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Compression Behavior of Wood Stud in Light Framed Wall as Functions of Moisture, Stress and Temperature*[1]

Joo-Saeng Park*[2]† and Jun-Jae Lee*[3]

ABSTRACT

There has been considerable research in recent times in light-timber framed structures in fires. These structures have included horizontal (floor-like) panels in bending and walls under eccentric and approximately concentric vertical loading. It has been shown that compression properties are the most dominant mechanical properties in affecting structural response of these structures in fire. Compression properties have been obtained by various means as functions of one variable only, temperature. It has always been expected that compression properties would be significantly affected by moisture and stress, as well. However, these variables have been largely ignored to simplify the complex problem of predicting the response of light-timber framed structures in fire. Full-scale experiments on both the panels and walls have demonstrated the high level of significance of moisture and stress for a limited range of conditions. Described in this paper is an overview of these conditions and experiments undertaken to obtain compression properties as a functions of moisture, stress and temperature. The experiments limited temperatures to 20 ~ 100°C. At higher temperatures moisture vaporizes and moisture and stress are less significant. Described also is a creep model for wood at high temperatures.

Keywords : compression behavior, light-timber framed wall, moisture, stress, temperature, creep

1. INTRODUCTION

It is well known that fire degradation of light-timber framed structures is more complex than the degradation heavy timber structures. Fire degradation of heavy timber members can be modeled one-dimensionally with simple constant char rates, typically 0.6 mm/min. The degradation of light-timber framed structures is two-dimensional and has to be modeled generally with heat transfer analysis and structural numerical methods. It is assumed that char occurs where temperatures exceed 300°C and that the mechanical properties of uncharred wood are a function of temperature alone. The dominant mechanical property that governs the behavior of light-timber framed walls is the elastic modulus of wood in compression, Ec, because

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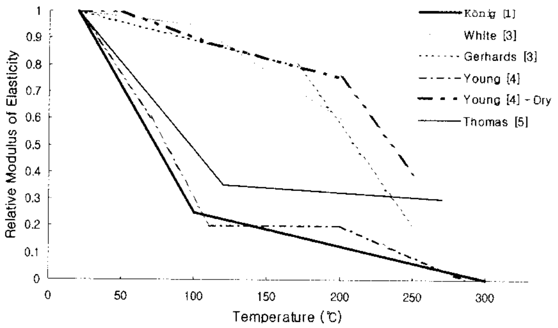


Fig. 1. Relative elastic moduli versus temperature published by various researchers.

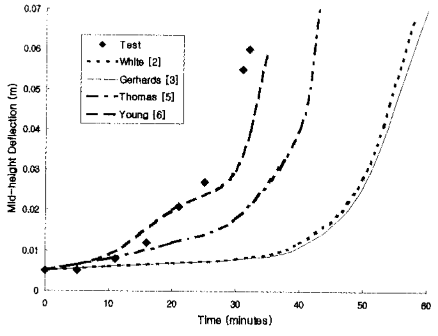


Fig. 2. Deflection of composite pin-ended wall.

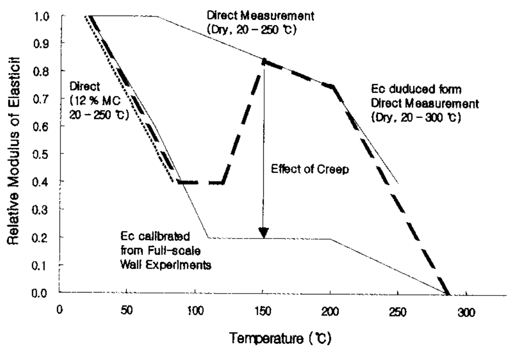


Fig. 3. Effect of creep on elastic modulus deduced from measurements[8].

walls tend to fail by buckling and buckling capacity is a function of Ec. It is known [1] that the compression behavior of lighttimber framed structures in fire is affected by creep which is a function of stress and moisture as well as temperature. König [1] demonstrated that wood in compression creeps far more than wood in tension.

Relationships for Ec obtained by various researchers are shown in Fig. 1. White [2] and Gehards [3] obtained their relationships from experiments involving small specimens of wood. Their relationships are similar to the relationship obtained by Young [4] for dry wood.

It appears that the small specimens dried quickly when experiments were undertaken at elevated temperatures. More recent relationships incorporating the effects of moisture were obtained by König [1] and Thomas [5], as well as Young. These relationships were obtained by calibrating models of studs or joists against the results of full-scale experiments. The mid height deflection of a pin-supported wall predicted with various relationships mentioned, are plotted in Fig. 2. The structural wall model used to obtain the plots is Young's model [6].

Young also obtained relationships by direct measurement of wood samples 300 mm×90 mm ×35 mm in concentric compression. These relationships are shown in Fig. 3. He took measurements on specimens with 12% moisture content in a temperature range of 20 ~ 100°C. He also tested dry specimens. The relationship he deduced for temperatures between 20~300°C is shown as the dashed line. This relationship was substantially above the relationship obtained by calibration. The difference was attributed to creep.

It is apparent that the effect of creep is substantial. Several causes of creep seem possible. These include:

- Creep due to the presence of moisture, heat and stress in the temperature range of 20 ~ 100°C
- Creep due to mechano-sorptive effects
- Creep due to heat and stress in the temperature range 100~300°C

Mechano-sorptive creep arises from changing moisture content including wetting and drying. It is common for the deflection of timber structures to gradually increase in climates of greatly varying humidity. This increase is not restricted to a maximum limit.

It is worth noting that these causes of creep were known centuries ago except they were not as elaborately explained as they are today. Timber framing members of galleons were bent in fire. Wood in furniture is shaped by applying water, and bending while drying.

The research described in this paper aimed to identify the causes of creep of light-timber structures in fire. In particular, it aimed to check whether all the creep observed in compression property experiments and standard fire [7] wall furnace experiments undertaken by Young [8] could be explained from the identified causes. From this check, it was desired to determine whether calibrated relationships in general needed further refinement. Finally it was desired to develop models for creep for general use and for adoption in Young's structural model [6]. To achieve these aims creep experiments on specimens of wood similar in size to Young's were undertaken.

2. MATERIALS and METHODS

2.1. General

To evaluate all of the axial related compression deflection of timber members, experiments were undertaken to measure the elastic modulus and creep. For both of these types of experiments the following general procedures were adopted.

Compression deflection due to elastic and and creep behavior were measured for the following range of moisture contents and temperatures:

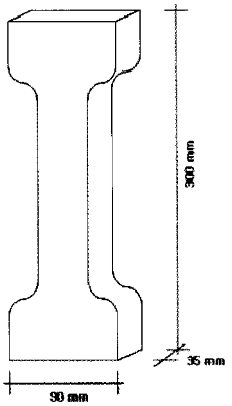


Fig. 4. Specimens cut to form bone shapes to prevent end crushing.

- Dry (0% moisture content), 20~250°C
- 12% MC, 20~100°C
- 30% MC, 20~100°C

These moisture contents cover the full range in structural timber. The 12% value is typical for seasoned timber in most applications. The 30% value corresponds to fiber saturation conditions. Higher moisture contents are possible but will not alter the moisture content bound in the wood fiber and thus not affect the structural response differently with any degree of significance.

The moisture content of dry specimens was achieved by oven drying at 105°C for three days. Repeated weighing of specimens showed no further weight loss after this period. The weighing and drying of these specimens showed that ordinary specimens had a moisture content of 12%. These specimens were coated with three coats of acrylic paint to seal in the moisture. The moisture content of 30% was achieved by soaking specimens in water at ambient temperature for 24 hours. The specimens were then placed in sealed plastic bags. The level of the moisture content was checked for some specimens by weighing and drying.

Specimens were cut from 90 mm×35 mm radiata pine. The moist specimens were cut to form a bone shape as shown in Fig. 4. This shape was used to reduce bearing stresses and prevent crushing at the ends of the specimens which can be a problem for wood specimens with high moisture contents.

The moist specimens tested between 20～100°C were placed in a metal tank filled with water. The submersion in water helped maintain the moisture content at a constant level better than open air heating. The paint controlled the increase in moisture content of 12% specimens to 1～3%. It was found that the 30% specimens increased in moisture content by 1～5%.

The experiments were non-destructive. Specimens were re-used to minimize variability in the results.

The target temperatures for testing the moist specimens were achieved within 5°C in 30 minutes according to measurements taken with thermocouples wires inserted in the core of trial specimens. All specimens were heated for 40 minutes, which was similar to the period of heating of wood in wall furnace experiments [8]. Thus the heating procedure replicated the heating of wood in the wall furnace experiments well. A longer period could increase the creep in the specimens more than the creep in the wall furnace experiments. The use of water to heat specimens was much faster than the use of metal heating plates in air which took 150 minutes.

The dry specimens were heated with metal plates. Loads of 6.0 and 8.0 Mpa were applied. These are approximately three times the average stress and 50% greater than the peak stress applied by Young in his full-scale wall furnace experiments. The larger stresses were required to obtain measurable deflections. The larger stresses also enabled investigation of the behavior of timber at the upper limit of practical loads.

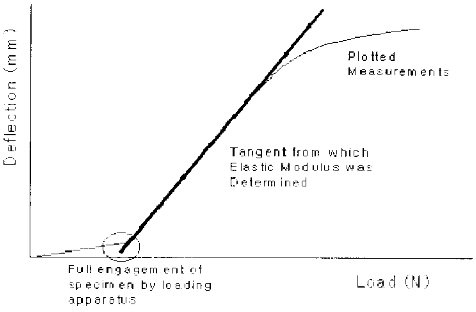


Fig. 5. Graphical approach for determining the elastic molulus of wood in compression

The apparatus was fabricated to measure the deflection of a 100 mm gauge length at the middle of specimens using LVDT. Measurements were in the range of 0.01～0.07 mm.

2.2. Elastic Modulus of Wood in Compression

All specimens were loaded to 8 Mpa. The loads were applied in the minimum time that the loading apparatus could achieve, which was 1～2 minutes. Unlike Young's experiments to measure elastic modulus, the standard, ASTM D198 [9] was not used. It prescribes a rate of 0.001 strain per minutes. This rate would have required a period of five minutes for the target load to be applied. It was found that creep during a period of five minutes was substantial. To remove creep from the measurements that were taken, the procedure illustrated in Fig. 5 was carried out. During the initial application of load, the gradient of the load deflection plot was low as the loading apparatus engaged the specimen. Once the specimen was engaged, the gradient of the plot achieved maximum steepness. Thereafter, the plot drifted to the right, most likely due to small but significant creep. This creep was discarded by calculating the elastic modulus of steepest tangent when the specimen was engaged.

Elastic moduli were calculated graphically for the range of specimens listed in the previous section. Four dry specimens were tested at temperature of 20, 150, 200 and 250°C. Four 12% specimens and seven 30% specimens were tested at 20, 60, 80 and 100°C.

2.3. Compression Creep

Experiments were designed to measure the three types of creep identified in the introduction :

- ▶ Creep due to the presence of moisture, heat and stress in the temperature range 20~100°C
- ▶ Creep due to mechano-sorptive effects
- ▶ Creep due to heat and stress in the temperature range 100~300°C.

The following procedure was undertaken to evaluate the significance of mechano-sorptive creep. The scope of the testing was limited to desorption. Adsorption testing was not undertaken because the time for adsorption would greatly exceed the creep periods of interest, 5~30 minutes. Further, it has been reported [12-14] that desorption leads to greater creep than adsorption. Bone-shaped specimens were used with minimum section of 30×15 mm. This small size was chosen to facilitate desorption while maintaining a level of capacity that enabled measurable load to be applied. A constant load of 8 MPa was maintained throughout the experiment. The specimens had an initial moisture content of 30%. The experiment was undertaken in two stages. In the first stage of the specimens were heated to 100°C in the tank. Constant moisture and load was maintained for 40 minutes. The water was drained from the tank. The tank was externally insulated. Hot air at 100°C was blown through the empty tank still containing the loaded specimen. The core temperature of specimens dropped to 65°C according to preparatory experiments used to establish the procedure. Deflection reduced substantially. After 10 minutes of blowing hotair into the tank the deflections increased and the specimen began to dry.

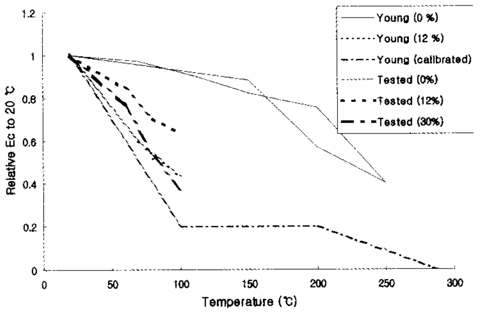


Fig. 6. Relative elastic modulus versus temperature.

3. RESULTS and DISCUSSION

3.1. Elastic Modulus of Wood in Compression

The calculated elastic modulus at ambient conditions was 15,000 ± 1,300 Mpa for the dry specimens; 14,500 ± 1,000 for the 12% specimens and 10,200 ± 1,600 Mpa for the 30% specimens. The similarity of elastic moduli for dry specimens compared with the 12% specimens is consistent with Young's findings. The elastic moduli relative to initial values for ambient conditions are plotted in Fig. 6. Results from Young are shown for comparison.

3.2. Compression Creep

Key results for creep experiments in the temperature range 20 ~ 100°C are shown in Fig. 7, Fig. 8 and Fig. 9. The results shown are average of groups of three similar experiments. The variations in the results of similar experiments were less than 10%.

The creep for a 100 mm gauge length of radiata pine with 12% moisture content and a constant load of 8 MPa is shown in Fig. 7. To gauge the significance of the creep in the wall

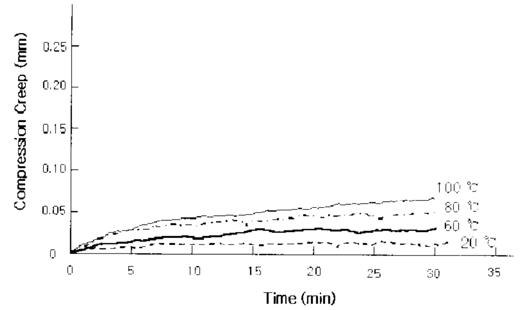


Fig. 7. Compression creep for specimen with 12% moisture content and 8 MPa loading.

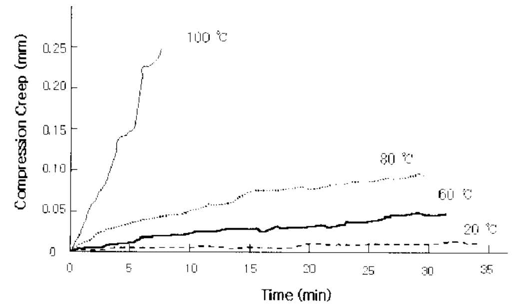


Fig. 8. Compression creep for specimen with 30% moisture content and 8 MPa loading.

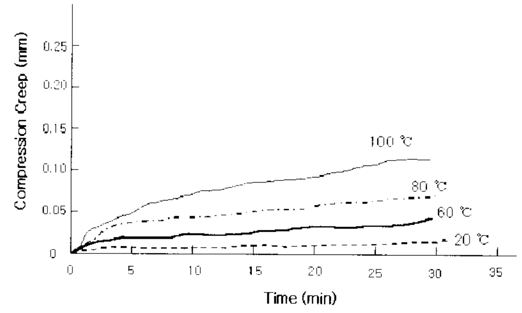
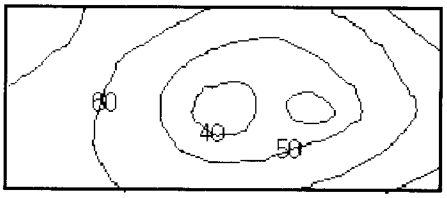
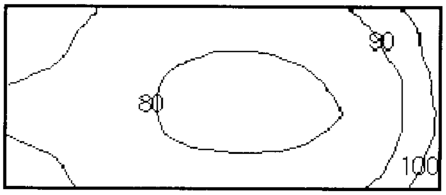


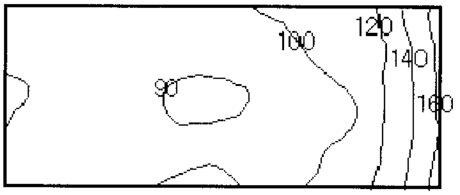
Fig. 9. Compression creep for specimen with 30% moisture content and 6 MPa loading.



(a) At 15 minutes



(b) At 25 minutes



(c) At 35 minutes

Fig. 10. Temperatures in studs in full scale wall furnace experiments.

furnace experiments, distributions of temperature obtained from thermocouple measurements in studs are given in Fig. 10.

From Fig. 7, an estimate of the creep in the specimens is 0.05 mm. Elastic compression deflections can be deduced from Fig. 6. The elastic deflection at 20°C is 0.055 mm. At 80 ~ 100°C, the moisture content approximately doubles to, say 25%. This doubling has been demonstrated experimentally and theoretically [10,11]. The moisture increases in wood at this temperature due to vaporization in nearby wood at 100~120°C being dispersed by the pressure created and condensing in cooler regions. The elastic deflection for wood at 80~100°C at 25% moisture content is expected to be approximately 0.07 mm. The creep due to temperature, stress and the presence of moisture would be approximately 75% of the elastic deflection. The creep experiments directly demonstrate that creep can almost double deflection.

The creep for a 100 mm gauge length of radiata pine with 30% moisture content and a constant load of 8 MPa is shown in Fig. 8. The increase in creep due to the larger moisture content of 30% compared with 12% is dramatic, particularly for temperatures approaching 100°C. It appears that plastic behavior of wood compression was approached.

The creep for an experiment similar to the previous one described but with a load of 6 MPa is shown in Fig. 9. At this lower load no plastic behavior is apparent and the effect of moisture on creep is substantial.

Another important observation from Fig. 7, Fig. 8 and Fig. 9 is that the creep for a period as short as 5 minutes is highly significant compared with elastic deflections. Creep of wood thus a significant phenomenon during the exposure of light timber framed walls in fire. Creep in this application contrast to creep in many other structural applications in which creep is significant over long periods of time years.

Developing a procedure to measure mechanosorptive effects is difficult. Ideally, moisture content is virtually impossible measure. It may have taken up to the 100th minute in Fig. 11 for sufficient moisture to evaporate for mechanosorptive action to commence. The mechano-sorptive deflection does not appear to be significantly greater than the expected deflection projected as if stage one was con tinued beyond the 40th minute. From the crude mechano-sorptive experiment, it appears that the creep experiments involving constant moisture conditions, as previously described in this paper, are sufficient to predict deflections at temperature less than 100°C.

The results of experiments to measure creep due to heat and stress in the temperature range 100～300°C are given in Fig. 12. Schaffer [15] documented creep of Douglas-fir in the conditions of 0% moisture content and temperature between 150～300°C. Creep of the radiata pine specimens was measured for these conditions. From Fig. 6, the elastic deflection of a 100 mm gauge length of dry wood at 200°C is approximately 0.09 mm. The creep is 0.12 mm at 30 minutes. Creep more than doubles the elastic deflection. It appears that Young's plot should be lowered further at high temperature, to be more similar to König's plot in Fig. 1.

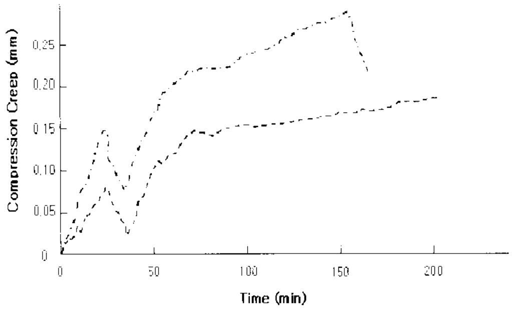


Fig. 11. Compression creep for dry specimens with 8 MPa loading and temperatures at 100°C.

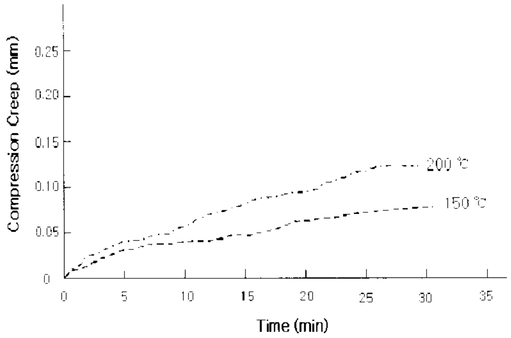


Fig. 12. Compression creep for dry specimens with 8 MPa loading and temperatures above 100°C.

These conditions of 0% moisture content and temperatures between 150～300°C occurred in studs in furnace experiments on a wall with fixed supports, just prior to failure at 60 minutes. The temperature distribution, at this time, obtained from thermocouple measurements in unloaded studs, is shown in Fig. 13.

3.3. Elasto-creep Material Model

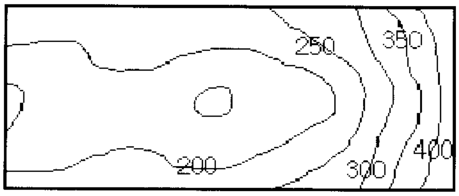


Fig. 13. Temperatures in studs in wall at 60 minutes.

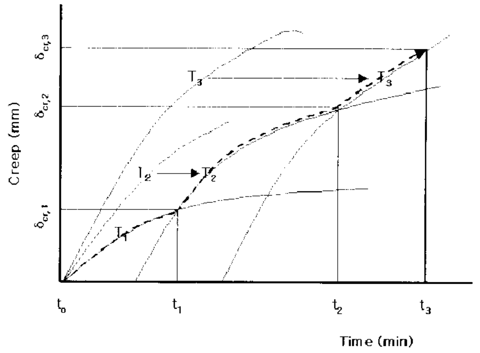


Fig. 14. Calculation of creep involving changes in temperature.

The simplest model of creep for general use is a reduction of the elastic modulus to allow for the additional deflection caused by creep. This type of model will be called an elasto-creep material model. The relationships for elastic modulus developed by calibration [5,14] in Fig. 1 are effectively elasto-creep models. Discussion on such a model will address the aim of checking whether all the causes of creep discussed in the previous section could account for the difference between measured and calibrated compression properties of Young's [4] in Fig. 2. This section will focus on the experimental results for radiata pine with an initial moisture content of 12% and a load of 6.0 MPa.

The elastic compression deflection of a gauge length of 100 mm for such specimens at 20°C is 0.041 mm according to experimental result (12%) in Fig. 6. The calculation of the deflection at 100°C involves elastic deflection and creep. The moisture content of wood at 100°C can be expected to double, as previously explained, to approximately 25%. Interpolation of deflections deduced from the measurements of specimens wi0th moisture contents of 12% and 30% is required.

The elastic deflection for a specimen with 12% moisture content at 100°C is 0.065 mm. The creep deflection has been calculated in accordance with the procedure demonstrated in Fig. 14. The creep deflection for a particular time period such as t0 to t1 was deduced from an experimental plot for the average and section temperature, T1, during the period. The average temperature was estimated from temperature distributions in Fig. 10. The creep for the succeeding time period, t1 to t2, was deduced assuming that the creep continued at the rate of measured for the average temperature, T2, for the succeeding period. The average temperature during the first 10 minutes was estimated to be insufficient to cause any significant creep. The average temperature for 10~20 minutes was estimated as 50°C, for 20~30 minutes as 80°C and for 30~35 minutes as 100°C. The creep deduced was 0.034 mm. The total deflection deduced was 0.099 mm.

Similarly the total deflection deduced for a specimen with a 30% moisture content was 0.228 mm. By interpolation, the total deflection expected for a specimen of wood subjected to temperature increasing 20°C to 100°C is 0.041 mm increasing to 0.192 mm that is the effective elastic modulus reduced to 21% of its initial value. This results compares well with König's plot in Fig. 1. The good comparison gives confidence in the accuracy of the measurements for elastic modulus and creep.

Fig. 6 is repeated with the simple elasto-creep model superimposed in Fig. 15. The model is simply bilinear with the linear plots intersecting at 100°C. More elaborate plots could be made. The plot could be kinked to account for the change in moisture content from 12% to 25% as temperature rose to 100°C. As well, the two linear plots could intersect at a relative modulus of 0.21 instead the value 0.20. However, such elaboration would be pretentious accuracy. The model is similar to König's in Fig. 1, except the relative elastic modulus at 100°C is 0.2 instead 0.25.

Although the model supports the results of previous research, it still suffers similar limitations. The model is applicable to light timber framed structures which experience similar histories of temperature, moisture content and stress as the specimens in the experiments. A more rigorous model, which incorporates the variable of time explicitly, needs to be investigated.

4. CONCLUSIONS

Creep of wood specimens has been measured for a range of loads, moisture contents and temperature. The significant types of creep observed were :

- ▶ Creep due to the presence of moisture, heat and stress in the temperature range of 20~100°C
- ▶ Creep due to heat and stress in the temperature range of 100~300°C

Experimentation involving desorption of moisture in wood specimens did not reveal significant creep due to mechano-sorptive effects.

The first type of creep mentioned above was sufficient for explaining the difference between the elastic modulus obtained by calibration and direct measurement.

The relationships for the elastic modulus of wood in compression obtained by several researchers through the calibration of models to full-scale experiments represent simple elasto-creep models for predicting the effects of creep of light-timber framed structures in fire. The models are limited to applications in which the wood is subjected to temperatures, moistures and stresses similar to values that occurred in the experiments.

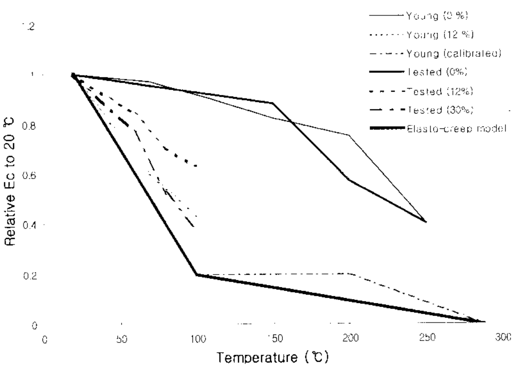


Fig. 15. Results of elasto-creep model.

Creep due to rises in temperature (above 70°C), moisture content or stress is significant compared with elastic deflections, in a time period as short as 5 minutes.

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