Experimental Study on the Creep Behaviour of Structural Component of Traditional Wooden Buildings

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Abstract
The purpose of this study is to identify the bending creep behaviour of sawn lumber beam of Japanese Cypress and the compressive creep behaviour of full-size masugumi, which is one of the most important components in old wooden Japanese buildings in terms of both structure and decoration. As the former, practical size sawing (120×240×6000mm) was applied, and bending creep test was carried out for 4 years. As a result, approximate formula for bending creep behaviour was obtained. According to this formula, total deflection after 100 years later is estimated to be about two and a half times as big as initial deflection. As the latter, by using full-size masugumi component, which was modeled on that in national treasure building “Toshodaiji Kondo”, compressive creep test was carried out for 4 years. As a result, approximate formula for compressive creep behaviour was obtained. According to this formula, total compressive deformation after 100 years is estimated to be about five times as big as initial deformation.

Keywords: traditional building construction; bending creep; compressive creep; static loading test; masugumi

1. Introduction
Japan abounds in wooden buildings from the old days, and repair projects for such buildings have been increasing in recent years. Seemingly in response to the situation, studies began to be done on Japanese traditional wooden construction. One of the subjects of these studies is creep, and of particular concern is bending creep. For example, deep eaves of traditional wooden buildings may bend downward considerably owing to the bending creep of rafters or other members. Repair works, therefore, needs to be done carefully for reasons not only of structural safety but also of appearance. Conventional bending creep tests of wooden members often use small-cross-section, defect-free lumber test specimens [2,3,etc.], and according to studies [2-5], the bending creep limit of lumber is usually 40 to 60% of static flexural strength. Tests on full-scale lumber specimens, however, are very rare because of restrictions associated with apparatus requirements, and the relationship between the test results for defect-free small specimens and practical performance is not yet known clearly. In this study, therefore, a bending creep test on a full-scale specimen was conducted over a period of four years, and by using a creep curve equation based on the test results, bending creep was predicted.

In traditional wooden buildings such as temples, shrines and palaces, it is common practice to use eaves-supporting assemblies called “masugumi” consisting of blocks such as “daito”, “houto” and “makito”, and bracket arms such as “hijiki”, on top of columns. These eaves-supporting assemblies are important from both structural and decorative points of view. Structural characteristics of masugumi have become one of the subjects of studies in recent years, and the lateral mechanical behavior of masugumi have been gradually elucidated by the studies, such as the study by Hayashi et al. [6] to investigate the structural characteristics of palatial style frames constructed during the Nara Period (710-784) and the study by Fujita et al. [7] concerning static horizontal loading tests and shaking table tests on specimens modeling typical masugumi found in “Important Cultural Property” buildings. Members constituting masugumi are assembled in the direction perpendicular to the direction of wood fibers. Assemblies of this type are subject to partial compression creep due to sustained vertical force. The partial compression creep is by far larger than the compression creep in the fiber direction, so creep of the former type could seriously affect structural safety. Partial compression creep has
been studied by Sugiyama, who found out that partial compression creep is considerably influenced by temperature and humidity and that only a limited creep recovery can be expected \cite{8, 9}. The study on the compression creep properties of \textit{masugumi} has not been published to date. In this study, compression creep tests of \textit{masugumi} specimens under sustained vertical forces were conducted over a period of four years. On the basis of the test results thus obtained, creep curves were formulated and prediction was made. This paper introduces the creep data collected over a period of four years and contains the validity of the measurement period for creep curve formulation.

2. Bending creep test on Japanese cypress beam

2.1 Test specimens

A 6-m-long 120mm x 240mm timber specimens of Japanese cypress (\textit{Yoshino-Hinoki}) was used in the test. The specimen was a sawn lumber cut out of a 300-mm-diameter log. As shown in Figure 1, six smaller (50mm x 100mm cross section; 1.6 m long) specimens were made from the pieces of wood left after the sawn lumber specimen was cut out, and these specimens were used in a loading test conducted to investigate their Young’s modulus. The surface moisture content of the test specimens just before the loading for creep testing was around 13%.

2.2 Test method

Figure 2 shows the test apparatus and Figure 3 shows the setup for the test. The test specimen on the reinforced concrete base was pin-supported on one side and roller-supported on the other side. In the test, that the maximum extreme fiber stress became equal to the allowable bending stress under sustained loading (8.83 N/mm$^2$). The weights used were composed of two 5m-long steel sheet piles and a small number of plate weights used for adjustment purposes. Displacement of the test specimen at five locations (support points, loading points, midpoint) was measured with displacement transducers installed on the upper part of the specimen. The steel frame to which the displacement transducers were installed was secured to the reinforced concrete base by anchor bolts. Displacement was measured at 30-second intervals for the first one hour, at 15-minute intervals during the first six hours, at one-hour intervals until the end of the first one week, and at intervals of one week to one month thereafter. To investigate the strain during creep deformation, strain gauges were attached to the center of the specimen, and strain measurement was performed concurrently with the displacement measurement until day 35 in the creep test. The loading was performed on June 14, 1996.

The six small test specimens were subjected to midspan concentrated-load testing as shown in Figure 4. In this test, loads were increased only to the allowable stress level for short-term loading, and Young’s modulus in bending was calculated on the basis of the data for the part showing a linear load-deformation relationship. Table 1 shows Young’s modulus of the six specimens.
Table 1. Young’s Modulus of Six Sawn Wood

<table>
<thead>
<tr>
<th>specimen</th>
<th>No. 1</th>
<th>No. 2</th>
<th>No. 3</th>
<th>No. 4</th>
<th>No. 5</th>
<th>No. 6</th>
<th>Eave.</th>
</tr>
</thead>
<tbody>
<tr>
<td>E (MPa)</td>
<td>10699</td>
<td>10111</td>
<td>9434</td>
<td>9012</td>
<td>10297</td>
<td>9542</td>
<td>9849</td>
</tr>
</tbody>
</table>

2.3 Test results

Figure 5 shows measured midspan displacement of the specimen during the test period (1462 days). The figure also shows the temperature and humidity measured concurrently with displacement. Young’s modulus in bending of the specimen calculated from the initial deflection (27.93 mm) is 9640 N/mm², which is roughly equal to the average value of Young’s modulus in bending of the six small specimens of 9849 N/mm². The displacement on day 1462 was 50.75 mm, and the relative creep at that time was 1.82. The maximum displacement during the test period was 51.69 mm on day 1400.

2.4 Prediction of creep deformation

2.4.1 Creep curve equation

The following general formula for the creep deformation of timber is used as a creep curve formula for the bending creep of the full-scale Japanese cypress beam:

\[ \frac{\delta}{\delta_0} = 1 + a / \delta_0 \cdot t^N \]  

where \( \delta \): overall deformation  
\( \delta_0 \): initial deformation  
\( t \): time (days)

where \( a \) and \( N \) are constants. Equation (1) can be rewritten as

\[ \Delta = A + N \cdot T \]  

where \( \Delta = \log (\delta / \delta_0 - 1) \)  
\( A = \log (a / \delta_0) \)  
\( T = \log t \)

Figure 6 shows changes in strain at three midspan locations during the first 35 days. The strain on the compression side and the tension side immediately after the loading was started were roughly equal. During the next five days, strains on the tension side increased, but on day 30 the strain on the compression side and the tension side were roughly equal.

Figure 7 is a logarithmic graph of the test results. The vertical axis represents incremental relative creep \( (\delta / \delta_0 - 1) \) and the horizontal axis represents time. According to Eq. (2), a straight line that intersects the vertical at A and that rises to the right at slope N emerges. In this study, the straight-line part of the graph is extracted, and regression analysis is performed for each section of the line.

The part immediately after loading was excluded, and next two sections were considered:

Section 1: day 0.2 to day 110  
Section 2: day 376 to the end of the test (day 1462)
Table 2 shows the results of the regression analysis for each section. Figure 8 shows the regression line for each section with the test results.

Table 2. Results of the Regression Analysis

<table>
<thead>
<tr>
<th>Part</th>
<th>Period (day)</th>
<th>Number of data</th>
<th>Const. a</th>
<th>Const. N</th>
<th>Correlation coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>①</td>
<td>0.2 ~ 110</td>
<td>354</td>
<td>2.4413</td>
<td>0.38726</td>
<td>0.9976</td>
</tr>
<tr>
<td>②</td>
<td>376 ~ 1462</td>
<td>37</td>
<td>6.6996</td>
<td>0.16913</td>
<td>0.9478</td>
</tr>
</tbody>
</table>

Fig.8. Regression Line for Each Section

If a regression formula is derived on the basis of the measurement results for Section 1, the rate of increase in displacement becomes unrealistically high. The overall deformation during the 10th, 50th and 100th years are calculated on the basis of the regression analysis results for Section 2.

10th year: $\delta_1 = 54.76$ mm (relative creep=1.96)
50th year: $\delta_5 = 63.15$ mm (relative creep=2.26)
100th year: $\delta_{100} = 67.53$ mm (relative creep=2.42)

These analytical results indicate that 75% of the displacement occurring over a period of 100 years is reached in four years after loading is started.

According to the Japanese current design code recommends ($a/\delta_0 = 0.2, N = 0.2$ in Eq.(1)), relative creep after 100 years will be 2.63. This calculated result agrees well with the predicted value obtained by this study.

Generally, the deflection by the bending creep varies according to the loading conditions, member sizes, and so on. Therefore, in order to accurately estimate the long term deflection of a beam, the test results must be analyzed and the effect of parameters on the creep deflection must be defined.

3. Compression creep test

3.1 Test specimen

The test specimen is a full-scale model of a masugumi located on top of a column of the Kondo (Main hall of the temple) of Toshodai-ji Temple (National Treasure), a representative example of masugumi as part of traditional wooden construction. Figure 9 shows the configuration and dimensions of the model. The actual structural frame has a 15 mm-thick circular steel plate between the daito (large bearing block) and the column, so the same construction was used for the model used in the test. The model was built with newly made cypress members. The makito (one-way bearing block), houto (two-way bearing block) and daito (large bearing block) were dowelled (with a cypress dowel), and the dowel under the daito penetrated the square hole (75 x 75 mm) at the center of the circular steel plate. Just before the test, the surface moisture content of each member of masugumi was measured with a high-frequency moisture meter. The average value of several moisture-content measurements of each member ranged from 14 to 22%.

3.2 Test method

Figure 10 shows the test apparatus and Figure 11 shows the setup for the test. The test specimen was placed on a steel base. The arrangement of the dowel under the daito, steel circular plate and wood plugs was the same as the actual construction. Wood plug took place of the top part of column. Actually, houto was placed on the top of specimen (masugumi), therefore in the test, a loading plate was made the same size (210 x 210 mm) as the bottom of the houto. Compressive load was applied by hydraulic jack and spring. While compressive deformation was in progress at a high rate, a constant load was applied by the automatically controlled hydraulic system. The load level (1081 kN) is equivalent to the allowable stress level (2.45 N/mm$^2$) to prevent sinking into the wood surface under sustained loading. The hydraulic system was stopped when it was judged that creep deformation began to increase monotonically and gradually, and the subsequent loading was continued by means of spring reaction alone. When spring reaction decreased with the progress of deformation, the load was increased again by hydraulic jacking and nut tightening.

Fig.9. Full-scale Test Specimen (Masugumi)
Conversely, when spring reaction increased because of the expansion of the test specimen, the load was reduced. Changes in the height (960 mm) of the test specimen were measured in the test. As shown in Figure 12, the ends of the loading plate were extended, and two displacement transducers were installed so as not to interfere with the crossbeam directly above, and the measured values were averaged. The measured values thus obtained were displacements relative to the steel base. Measurement was performed automatically at constant intervals: 30 seconds to one hour immediately after the loading was started, and one day to one week after the progress of deformation became slow. For temperature and humidity measurement during the entire test period, a continuous temperature and humidity recorder was installed near the test specimen.
3.3 Test results

Loading was started on June 27, 2000. Figure 13 shows the measurement results for the four years until June 28, 2004. The figure also shows the daily maximum temperatures and maximum humidities during the test period. The initial displacement was 8.82 mm. On the 493rd day after the loading was started, it was judged that a rapid increase in displacement would no longer occur, and loading by spring reaction was started.

In July, 2004 (around day 370 to day 400), which was one of the warmest months on record, displacement showed marked increases in displacement. It seemed that the moisture content of the members fell sharply during that period, and mechano-sorptive deformation occurred. On around day 650, deformation began to decrease, and on around day 1000, that is, about one year later, a similar decreasing tendency appeared. This is thought to be because of expansion and shrinkage due to temperature and humidity fluctuations. The maximum value of displacement during the four-year period was 40.52 mm recorded on day 1340, and relative creep based on the initial displacement was 4.60.

3.4 Discussion

In general, the relationship between the creep deformation of wood and elapsed time can be expressed by Eq. (1), and for the purposes of discussion in this study, it is assumed that the same relation holds true for partial compression. In Figure 14, the vertical axis represents incremental relative creep \( \frac{d}{d_0} - 1 \) and the horizontal axis represents time \( t \), both of which are shown logarithmically. If Eq. (1) is assumed to hold true, a rightward-rising straight line with a slope of \( N \) should be obtained. In this section, straight-line sections are extracted from the test results, and regression analysis is performed for each section. The part immediately after loading was excluded, and next three sections were remarked:

Section 1: day 10 to 10 weeks
(actual period: day 11 to day 70)

Section 2: 10 weeks to one year
(actual period: day 70 to day 367)

Section 3: 1.5 years to 4 years
(actual period: day 549 to day 1462)

It is thought likely that cyclic changes in deformation due to expansion and shrinkage induced by temperature and humidity fluctuations began on around day 550. The period from the occurrence of mechano-sorptive deformation and day 550 is excluded from the scope of study, assuming that deformation properties during that period are unstable. Assuming that displacement fluctuations due to expansion and shrinkage recur on a cycle of one year, the periods of one year or its integral multiples should be considered in regression analysis. It is therefore assumed that the period for Section 3 is one year, and another section, Section 4, corresponding to a period of two years is considered. Table 3 shows the analytical results for each section, and Figure 15 shows the regression results (straight line) for each section.

<table>
<thead>
<tr>
<th>Part</th>
<th>Period (day)</th>
<th>Number of data</th>
<th>Const. a</th>
<th>Const. N</th>
<th>Correlation coefficient</th>
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</thead>
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<td>0.60424</td>
<td>0.9982</td>
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<tr>
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<td>167</td>
<td>3.1217</td>
<td>0.34079</td>
<td>0.9927</td>
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<td>3</td>
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<td>19.386</td>
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<td>4</td>
<td>549 ~ 1277</td>
<td>105</td>
<td>22.470</td>
<td>0.04043</td>
<td>0.3452</td>
</tr>
</tbody>
</table>
tendency of displacement increase over a period of time long enough to cover displacement fluctuation cycles under the influence of temperature and humidity. Overall displacement $\delta_{100}$ in year 100 is calculated on the basis of the regression analysis results for Section 3 and Section 4.

From the results for Section 3:
$\delta_{100} = 46.10 \text{ mm (relative creep=5.23)}$

From the results for Section 4:
$\delta_{100} = 43.18 \text{ mm (relative creep=4.90)}$

According to these analytical results, about 90% of the displacement that occurs during the first 100 years occurs in the first four years after the loading is started.

According to Sugiyama’s studies, it is confirmed that the relative creep of partial compression of small clear specimen under nearly the same stress level as this study will be over 6. Consequently, the predicted relative creep in the future of masugumi is lower than the test results obtained by Sugiyama’s studies.

4. Conclusion

With the aim of investigating the bending creep properties of beams and the compression creep properties of masugumi used in traditional wooden buildings in Japan, the following tests were conducted:

(1) Bending creep test on full-scale Japanese cypress beam conducted over four years
(2) Constant vertical force compression creep test on a full-scale masugumi conducted over four years

The findings from the above tests can be summarized as follows:

- According to a creep curve equation derived through regression from the results of a bending creep test on Japanese cypress beam conducted over a period long enough to cover temperature and humidity fluctuation cycles, relative creep after 50 years and 100 years is about 2.3 and 2.4, respectively.
- The compression creep deformation of masugumi varies widely depending on temperature and humidity, but relative creep after 100 years calculated from a creep curve equation derived through regression for a period long enough to cover temperature and humidity fluctuation cycles is 5 or so. A compression creep test conducted over a period of one year or so is not enough to store data that enable the determination of the compression creep properties of masugumi.

Acknowledgments

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