Study of strength deterioration of wooden civil structures as a result of aging – A case study of wooden civil structures in Tochigi prefecture, Japan

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Abstract:
Strengths of wooden civil structures of different ages, namely 1, 3, 5, 6, and 9 years, in the Tochigi prefecture, Japan were measured using Pilodyn and FAKOPP. Pilodyn examined the decay by driving a pin into the test object at a constant stress and measuring the intrusive depth. The larger the value of the intrusive depth, the lower is the strength. On the other hand, the stress wave propagation velocity was measured by FAKOPP. A lower stress wave propagation velocity indicated more deterioration. The deterioration of material strength was confirmed by both measurements. Then, the bending strength was estimated using these values and compared with the allowable bending stress calculated from the earth loads on the wooden civil structure. By this method, we found whether the wood materials used for the wooden civil structures have enough strength to be used for more than 10 years.

Keywords: wooden civil structure, strength, Pilodyn, FAKOPP

1 Introduction

In Japan, forest roads are often constructed with wooden civil structures in order to reinforce the slope. The use of wood for slope protection has merits such as obtaining materials from construction sites and, therefore, relatively low construction costs. However, a guide for construction using wood materials has not yet been satisfactorily established, unlike that for concrete, because of wood deterioration. Based on the strength of wooden structures, Iijima (1999) proposed a simple criterion using a Pilodyn, but Kawaguchi and Kobayashi (2003) argued that many wooden structures functioned without problems, even if this criterion is violated. In this study, we measured the strengths of wooden civil structures of different ages, namely 1, 3, 5, 6, and 9 years, in Nikko city, Kanuma city, Shioya town, and the Funyu experimental forest of Utsunomiya University in Tochigi prefecture, Japan and developed a method to predict strength deterioration.

2 Materials and Methods

2.1 Wooden Civil Structures

The wooden civil structures investigated in this study did not undergo antiseptic processing and had been in use for slope protection of forest roads for less than 10 years. Iijima (1999) reported that wooden civil structures without antiseptic processing decay within 6 years of being constructed. However, this period would be enough for vegetation to thrive and begin protecting the slopes of forest roads in place of the decayed wooden civil structures. Thus, we investigated only those wooden civil structures that were less than 10 years old.

Figure 1 shows the standard structures investigated at Nikko city (1 and 5 years old), Kanuma City (1 and 6 years old), and Shioya town (3 and 5 years old). In the standard structure, the girder diameter was 0.18 m and the bar diameter was 0.14 m at the tip. The wooden civil structures investigated in the Funyu experimental forest were 9-year-old fence structures. The average diameter of materials at the tip end was about 0.10 m. The tree species used for these wooden civil structures was Japanese cedar (*Cryptomeria japonica*).

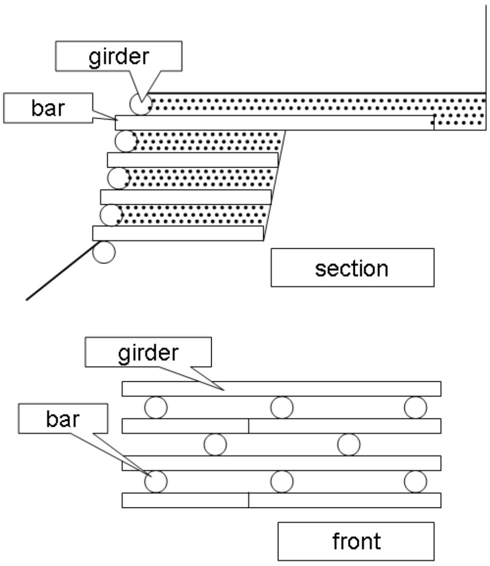

Figure 1: Wooden civil structure

2.2 Methods

The strength of the wooden structures was measured using two kinds of apparatus, i.e., Pilodyn (Figure 2), a pin-driving examination instrument, and FAKOPP (Figure 3), a stress wave propagation velocity measuring instrument. Pilodyn examines the decay by driving a pin into the object at a constant stress and measuring its intrusive depth. The larger the value of the intrusive depth, the lower is the strength. The measurement limit of Pilodyn is 40 mm. FAKOPP measures the stress wave propagation velocity. A lower stress wave propagation velocity indicates more deterioration. However, FAKOPP could not accurately measure the velocity of high water content materials. Therefore, the measurements by FAKOPP were conducted five or more days after rainfall. Pilodyn measurements were conducted three times at the center of the materials and on both sides, 0.50 m away from the center (Figure 4). FAKOPP measurements were conducted six times on both sides, 0.50 m away from the center.

Figure 2: Pilodyn

Figure 3: FAKOPP

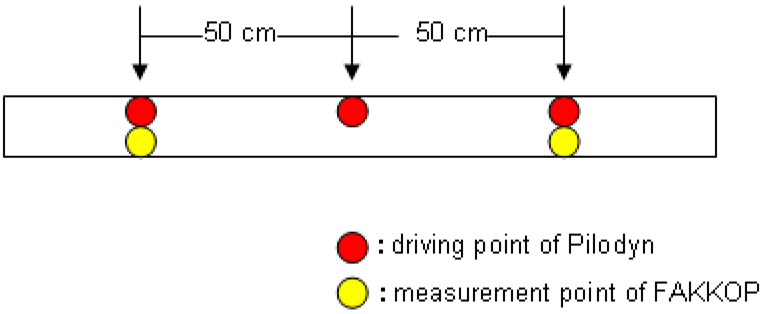

Figure 4: Measurement point on a material

2.3 Prediction of Strength

Bending stresses and deflections were examined to determine the strength. First, the material densities ρ (kg/m^3) were estimated from equation (1) using the Pilodyn's driving depth P_r (mm) (Yamashita et al., 2007).

$$\rho = -9.61 \times P_r \times 564 \qquad (1)$$

The Young's modulus E (Pa) was estimated from equation (2) using the material densities and stress wave propagation velocity V_e (m/s) (Takahashi and Nakayama, 1995).

$$E = \rho \times V_e^2 \qquad (2)$$

The modulus of rupture F_b (N/m^2) was determined from equation (3) using Young's modulus (Ishikawa et al., 2003).

$$F_b = 0.0115 \times E + 10.3 \times 10^6 \qquad (3)$$

The allowable unit stresses for the long term were estimated by multiplying the modulus of rupture by 1.1/3 (Ministry of Internal Affairs and Telecommunications). Then, the bending stresses caused by the earth load were estimated and compared with the allowable unit stresses. The periods when the bending stresses did not exceed the allowable unit stresses were predicted to be the lifetimes of the materials. The bending stresses σ (N/m^2) were estimated from the following equation using the maximum bending moments M (N m) and section modulus Z (m^3).

$$\sigma = M/Z \qquad (4)$$

Maximum bending moments were estimated from the following equation using Terzaghi's earth loads on low retaining walls of roads (Fukuoka, 1968).

$$M = P_H \times (D_a + D_b) \times L^2/8 \qquad (5)$$

where P_H is the horizontal component of the earth load (N/m^2), D_a is the mean diameter of the bar (m), D_b is the mean diameter of the girder (m), and L is the bar interval (m).

$$P_H = K_H \times H^2/2 \qquad (6)$$

where K_H is the coefficient of the horizontal component of the earth load (N/m^4) and H is the height of the road wall (m).

$$Z = \pi \times D_b^3/32 \qquad (7)$$

The deflections were also estimated from the following equation using Terzaghi's earth loads on low retaining walls of roads, assuming that both ends of the girders were fixed.

$$\delta = P_H \times (D_a + D_b) \times L^4/(384EI) \qquad (8)$$

where I is the second moment of the area (m^4) and L is the bar interval (m).

$$I = \pi \times D_b^4/64 \qquad (9)$$

The deflections were adjusted by multiplying the value estimated from equation (8) by 2 for the adjustment of the increasing deflections resulting from a long-term load on the wooden structures (transformation increase coefficient) (Ministry of Land, Infrastructure, Transport and Tourism, 2000). The allowable deflections were estimated to be 0.002 m or less, which was 1/250 of L (0.50 m), and compared with the deflections. The periods when the deflections did not exceed the allowable value were predicted to be the lifetimes of the materials.

D_a (0.14 m), D_b (0.18 m), L (0.50 m), H (1.46 m), and K_H (5.88 kN/m^4) were substituted in these equations as the standard conditions by considering structures constructed in Nikko city, Kanuma city, and Shioya town. D_a (0.08 m) and D_b (0.12 m) were also substituted as other conditions by considering the Funyu experimental forest.

3 Result and Discussion

3.1 Pilodyn and Stress Wave Propagation Velocity

Figures 5 and 6 show the results of the measurements using Pilodyn and those using the stress wave propagation velocity, respectively. The measurement limit of Pilodyn was 40 mm. Some 3-year-old wooden civil structures have reached this limit (Figure 5). Iijima (1999) proposed the criterion for unusable materials to be 35 mm for the Pilodyn measurement values. From the regression equation (Figure 5), the age when the Pilodyn measurement values reached 35 mm was found to be about 6 years. However, there was no decay in the investigated materials even 6 years after construction. On the other hand, the stress wave propagation velocity measured by FAKOPP decreased according to age (Figure 6). Therefore, the deterioration of material strength was confirmed by both measurements.

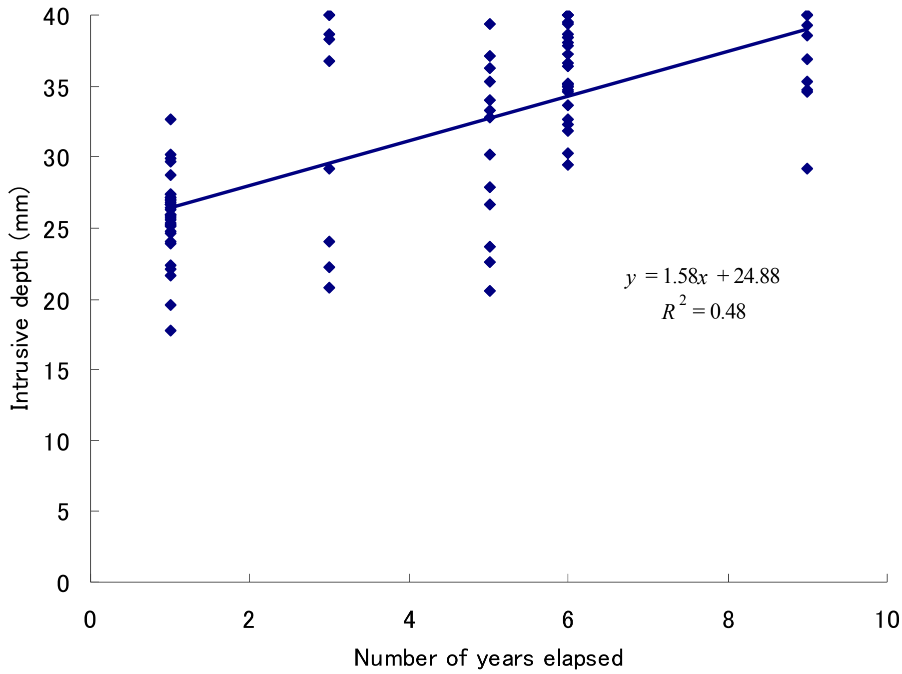

Figure 5: Measurement results using Pilodyn

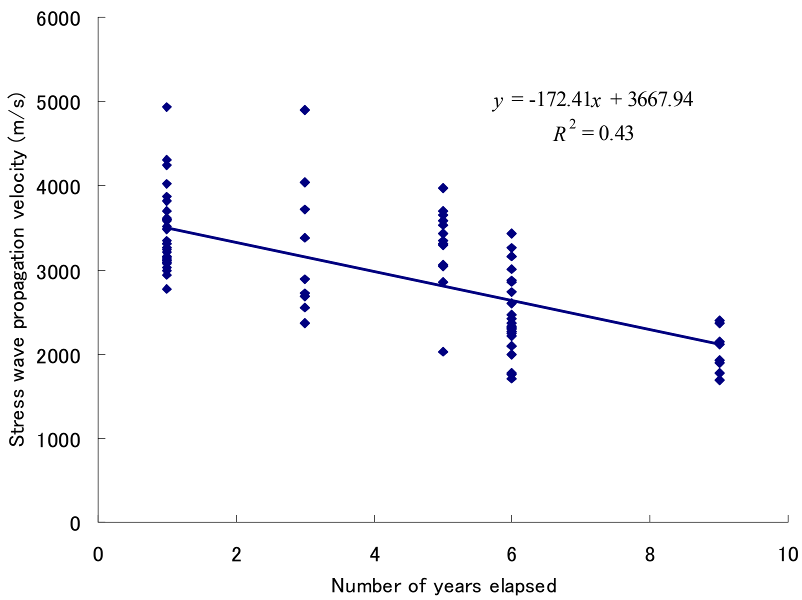

Figure 6: Measurement results using stress wave propagation velocity

3.2 Young's Modulus

The Young's modulus was estimated from equations (1) and (2) (Figure 7). The regression curve was determined using the minimum values of Young's modulus for each year after construction because the minimum values should be used for strength prediction. This regression curve of the Young's modulus was used for the following analyses.

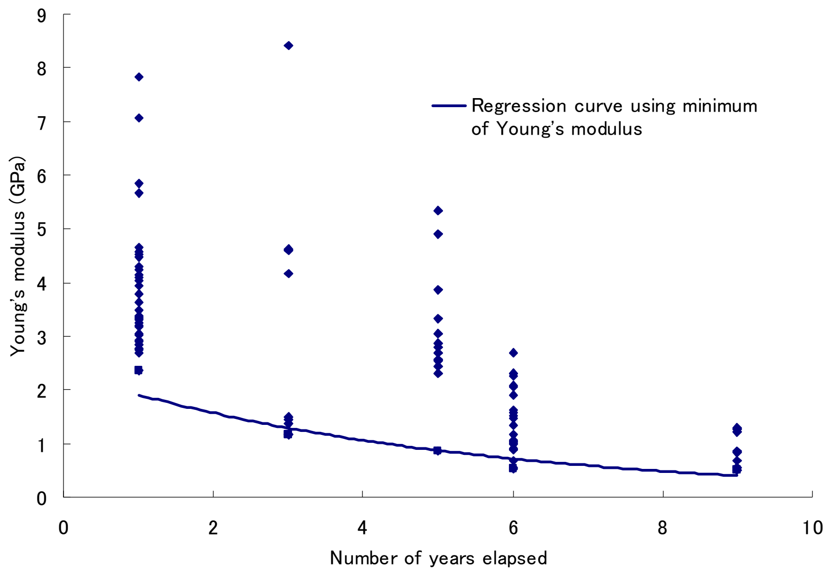

Figure 7: Young's modulus

3.3 Lifetimes of Wooden Civil Structures

Figures 8 and 9 showed the numerical results for the bending stresses and deflections for log diameters of 0.18 m and 0.12 m, respectively. Both the results showed that there is no strength problem for the materials even 10 years after construction, and their lifetimes were predicted to be more than 10 years. Iijima (1999) proposed the lifetime of wood materials to be 6 years. The reason for the difference between the results of this study and those of Iijima (1999) is that Iijima (1999) used only the Pilodyn to predict the lifetime. The Pilodyn measurements were conducted on the sap-wood part, which is subject to decay. This would cause an underestimation of the lifetime. However, the present study also used FAKOPP, which could measure decay of the entire wood, including the heart of the wood, which did not decay. Thus, this study predicted the decay more accurately.

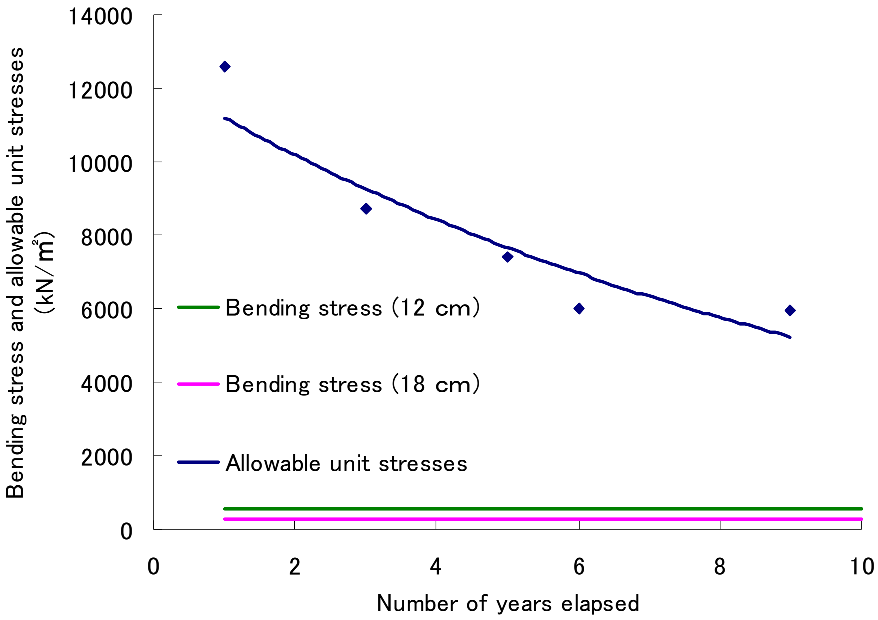

Figure 8: Bending stresses and allowable unit stresses

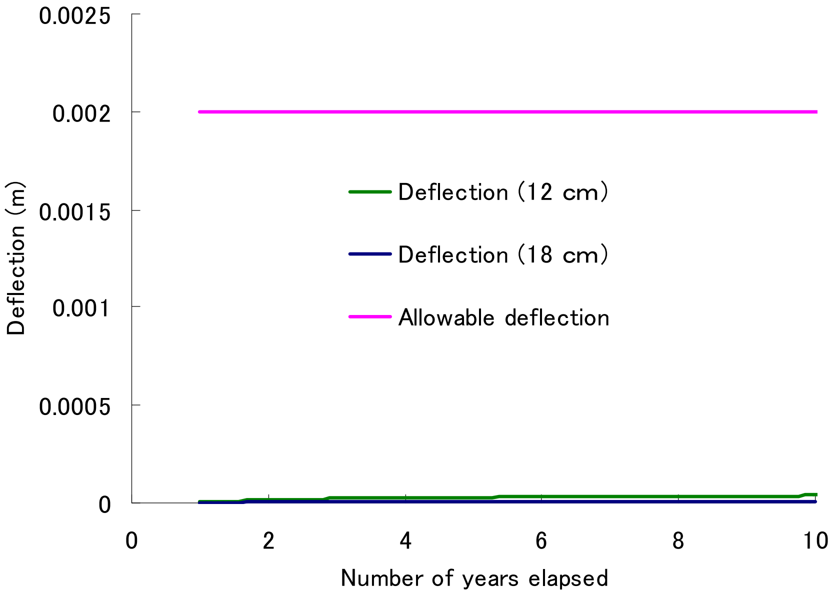

Figure 9: Deflections

4 Conclusions

This study measured the materials strengths of wooden civil structures using Pilodyn and FAKOPP. The deterioration of the entire material could be measured by using FAKOPP in addition to Pilodyn; Pilodyn measured only the external deterioration. This method could predict the lifetime of materials more accurately. The lifetimes of wood materials predicted by this study were considerably longer than those previously predicted (Iijima, 1999).

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*Tentative translations by authors.