 mm, 4.5 mm, or 6.5 mm were drilled, depending on the diameters of the screws.

Lap-shear test

As illustrated in Fig. 1b, the specimens were subjected to lap-shear tests at a tensile speed of 2 mm/min by employing a universal testing machine (Autograph AGIS-100 kN, Shimadzu Corporation, Japan), a data logger (TDS-540, Tokyo Measuring Instruments Laboratory Co., Ltd., Japan), and a displacement sensor (CDP-50, Tokyo Measuring Instruments Laboratory Co., Ltd., Japan). The displacement of the joint was measured by contacting the displacement sensor with an acrylic plate attached to the wood. The sampling frequency of the load and displacement data was 1 Hz. The test was conducted until the joint completely fractured and the load was reduced to zero.

Adhesives

Three types of adhesives were used: two-component aqueous polymer–isocyanate (API, P.I. BOND PI-5340S, Oshika Corporation, Japan), one-component polyurethane (PU, 44503, Konishi Co., Ltd., Japan), and one-component silylated urethane (PUE, 05144, Konishi Co., Ltd., Japan). The stress–strain curves for the uni-axial tensile tests of adhesive films are presented in Fig. 2. The Young's modulus, maximum stress, and maximum strain for API, PU and PUE adhesives were (1.40 ± 0.19 GPa, 30.1 ± 5.1 MPa, 0.0382 ± 0.0107), (368 ± 76 MPa, 7.74 ± 0.94 MPa, 0.0298 ± 0.0057), and (7.68 ± 0.17 MPa, 10.9 ± 3.2 MPa, 1.04 ± 0.26), respectively.

Preparation of joint specimens

Table 1 presents the specimens prepared in this study. For each of the three types of adhesives (API, PU, and PUE), specimens with the adhesive joint, specimens with

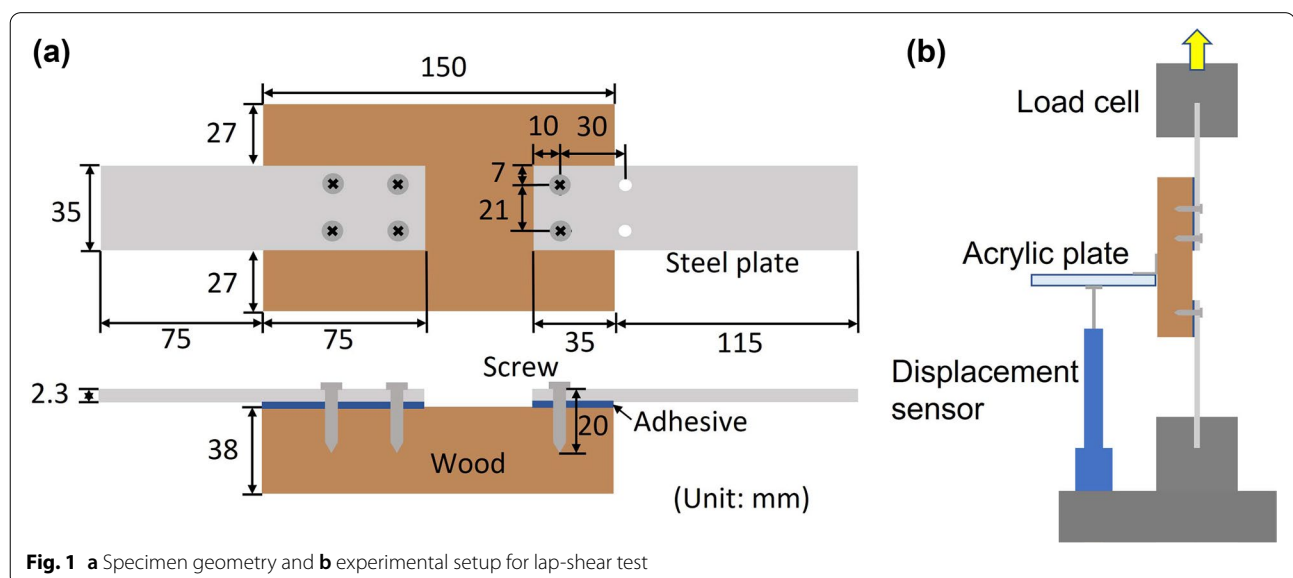


Fig. 1 a Specimen geometry and b experimental setup for lap-shear test

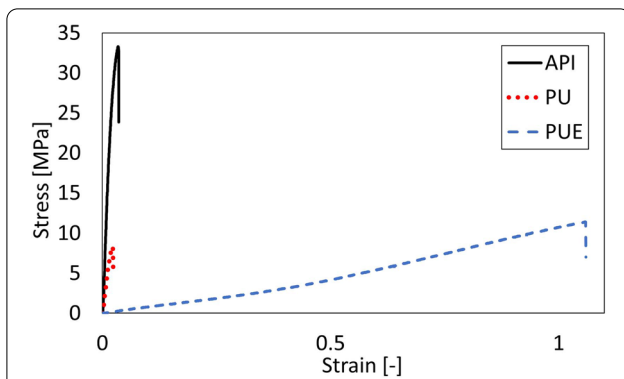


Fig. 2 Stress–strain curves for three types of adhesive films in uni-axial tensile tests

the hybrid joint using 4-mm-diameter screws, and specimens with the hybrid joint plus adhesive fillet [27, 28] (i.e., coated onto a larger area than that of a steel plate, refer to Fig. 3) were prepared. For the API adhesives, specimens with screws of different diameters (2 mm and 6 mm) were also prepared. For the PU adhesive, specimens with wider fillets were also fabricated. In addition, specimens with only 4-mm-diameter screws were also

prepared. Three specimens were prepared for each specimen type.

The fabrication method of the hybrid joint specimen is presented as follows. First, the prepared holes of a 10 mm depth were drilled into a wood. The diameters of the prepared holes were 2.8 mm and 4.0 mm for 4-mm and 6-mm screws, respectively, while the prepared holes were omitted for a 2-mm screw. Subsequently, an adhesive with an amount of 250 g/m² was applied uniformly, the steel plates were overlapped, the screws were tightened with a drill driver at 4.0 N m, and then the squeezed adhesive was carefully removed, to observe a clear difference from an adhesive fillet (see below). A schematic diagram is presented in Fig. 3a. Regarding the hybrid joint with an adhesive fillet, an adhesive was applied not only in between a plate and wood, but also outside and on the top surface of the steel plate, as illustrated in Fig. 3b, c. The excess widths of the fillet were approximately 5 mm and 20 mm for the narrow (Fig. 3b) and wide (Fig. 3c), respectively, while the thickness and the amount of the adhesive in the fillet part were not controlled. The prepared specimens were cured at 23 °C and relative humidity of 50%. The curing time was 4 days for API and PU, and 1 day for PUE.

Table 1 Specimen type and name

Adhesive	Joint type	Screws only	Adhesive only	Hybrid joint			Hybrid joint + adhesive fillet (narrow)	Hybrid joint + adhesive fillet (wide)
				Screw diameter	4 mm	–		
–		S4						
2-Component API adhesive (API)			API	API + S2	API + S4	API + S6	API + S4 + F1	
1-Component polyurethane adhesive (PU)			PU		PU + S4		PU + S4 + F1	PU + S4 + F2
1-Component silylated urethane elastic adhesive (PUE)			PUE		PUE + S4		PUE + S4 + F1	

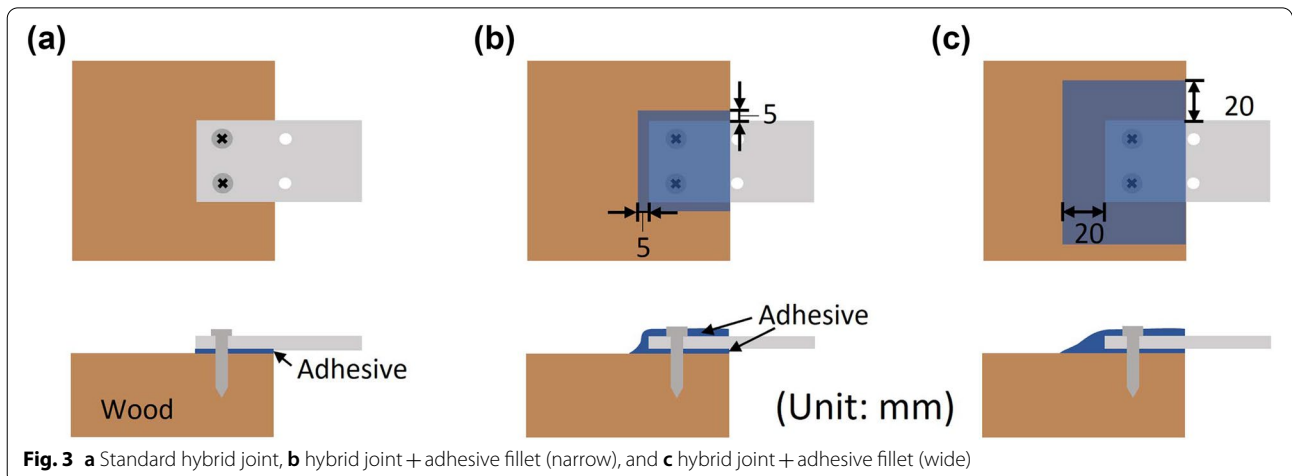


Fig. 3 a Standard hybrid joint, b hybrid joint + adhesive fillet (narrow), and c hybrid joint + adhesive fillet (wide)

Regarding the adhesive-only joint, the same amount of adhesive as the hybrid-only joint was applied to the wood, overlapped with a steel plate for 4-mm screws, fixed with an adhesive tape, and then cured under the same conditions as the hybrid joint.

For the screw-only joint, the steel plates were fixed with 4-mm screws after drilling prepared holes, similarly to the hybrid joint.

Results and discussion

Characteristic behavior

Figure 4 presents the characteristic behavior for the load–displacement curve and the deformation of a hybrid joint specimen with API and screws of a 4-mm-diameter (“API+S4”). The load–displacement curves for the adhesive-only (“API”) and screw-only (“S4”) joints are also plotted in Fig. 4a for comparison.

In the initial stage (displacement $d < 1$ mm), the load increased rapidly, and then dropped quickly for the hybrid joint specimen, as clearly illustrated in Fig. 4a. This is because the hard adhesive layer was subjected to shear and fractured in a brittle manner, similarly to the case for the adhesive-only joint. In contrast, the load was supported by the screws in the late stage ($1 \text{ mm} < d < 20 \text{ mm}$), similarly to the case for the screw-only joint. This indicates that the hybrid joint possesses both the advantages of high stiffness and large fracture energy. Similar

behaviors were observed for the hybrid joint specimens with other types of adhesives (PU and PUE).

The snapshots for the deformation of the hybrid joint are presented in Fig. 4b. Although it is difficult to observe the fracture of the adhesive layer and the bending/pull-out of the screws, the severe damage of the wood surface, large deformation of screws, and bending of the steel plate were observed (see Fig. 4b D and E). The bending deformation of the timber was not recognized from our experimental observations.

Definition of mechanical parameters

To discuss the mechanical behavior of the joints quantitatively, we defined three types of parameters: stiffness, bearing capacity, and fracture energy. Figure 5 illustrates these parameters extracted by a load–displacement curve. The bearing capacity F_{\max} is determined as the maximum load for the screw-only joint, and as the maxima at small displacements owing to the failure of the adhesive joint for the other specimens. The stiffness is calculated as the slope of the curve from 0.2 to 0.8 F_{\max} . The fracture energy is obtained by the integral of the load–displacement curve.

Stiffness

Figure 6a presents the stiffness values of the hybrid joint specimens with API adhesives, plotted against the screw diameter. The error bars indicate the standard deviations.

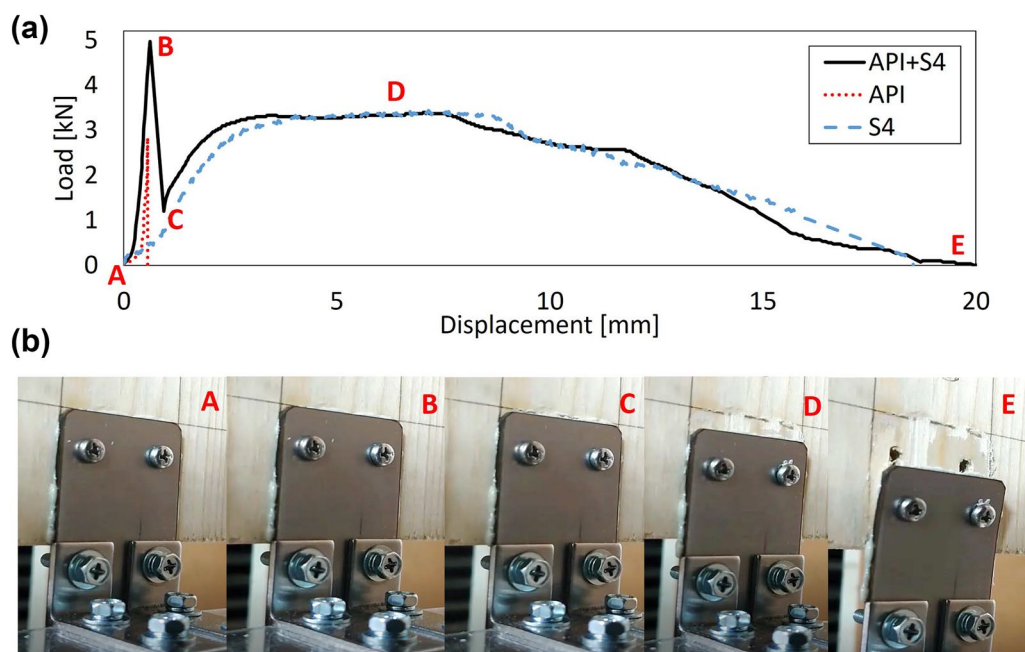
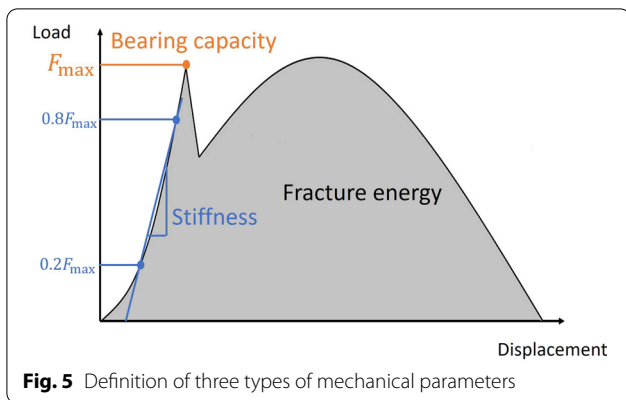


Fig. 4 a Load–displacement curves for the specimens with API; screw-only (“S4”), API adhesive-only (“API”), and hybrid (“API+S4”) joints. b Snapshots of deformation and failure processes for the hybrid joint. The letters “A” to “E” correspond to those in a



Evidently, the stiffness of all hybrid joints was significantly higher than that of the screw-only joint (“S4”), because the load is primarily supported by the adhesive layer at small displacements and the stiffness is dominated by the shear response of the layer. This implies that the combination of the adhesive joint is effective in improving the stiffness of a structural joint. In contrast, no significant difference was observed for the screw diameter, as clearly understood by the dominant contribution of the adhesive layer at small displacements.

In Fig. 6b, the stiffness values for different types of hybrid joints other than the adhesive-only and screw-only joints are plotted. It can be observed that the stiffness was significantly larger than that of the screw-only joint and changed substantially with the type of adhesive material. In contrast, the effects of the hybrid joint component are not significant; for the hybrid joint with PU, the stiffness was equivalent to that of the adhesive-only joint and did not vary substantially with the excess area

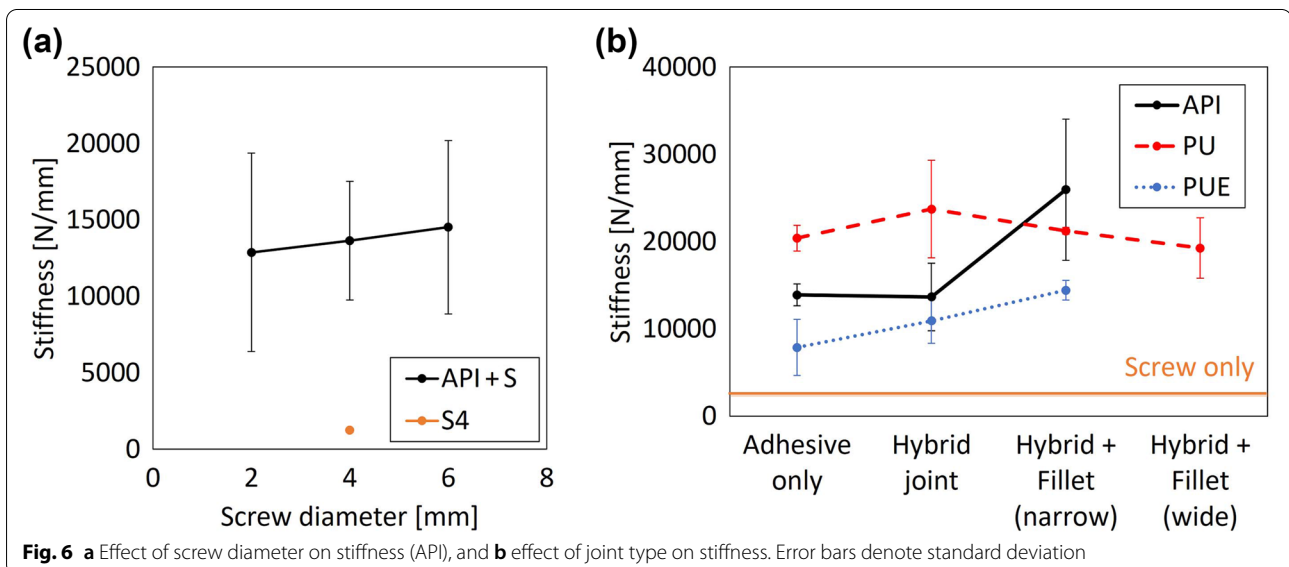
of the applied adhesive fillet, while the curves appear increasing with the excess adhesion area for the hybrid joints with API and PUE. This could be explained by the fact that the larger elastic energy is stored for the larger adhesion area and leads to the larger stiffness value. Further studies are required for definite conclusions.

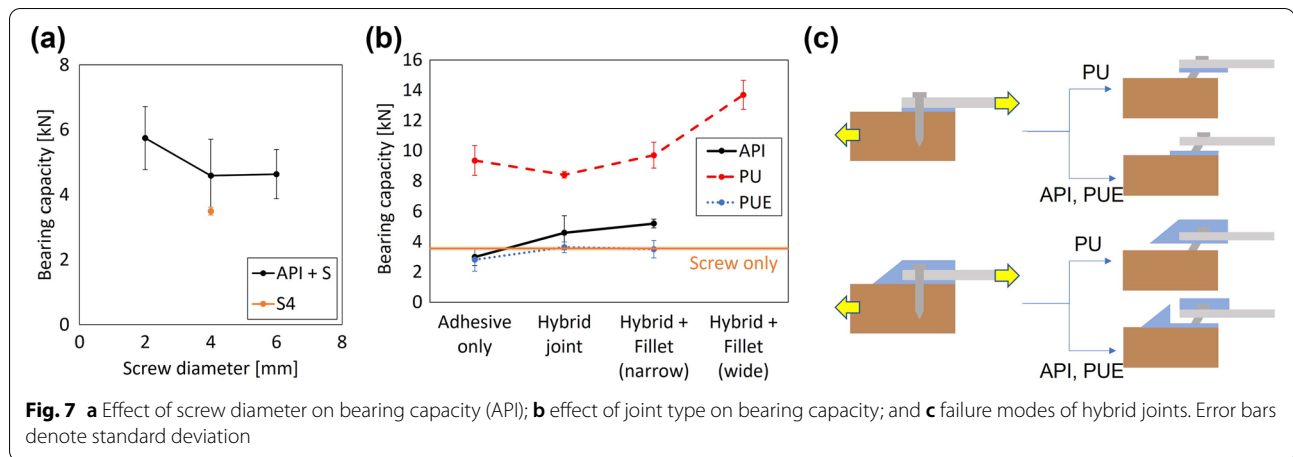
Bearing capacity

Figure 7a presents the relationship between the bearing capacity and the screw diameter for the hybrid joints with API adhesives. The value of the screw-only joint is also plotted for comparison. No clear dependence on the screw diameter was observed, although it was larger than that of the screw-only joint. This is because the bearing capacity is again dominated by the mechanical property of the adhesive layer in the initial stage.

However, as illustrated in Fig. 7b, the bearing capacity changed significantly with the type of adhesive; unlike the stiffness, the bearing capacity of the hybrid joint with API and PUE was comparable to that of the screw-only joint, while that of PU exhibited a significantly higher bearing capacity than those of the other two and that of the screw-only joint. Furthermore, the bearing capacity of PU increased with the increase in the coated adhesion area.

The reason for the difference in the bearing capacity of the standard hybrid joint is considered to be the difference in the failure mode of the adhesive joint; as illustrated in the top image of Fig. 7c, the failure at the adhesive–metal interface occurred for the hybrid joints with API and PUE, while the wood failure occurred for the hybrid joint with PU and facilitates a larger bearing capacity than those for API and PUE. This difference in





the failure mode is owing to the difference in the interfacial strength of the adhesive against the wood and the steel plate.

However, for the hybrid joint with PU and fillet (refer to the bottom of Fig. 7c), the bearing capacity increased with the increase in adhesion area. This can be explained by the distance between the edge of the steel plate with the highest concentration of stress and the edge of the adhesion area; the further the two points are separated, the less likely it is for failure to occur. In contrast, for the hybrid joint of API and PUE with fillet, the failure of the adhesive joint occurs at the interface between the adhesive and steel, even with fillet. It suggests that the appropriate choice of the adhesives and coating method is important for obtaining large bearing capacities.

Fracture energy

Finally, the fracture energy calculated from the load–displacement curves is presented in Fig. 8a, b. As illustrated in Fig. 8a, the larger the screw diameter, the greater the fracture energies of the hybrid joint. Furthermore, relatively large difference was observed between the fracture energy for the hybrid joint and that for the screw-only joint (“S4”). This can be easily understood by the dominant contributions from the pull-out of the screws (see Fig. 4a).

However, as illustrated in Fig. 8b, there were no significant differences in the fracture energy for the hybrid joints with different types of adhesives, and they were all equivalent to or slightly higher than that for the screw-only joint.

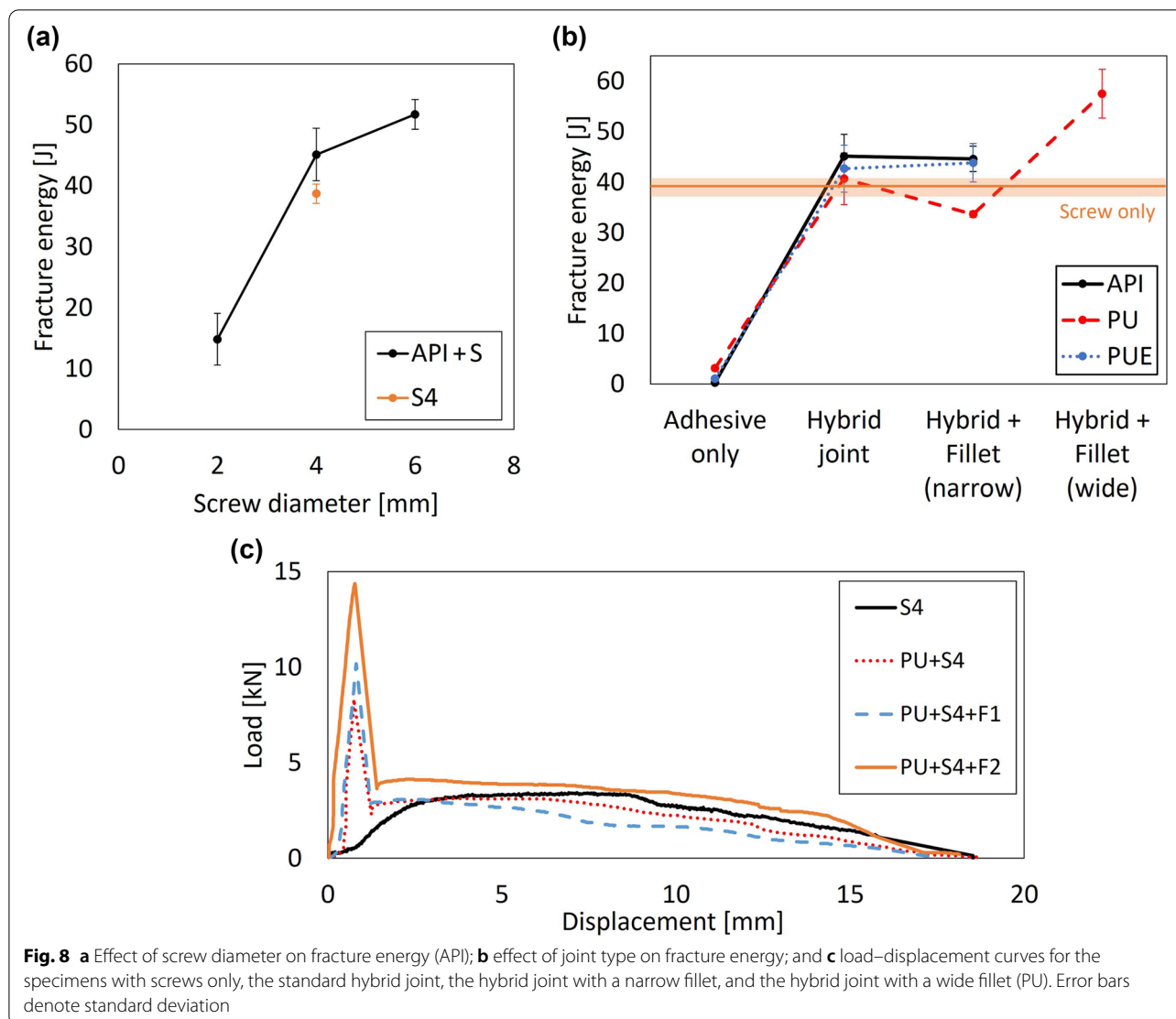
Comparing the fracture energy for the standard hybrid joint and that for the hybrid joint with fillet (narrow), there were again small differences for API and PUE, while the fracture energy of the hybrid joint with the fillet were smaller than that of the standard joint for PU. The

reduction in fracture energy triggered by the introduction of the fillet may be owing to the fact that the wood failure of the adhesive joint in the initial stage causes damages in the fastened region and leads to early pull-out of the screws.

Then, by comparing the narrow fillet and wide fillet in PU, the wide fillet exhibited greater fracture energy. This can be explained by the following two mechanisms. The first mechanism is the enhancement of fracture energy owing to the failure of the larger adhesion area, which compensates the reduction in fracture energy due to damages in the fastened region and early pull-out of the screws. The second is that the distance between the region of wood failure and the fastened region of the screws becomes larger for the samples with a wider fillet. If the two regions are separated from each other, the wood failure in the fastened region may be suppressed. It is important to note that the size of the wood failure may be influenced by factors of the wood, such as the density and direction of the grain. Hence, further research is required to determine what affects the size of the wood failure in the hybrid joints. Finally, to re-confirm the improvement of fracture energy due to the introduction of the wide fillet, we plotted the load–displacement curves for the specimens with PU adhesives in Fig. 8c. Larger loads can be clearly seen for the whole displacement range, relative to those for the other three types of specimens.

Conclusion

We studied mechanical properties of hybrid joints comprising wood and steel plates jointed by screws of three different diameters and three types of adhesives. We conducted lap-shear tests and investigated the effects of screws and adhesives on the fracture behavior. We also evaluated the bearing capacity, stiffness, and fracture



energy. Consequently, we determined that the hybrid joint specimens exhibit high stiffness caused by the adhesive, and high fracture energy that is comparable to that for the screw-only joint. We also determined the overall trends; the stiffness and bearing capacity of the hybrid joints change with the type of adhesive, while the fracture energy depends primarily on the diameter of the screws. Furthermore, we discussed the effects of adhesive fillet; using an appropriate choice of adhesive and fillet area, we could improve the bearing capacity and fracture energy. This indicates that the use of adhesives in combination with screws can improve the stiffness, bearing capacity and fracture energy.

However, several problems remain to be solved: in situ observations of fracture/damage processes, evaluation of damages in wood surfaces after the tests,

numerical and theoretical analyses, and full-scale experiments in practical conditions are other important issues. These topics need to be studied in the future.

Abbreviations

FRP: Fiber-reinforced plastics; SPF: Spruce–pine–fir; SUS: Stainless steel; SPCC: Steel plate cold commercial; API: Aqueous polymer–isocyanate adhesive; PU: Polyurethane adhesive; PUE: Silylated polyurethane elastic adhesive; S2: Mechanical joint with 2-mm screws; S4: Mechanical joint with 4-mm screws; S6: Mechanical joint with 6-mm screws; F1: Narrow fillet; F2: Wide fillet.

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Author contributions

KI, YO, and TY conducted experiments, analyzed the data, and prepared the manuscript. KA, NH, and AT participated in the discussion. TY got research funding. All authors read and approved the final manuscript.

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Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests

The authors declare that they have no competing interests.

Author details

¹Department of Biomaterial Sciences, The University of Tokyo, 1-1-1 Yayoi, Bunkyo-ku, Tokyo 113-8657, Japan. ²Department of Architecture, Tokyo City University, 1-28-1 Tamazutsumi, Setagaya-ku, Tokyo 158-8557, Japan.

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