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EFFECT OF RESIN IMPREGNAITON INTO WOOD CELL ON LATERAL RESISTANCE OF SCREWED JOINT CONNECTING SOLID WOOD AND STEEL PLATE

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ABSTRACT: During lateral loading to dowel-type timber joints, embedment deformation occurs around the contacting parts of dowels and wood. Hence, the embedment properties of wood are vital to the development of joints with high lateral resistance. In this study, the potential of resin impregnation for strengthening the embedment properties is analyzed. A lateral loading test is conducted using a screwed joint connecting solid wood and a steel plate. Resins are impregnated into the cell walls around the screws. Test results indicate that the initial stiffness is twice that of the control specimen. The yield load and maximum load are not significantly affected by the resin impregnation. Additionally, the resin-impregnated specimens indicate brittle fracture and low deformability, particularly in the case involving sapwood screwing.

KEYWORDS: Screwed joint, Lateral resistance, Resin Impregnation, Initial stiffness

1 INTRODUCTION

Owing to increasing interest in large-scale timber buildings, the development of timber joints with higher resistance performance has received significant attention. Dowel-type joints are one of the most general connecting methods used not only in housing, but also in large-scale buildings.

The lateral resistance of the joints significantly affect the seismic performance of buildings constructed using them. When a lateral load is exerted on a dowel-type joint, the dowel locally embeds the wood member around the contact part between the dowel and wood. Therefore, the strengthening of wood against embedment loads is effective for developing joints with higher lateral resistance.

Based on a micro-level observation of wood embedment, embedment can be regarded as the crushing of wood cells (Figure 1), and a method for preventing this crush is desired. In this regard, the authors investigated the potential of resin impregnation [1], which allows the local impregnation of resin into wood cells. If the wood cells around the dowel are filled with resin before the lateral load is applied, then an improvement in the embedment property can be expected.

Previously, the authors attempted to apply resin impregnation techniques to bolted joints [2]. Consequently, the initial stiffness and yield load improved significantly, i.e., by 104% and 73%, respectively. Additionally, the embedment properties of Japanese cedar (*Cryptomeria japonica* D.DON) were revealed using an embedment test [3], i.e., its stiffness improved by 278% and 94% under parallel and perpendicular loading, respectively. Resin impregnation is expected to improve other dowel-type joints.

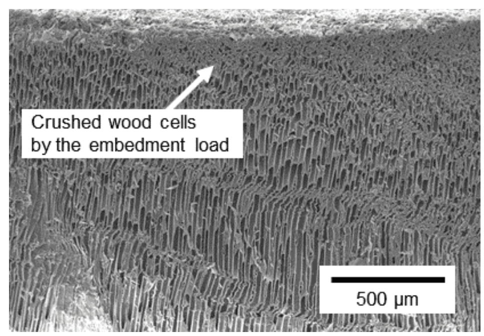

Figure 1: *Crushed wood cells under the embedment load by dowel-type fasteners*

Screwed joints are typically used in modern timber construction. Although the diameter of a screw is smaller than that of a bolt, their main mechanism is similar. In this study, the authors attempted to apply a resin impregnation to a screwed joint. A lateral load test was conducted to evaluate the effects of the impregnation.

2 MATERIALS AND METHOD

2.1 SPECIMEN PREPARATION

A lateral load test with screw joints was conducted based on ASTM D1761-20 [4], as shown in Figure 2. Air-dried

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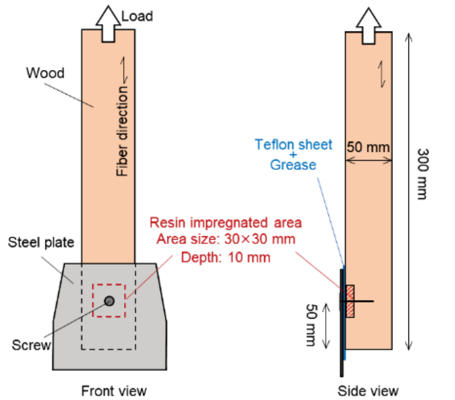

Figure 2: *Screwed joint specimen and loading method*

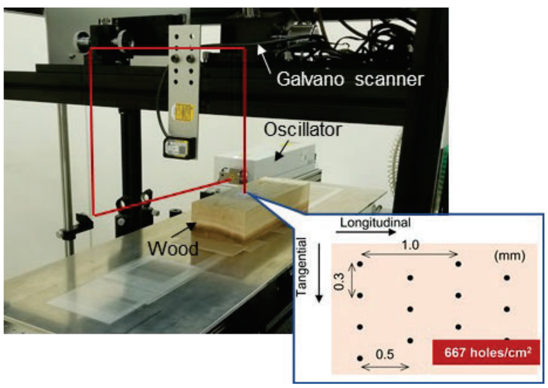

Figure 3: *UV laser incision. Red line shows trajectory of UV laser from oscillator to wood surface*

Japanese cedar (*Cryptomeria japonica* D.DON), a steel plate measuring 2.3 mm thick, a TB-45 screw (Tanaka Co. Ltd.; diameter: 5.1 mm; length: 43 mm) were used. To assemble the joint specimen, Teflon sheets and grease were inserted between the wood member and steel plate to prevent friction [5].

The wood members were treated via resin impregnation on their surfaces. First, microscopic incisions were created using an ultraviolet (UV) laser around the area where the screw was tapped. As shown by the red square in Figure 2, the area measured 30 mm × 30 mm. A diode-pumped solid-state Q-switched laser (Talon355-15SH, Spectra-Physics) was used for laser oscillation, and a Galvano scanner was used to create the incision pattern, as shown in Figure 3. The diameter, depth, and density of the incision were approximately 80 µm, 10 mm, and 667 holes/cm^2, respectively.

Next, the resin was impregnated from the incised area by brush painting operation. Two types of resins were used in this study: acrylic monomers (DIAKITE PE-2730, Toeikasei Co. Ltd.) and urethane prepolymers (PS-NY6, Kotobukikakoku Co. Ltd.); hereinafter, they are referred to as acryl and urethane, respectively. In the case of acryl, 2.2'-azobisisobutyronitrile (0.6 parts by weight) was incorporated as a polymerization initiator; it was heated at 140 °C and cured for 30 min. In urethane, the wood members were cured for one week in a testing room. The evaporation residue of urethane was approximately 40%.

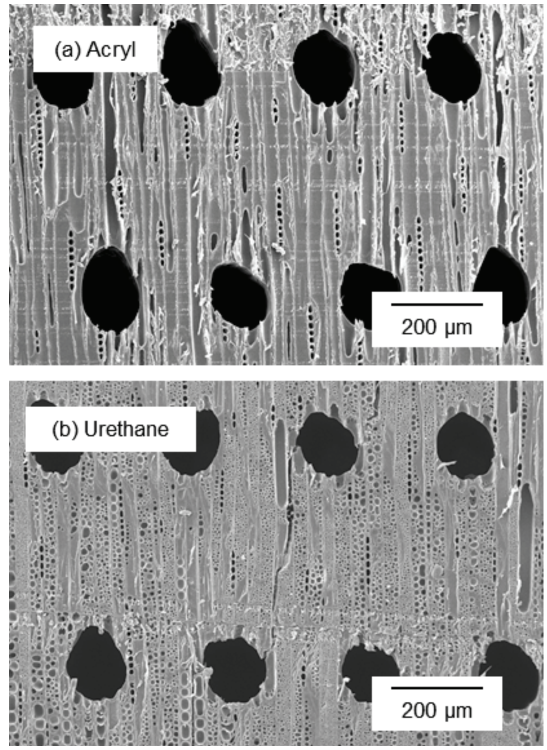

Figure 4: *Holes created using UV laser and resins filled into wood cells*

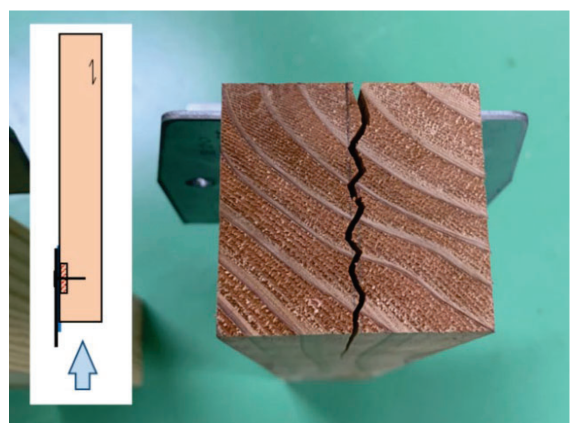

Figure 5: *Crack observed (from blue arrow) at screwing location in test groups with resin impregnation.*

Examples of scanning electron microscopy images are shown in Figure 4. Both images show that the resins filled the wood cells.

The amount of impregnated resin differed for each specimen. As described in our previous study [2], resins impregnate more in sapwood than in heartwood. The specimens used in this study exhibited the same tendency. In one incision area (represented as the red square in Figure 1), 16.32 ± 3.43 g of acryl was impregnated into the sapwood. Subsequently, the amount R per incision volume was calculated as follows:

$$R = \frac{W}{V} = \frac{W}{A \times d}, \qquad (1)$$

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Table 1: Number of spesimen for each specimen group

Group	Resin	Number of speciems			
		Prepared		Tested	
		Heartwood	Sapwood	Heartwood	Sapwood
Control	None	10	8	9	8
Acryl	Acryl	10	8	10	4
Urethane	Urethane	10	8	9	0

where W is the mass of the impregnated resin; V is the incision volume; and A and d are the incision (30 mm × 30 mm) and depth (10 mm), respectively. Using the equation above, the R of acryl impregnated into sapwood was calculated to be 1813 ± 381 kg/m^3, whereas that impregnated into heartwood was 430 ± 413 kg/m^3. Meanwhile, 1971 ± 576 kg/m^3 and 318 ± 2.93 kg/m^3 of urethane were impregnated into the sapwood and heartwood, respectively.

Three testing groups were prepared for this study: two types of resin (acryl and urethane) and a control group. Eighteen specimens were prepared for each group. However, a prominent crack beginning from the screwed point to the bottom face of the wood member occurred in some specimens, as shown in Figure 5. Subsequently, lateral loading tests were halted on the specimens. The replicates for each group are presented in Table 1. Cracks occurred in many specimens of sapwood. This implies that a higher amount of resin impregnation may cause brittleness in wood.

2.2 TESTING METHOD

The lateral loading test was conducted using a universal testing machine (AG-I 250kN, Shimadzu Co., Ltd.), as shown in Figure 6. A steel plate was fixed to the testing machine and an upward load was applied to the wood member. During the test, the load and relative slip between the wood member and steel plate were recorded. A load cell equipped with a testing machine (SFL-50kNAG, Shimadzu Co. Ltd.) was used to measure the load. To measure the relative slip, a displacement transducer (SDP-100CT, Tokyo Measuring Instruments Lab.) was attached to the wood member and the target was attached to the steel plate. The alignment support was adjusted to correct the load axis during the testing.

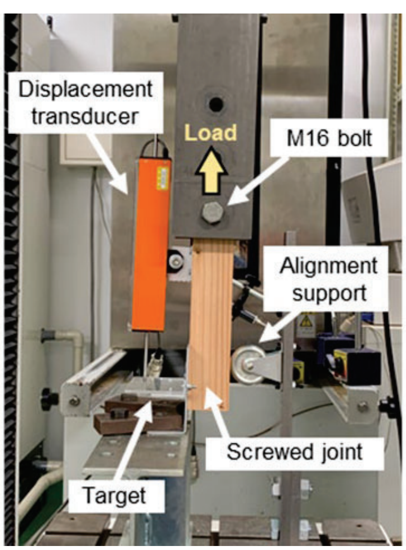

Figure6: *Experimental setup*

3 RESULTS AND DISCUSSIONS

3.1 RELATIONSHIP BETWEEN LOAD AND SLIP

The relationship between the load and slip for each specimen group obtained via the lateral test is shown in Figure 7. For the control group (Figure 7(a)), the load increased linearly with slip at the beginning of testing. When the load reached approximately 1.5 kN, the slope began to decrease. When the slope decreased, the load did not decrease, and most specimens maintained their load until the slip reached approximately 30 mm.

Compared with the control group, acryl and urethane indicated higher slopes at the beginning of the test. However, the load decreased significantly in some specimens after linearity was observed. Cracks occurred from the screwed point to the bottom surface of the wood member. The loads of four of the specimens decreased significantly before the slip reached 5 mm. These specimens were screwed onto sapwood. This result shows that even though cracks did not occur during the joint assembly, the joint was in the limit state of brittle failure. The load of most joint specimens screwed onto the heartwood did not decrease drastically until the slip reached approximately 20 mm.

3.2 CHARACTERISTICS

To evaluate the characteristics of the joint specimens, the relationship between the load and slip was further analyzed using a perfect elasto-plastic model [6, 7]. The method to obtain the characteristic values is explained below and shown in Figure 8. The black line indicates the relationship between the load and slip obtained from the lateral loading test. Here, P_{max} and δ_{max} are the mean maximum load and the slip at the maximum load, respectively. First, a direct line is drawn between $0.1P_{max}$ and $0.4P_{max}$, and between $0.4P_{max}$ and $0.9P_{max}$; the lines drawn for the former and latter are referred to as lines I and II, respectively. Line II shifts until it satisfies the load-slip relationship, and the shifted line is named Line III. Subsequently, a new line parallel to the horizontal axis that passes through the intersection of Lines I and III is

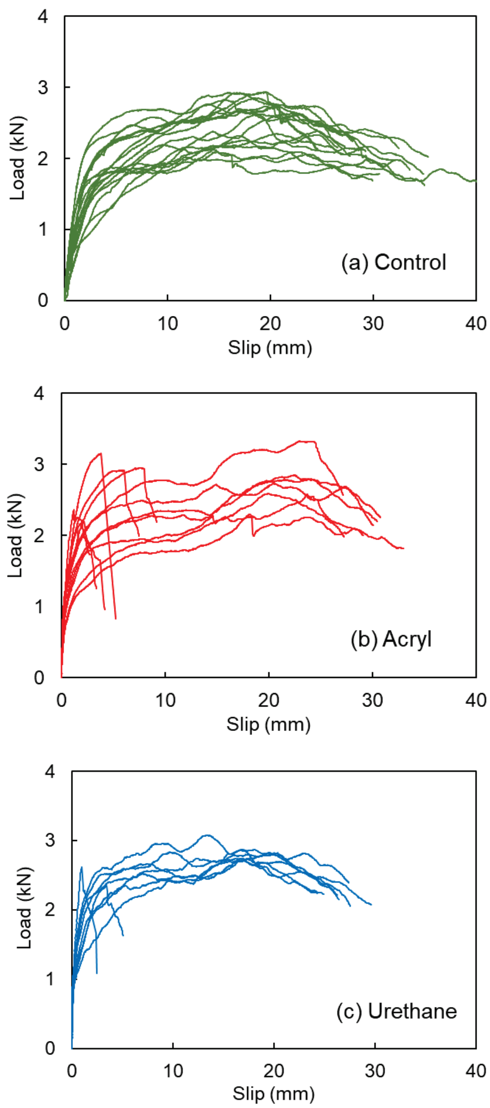

Figure 7: *Relationship between load and slip*

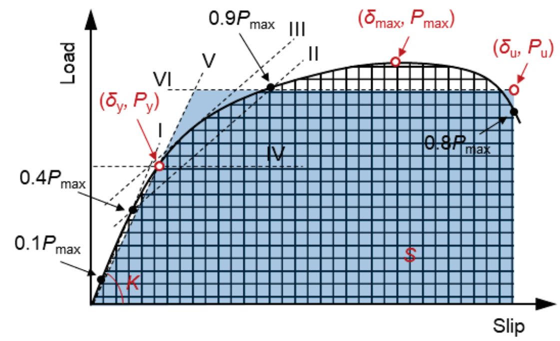

Figure 8: *Perfect elasto-plastic model [7]*

drawn and named Line IV. The intersection of Line IV with the load-slip relationship is regarded as the yield point, and the abscissa and ordinate of the point are the slip at yielding δ_y and the yield load P_y, respectively. The line connecting the origin and yield point is named Line V, and the slope of Line V is regarded as the stiffness K. Next, the slip at the ultimate load δ_u is determined as the abscissa of a point when the load is decreased to 0.8P_{max} after surpassing the maximum load. If the load does not decrease until the slip reaches 30 mm, then δ_u = 30 mm is used instead of the point at 0.8P_{max}. Subsequently, the energy based on the load-slip relationship from the origin to δ_u (hatched region in Figure 8) is determined and denoted as S. Next, a line parallel to the horizontal axis, named Line VI, is drawn such that the area of the trapezoid, which comprises Line V, Line VI, the horizontal axis, and the line X = δ_u (blue region in Figure 8), is equivalent to the energy S. The ordinate of Line VI is regarded as the ultimate load P_u. The characteristics obtained using the model are listed in Table 2.

The most improved characteristic owing to resin impregnation was the initial stiffness. Whereas the initial stiffness of the control was 0.75 kN/mm, those of acryl and urethane were 1.57 and 2.01 kN/mm, respectively. This implies that the initial stiffness was more than doubled by the resin impregnation. Table 2 shows similar average values for the parameters related to the load, i.e.,

Table 2: *Characteristics obtained using perfect elasto-plastic model*

Group		P_y	δ_y	K	P_{max}	δ_{max}	P_u	δ_u
		(kN)	(mm)	(kN/mm)	(kN)	(mm)	(kN)	(mm)
Control	Average	1.60	2.47	0.75	2.50	17.78	2.27	30.06
	SD	0.20	1.10	0.28	0.32	3.06	0.27	4.46
Acryl	Average	1.64	1.11	2.01	2.77	12.79	2.47	20.90
	SD	0.31	0.68	1.05	0.19	6.31	0.23	9.65
Urethane	Average	1.56	1.54	1.57	2.68	13.37	2.39	17.93
	SD	0.27	0.97	0.94	0.35	9.23	0.34	12.50

P_y: Yield load; δ_y: Slip at yielding; K : Initial stiffness; P_{max}: Maximum load

δ_{max}: Slip at maximum load; P_u: Ultimate load; δ_u: Slip at ultimate load

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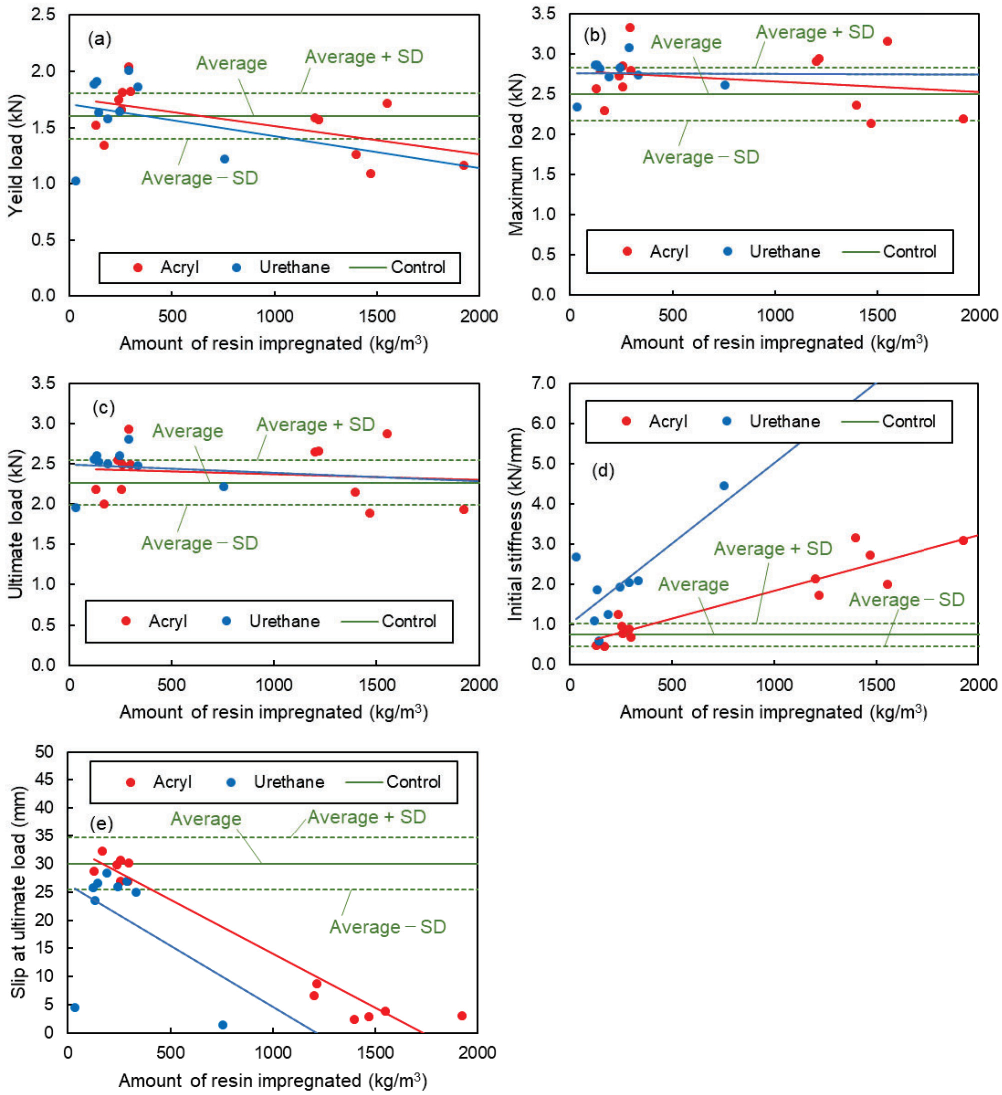

Figure 9: *Relationship between characteristics and amount of resin impregnated*

the yield load, maximum load, and ultimate load. In summary, resin impregnation can improve the lateral resistance of the joint; however, the effect was limited to the range of small slips. Meanwhile, the values of parameters related to deformation, such as slip at yielding, slip at the maximum load, and slip at the ultimate load, decreased due to resin impregnation. This shows that resin impregnation results in decreased deformability. The result indicating the increasing brittleness of the joints is a critical issue that must be addressed closely.

3.3 INFLUENCE OF AMOUNT OF IMPREGNATED RESIN ON CHARACTERISTICS

As described in Section 2.1, the amount of impregnated resin differed between sapwood and heartwood. In this section, the effect of the amount of impregnated resin on the characteristics of sapwood and heartwood is discussed.

Figure 9 shows the relationship between the characteristics and amount R of impregnated resin calculated using Equation (1). The characteristics related to the load, yield load, maximum load, and ultimate load are shown in this figure. Figure 9(a) shows that the yield load decreased as the impregnated resin increased. Specimens with a higher amount of impregnated resin exhibited higher brittleness, and micro-level cracks were assumed to have occurred in the small slip. Meanwhile, the maximum and ultimate loads decreased slightly (as shown in Figures 9 (b) and (c), respectively), as the amount of impregnated resin increased.

As described in the previous section, resin impregnation significantly affected the initial stiffness. Based on Figure 9(d), the initial stiffness increased with the amount of impregnated resin. When a low amount of acryl (less than 500 kg/m^3) was impregnated, the initial stiffness did not differ significantly from that of the control. In specimens with a high amount acryl (more than 1000 kg/m^3), the initial stiffness increased significantly. Meanwhile, the impregnation of a low amount of urethane resulted in a higher initial stiffness.

To investigate the deformability, the authors examined the relationship between the slip at the ultimate load and the amount of impregnated resin (see Figure 9(e)). In both resins, the slip at the ultimate load decreased as the impregnated amount increased. The specimens with small amount, slip at ultimate load was almost similar with control specimens. In specimens with a high amount of resin (more than 500 kg/m^3), a decrease in slip was clearly observed.

4 CONCLUSION

In this study, the effect of resin impregnation on the lateral resistance of screwed joints connecting wood and steel plates were investigated. Screwed joint specimens impregnated with acryl- and urethane-type resins were tested via lateral loading tests, and the results obtained were compared to those of the control specimen.

A significant improvement in the initial stiffness was indicated. Based on the average value, the initial stiffness more than doubled owing to resin impregnation. For the case of acryl impregnation, the initial stiffness of the specimen was higher than that of the control specimen when the impregnated amount was high. For the case of urethane, the specimen indicated a higher initial stiffness was observed even if the impregnated amount was low.

Additionally, resin impregnation resulted in decreased deformability. When the amount of impregnated resin exceeded 500 kg/m^3, the slip at the ultimate load became much lower than that of the control. The result indicating the increasing brittleness of the joints is a critical issue that must be addressed.

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