Strain Analysis of Traditional Japanese Timber Joints under Tensile Loading

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Summary

The strain distribution of traditional joints under tensile loading was analyzed using the digital image correlation technique (DIC) and the finite element method (FEM). Two types of splice joints; Kama Tsugi (a half-lapped “gooseneck” splice joint) and Okkake Daisen Tsugi (a wedged tabled joint with dowels), were studied. The proportions of the joints were altered in order to investigate the effect of shear plane (a plane parallel to the grain) length on tensile strength.

In both types of joints, shear strain was concentrated near the re-entrant corner of the joints. The degree of shear strain concentration tended to increase as the shear plane length increased. It was found that the tensile strength could be estimated by considering the degree of shear strain (stress) concentration.

1. Introduction

In traditional Japanese wooden construction, various types of timber to timber joints have been utilized. Lumber is cut and trimmed into a special shape, not only to provide strength and perfect contact but also beautiful appearance. This would have been particularly important in traditional Japanese wooden structures, because the structural elements were usually visible from outside. In addition to the aesthetic advantage, traditional joints made it possible for the whole structure to be disassembled and then reassembled, which made the replacement of damaged structural elements possible.

The configurations and dimensions of the joints are based on empirical rules acquired by each carpenters. The relative relation of each dimension is usually determined with the aid of a L-shaped square (Sashigane), the absolute value of the dimension, however, is chosen according to rule of thumb.

Although there have been numerous experimental studies on the relation between dimension and the strength of traditional joints, analytical studies have rarely been carried out. Traditional joints usually exhibit non-uniform stress distribution due to their elaborate shape. The estimation of strength of traditional joints should inevitably include stress analysis.

The objective of the present study is to reveal the strain distribution of traditional joints by using the digital image correlation method [1] [2]. Two types of splice joints; Kama Tsugi (a half-lapped “gooseneck” splice joint, hereinafter called KM) and Okkake Daisen Tsugi (a wedged tabled joint with dowels, hereinafter called OKD), were studied. The proportions of the joints were altered in order to investigate the effect of dimension on the tensile strength. Finally, prediction of the tensile strength of the joints was attempted based on the relation between the strain/stress distribution and the dimension of the joints.
2. Materials and Method

2.1 Test specimen

The KM (Kama Tsugi) specimens were fabricated from lumber made of Japanese cedar (Cryptomeria japonica D. Don), and the OKD (Okkake Daisen Tsugi) specimens were fabricated from glued-laminated timber of Japanese cedar. The glued-laminated timbers were composed of laminae of similar MOEs. The lumber and the glued-laminated timber were selected to exclude the influence of knots and drying checks on the joints strength. All specimens were end-matched. The ‘Daisen’ dowels in OKD were made from Japanese oak (Quercus spp.).

The configuration of KM is shown in Fig. 1. The longitudinal length of the tenon was altered in order to investigate the effect of shear plane length (L) on the tensile strength. The width of the compression plane (d) was fixed at 7.5mm. The section of lumber was reduced to half size at both ends. This was done to minimize eccentric loads being introduced to joints.

The configuration of the OKD is shown in Fig. 2 and Table 1. The longitudinal length of the shear plane (L) as well as the width of the compression plane (d) was changed (See Table 1). The compression planes were slightly tilted in order to draw each part of the joinery towards one another. The dowel was fabricated to have a tapered shape. This shape allows tight fit between the dowel and the hole. The dimensions of key-shaped part (hereinafter called KEY) were fixed at 15mm in length and in width. Both in KM and OKD, each condition consisted of three replicates.

Table 1 Variation in dimension of OKD

<table>
<thead>
<tr>
<th>L [mm]</th>
<th>d [mm]</th>
</tr>
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<tbody>
<tr>
<td>105</td>
<td>12</td>
</tr>
<tr>
<td>150</td>
<td>15</td>
</tr>
<tr>
<td>180</td>
<td>15</td>
</tr>
<tr>
<td>180 (w/o dowel)</td>
<td>15</td>
</tr>
<tr>
<td>225</td>
<td>15</td>
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</table>

Fig. 1 Schematics of Kama Tsugi (The half-lapped ‘gooseneck’ splice joint). The shear plane lengths (L) were L = 30, 60, 75, 90, 105, 135mm.

Fig. 2 Schematics of Okkake Daisen Tsugi (A wedged tabled joint with dowels).
2.2 Tensile test

Fig. 3 shows the setup of the tensile test. The specimens were fixed to the testing machine with 30mm diameter drift pins. Relative displacements between joints were measured using two displacement transducers.

During testing, digital images were taken at regular intervals in order to obtain the strain distribution of the joints. Photographed areas are shown in the Fig. 3. In the testing of KM, one camera was used, while in the testing of OKD, two cameras were used. The digital image correlation method requires specimen surface patterns to have sufficient contrast and to be randomly distributed. The surface of Japanese cedar in its natural form cannot provide this. Thus, black ink was sprayed onto the surface of the specimen to generate randomly distributed patterns.

3. Results and Discussion

3.1 Load-displacement characteristic and fracture morphology

Examples of the load-displacement curve with KM are shown in Fig. 4. Ultimate displacement was relatively small when the shear plane length (L) was L=30, 60, 75mm, in which complete shear failure in the tenon was observed. More ductile deformation behavior was observed with shear plane lengths greater than L=75mm, in which mixed fractures of crushing failure in the compression plane and the partial shear failure in the shear plane were observed.
Examples of the load-displacement curve with OKD are shown in Fig. 5. Independent of shear plane length ($L$), the deformation behaviors of OKD were brittle compared to KM joints. All samples finally exhibited complete failure in the shear plane.

The effect of shear plane length ($L$) on the maximum loads of KM and OKD are shown in Fig. 6 and Fig. 7 respectively. In KM, the maximum load leveled off as the shear plane length increased. On the other hand, the maximum load of OKD increased as the shear plane length increased. The increasing rate of maximum load, however, was less than the increasing rate of shear plane length. Fig. 8 shows the effect of compression plane width ($d$) and the existence of the dowel on the tensile strength of OKD. The tensile strength was not affected either by the width of the compression plane or by the existence of dowels.

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**Fig. 6** Effect of shear plane lengths ($L$) on the tensile strength of KM.

**Fig. 7** Effect of shear plane lengths ($L$) on the tensile strength of OKD.

**Fig. 8** Effect of compression plane width ($d$) on the tensile strength of OKD.
3.2 Strain distribution measured with Digital Image Correlation

The strain distributions of KM and OKD when the load was 80% of the maximum load (before the maximum load was reached) are shown in Fig. 9 and Fig. 10 respectively. Both KM and OKD exhibited large shear strain near the re-entrant corner of the joints which is indicated by arrows in the figure.

Large tensile strain perpendicular to the grain direction was observed near the re-entrant corner of KM, whereas in the corner of OKD tensile strain was less remarkable.
Finite element analyses were also conducted in order to complement the experimental observations. The schematic diagrams of the analyses model are shown in Fig. 11. Finite element analyses were performed using commercial software ANSYS v10.0. The linear elastic material behavior was assumed. The material constants being used are listed in Table 2. 3-dimensional element (SOLID186: a 20-node solid element) was used for the modeling of KM, and 2-dimensional plane element (PLANE183; a 8-node plane element) was used for the modeling of OKD. For the modeling of OKD, plane stress condition was assumed. In both types of joints, the contact elements were introduced in order to account for the interactions between contacting surfaces of the joints.

The strain distribution of KM is shown in Fig. 12. The strain profiles along the shear plane indicate that the shear strain is larger on the inner surface compared to the outer surface. And to the contrary, tensile strain perpendicular to the grain was larger on the outer surface.

The effect of the KEY parts of OKD on the strain distribution of the shear plane is shown in Fig. 13. When the KEY parts are effective, the tensile strain perpendicular to the grain becomes almost zero. This is in line with the experimental observations (See Fig. 10).

### Table 2 Material properties used for FEM analyses

<table>
<thead>
<tr>
<th>Modulus [MPa]</th>
<th>ratio/constant</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_X (E_L)$</td>
<td>7350</td>
</tr>
<tr>
<td>$E_Y (E_R)$</td>
<td>590</td>
</tr>
<tr>
<td>$E_Z (E_T)$</td>
<td>290</td>
</tr>
<tr>
<td>$G_{XY} (G_{LR})$</td>
<td>637</td>
</tr>
<tr>
<td>$G_{YZ} (G_{RT})$</td>
<td>15</td>
</tr>
<tr>
<td>$G_{ZX} (G_{TL})$</td>
<td>343</td>
</tr>
</tbody>
</table>

Values were taken from literature [3].
3.4 Estimation of tensile strength

As seen in the strain distribution, strain/stress in the shear plane was concentrated near the re-entrant corner. It is obvious that the tensile strength of the joints is governed by the fracture in this area. The relation between the shear plane length ($L$) and the degree of shear strain concentration (DSC: defined as the ratio of the maximum shear strain to the average shear strain) in the KM joint is shown in Fig. 14. The strain data measured with DIC was used. The DSC increases as the shear plane length ($L$) increases.

The tensile strength was estimated based on the relation between the shear plane length ($L$) and the DSC, assuming the maximum shear stress failure criterion. The stress-strain relation in shear was assumed to be linear elastic to failure. The shear strength of Japanese cedar was adopted from the literature [3]. A good relation was found between the estimated and measured strengths (See Fig.15).

Table 3 shows the degree of shear stress/strain concentration (DSC) of OKD, which was calculated with the FEM results. The DSC in OKD also tended to increase. The DSC and measured tensile strength had a linear relation, which indicates that tensile strength of OKD can also be estimated in terms of dimension and shear strength using the maximum shear stress failure criterion.
4. Conclusion

The strain analyses of traditional Japanese joints were carried out using the Digital Image Correlation technique. The FEM strain analyses were also conducted in order to supplement the experimental observation.

In both Kama Tsugi and Okkake Daisen Tsugi, parallel to grain shear strain was concentrated near the re-entrant corner of the joints. The degree of shear strain concentration (defined as the ratio of the maximum shear strain to the average shear strain) tended to increase as the length of shear plane increased. This result accounted for the relation between the tensile strength and the shear plane length. The tensile strengths of Kama Tsugi were estimated based on the relation of shear strain concentration and the dimension. A good relation was found between the estimated and measured strengths.

5. References


6. Acknowledgement

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