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Studies on Prediction about Behavior of Wood Beam under Standard Fire Condition*1

Lee-Gun Kim*2 · Jun-Jae Lee*2

標準火焰 露出時 木材 보의 擧動 豫測에 關한 硏究*1

金 利 建*2 · 李 銓 濟*2

要 約

본 연구는 화염에 노출된 목재 부재의 거동에 관련된 자료를 얻기 위해 수행되었다. 목재 보에 대한 현행 내화 모델들은 외곽부 섬유의 MOE나 휨강도의 감소, 그리고 화염노출의 계속으로 인한 단면의 감소 등에 기초하고 있다. 하지만 이런 모델들은 정확한 거동 예측이 힘들다. 따라서 목재 보의 거동을 정확히 예측하기 위해 본 연구에서는 변형 단면을 이용한 내화거동 모델을 개발하고자 하였다.

이 변형 단면모델을 개발하기 위하여 온도분포, 온도와 목재의 물리적 성질간의 상관관계를 이용하였다. 본 연구를 통해 온도와 목재의 휨성질간의 정확한 관계가 제공되기만 한다면 본 방법이 화염에 노출된 목재 보의 변형을 잘 예측할 수 있음을 알 수 있었다.

Keywords : Fire endurance model, transformed cross-section, flame

1. INTRODUCTION

In spite of increasing of the amount of wood as structural members, only a few researches about fire endurance have been processed in Korea and the properties of wood on fire are rarely understood. It means that if wood members are used in bearing parts, the assemblies or the structures are considered weak with the concepts of combustible material. The wood has very small coefficients of heat transfer and thermal expansion. Moreover, the charred layer can decrease the charring rate. As these reasons, wood structures have a good performance on fire.

There are two methods to enhance the performance of wood structure. The first is surface coverage of the noncombustible materials to protect members from the direct fire exposure. The second is the limitation for the use of wood members with the fire endurance performance(Shaffer, 1977). The performance is expressed with the term, endurance time. It means the time to rescue people or to admit fire fighter working during fire.

Several years ago, the only method for

*1 접수 1995년 4월 6일 Received April 6, 1995
*2 서울대학교 농업생명과학대학 College of Agriculture and Life Sciences, Seoul National University, Suwon 441-744, Korea

obtaining code acceptance of an assembly was to conduct a fire test using verification agencies. Today, however, code authorities have increasingly accepted engineering analyses. Therefore, the fire researches have concentrated on developing the models for determining the fire endurance ratings of wood members and assemblies.

However, the most of them can not consider the weakening of uncharred part at high temperature. In addition, they can not consider the rounding effect, because these analyses assume the cross section of beam as rectangle(Shaffer, 1984 ; White, 1988). Because of these reasons, a precise section analysis method is necessary in order to develop a precise model.

The effect of temperature on wood properties was defined to obtain the transformed section. It was reported that dynamic MOE values were completely unaffected by temperature(Knudson, 1974). According to the previous report(Preusser, 1968), 90% of initial MOE remained at 160 , and the thermal effect coefficient increased up to 255. Hearmon *et al.*(1948) reported that MOE decreased with -0.0050 / , as the thermal effect coefficient. That is, as temperature of 1 ℃ elevates, 0.5% of MOE decrease. Knudson *et al.*(1974) reported that the thermal effect coefficient was -0.0026 / between temperature and tensile strength.

Moisture contents(MC) is also another important factor on mechanical properties. Thus, it was necessary to be considered. It was reported that the surface is dried rapidly, but MC of inner part increase slightly. Therefore, most of the uncharred section maintained the initial M.C. condition(Shaffer, 1977). According to the results, only the temperature effect was considered and M.C. could be neglected in this study.

The method, which can calculate the transformed section based upon the existing relationships among temperature and MOE, and experimental temperature data was developed. To verify the method, the predictions were compared with actual fire test deflection data. If the behavior of wood beam can be predicted precisely with the method, it can be used for the fire endurance time model, and can use the material efficiently.

2. MATERIALS & METHODS

2.1 Materials

Test specimens were prepared from air-dry Douglas-fir lumbers having 0.53 of specific gravity and 15.08% of M.C.. The MOE of the specimens yielded a mean value of 105,400 kgf/cm^2 and standard deviation of 2,700kgf/cm^2. The corresponding values for MOR were 850 kgf/cm^2 and 138kgf/cm^2.

Seven pairs of lumbers were laminated with glue, as a result, seven beams were prepared with 6 by 10 cm cross sections. The phenolic adhesive was used for laminating. These beams were exposed to standard fire condition.

2.2 Experimental Methods

The furnace of the Fire Insurers Laboratories of Korea was used for the standard fire exposure condition. It was designed with floor area, 320 by 400 cm, and to measure the temperature of inner part.

To measure the temperature of the cross sec-

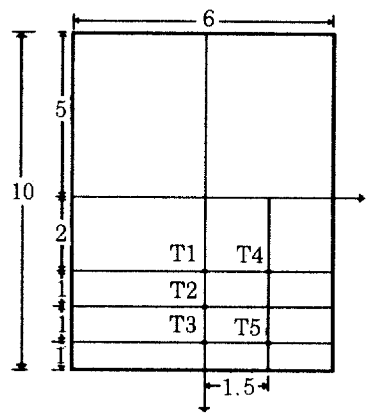

Fig. 1. The equipment of the test.

tion, thermocouples with the accuracy of ±1℃ were used. The deflections were measured with the deflectometers with the accuracy of ± 1℃ mm.

The exposure condition was controlled by the time-temperature curve specified in ASTM E 119 (1988), and the four sides of the beams were exposed to fire. Fig. 1 shows the test assembly, and there is a comparison of the time-temperature curve and the actual furnace temperature in Fig. 2.

The furnace was covered with the fireproof concrete blocks and the beams were laid between the blocks. The exposure condition was

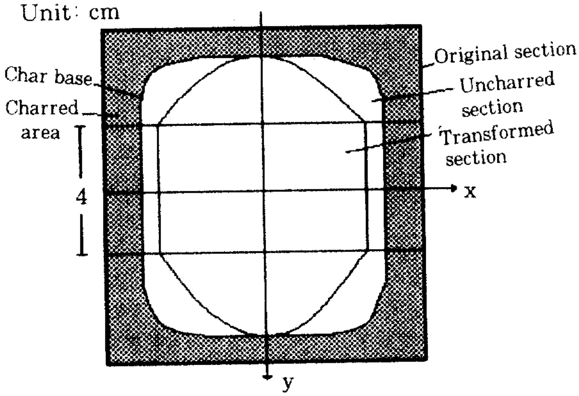

Fig. 2. Time-Temperature curve of the Furnace.

kept for 30 minutes. Two types of weights, 50 and 80kgf, were loaded on the center of the beam span. Each loading condition was repeated three times. The 80kgf loading condition was designed as 90% of allowable stress approximately(NDS, 1991). The deflection was measured per each minute at the center of the beam span. To measure the temperature of cross section, the thermocouples were installed on the locations which shown in Fig. 3

2.3 Transformed Section

The transformed section assumed in this study was based upon the elastic transformed section analysis. To obtain it, weakening by high temperature was changed into the shortening of width. It means that the decreasing of mechanical properties could be expressed by the reduction of width. Therefore, the transformed section was smaller than uncharred section, and its MOR and MOE could be assumed as same that the value at room temperature.

2.3.1 Transformed Width

Inserting the thermal effect coefficients to the time-temperature regression equations measured at each thermocouple location(Fig.

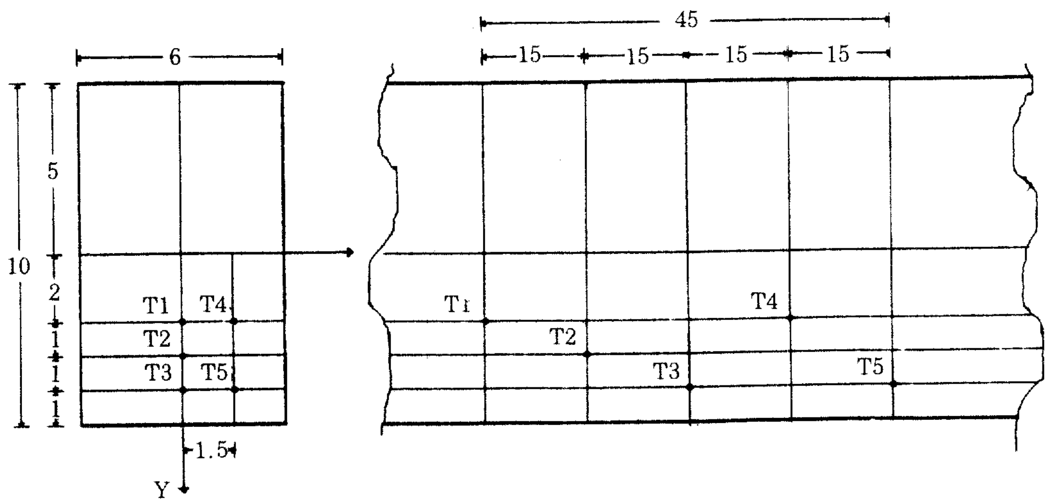

Fig .3. Illustration of thermocouple location(unit: cm).

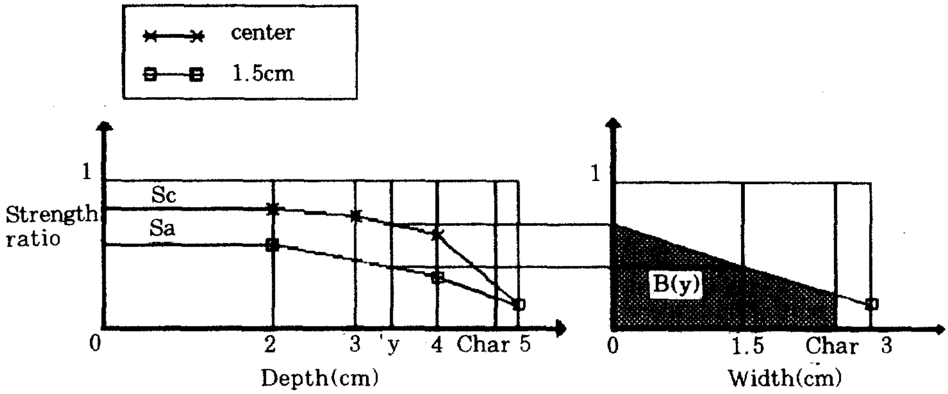

Fig. 4. Distribution for relative stiffness and transformed width.

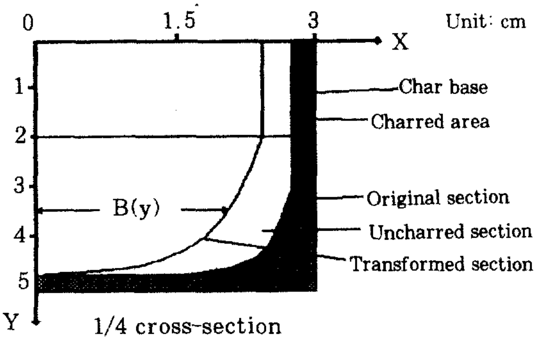

Fig. 5. Width of transformed section.

3), the equations of relative MOE and MOR were obtained, respectively. Their general form was :

$$R_i = a_i \quad t + 1 \quad \cdots\cdots (1)$$

where, R: Relative MOE or MOR as fraction of room temperature value
a : Slope of strength reduction
t : Time
i : Locations of thermocouples(1,2,..,5)

Equation (1) means relative MOE or MOR at arbitrary time, t, and at arbitrary thermocouple location, i. If the relative values at the adjacent thermocouples were connected by linear equation, distribution of the relative MOE or MOR could be obtained, as shown in Fig.4.

In Fig. 4(a), the horizontal axis indicates the depth of quarter of section and the vertical indicates relative value. The horizontal axis of (b) indicates the width of quarter of section. Assuming that Sc(t) is the line which connects three relative values of the center thermocouple locations, and Sa(t) is the line which connects two relative values of others, Sc(t′,y′) and Sa(t′,y′) could be determined at arbitrary time, t′ and depth, y′. Consequently, the area of the polygon, B(y) which is defined by three points, Sa, Sc and R(288), relative value at charring point means the half width of transformed section, shown as Fig. 5.

2.3.2 Area and Inertia Moment of transformed section

Because B(y) means the transformed width of quarter section, the area of transformed section can be calculated by integration. The range of integration is from center to char base. Since the result is for quarter section, it has to be multiplied by 4. The equation can be expressed as follows :

$$A(t) = 4 \cdot \int_0^{D_0 - Ct} B(t,\ y)\ dy \quad \cdots\cdots (2)$$

where,

B(t, y): Width of transformed section as a function of depth and time.

$A(t)$: Area of transformed section as a function of time.

D_0 : Original depth.

C : Charring rate.

t : time.

The inertia moment can be calculated by the same way. The equation can be expressed (Merian, 1986 ; Timoshenko, 1968) :

$$I_x(t) = 4 \cdot \int_0^{D_0 - Ct} y^2 \, B(t, y) \, dy \quad \cdots\cdots (3)$$

where, $I_x(t)$: Inertia moment.

It was used as charring rate of 0.051㎜/min (Schaffer, 1977). The integration was solved by PC mathematical package, Matlab. Where, the length of the strip, dy, was 0.1 ㎜.

2.3.3 Prediction of Deflection

The equation of deflection of simply supported beam under center loading is :

$$\delta = \frac{Pl^3}{48IE} \quad \cdots\cdots (4)$$

where,

δ : Maximum deflection at center of beam.

P : Concentrated load.

l : Span.

I : Inertia moment of transformed cross-section as a function of time.

E : Modulus of elasticity.

Shear contribution to deflection was neglected. The relationship between deflection and exposure time was calculated by inserting the inertia moments. It was demonstrated by comparison with the experimental data.

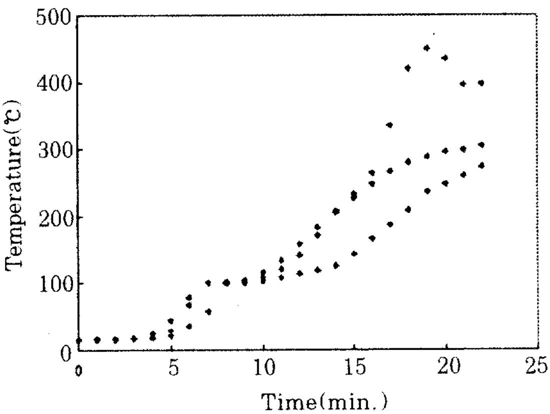

Fig. 6. Temperature data obtained from thermocouple location T4.

3. RESULTS & DISCUSSION

3.1 Temperature Distribution

The relationship between exposure time and section temperature obtained from the thermocouple locations, T4 in Fig. 3, was shown in Fig. 6. The relationship from T4 was most typical. Seeing Fig. 6, the relationships could be divided to 4 different stages : 1st stage has the gradual stage, 2nd stage has steep slope, 3rd

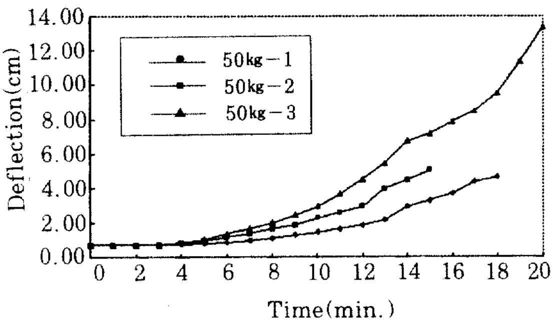

Fig. 7. Relationship between deflection and exposure time for concentrated load 50㎏.

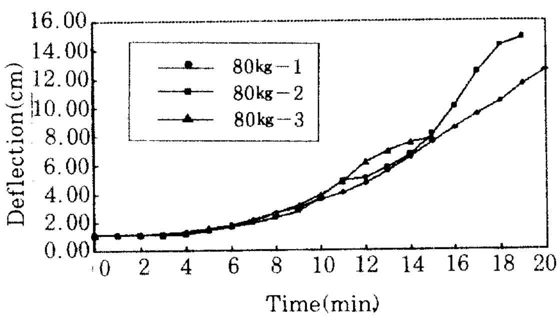

Fig. 8. Relationship between deflection and exposure time for concentrated load 80㎏.

Table 1. Slopes of temperature increase at each locations.

Location	Section*1	Time(min.)	Slope	R^2
T1	1	0~ 6	0.381	0.38
	2	~15	12.657	0.85
	3	~30	2.749	0.19
T2	1	0~ 6	0.476	0.48
	2	~11	17.114	0.88
	3	~30	2.816	0.48
T3	1	0~ 5	1.800	0.58
	2	~ 7	36.333	0.87
	3	~30	10.886	0.83
T4	1	0~ 5	0.429	0.43
	2	~11	15.232	0.92
	3	~30	4.500	0.59
T5	1	0~ 5	2.667	0.45
	2	~ 8	23.133	0.76
	3	~30	19.790	0.72

*1 Section: division of exposure time according to the tendency of temperature increase.
1 : the first section with gradual slope.
2 : the second section with steep slope.
3 : the last section with middle slope.

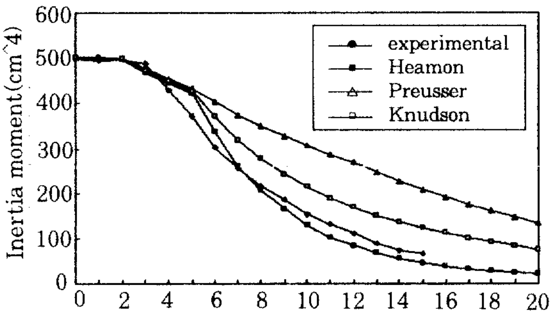

Fig. 9. Comparison of experimental inertia moment with predicted value at 50kg load.

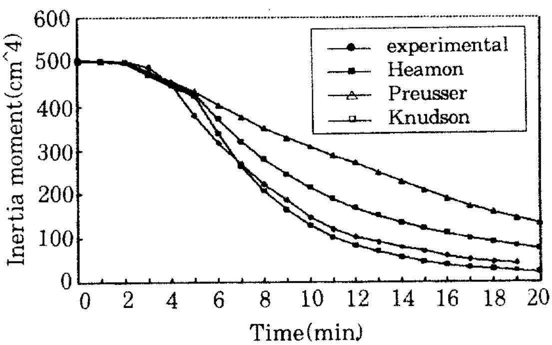

Fig. 10. Comparison experimental inertia moment with predicted value at 80kg load.

stage is horizontal, and 4th stage has another steep stage. However, the 3rd stage is maintained for shorter time, and then this stage could be neglected.

Therefore, three periods could be divided by the gradual slope, the steep slope and then intermediate slope. This tendency of temperature increasing agreed well with the results of Yeo *et al*(1994).

The slopes were calculated with regression analysis, and shown in Table 1.

3.2 Deflection

The deflections of beams increased according to reduction of section area and weakening of outer fibers. The relationships between exposure time and deflection were shown in Fig. 7

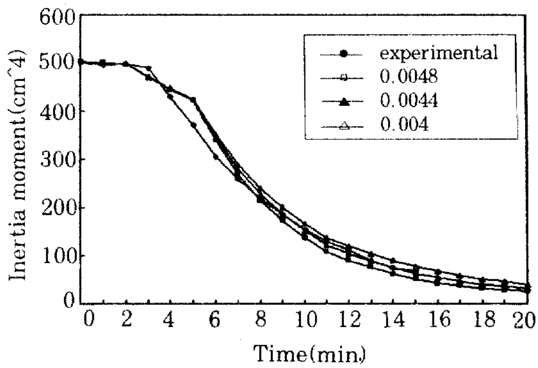

Fig. 11. Comparison of experimental inertia moment with predicted values using various coefficients at 50kg load.

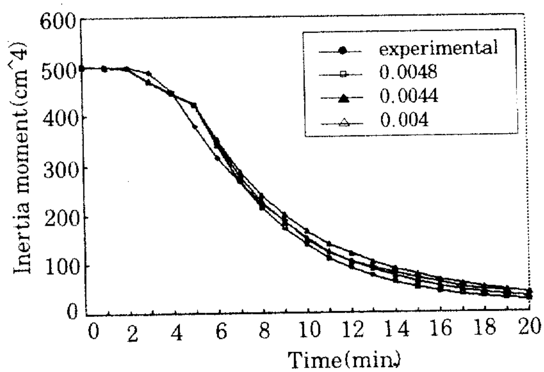

Fig. 12. Comparison experimental inertia moment with predicted values using various coefficients at 80kg load.

and 8. Ratio of two deflection data(50 and 80kg loading condition) were similar to the value calculated using elementary beam theory. Therefore, it was thought that deflection was mainly affected by elastic deformation. Cross section of beams was rounding at corner, and charring depths were nearly same at 4 sides.

3.3 Inertia Moment of transformed section

Fig. 9 and Fig. 10 shows the inertia moments calculated by measured deflections and predicted section area which use the various coefficients proposed by Preusser, Hearmon, and Knudson. Inertia moment based on Hearmon's result is closer to the experimental result of others. Otherwise, when Preusser's coefficient was used, it was overestimated. The experimental values lay on among predicted ones, except for first 5 minutes.

Experimental data were smaller than predicted values in the time from 4 to 7 minute. The reason may be considered that temperature of surface was assumed as same with thermocouple location, T3 and T5(see Fig. 3). It means that lower temperature was inputted to the range, from the surface to depth of 1cm. However, the range which wrong temperature was inputted was reduced with time, so the error might be eliminated.

After 3 minutes, experimental value was larger than predicative values. The reason may be that it was assumed charring started from the time when furnace temperature rose up to 300 . However, actual charring did not leach to steady state. Since there is a large difference among the foregoing informations, and Hearmon's result was obtained from temperature range only upto 100, it is needed to research furthermore about the effect of temperature on wood properties.

From comparison of experimental deflections with predicted values using transformed section method, the most appropriate thermal effect coefficient was 0.0044 / . Inertia moments calculated by various coefficients were shown in Fig. 11 and 12. They showed good approximation. Substituting the coefficient to equation (4), the model was able to predict deflection within 15% of actual deflection, and had a mean residue of 5% for the observed value. No tendency for the model to overestimate or underestimate deflection was noted.

So, the result indicates that this method is very useful in structural applications by architectures and engineers to determine structural behavior of wood members during fire exposure.

4. CONCLUSION

To develop the fire endurance model, the behavior of wood beam under standard fire condition was investigated using the transformed section method. The prediction were summarized as follows.

1. When wood beam was exposed to fire, the temperature of section were divided three peri ods by upward slope. The first period had the gradual slope, the second period showed the steepest slope to 100 , and the third was intermediate.
2. The most appropriate thermal coefficient was 0.0044 / which was obtained from the comparison experimental deflection with predicted value. When the coefficient was used to predict inertia moment, the residuals for experimental value were mean of 5% in both 50 and 80 kgf loading condition.
3. The coefficient, obtained from this study, had large difference from other values. However, it could not be well explained with only the results from this study. Therefore, the research on the relationship between temperature and wood properties might be needed furthermore.

REFERENCES

1. American Society for Testing and Materials.

1988. Standard Test Methods for Fire Tests for Building Construction and Materials. ASTM E 119. ASTM. Philadelphia. PA.

2. Hearmon. RF.S. The Elasticity of wood and Plywood. Dept. Sci. Indus. Res., For Prod. Res. Special Rept. No. 7. HMSO. LONDON : 1948
3. Knudson. R. M. and A. P. Schniewind. 1974. Performance of Structural Wood Members Exposed to Fire. *Forest Prod. J.* 25(2) : 23~32
4. National Forest Products Association. 1991. National Design Specification for Wood Construction. Washington D.C.
5. Preusser. R. 1968. Plastic and elastic behavior of wood affected by heat in open systems. *Holztechnologie* 9(4) : 229~231
6. Schaffer. E. L. 1977. State of Structural Timber Fire Endurance. ***Wood & Fiber*** 9(2) : 145~170
7. Schaffer. E. L. 1984. Structural Fire Design : Wood. U.S. Dep. Agric., For. Serv. Res. Pap. FPL 450. Forest Products Laboratory. Madison. Wis.
8. White. R. H. 1988. Analytical Methods for Determining Fire Resistance of Timber Members. The SFPE handbook of fire prtection engineering. National Fire Protection Association : 3-130-3-142. Chap. 8
9. Yeo. H. M. and H. S. Jung. 1994. Distribution Model Based Computer Simulation for Internal Temperature and Moisture Content in Press Drying of Tree Disks. ***Mokchae Konghak*** 22(2) : 61~72