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Research Article

Residual Life Prediction of Ancient Timber Components Based on Cumulative Damage Model: a Literature Review

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Abstract: Ancient timber structure is a common cultural heritage of mankind. How to be aware of the current working performance, make accurate maintenance plan and evaluate its residual life has became a common concern of the academic circles. This paper is a literature review of the development of cumulative damage models and the combination of these models and residual life prediction of ancient timber structures. Wood's experimental data (1951) showed that the mechanical property of timber would decreases over time. Gerhards (1979) proposed the cumulative damage model of da/dt=exp(-a+bσ(t)/σs) that had been widely used around the world. During the last 30 years, the direction of research was more focused on the effects of environment based on the previous experimental data. Most of the research did not take it into consideration that the σs in Gerhards's model is not invariable, it will decrease over time like the description in Madison curve. And it is advised to perform a much more accurate and detailed test for current research.

Keywords: Residual life, Ancient timber component, Cumulative damage model, Load duration

INTRODUCTION

China has a long history, during the past five thousand years, timber structure has been the main form of structures and a symbol of the wisdom and hardworking of our ancestor. Timber structure has been widely used because of the following advantages: timber is a kind of material which is convenient to obtain, it has good mechanical properties and outstanding seismic performance. There are many ancient architectures has experienced both environment and human destruction thousands of years and survive. Not only benefit from the form of the structure and carefully renovation, but also the specialty of timber as a kind of biological materials which has unusual properties. Nowadays, how to be aware of its current working performance, make accurate maintenance plan and evaluate its residual life reasonably has become a common concern of the academic circles. This paper is a literature review of the development of cumulative damage models and the combination of these models and residual life prediction of ancient timber structures.

EXPERIMENTAL STUDY ON CREEP RUPUTURE OF TIMBER

The Madison curve

The earliest studies of timber's cumulative model was the study of creep rupture of load-duration phenomenon began in the 1950s. In 1951, Wood [1] published a report on the relationship between the bending strength and load duration of Douglas fir. Wood's experimental study was began in 1943 and lasted 8 years. The longest loading time of a single specimen was more than 5 years. As a comparison, Wood's tests were divided into two parts: a long-term loading test and a rapid loading test. In the long-term loading test, the standard static-bending test of about 5 minutes was first performed and this load was set as the standard load. Then, 126 specimens divided into 6% and 12% moisture content levels, respectively, were subjected to constant load ranging from 60% to 95% of the standard load. The failure time of each specimens was ranging from 6 minutes to more than 5 years. Unlike the long-term loading test, the rapid loading test was loaded with a fixed rate until the specimens were destroyed. Then the failure time was recording ranging from 1 second to 100 sec. The experimental bending strength of the testing specimens was 0% to 40% higher than the standard one. In addition, there was a compared test of impact loading. It was found that when the failure time was 0.015 seconds, the experimental bending strength of the specimen was 75% higher the standard strength.

The original intention of this study was to explore the design strength of the timber structure with different designing life. It is found that the bending strength of the long-term loading specimens is much lower than that of the specimens under standard tests. Wood then integrates the results of the two sets of experiments and obtain the curve shown in Figure 1

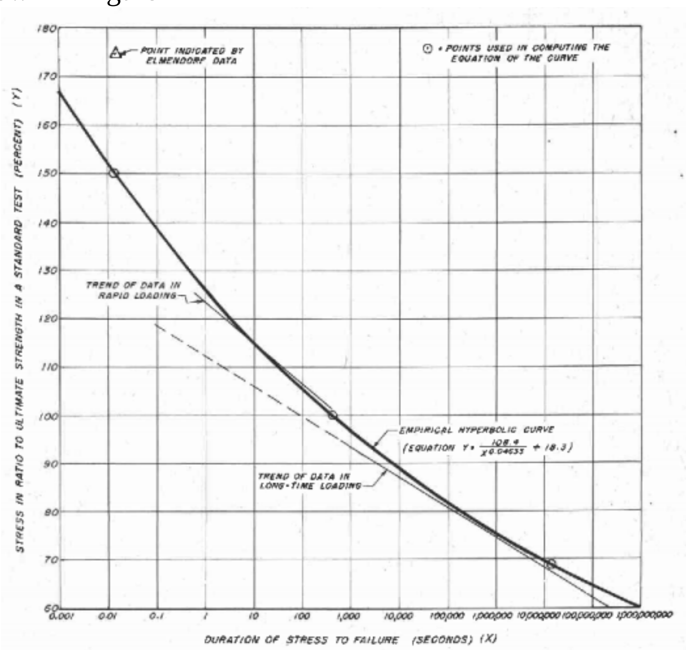

Figure 1: Madison curve

As it was shown in Figure 1, the bending strength of the specimens obtained by the rapid loading tests were higher than that of the long-term loading tests. The expression of the fitting curve is shown in equation (1), which is also called the Madison curve.

$$\gamma = \frac{108.4}{x^{0.04635}} + 18.3 \quad (1)$$

Based on the experimental results, Wood proposed the earliest cumulative damage model, as in formula (2):

$$\frac{d\alpha}{dt} = A(\tau - \tau_0)^B \quad (2)$$

In the formula, τ is the ratio of the applied loads divided by the short term ultimate stress; τ_0 is a threshold below which the damage is assumed not to accumulate.

Barrett and Foschi (1978) used the experimental data of Wood’s, and proposed two kinds of cumulative damage model [2], as shown in the following formula (3) and (4):

$$\frac{d\alpha}{dt} = a(\sigma - \sigma_0)^b a^c \qquad \sigma > \sigma_0 \tag{3}$$
$$\frac{d\alpha}{dt} = 0 \qquad \sigma > \sigma_0$$

$$\frac{d\alpha}{dt} = a(\sigma - \sigma_0)^b + \lambda\alpha \qquad \sigma > \sigma_0 \tag{4}$$
$$\frac{d\alpha}{dt} = 0 \qquad \sigma > \sigma_0$$

α is the damage state variable defined as zero in the undamaged state and unity at failure; σ is the applied load and $\sigma 0$ is a threshold stress below which the damage rate is zero; λ, a, b, c are constants based on the experimental data.

Gerhard's Cumulative Damage Model

From 1963 to 1974, Gerhards researched the strength of Hawaiian eucalyptus, white fir, Nepal alder, Western hemlock, black eucalyptus and southern pine[3]~[8]. And then he proposed the Gerhards cumulative damage model [9], as in formula (5)

$$\frac{d\alpha}{dt} = exp[-a + b\frac{\sigma(t)}{\sigma_s}] \tag{5}$$

α is the same as in formula (4); σ_S is the static strength; $\sigma(t)$ is the applied load; a and b are constants.

In 1987, Gerhards conducted a further study of the model, he analyzed the effects of different ramp loads and constant loads on the damage model [10], and then discussed the parameters [11]. Gerhards has a wide range of research on the properties of timber, his cumulative damage model has been widely used by academics, and many studies have been improved on the basis of his cumulative damage model.

ENVIRONMENTAL EFFECTS ON CUMULATIVE DAMAGE MODEL

Effect of temperature and moisture content

Timber is exposed to the environment in the practical application. Its performance is affected by the ambient temperature and humidity, fungal corrosion, termite erosion and other environmental factors. The environmental impact was not considered to be in the cumulative damage model until 1990s.

Schniewind considered the cycle environmental impact of timber structure, he found that the environmental factors did shortened the failure time of timber under constant load [12]. Then, based on Gerhards cumulative damage model, Fridley (1989~1991) improved the model under different constant temperature, cycle temperature and different relative humidity [13]~[15], and proposed the following formulas (6)~(8)

$$\frac{d\alpha}{dt} = exp[-A + B\sigma + C(\tau - 1)] \tag{6}$$

is the ratio of the actual temperature divided by the standard temperature as in the test; A, B, and C are parameters based on the test

$$\Delta\alpha_i = \frac{1}{Ck_r}\{exp[-A + B\sigma + Ck_\tau\Delta t_i] - \exp[-A + B\sigma]\} \quad (7)$$

$$\alpha(t) = \sum_{i=1}^{m} \Delta\alpha_i$$

k_r is the rate of the changing temperature in one cycle. Other parameters are the same with formula (6)

$$\frac{d\alpha}{dt} = exp(-A + B\sigma + C\omega + D\omega^2) \quad (8)$$

$$\omega = (M - M_0)/M_0$$

M is for the actual moisture content of timber; $M0$ is the standard moisture content as in the test; Other parameters are the same with formula (6)

Effect of Fungi

The effects of fungi were mainly on reducing the strength and the effective cross section of timber, and this study was carried out first by Liese and Stamer in 1943 as shown in Figure 2. It shows the strength of timber that had different species of fungi was changing over time.

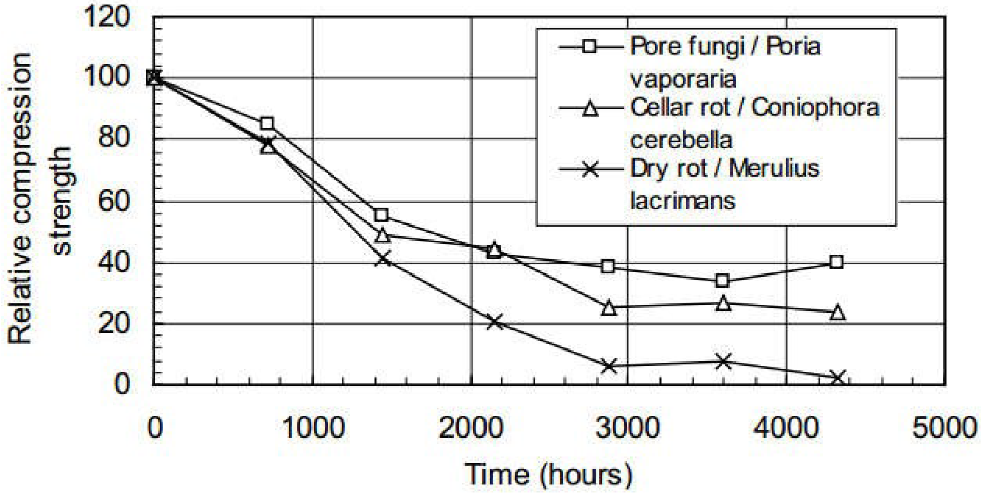

Figure 2: The strength of timber changing over time under the effect of fungi

Kuilen considered the reduction of the cross section of the timber and the reduction of the strength of σ_S in Gerhards cumulative damage model[16][17]. σ_S will reduce over time, as shown in formula (9)

$$F_u(t) = f_{c,0}A_{rem} + f_{c,0,dec}A_{dec} \quad (9)$$

$Fc,0$ is the initial compressive strength of timber; $Fc,0,dec$ is the compressive strength for the decayed part; $Arem$ is the area of the effective cross section and $Adec$ is the decayed cross sectional area.

TIMBER'S STRENGTH UNDER LONG-TERM LOADING IN CHINESE CODE

Chinese code [18] [19] describe the strength of timber under long time loading with Long-term Strength, as in Figure (3).

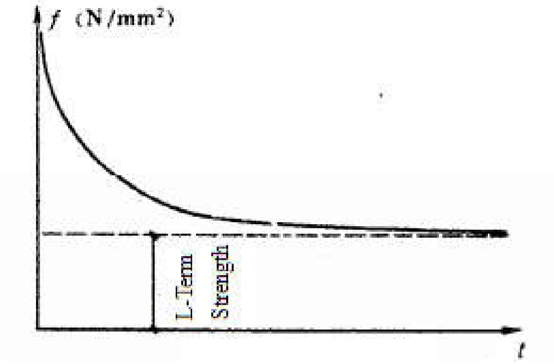

Figure 3: Long-term Strength in Chinese code

The ratio of the Long-term Strength and the impact strength of the timber varies depending on the species and mechanical properties of different kind of trees. The general values are shown in Table 1.

Table 1. The general value of Long-term (parallel-to-grain) Strength in Chinese code

Compressive strength	0.5~0.9	Tensile strength	0.5
Bending strength	0.5~0.64	Shearing strength	0.5~0.55

As an example, Chinese code gives the relationship between strength and time of pine in Table 2. The impact strength is measured under impact load.

Table 2. Relationship between strength and time (parallel-to-grain)

Strength type	Impact Strength (%)	The percentage of impact strength under the following days				
		1	10	100	1000	10000
Compressive	100	78.5	72.5	66.2	60.2	54.2
Bending	100	78.6	72.6	66.8	60.9	55.0
Shearing	100	73.2	66.0	58.5	51.2	43.8

With different designing life, the designing strength has been adjusted as in Table 3.

Table 3. Adjustment coefficient of the designing strength of timber arranging from the flowing years

Designing service life (Years)	Adjustment coefficient	
	Strength values	Modulus of elasticity
5	1.1	1.1
25	1.05	1.05
50	1.0	1.0
100 and above	0.9	0.9

CONCLUSION

- The earliest studies of cumulative damage model were based on experimental data. Wood's and Gerhards's experimental data made a great contribution to the studies of this researching area. Until now, part of the studies are still based on their data.
- During the last 30 years, especially after 2000, the direction of research is more focused on the effects of environment, such as temperature and humidity, fungal corrosion, termite erosion and other environmental factors. How to simulate the damage process of timber under environmental

effect accounted for a large proportion.

- Although the consideration of environmental effect has been comprehensive, there are still aspect should be taken into consideration. For example, the $F_{c,0}$ in formula (7) is not invariable, it will decrease over time like the description in Madison curve. So the value of $f_u(t)$ in formula (7) is not conservative.
- Experimental research should be performed. The experimental data from Wood or Gerhards that has been widely used has been long ago. It is necessary to perform a much more accurate and detailed test for the current research of cumulative damage model.

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