World Conference on Timber Engineering
Oslo 2023

PROPOSAL OF A METHOD FOR ESTIMATING THE RESIDUAL STRENGTH FROM THE DEPTH OF PILODYN PENETRATING FOR A CYLINDRICAL MEMBER

Makoto Imai[1], Hironobu Kobayashi[2], Tadashi Hara[3]

ABSTRACT: A method for estimating the residual strength from the depth of Pilodyn penetrating for a cylindrical member (thereafter, Pe) was investigated. Conventionally, a relational expression for estimating the residual strength from the results of Pe and the strength test has been sought. However, it is not always possible to carry out a fracture test, and the residual strength should be theoretically derived from Pe and the like. The defect model by Pe was generally a circular cross-section model based on the average value, but since the decay was not uniform, it was thought that the elliptical model could estimate the residual strength more realistically. We acquired Pe and conducted strength tests on members used outdoors, and verified the fit between the residual strength estimation results based on the elliptical model and the actual strength test results. With this method, it is possible to estimate the residual strength simply by acquiring Pe, and it is expected that it will be easier to determine the renewal time of the structure.

KEYWORDS: Pilodyn penetration, Section modulus, Elliptical approximation, Estimating the residual strength

1 INTRODUCTION

Japan is a hot and humid environment that is unfavorable for wood, which is very different from the dry summer conditions in Northern Europe and Canada [1]. Wood and wood products used outdoors are constantly exposed to wind and rain and wood-rotting fungi in such an environment, and deterioration over time such as decay is inevitable. Aging causes not only a deterioration in appearance, but also a reduction in the strength of materials and joints. As a preventive measure against deterioration, treatment with antiseptic agents, protection using other materials, etc. are performed, but deterioration cannot be completely prevented. Therefore, it is necessary to periodically diagnose deterioration.

Deterioration is generally diagnosed by visual observation or palpation, and if any abnormality is confirmed, secondary diagnosis using dedicated equipment is performed to acquire quantitative data [2]. Dedicated equipment used for secondary diagnosis is mainly non-destructive diagnostic equipment such as FFT Analyzer (Hammering sound frequency analyzer) and FAKOPP (Stress wave measuring device), and micro-destructive diagnostic equipment such as RESISTOGRAPH (Penetration resistance measuring instrument) and Pilodyn (Figure 1).

Pilodyn is a device that ejects a steel pin with a diameter of 3 mm and a length of 40 mm by the force of a spring and measures the depth of the pin driven into wood. This equipment diagnoses deterioration by estimating the density from the obtained penetration depth. Since the density has a high correlation with the bending strength, the method of estimating the residual strength by deriving the relational expression between the Pilodyn penetration depth *Pe* and the bending strength σ by strength test is generally performed [3].

Figure 1: A scene of driving a Pilodyn pin into a pillar

Simply put, when Pe exceeds 30 mm, it is considered to be the service life limit [4], but since Pe is affected by the moisture content [5][6], the evaluation may differ depending on the condition of the material to be driven.

[1] Makoto Imai, Hokkaido Research Organization, Japan, imai-makoto@hro.or.jp
[2] Hironobu Kobayashi, Hokkaido Research Organization, Japan, kobayashi-hironobu@hro.or.jp
[3] Tadashi Hara, Kochi University, Japan, haratd@kochi-u.ac.jp

https://doi.org/10.52202/069179-0120

Since Pe fluctuates depending on the moisture content, it is difficult to judge the initial deterioration from Pe within the range of 30 mm from sound material (approximately 15 mm). The authors are also working on an initial deterioration detection method that applies the preventive design technology of quality engineering (MT system) [7]. Mori et al. [4] regarded the rotten part of the processed material as a defect, and defined the ratio of the sound part other than the defect in the cross-sectional area as the cross-sectional survival rate. As a result of the strength test, it was shown that the relationship between the section survival rate and the bending strength fits well when it is hypothesized that decay progresses uniformly from the outer periphery. Based on this result, the average thickness of the cross-sectional loss due to decay (hereinafter referred to as the defect depths) was estimated from the average *Pe* values at multiple points on the outer circumference, and we devised a method to evaluate the residual strength by calculating the section modulus of the remaining circular cross section from the defect depths (hereinafter referred to as the circular approximation method) (Figure 2).

However, in actual wood, it is thought that decay progresses locally from the part where the efficacy barrier of antiseptic agents is weak, and the hypothesis that "decay progresses uniformly from the outer periphery" does not necessarily hold. Therefore, it is necessary to examine the appropriateness of simply averaging the defect depths. In addition, for structures such as fences, it is important to evaluate the soundness against external forces from outside the plane to prevent overturning. If the defects are concentrated in the direction of the external force, the circular approximation method may give a poor evaluation of the out-of-plane external force, resulting in a dangerous judgment result.

Therefore, we devised a method to calculate the residual strength from *Pe* by assuming that the residual cross section is elliptical rather than circular, and using the section modulus that reflects the anisotropy of the defect (Figure 3). This method is hereinafter referred to as the elliptical approximation method.

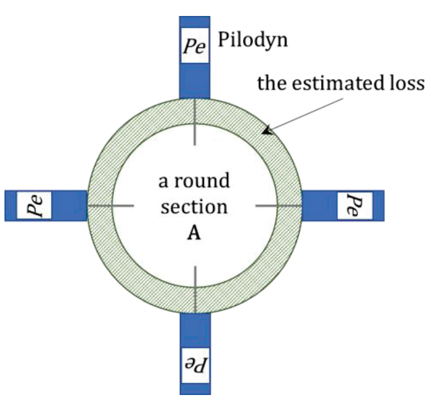

Figure 2: *The method of Mori et al. (Circular approximation)*

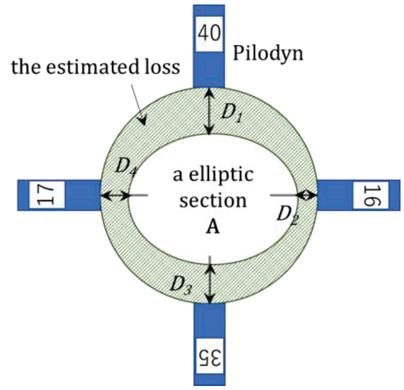

Figure 3: *The new idea of ellipse approximation (Pilodyn values are examples)*

2 SPECIMEN AND TEST METHOD

2.1 OVERVIEW OF THE SPECIMEN

The object of the investigation is a column material (φ150 mm) made of Japanese larch, which has been preserved with antiseptic chemicals for more than 10 years since it was installed as access prevention fences on a high-standard road (Figure 4).

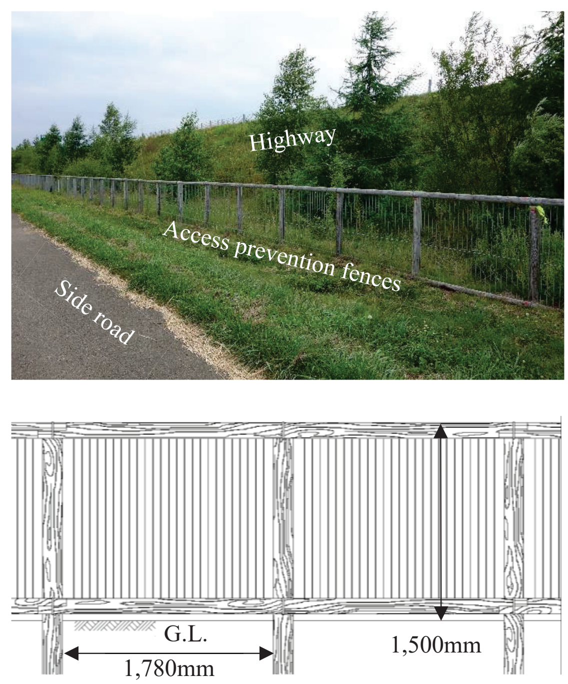

Figure 4: *Access prevention fences on a high-standard road*
Upper: Fences seen from side road, Lower: Fences front view

Two types of bending strength tests were conducted: a full-scale test and a sample test. A full-scale test specimen (n=10) was used for the test with the original cross-sectional dimensions (φ150 mm × 2,900 mm) of the cylindrical material. Sample specimens (n = 307) were prepared by cutting a cylindrical material into rectangular

https://doi.org/10.52202/069179-0120

cross sections of 25 mm × 25 mm × 550 mm. In addition, the samples were taken from the outer part without the heartwood so as to include the rotten part as much as possible (Figure 5).

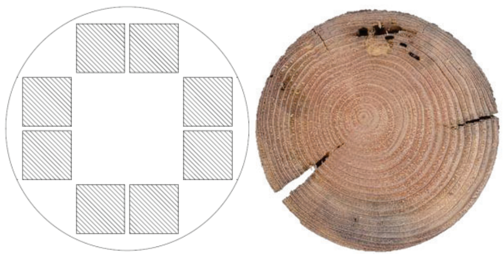

Figure 5: *Image of cutting out sample specimens from a cylindrical material (The shaded area is the sample specimen)*

2.2 BENDING STRENGTH TEST METHOD

The bending strength test was carried out by the trisecting four-point loading method with the bending span set to 18 times the height of the specimen for both the full-scale test and the sample test. In both tests, the decayed surface was taken as the upper surface (Figure 6).

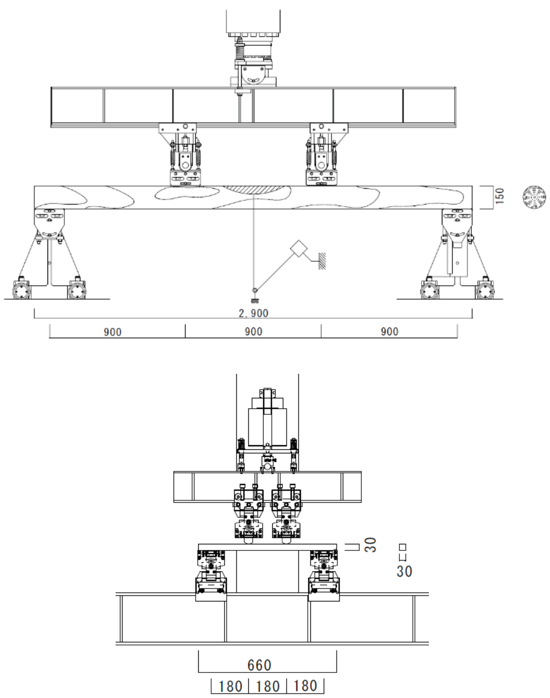

Figure 6: *The trisecting four-point loading method (The shaded area is the decayed area), Upper: full-scale test, Lower: sample test*

For the full-scale test specimen, the presence or absence of decay was visually observed before the test was conducted, and the average *Pe* was calculated from the *Pe* obtained by injecting Pilodyn into four points on the outer periphery of the center of the span.

For the sample specimen, both butt ends were observed before the test, the defect depths *D* due to decay was actually measured (Figure 7), and the section modulus Z_1 was calculated from the remaining cross section. The section modulus reduction rate R_d was calculated from the ratio to the original section modulus Z_0 without defect (Equation(1)).

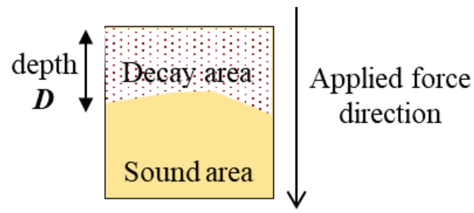

Figure 7: *The cross-sectional defect depth D of the sample specimen*

$$R_d = 1 - \frac{Z_1}{Z_0} \tag{1}$$

The bending strength σ was calculated from the maximum load values P_{max} obtained from the bending test and Z_0. (Equation(2)).

$$\sigma = \frac{aP_{max}}{2Z_0} \tag{2}$$

Here, *a* = Distance between fulcrum to load points.
Considering the average bending strength of specimens without cross-sectional defects as the bending strength of sound material σ_0, the ratio of the bending strengths σ_1 and σ_0 of each specimen with cross-sectional defects was used to calculate the residual rate of bending strength R_σ (Equation(3)).

$$R_\sigma = \frac{\sigma_1}{\sigma_0} \tag{3}$$

Imai et al. [8] obtained *Pe* by penetrating Pilodyn into larch columns. After that, the material was cut at the place where the pin was driven, the defect depths *D* was measured from the cross section (Figure 8), and the relationship between *Pe* and *D* was derived as Equation(4). This indicates that Pilodyn has enough energy to allow the pin to penetrate the sound larch wood by an average thickness of 14.5 mm. It also indicates that the driving depth of the pin increases as the sound portion and density decrease due to decay or the like. In other words, by using this equation, it is possible to estimate the defect depths (degree of decay) at that location from the measured Pilodyn penetration depth.

$$D = 0.94Pe - 14.5 \quad (n = 664, R = 0.946) \tag{4}$$

Using these Equations (1) to (4), a method for estimating residual strength from measured *Pe* is examined.

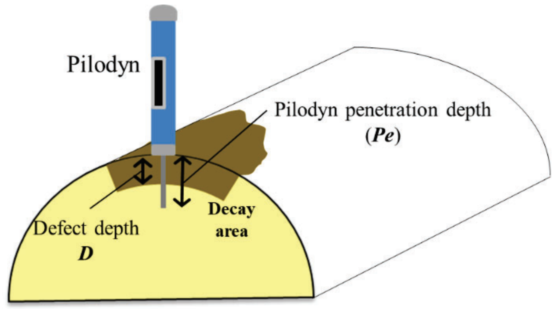

Figure 8: *The defect depth D observed by cutting at the Pilodyn penetration position*

3 VALIDATION OF THE ESTIMATION METHOD

3.1 RELATIONSHIP BETWEEN BENDING STRENGTH AND DRIVING DEPTH OF FULL-SCALE SPECIMEN

As a result of visual observation of full-scale test specimens, decay was confirmed in 5 out of 10 specimens. Table 1 shows the bending test results. The average bending strength σ_d of the 5 specimens with decayed parts is 12.2 N/mm^2 (standard deviation 6.3 N/mm^2), and the average bending strength σ_h of the remaining 5 specimens is 16.1 N/mm^2 (standard deviation 2.4 N/mm^2).

Table 1: *A result of the full-scale specimens bending test*

Specimens	P_{max} (kN)	Bending Strength σ (N/mm^2)
Decay_1	7.6	10.3
Decay_2	14.5	19.7
Decay_3	10.3	14.0
Decay_4	1.9	2.6
Decay_5	10.5	14.2
Ave. (S.D.)	**9.0**	**12.2 (6.3)**
C.V.	**52.0**	**51.6**
Sound_1	12.5	16.9
Sound_2	11.3	15.3
Sound_3	10.1	13.7
Sound_4	10.7	14.5
Sound_5	14.6	19.9
Ave. (S.D.)	**11.8**	**16.1 (2.4)**
C.V.	**15.2**	**14.9**

Table 2 shows the Pilodyn measurement results. Figure 9 shows the relationship between the bending strength σ calculated from the results of the full-scale test and the average value of *Pe*, and the regression equation is shown in Equation(5). A strong correlation was found between σ and the average *Pe* (R = 0.887).

$$\sigma = 125.37e^{-0.146Pe} \quad (R^2 = 0.760,\ P < 0.01) \qquad (5)$$

Table 2: *A result of Pilodyn measurement results*

Specimens	Pe_1 (mm)	Pe_2 (mm)	Pe_3 (mm)	Pe_4 (mm)	***Ave.* (mm)**
Decay_1	12.0	40.0	14.0	17.0	**20.8**
Decay_2	11.0	11.0	13.0	13.0	**12.0**
Decay_3	14.0	13.0	16.0	13.0	**14.0**
Decay_4	40.0	23.0	14.0	11.0	**22.0**
Decay_5	13.0	23.0	16.0	14.0	**16.5**
Sound_1	13.0	15.0	17.0	13.0	**14.5**
Sound_2	13.0	14.0	18.0	13.0	**14.5**
Sound_3	12.0	14.0	14.0	13.0	**13.3**
Sound_4	17.0	15.0	18.0	17.0	**16.8**
Sound_5	12.0	13.0	15.0	11.0	**12.8**

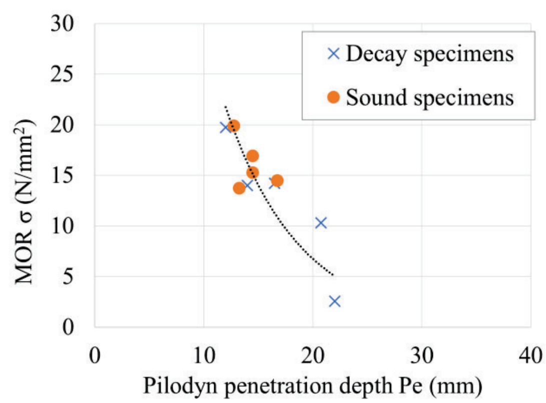

Figure 9: *A relationship between bending strength and Pilodyn penetration depth*

3.2 RELATIONSHIP BETWEEN SECTION MODULUS REDUCTION RATE AND BENDING STRENGTH RETENTION RATE

As a result of observing the butt end of the sample specimen, 224 specimens out of 307 specimens were sound specimens without defects. Table 3 shows the bending test results. The average bending strength σ_0 of the sound body was 56.4 N/mm^2 (standard deviation 12.5 N/mm^2).

The section modulus reduction rate R_d was calculated from the specimen in which defects were observed, and the relationship between the bending strength residual rate R_σ calculated from the bending strength obtained in the test and R_d is shown in Figure 10, and the regression equation is expressed by the Equation(6). A strong negative correlation was observed between R_σ and R_d (R = 0.755).

$$R_\sigma = 1.1015e^{-2.75R_d} \quad (R^2 = 0.565,\ P < 0.01) \qquad (6)$$

https://doi.org/10.52202/069179-0120

Table 3: *A result of the sample specimens bending test*

Specimens	Quantity	Ave. D (mm)	**Ave. σ** (S.D.) (N/mm^2)
Decay	83	3.7	**40.0** (23.3)
Sound	224	0.0	**56.4** (12.5)

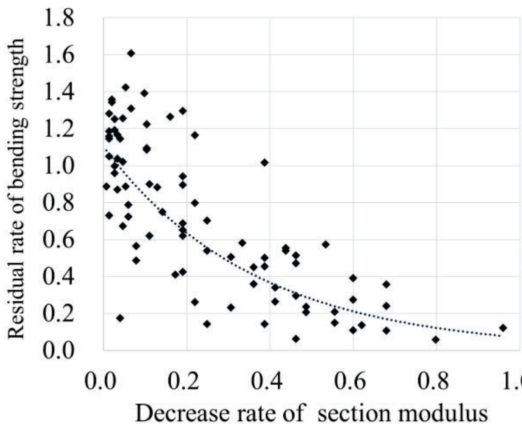

Figure 10: *A relationship between Residual rate of bending strength and decrease rate of section modulus*

3.3 EXAMINATION OF APPROXIMATION METHOD OF RESIDUAL CROSS-SECTIONAL SHAPE

First, Pe_1 to Pe_4 obtained from four points on the circumference of the full-scale specimen were substituted into Equation(4) to estimate the cross-sectional defect depths D_1 to D_4. The section modulus was obtained using the Equation(7) for the circular approximation method and the Equation(8) for the elliptical approximation method, and the section modulus reduction rate was calculated from the Equation(1). R_σ was estimated from the calculated R_d using Equation(6).

$$Z_{\mathrm{CA}} = \frac{\pi(r - D_{\mathrm{ave}})^3}{4} \tag{7}$$

$$Z_{\mathrm{EA}} = \frac{\pi(2r - D_1 - D_3)(2r - D_2 - D_4)^2}{32} \tag{8}$$

Here, r = original cross-sectional radius of the cylindrical material, D_{ave} = average value of D_1 to D_4, D_1 and D_3 are cross-sectional defect depths in the width direction, and D_2 and D_4 are cross-sectional defect depths in the external force direction.

Using the average bending strength σ_h of sound materials, the initial strength σ_0 is assumed to be 16.1 N/mm^2, and the estimated R_σ is substituted into Equation(3) to estimate the bending strength (remaining strength). Figure 11 shows the relationship between the estimated residual strength and the residual strength obtained from the full-scale strength test.

If the circular approximation plot is higher than the elliptical approximation plot, it means that the circular approximation method underestimates the effects of decay. 6 out of 10 specimens corresponded to this, but the remaining 2 out of 4 specimens were clearly underestimated by the elliptical approximation method rather than by the circular approximation method. In the elliptical approximation method, the major axis of the ellipse is in the direction of less decay, and the minor axis is in the direction of more decay, but there are cases in which there is less decay in the direction of applied force. In other words, it is thought that decay was concentrated in the areas perpendicular to the direction of the applied force in these two bodies, and it was found that the elliptical approximation method does not always result in a safer evaluation than the circular approximation method. In addition, almost all approximation methods lead the residual strength from Pe, but the estimated value exceeded the measured value. This is because, in the case of cylindrical timbers with heartwood, unlike rectangular sample specimens with small cross-sections, there are areas with high strength on the outside (mature timbers, etc.) [9]. In this case, it is considered that the reduction in strength is greater than the defect thickness estimated from Equation(4).

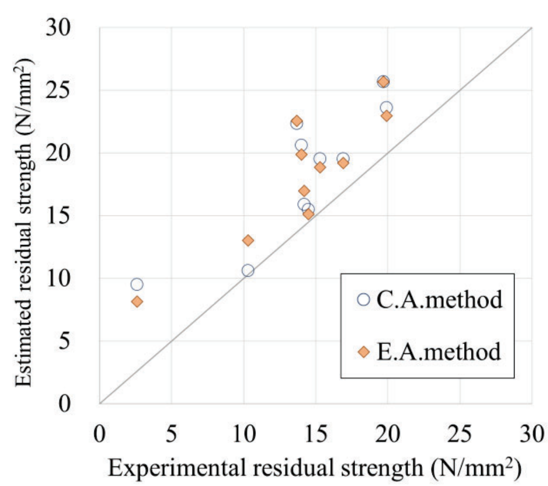

Figure 11: *A relationship between estimated residual strength and experimental residual strength*

4 CONCLUSION

The proposed method for estimating the residual strength by elliptical approximation of the residual cross section is to calculate the section modulus appropriately from the defect depths estimated by driving Pilodyn, considering the direction of the external force applied to the structure, and to calculate the residual strength against the external force. It is a method to estimate the intensity, and it was found that it is possible to make a sufficient estimation. In this test, the number of subjects was limited to 10, so it was not possible to fully confirm the merits of the elliptical approximation method. However, it is clear that it is a residual strength estimation technique that takes into consideration.

In the future, we would like to recommend the elliptical approximation method by proving the usefulness of the method through the enrichment of empirical data.

We are also considering applying this method to a diagnostic method at the field level. The elliptical approximation method requires calculation of the section modulus once, and is not suitable for diagnosing the state of deterioration immediately on site. Therefore, it is considered preferable to utilize *Pe* directly as a diagnostic parameter while maintaining the concept of the elliptical approximation method, that is, the concept of section modulus. In other words, this is a method of giving weight to *Pe* in the direction of force application for evaluation. For example, *Pe* in the applied direction is squared, and Pe in the orthogonal direction is treated as it is.

If it is possible to derive the relationship between the value calculated by this method and the state of deterioration (for example, residual bending strength, etc.), it will be possible to diagnose the state of deterioration without complicated calculations even at the site level.

ACKNOWLEDGEMENT

This research was carried out by the 2016-2018 Hokkaido Research Organization Priority Research and 2022-2023 Ordinary Research. We received cooperation from the Performance Department of the Forest Products Research Institute and research support staff in preparing sample specimens and assisting in bending tests. I would like to take this opportunity to express my deep gratitude.

In addition, Mr. Kasama, Researcher of the Regional Landscape Unit of the Civil Engineering Research Institute for Cold Region, provided valuable advice on the provision of the site, the provision of the full-scale test specimen, and the construction method. Thank you from the bottom of my heart.

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https://doi.org/10.52202/069179-0120