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Full-field Measurement of Deformation of a Mortise and Tenon Joint in Traditional Wooden Structures

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This study deals with the measurement of the two-dimensional deformation of wood joints, which are of traditional Japanese wooden frame construction, under compressive and tensile loads using an electronic speckle pattern interferometry (ESPI) technique. A mortise and tenon joint of western hemlock is used as specimens. Results reveal that a large two-dimensional deformation of the wood joints can be measured using the ESPI technique, the deformation values near the junction of the male and female parts of the joints are larger than those at other parts, and the female part of the joints moves complexly.

Key words: ESPI, Wood Joint, Mortise and Tenon Joint, Deformation, Strain

1. INTRODUCTION

Wood joints that are of traditional Japanese wooden frame construction may be used to join pieces of wood used in wooden structures such as columns and beams. Such wood joints are used to join pieces of wood straightly in the longitudinal direction or at certain angles. They are held together using only wood without the use of hardware such as nails, in principle [1].

To date, the mechanical properties of wood joints have mainly been evaluated based on average tensile, and compressive and bending strengths, which were determined from the results of tension, compression and bending tests [2],[3]. However, it is unlikely that the mechanical properties of wood, which is a complicated composite material whose properties differ throughout, can be fully grasped using such evaluation methods. A two-dimensional evaluation of the mechanical properties of wood is necessary to gain a better understanding of such properties.

A photoelastic coating technique [4],[5], a moire technique [6] and a digital image correlation technique [7]-[10] have been used to evaluate the mechanical properties of wood. However, a photoelastic coating technique requires a coating on a wood surface, and only the differences in principal strains and their directions can be obtained. Furthermore, this technique does not guarantee that we can obtain the differences in principal strains which precisely reflect the deformation of a material of complex organization such as wood. A moire technique requires that a grating be formed on a specimen. A digital image correlation technique does not require special processing of a wood surface, and the measurement equipment required for digital image correlation is simple. However, it is necessary to specify a correlation area and a search area in this technique, which affect correlation results.

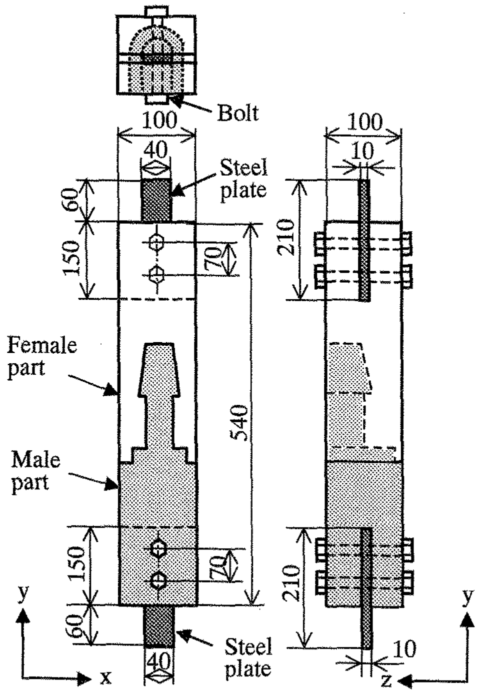
In this study, an ESPI technique, which requires only the application of white paint to a wood surface [11], was used to investigate the two-dimensional deformation of wood joints under compressive and tensile loads.

2. EXPERIMENTAL PROCESURES

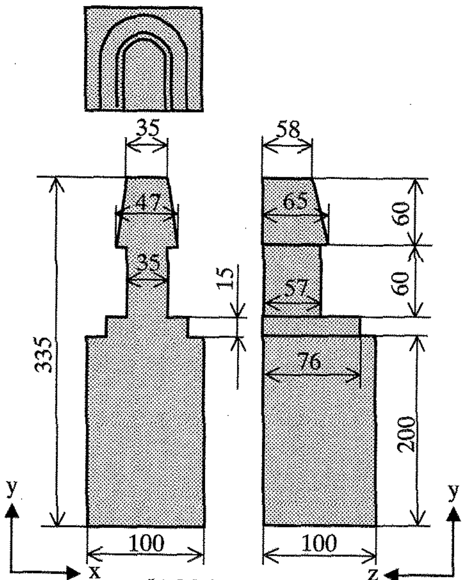
Figure 1 shows the shape and dimensions of the mortise and tenon joint specimens of western hemlock used for tension and compression tests. The specimens for compression tests have not the steel plates shown in Fig. 1. The pieces of western hemlock wood are often used as structural members in wooden structures. Logs were sawn into square bars with a 100 mm×100 mm cross section, which were used as joint specimens in the longitudinal direction. The specimens exhibited straight grain on the surface determined using the ESPI technique. The measured surfaces of the specimens were sandpapered (#1000) and sprayed with white paint. All of the specimens used were in an air-dried state.

Figure 2 shows the experimental setup used in this study. A universal test machine (AG-100kNG, Shimadzu Co.) was used to carry out compression and tension tests. The deformation and strain of the surfaces of the specimens were measured using an ESPI system (AG, Ettenmeyer Co.). A laser with a wavelength of 532 nm was used to illuminate the measured surfaces of the specimens. The compression and tension tests were carried out at compressive and tensile rates of 0.4 mm/min.

The ESPI system utilizes two digitized phase map images, which are called reference or undeformed phase map image, R, and deformed phase map image, D, to measure deformation by subtraction of the images; it can measure slight deformation. To obtain a phase map image in the *x* direction, as well as in the *y* direction four original digitized speckle pattern images captured at 10-ms intervals using a CCD camera, as shown in Fig. 2, were used. In general, for slight deformation, the two phase map images obtained at the initial and final loads are used as R and D, respectively. For the wood joints



(a) Mortise and tenon joint



(b) Male part

Fig.1 Shape and dimensions of specimen

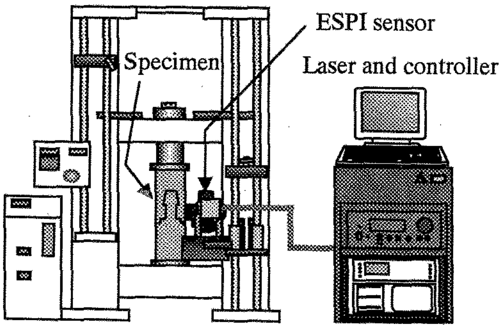


Fig.2 Experimental setup

used in this study, large deformation might have probably occurred. For large deformation, many sets of two phase map images were used, which were selected based on the amount of load among phase map images obtained for loads between the initial and final loads. In this case, a deformed phase map image used prior to the subtraction of images was used as a reference image for the present case. Using this technique, any large deformation can be measured.

3. EXPERIMENTAL RESULTS

Figure 3 shows the load-stroke curve for the mortise and tenon joint subjected to compressive loads. The maximum load and stroke were about 100 kN and 2 mm, respectively. Figures 4, 5 and 6 show strain ε_x, ε_y and γ_{xy} maps and displacements expressed by vectors for the mortise and tenon joint specimen under compressive loads of about 5 kN, 40 kN and 100 kN at points A, B and C in Fig. 3, respectively. The strains are shown in m strain units.

The strain maps indicate that the strains near the junction of the male and female parts of the joint were larger than those at other parts, and increased with increasing load. In particular, ε_y increased significantly near points a, b and d shown in Fig. 3 with increasing load.

The displacement expressed by vectors indicates that the deformation of the joint was complex. The upper male and female parts of the joint moved obliquely in the lower-left direction with increasing load, and thereafter moved downward at high loads. The female parts near points b and e moved laterally away from the male part, those between points b and c and points e and f moved downward, and those near points c and f moved with compression of the male part. Furthermore, the deformation of the female part did not show symmetry between the left and right halves. The upper-left and lower-right parts of the female part deformed significantly, and had a large strain ε_y. It was inferred that this is caused by the difference in the distributions of the mechanical properties of wood, which is a complicated composite material, and by gaps between the male and female parts, which are determined by the accuracy of the fabricated wood joint.

Figure 7 shows the load-stroke curve for the mortise and tenon joint subjected to tensile loads. The maximum load and stroke were about 6 kN and 3 mm. Figure 8 shows strain ε_x, ε_y and γ_{xy} maps and displacements expressed by vectors for the mortise and tenon joint specimen under tensile loads of about 6 kN at point A in Fig. 7.

The strain maps indicate that the strains near the junction of the male and female parts of the joint were larger than those at other parts, and increased with increasing load, which was similar to that under compressive loads. In particular, ε_y increased significantly near points a, b, d, e and g shown in Fig. 7 with increasing load. Negative values of ε_y existed near points a, c, d, f and g shown in Fig. 7, near which positive values of ε_y are expected, and positive values of existed near points b and e shown in Fig. 7, near which negative values of ε_y are expected, because of tensile loads applied to the joint. This tendency of ε_y indicates that the female part did not move simply upward and moved complexly.

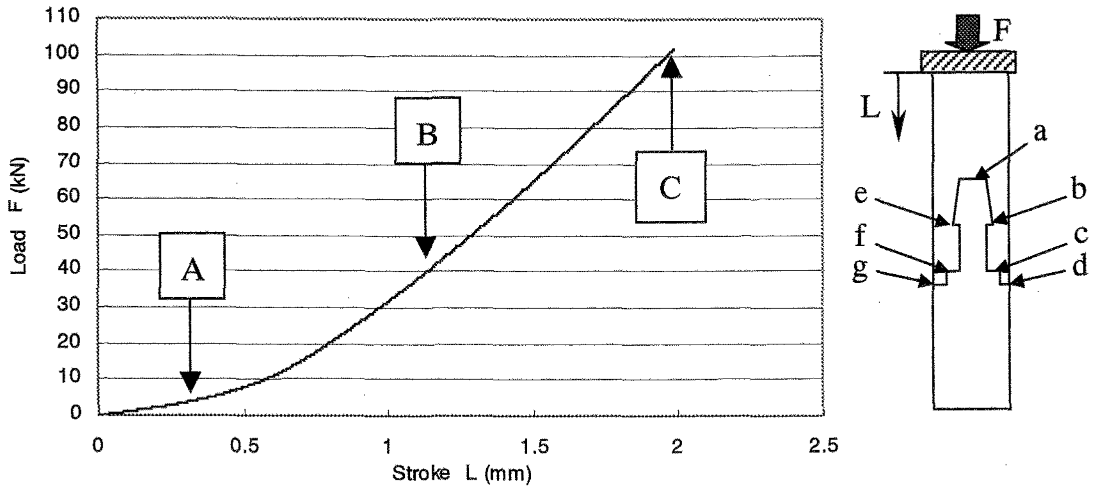
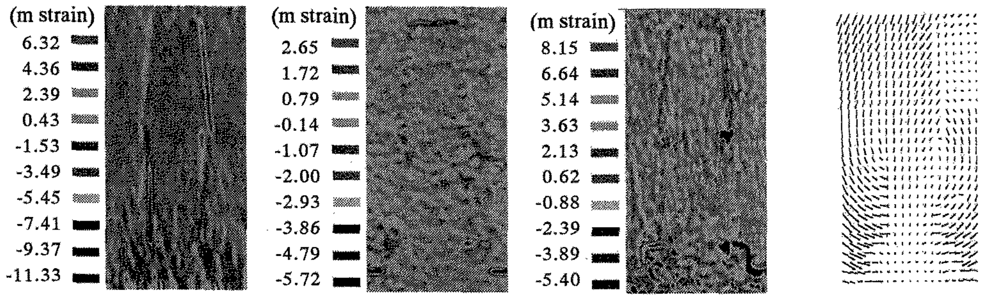
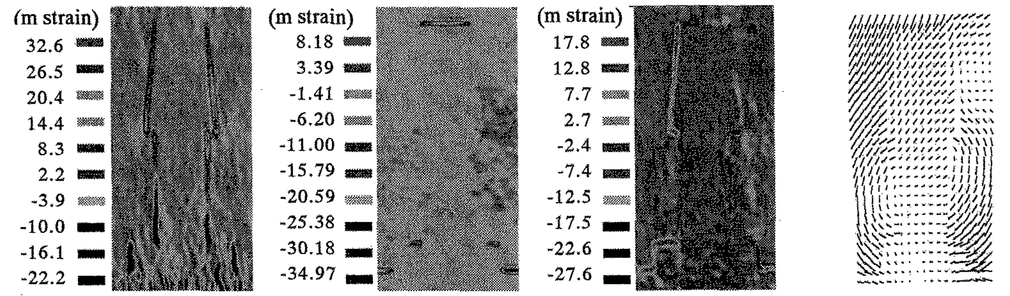


Fig. 3 Load-stroke curve for the mortise and tenon



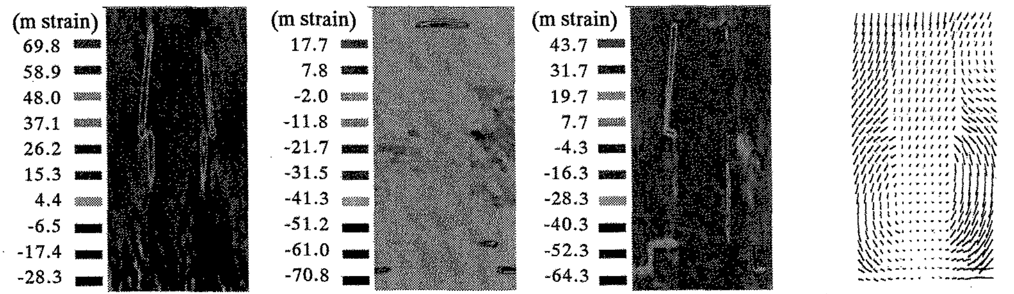
(a) ε_x (b) ε_y (c) γ_{xy} (d) Displacements expressed by vectors

Fig. 4 Strain maps and displacements for the mortise and tenon joint subjected to a compressive load at point A



(a) ε_x (b) ε_y (c) γ_{xy} (d) Displacements expressed by vectors

Fig. 5 Strain maps and displacements for the mortise and tenon joint subjected to a compressive load at point B



(a) ε_x (b) ε_y (c) γ_{xy} (d) Displacements expressed by vectors

Fig. 6 Strain maps and displacements for the mortise and tenon joint subjected to a compressive load at point C

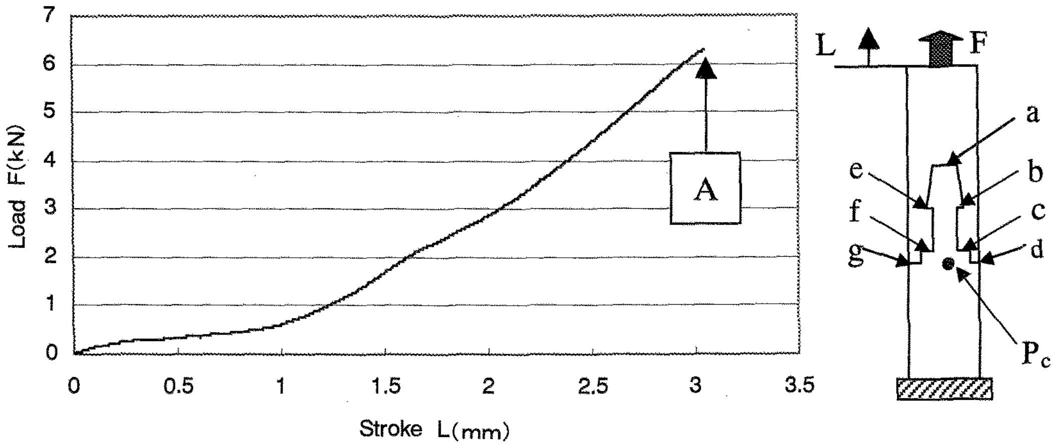
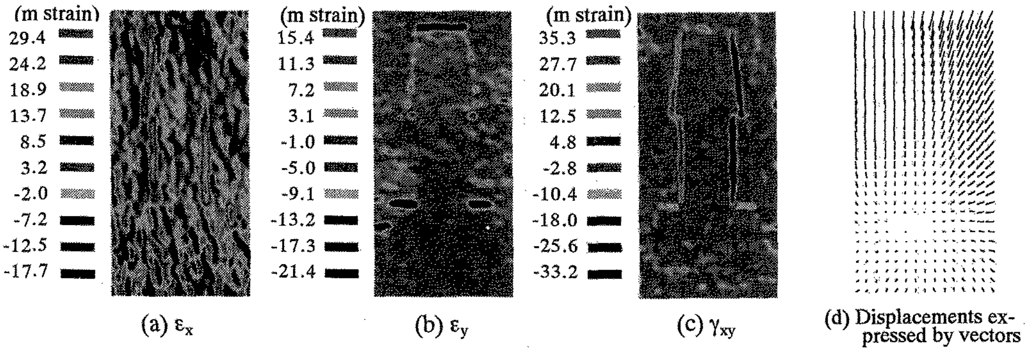


Fig.7 Load-stroke curve of the mortise and tenon joint under tensile loads



(a) ε_x (b) ε_y (c) γ_{xy} (d) Displacements expressed by vectors

Fig.8 Strain maps and displacements for the mortise and tenon joint subjected to a tensile load at point A

The displacement expressed by vectors indicates that the female part moved toward point P_c, which was located near the lowest position of the female part, and near the junction of the male and female parts of the joint shown by points d and g in Fig. 7. It was inferred that this is caused by the compression of the front surfaces of the specimen because of the inclination of the female part in the forward direction with increasing tensile load.

4. CONCLUSIONS

The deformation of wood joints subjected to compressive and tensile loads was measured using the ESPI technique. Results show that a large deformation of the wood joints can be measured using the ESPI technique, the deformation values significantly vary with every part of the wood joints, the deformation values near the junction of the male and female parts of the joints are larger than those at other parts, and the female part of the joints moves complexly.

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