Probability of Failure with Time for Wood Framed Walls in Real Fire

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ABSTRACT: Performance-based building fire regulations are being introduced around the world. Risk to life and property is used as a performance basis for the most major departures from traditional regulations. A model has been developed for estimating the time dependent probability of failure of wood-framed walls in standard and real fires. The model is fundamentally based and uses Monte Carlo analysis. Estimates of statistical characteristics of input variables have been obtained. Application of the model has shown that thermal properties of materials in wood-framed walls vary little. The coefficient of variation determined for a wall with realistic loads and variations of mechanical properties in standard and real fires was approximately 0.12.

KEY WORDS: probability, performance-based, wood, timber, wall, fire resistance.

INTRODUCTION

THE PRACTICE OF fire safety engineering in Australia involves several alternative approaches ranging from a simple approach for common design problems to a rigorous rational approach involving the assessment of the risk of death and property loss. The risk approach is most likely to be used to assess a new type of fire protection system or type of building well outside the current building classification system in the traditional rules. System, in this context, refers to the combination of active and passive fire protection measures including, for example, sprinklers, egress routes and

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barriers. The risk approach is also appropriate for formulating new fire protection regulations and removing obsolete regulations. For example, the risk approach has been used to introduce regulations in Australia for three-story walk-up apartments that were previously prohibited [1–3].

Evidence of risk analysis being the best rational means of decision making is apparent from its use in most modern structural engineering codes around the world. Risk analysis, however, often requires a considerable amount of judgment in choosing data and characteristics of probability functions which are not well known. The formalization of the incorporation of judgment alongside well-known data is called Bayesian risk analysis [4]. This judgment, in itself, does not make risk analysis less credible than simpler alternative methods of analysis which involve no apparent "guess-work". The simpler methods incorporate judgments indirectly; these judgments may, in fact, be quite crude. The main disadvantage with risk analysis is that it is difficult for it to be applied consistently among independent users and thus provide a fair basis for competitive engineering design. Risk analysis certainly has a valuable role in formulating rational rules which themselves can be applied consistently. The lack of knowledge, that is overcome with judgments, needs to be minimized. The research described in this paper generally aims to provide more knowledge on the probabilistic characteristics of the time-to-failure of light timber-framed wall barriers in fire.

It was apparent at the outset of the research that the probability of failure can also be affected by penetrations including service penetrations, doors, openings and construction defects. Penetrations were excluded from the scope of the research described in this paper and is recommended for research in the future.

The following aims for the research described in this paper were chosen:

- Develop a model for obtaining probability characteristics for time-to-failure of light timber-framed walls exposed to real fire.
- Obtain some insight into the probabilistic characteristics, particularly coefficients of variation (COVs), of variables affecting the time-to-failure of light timber framed walls in fires.
- Provide some typical plots of probability of failure with time, and thereby show typical variability of failure times of light timber framed walls in standard and real fires.

REVIEW

Previous research into probability modeling of the failure of timber structures in fire has been limited [5–7]. Woeste [5] estimated the probability of failure of light wood-framed floors in standard fire [8] with the use of char rates and first order second moment analysis (FOSM). The char rate method does not involve fundamental variables such as fire gas temperature, ventilation and fuel load. Bender [6] estimated the probability of failure of glulam beams using a similar methodology to Woeste's. Jönsson [7] described how to apply FOSMs to fire resistance problems in general. To use FOSMs, knowledge is required of probability characteristics of properties and other variables during fire exposure. These characteristics may be known for ambient conditions, but are less likely to be known for fire conditions. This limitation of FOSMs can be overcome with Monte Carlo analysis [4,9] which can use the characteristics at ambient conditions to estimate probability characteristics for high temperatures using many repeated simulations. It is potentially a very slow method of computation but it does minimize judgment.

Risk and fire research [10] prior to the mid 1980s tended to use FOSM. In more recent times, Monte Carlo analysis has been preferred [11–13] most likely because of improvements in computing power and the desirability of minimizing judgment.

DESCRIPTION

As for more recent research, the probability model developed in the research described in this paper used Monte Carlo analysis. This analysis incorporated a time-to-failure model, described in previous publications [14,15], into a loop for undertaking repeated computations of the time-to-failure. The probability model and the time-to-failure model are illustrated in Figures 1 and 2.

The time-to-failure model, as shown in Figure 1, numerically simulates the thermal and structural behavior of a light wood-framed wall exposed to a real fire. The simulation is theoretically based so that the model can be used to deduce the effects of a wide range of variables on the time-to-failure and hence on the probability of failure. The modes of failure that can be modeled are excessive temperature rise on the ambient facing side of the wall and structural collapse. Failure initiated by a loss of integrity of the gypsum board on the fire side and the subsequent rapid charring of studs is also modeled. The main sub-models are fire severity, heat transfer and structural response sub-models; that is, Boxes 1–3 respectively.

The fire severity sub-model predicts fire gas temperatures. Two fire severity sub-models were used in the research; namely the standard fire, AS1530.4 [16], which is virtually identical to the ISO834 standard fire [17], and a real fire sub-model [18] which relates fire temperatures to basic variables including ventilation and fuel load.

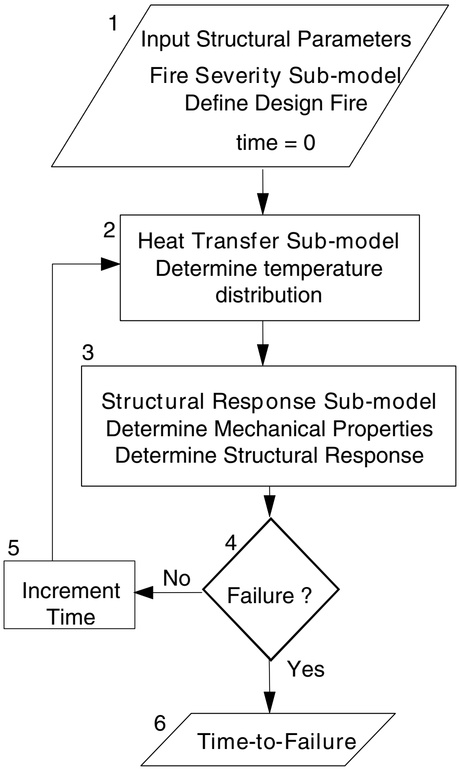

Figure 1. *Time-to-failure model.*

The heat transfer sub-model was developed in the course of the research. It uses a finite difference method of analysis for conductive heat transfer through solid materials [19]. It also uses discrete radiative heat transfer analysis for radiation through cavities. This method of analysis simulates many radiation rays emitted in all directions through space, from a large number of points distributed around the surfaces bounding the cavity. A number of rays are illustrated in Figure 3. This method of analysis can be applied to cavities with re-entrant corners. Hence, the model can be applied to a wide range of walls, examples of which are shown in Figure 4 including ordinary cavity walls, double stud walls and staggered stud walls. Convective heat transfer at surfaces is modeled approximately with heat transfer coefficients. Approximate modeling is considered acceptable because convection is not a dominant mode of heat transfer through walls [19]. The thermal properties used in the heat transfer sub-model are given in Appendix A.

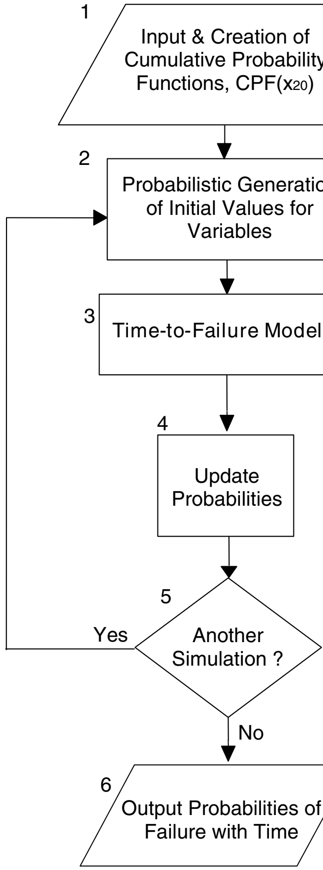

Figure 2. *Probability of failure with time model.*

The structural response sub-model [20,21] uses the same numerical grid as the heat transfer sub-model. It determines the heat-affected stiffness of each element of material bounded by grid lines. The mechanical properties used in determining stiffness are given in Appendix A. If an element of wood is charred, its temperature is greater than 300°C and hence its elastic modulus (Figure A-7) and its stiffness is zero. The structural sub-model determines the overall flexural stiffness of wall cross-sections using composite section theory. Beam-column line members are adopted with the same overall flexural stiffness. This line member model is analyzed with a second order direct stiffness analysis. The second order of the analysis enables the analysis of buckling. The structural response sub-model well satisfies the computational requirements for the repetitive random simulation of Monte Carlo

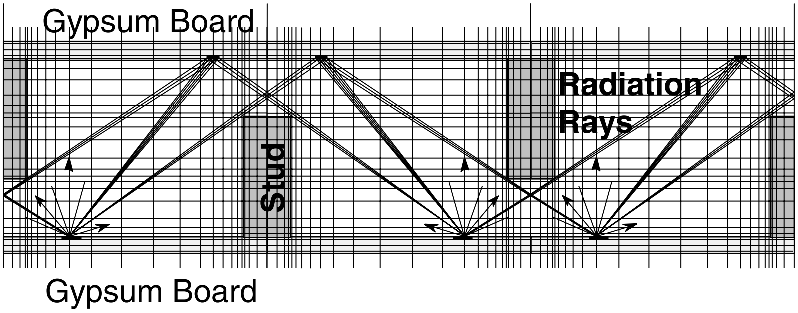

Figure 3. Examples of rays considered in a discrete radiative heat transfer analysis for a staggered stud wall.

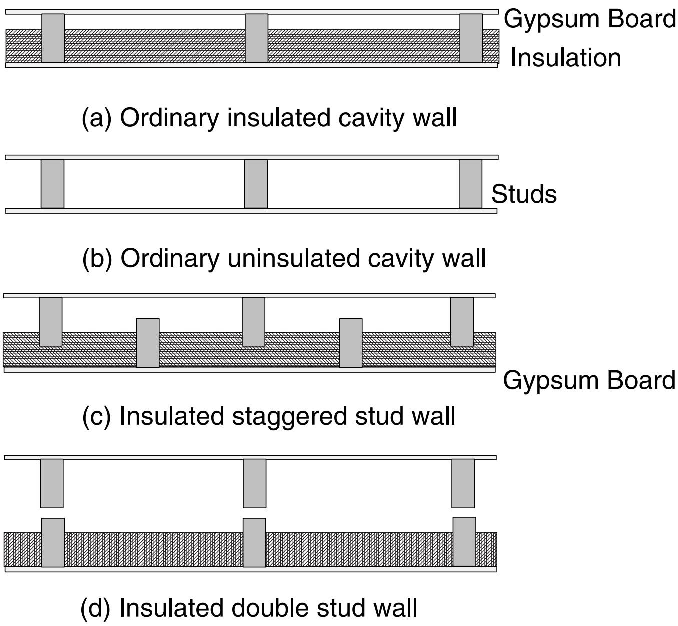

Figure 4. Range of light timber framed wall sections.

analysis – fast computation and numerical robustness. Robustness is required to ensure that any extreme values generated in a simulation do not cause numerical instability and the potential waste of many hours or days of computation.

The probability model is illustrated with the flowchart in Figure 2. The model incorporates the time-to-failure model (Box 3) in a Monte Carlo analysis involving the repetition of the loop of Boxes 2–5 for the required number of simulations. The required number, N, can be determined from expressions such as [22],

$$N > \frac{-\ln(1 - C)}{p_f} \tag{1}$$

where C is the confidence level and p_f is the probability of failure. To obtain a confidence level of 95% in the predicted probability of failure as small as 0.01, 300 simulations would be required. Each simulation commences (Box 2) with the generation of the initial values for variables. The time-to-failure is determined with the model in Box 3. Probabilities of failure with time are updated in Box 4 after finding the time-to-failure. Whether all of the specified number of simulations is completed is checked in Box 5. Output occurs in Box 6.

The probability model can take approximately one hour to undertake 100 or more simulations on current personal computers. The computation speed of the model could be improved with the incorporation of an importance sampling function [4] which is used to generate values for variables. These functions involve the use of conditional probability to greatly reduce the number of simulations required. The probability of failure is the product of the recorded proportion of simulations involving failure and the conditional probability associated with the importance sampling function. Great care is required in choosing the sampling function, otherwise the function can greatly increase the number of simulations required. An importance sampling function is only effective if approximate values are known for variables significantly affecting failure.

The generation of values involves independent random variables, dependent random variables and deterministic variables. Variables are considered to be random if it is suspected that they will significantly affect the time-to-failure; that is they are dominant variables and have a significant coefficient of variation, COV. A dependent random variable is one that has some correlation with one or several independent random variables. However, in the research, dependent variables were only considered to depend on the most dominant and independent random variable that influenced the dependency. Non-random variables are deterministic.

The probability model generates values for independent random variables for ambient conditions. It is assumed that the relationships for thermal degradation, such as those shown in Figures A-1–A-7, are deterministic. No random parameter is used to allow for inaccuracies in modeling [4]. Such parameters are used to allow for adverse effects of uncertainties arising from limitations in modeling accuracy when it is desired to estimate whether a risk is acceptable. The aim in using the probability model was to give "best" rather than conservative estimates of probabilities.

Generation of a value for a random independent variable, x_{20}, for initial ambient conditions was undertaken in accordance with the equation,

$$x_{20} = \alpha'_x \cdot \bar{x}_{20} \tag{2}$$

where $\bar{x}$ is the expected value and the subscript of 20 indicates that the value generated is for an initial temperature of 20°C. The expected value is the value that would be input into an analysis to obtain the best estimate of the time-to-failure. The variable, α'_x, is an independent random parameter with a mean of 1.00, and a coefficient of variation and probability distribution input by the user. Three distributions that are commonly used [23] in structural engineering are offered as options in the model. These are the normal, lognormal and Weibull distributions. Considering that the model was at a basic level of refinement, other probability distributions would not have led to clearer conclusions and were ignored. Normal distributions apply to data that is primarily affected by a summation of influences [24]. Lognormal distributions apply to data that is primarily affected by a product of influences. These distributions are restricted to data that does not have negative values. Weibull distributions apply to extreme data; for example, design live loads on building structures. The parameter, α'_x, is obtained using random number generation. A particular random number, $R^*_{x_{20}}$, is generated between zero and one. The number represents the cumulative probability of x_{20} exceeding other possible values; that is, CPF(x_{20}). From the random number the parameter, α'_x, is obtained numerically in a manner indicated in Figure 5.

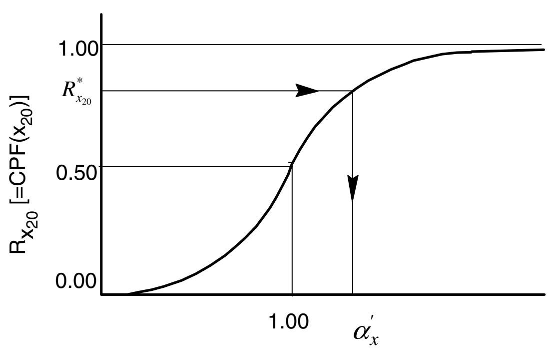

Figure 5. *Generation of independent random parameter, α'_x, from random number, $R^*_{x_{20}}$, and cumulative probability of failure function, CPF(x_{20}).*

Dependent random variables, y_{20}, for initial conditions are generated in accordance with the equation,

$$y_{20} = \alpha'_y \cdot \beta_{y/x_{20}} \cdot \bar{y}_{20} \tag{3}$$

where $\bar{y}_{20}$ is the expected value at 20°C when x_{20} equals $\bar{x}_{20}$; α'_y is the random parameter for independent characteristics; and $\beta_{y/x_{20}}$ is the parameter for dependence on the value generated for x_{20} given in the generalized expression,

$$\beta_{y/x_{20}} = \sum_{i=0}^{2} c_i \cdot \alpha_x^{b_i} \tag{4}$$

where c_i are coefficients and b_i are exponents set by the user.

It is convenient to refer to the term, "random parameter". For random dependent variable, y_{20}, the random parameter is defined as,

$$\alpha_y = \alpha'_y \cdot \beta_{y/x_{20}} \tag{5}$$

For random independent variable, x_{20}, the random parameter is the same as the independent random parameter; that is,

$$\alpha_x = \alpha'_x \tag{6}$$

The cumulative probability of failure with time for each mode of failure is found by summing the number of failures that are recorded prior to each minute of fire exposure, and dividing each sum by the total number of simulations.

The cumulative probability of failure, p_f, for any one of several modes of failure to occur is found, for example, for three modes from,

$$p_f = 1 - (1 - p_1)(1 - p_2)(1 - p_3) \tag{7}$$

where p_1, p_2 and p_3 are the independent probabilities of failure for Modes 1–3 respectively. The terms in Equation (7) are illustrated in Figure 6.

EVALUATION OF THE VALIDITY OF MODELING

Evaluation of the validity of the sub-models for heat transfer and structural response has been reported previously [19,21]. Model predictions

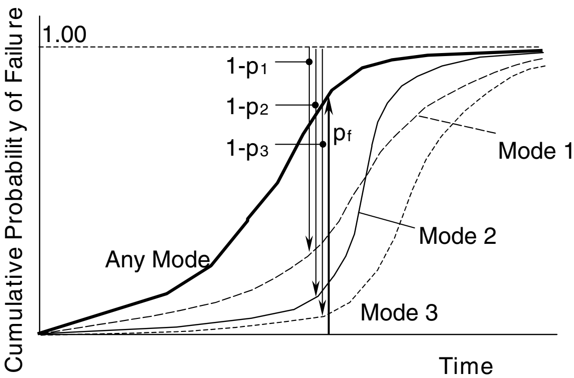

Figure 6. *Total probability of failure from three modes of failure.*

were compared with the results of full scale AS1530.4 [16] standard fire experiments on 3.0 m tall ordinary hollow cavity walls comprising studs 90 mm × 45 mm in cross-section spaced 380 mm between centers and a single sheet of 16 mm thick fire-rated gypsum board on each side. The top and bottom of the wall were restrained against rotation to the same degree as for conventionally-built walls. Thermal and mechanical properties of gypsum board and wood were obtained independently from the standard fire experiment on the wall. Some properties were obtained with small scale-tests during the research [19], and others were obtained from the most relevant results published in the literature such as Janssen's [25]. Although only one furnace experiment was undertaken on a restrained wall, three experiments were undertaken for nonloadbearing pin-supported walls, and two for loaded pin-ended walls. These repeated wall furnace experiments demonstrated remarkably consistent results. Observed times-to-failure for similar experiments were within a minute of each other. It was thus expected that the experiment on the restrained wall gave a time-to-failure that could be closely reproduced and was not repeated. Model predictions and the experimental observation of structural collapse of the restrained wall were both within a minute of each other, at approximately 59 min. Model predictions of the time-to-failure of the nonloadbearing walls were within 5% of the observed times-to-failure. Model predictions of the time-to-failure for pin-supported walls overestimated experimental times-to-failure by as much as 30%. It was believed that this overestimate was due to creep in the studs which is not directly simulated in the model. To indirectly model creep, some researchers [26,27] have adopted reduced elastic moduli for wood in compression. Using these reduced elastic moduli, the model predicted times-to-failure for pin-supported walls within 10% of the observed times-to-failure in the experiments. Overall, the close comparisons between predictions and observations give confidence in the modeling of time-to-failure. The probabilistic studies described in this paper are for the restrained wall only, which is more typical of walls in common building construction.

The Monte Carlo analysis was checked by evaluating the randomness of the random number generation [14]. It was found that there was no discernable bias in the numbers generated and that there was no repetition of numbers generated for as many as 10^8 generations. (The frequency of repetition indicates the smallest probability that can be deduced from the analysis.)

EVALUATION OF THE VARIATION THERMAL PROPERTIES OF WOOD IN STANDARD FIRES

Expected values for thermal and mechanical properties of wood and gypsum board that have been obtained in previous research and were adopted in the modeling described in this paper are summarized in Appendix A. Evaluation of the COVs for these properties was undertaken as follows.

The coefficients of variation, COVs, for various mechanical properties at ambient conditions can be obtained from available repeated measurements [20,28–30]. Repeated measurements do not appear to be available for thermal properties. The main thermal properties in walls are conductivity k ($W\,m^{-1}\,K^{-1}$), density ρ ($kg\,m^{-3}$) and specific heat c ($J\,kg^{-1}\,{}^{\circ}C^{-1}$) for gypsum board and wood. Gypsum board properties should not vary much because it is manufactured under controlled conditions. Sensitivity analyses [15] have shown that the thermal properties, k, ρ and c, of wood do significantly affect the time-to-failure. The focus of the evaluation was thus on the variation of thermal properties of wood. The evaluations were undertaken with several sets of numerical simulations. Each set had different trial values for the COVs for the thermal properties of wood. The numerical plots of temperature versus time were compared with measurements made at points through the stud sections during several wall furnace experiments. The positions of these points are shown in Figure 7. The COVs were deduced from the comparison of numerical and experimental plots with similar variations.

To obtain faithful numerical simulations, the random variation of all variables was considered. All thermal and mechanical properties were assumed to vary according to lognormal probability distributions to avoid

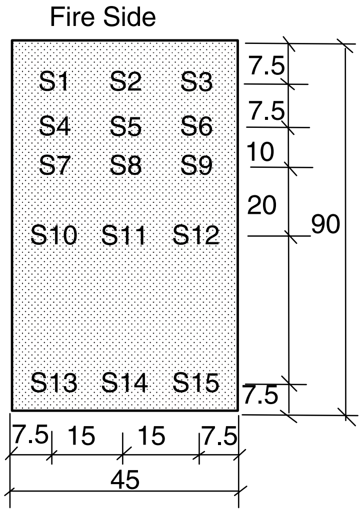

Figure 7. *Positions of thermocouples S1–S15 in studs; all dimensions in mm.*

the generation of negative values. Since the evaluation was not concerned with extreme events, Weibull distributions were not used.

The independent random parameters $\alpha'_k, \alpha'_\rho, \alpha'_c$, for the thermal properties of gypsum board were assumed to have minimal COVs of 0.02 because of the control in manufacturing the board. For both gypsum and wood, the thermal properties that were assumed not to have dependencies on other variables, were density and specific heat – which is apparent from research by Janssens [25].

Simple linear relationships between conductivity and density were deduced. For gypsum board, the relationship was deduced from the expression [25],

$$k = \pi_g k_g + \pi_s k_s \tag{8}$$

where π_g is the proportion of total volume of material which is occupied by gas; k_g is the conductivity of the gas (W m^{-1} K^{-1}); π_s is the proportion of volume of material occupied by solid; and k_s is the conductivity of the solid (W m^{-1} K^{-1}). Similar volume and conductivity terms should be added for free moisture. However, the proportion of volume occupied by free moisture was less than half of one percent and thus would not significantly affect the total conductivity, k. The proportions, π_g and π_s, determine the overall density. Equation (8) is based on the assumption that constituents – gas, solid and moisture – are in layers parallel to the direction of conduction. Another expression is available for the alternative assumption of parallel layers perpendicular to the direction of conduction. It was found that this assumption gave a nonsensical relationship between conductivity and density.

From Equation (8), the parameter, $\beta_{k/\rho 20}$, for the conductivity of gypsum board dependent on density was deduced as,

$$\beta_{k/\rho 20} = 0.1 + 0.9\alpha'_{\rho} \tag{9}$$

The total random parameter for conductivity for gypsum board was thus,

$$\alpha_k = \alpha'_k \cdot \beta_{k/\rho 20} \tag{10}$$

For the restrained wall, it was found that the mechanical properties of gypsum board had deteriorated to insignificant values at the time of failure, and were thus not considered as random.

From Janssens' [25] model for the conductivity of wood, a 10% increase in density corresponds with a 6% increase in conductivity. Hence, the dependency factor $\beta_{k/\rho 20}$ was determined from the independent random parameter α'_{ρ} for density in accordance with Equation (11) as follows,

$$\beta_{k/\rho 20} = 0.4 + 0.6\alpha'_{\rho} \tag{11}$$

The COV for the independent random parameter α'_{ρ} for density was deduced from weight measurements of the studs as 0.03. The independent random parameter α'_k for wood was a subject of the evaluation. Trial values of 0.02 and 0.10 were used for the coefficient of variation. The random parameter, α_k, for the conductivity of timber was found according to the method shown in Equation (10).

The random parameter, α_c, for the specific heat of wood was also the subject of the evaluation. Trial values of 0.02 and 0.10 were used for the COV.

The COV of the elastic modulus of the wood studs was deduced as 0.013 from deformation measurements [14,20] of all studs prior to the construction of the walls. It was not necessary to use accurate values for the COVs for the tensile and compression strengths of wood because these properties had little effect on structural collapse. Collapse was caused by buckling which is a function of the elastic modulus. Consequently, a COV of 0.013 was adopted arbitrarily for these strength properties.

The loads were 8.0 kN blocks of steel. One block was placed on the top of each stud. There was no variation and, hence, the loads were deterministic.

The fire variables, although dominant, were assumed not to be random because the experiments used standard fires which were undertaken in accordance with the standard, AS1530 [16]. The aim was to have reproducible fires and, hence, fire variables did not vary significantly. The fire variables were modeled deterministically.

Two sets of simulations were undertaken in the evaluation of the COVs of the thermal properties of wood. In the first set, 10 simulations to failure were undertaken to demonstrate the sensitivity of temperature plots to the coefficient of variations of the independent random parameters for properties of wood. The plots resulting from these simulations are shown as dotted lines in Figure 8. The plots of measured temperatures are shown with thin continuous lines. Anomalous plots are indicated with asterisks. These plots were obtained with the surface thermocouples exposed. The other plots were obtained from surface thermocouples which were covered with thin pieces of calcium silicate, in accordance with the standard AS1530.4 [16], to shield against direct exposure to radiation and thus obtain a better measurement of surface temperature. Because of the expense and time in undertaking experiments, plots of measured temperatures are limited. However, the few plots do provide an indication of the COVs which is better than conjecture without any experimental evidence. The simulations with a COV of 0.02 gave the best comparisons between the ranges in predicted and experimental plots. A COV of 0.10 appears to be too large. It is apparent that the variations in thermal properties of wood are small and more likely to be around 0.02.

In the second set 100 simulations were undertaken for a COV of 0.02 and another 100 for a COV of 0.10 for the independent random parameters for the conductivity, density and specific heat of wood. From the recorded times-to-failure the cumulative probabilities of failure were plotted as shown in Figure 9. It is apparent that coefficients of variation as large as 0.10 produce a cumulative probability plot that would not lead to the reproducible times-to-failure that were obtained in the wall furnace experiments. Figure 9 thus provides further evidence that the variation of the thermal properties of wood is small, and is likely to be approximately 0.02.

To some extent, the conclusion that the COVs of the thermal properties of wood are small, approximately 0.02, is expected from the consistency of the constituents of cellulose and lignin in wood among many species [31]. It is apparent that although mechanical properties of wood are highly variable [28,29], the thermal properties of conductivity and specific heat are not. The variability of the mechanical properties is affected more by the variation in growth characteristics, such as knots, rings and splits, than by variations in chemicals in cellulose and lignin.

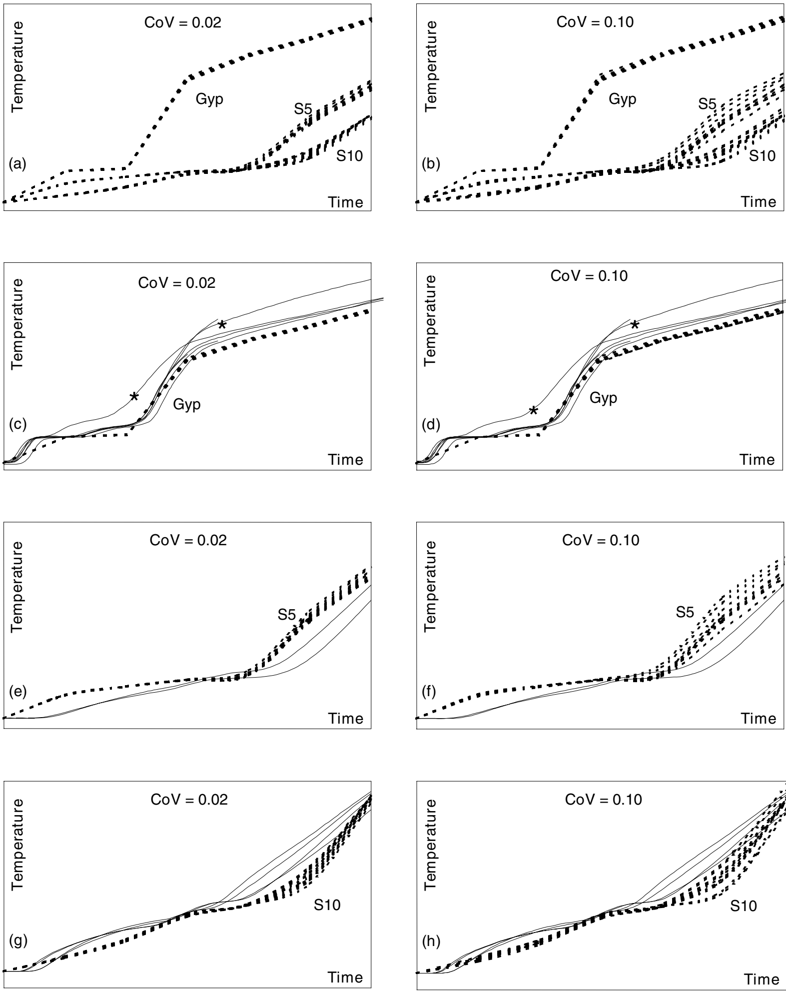

Figure 8. *Temperature vs. time for different COVs: (1) dotted lines refer to model predictions and continuous lines refer to measured temperatures; (2) COV refers to the coefficient of variation of the random parameters for the specific heat and thermal conductivity of timber; (3) Gyp, refers to temperature measured on the cavity facing surface of gypsum board on the fire side; (4) S5 and S10 refer to thermocouples in the studs and the positions for which are shown in Figure 7; (5) plots marked with asterisks are anomalous and are explained further in the text.*

The practical implication of these low COVs for thermal properties is that the time-to-failure of loadbearing wood-framed walls in standard fire tests will vary little provided that studs are selected so that the variation in the elastic modulus wood in compression is small (COV less than 0.013). Hence,

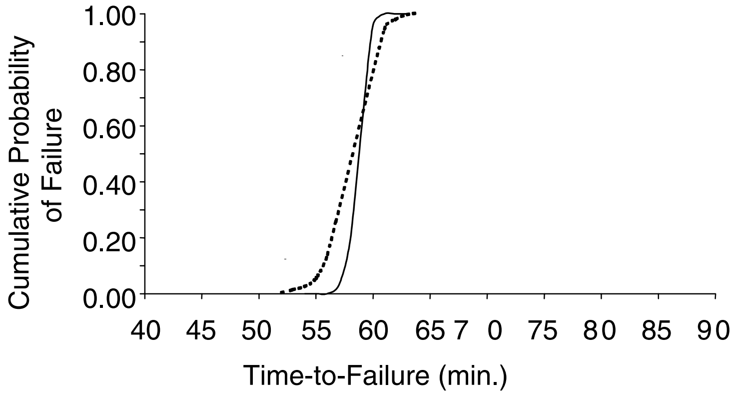

Figure 9. *Cumulative probability of failure with time for wood-framed wall with controlled selection of studs: —— CoV for specific heat and conductivity of timber = 0.02; - - - - CoV for specific heat and conductivity of timber = 0.10.*

the practice of testing only one wall in a standard fire test to obtain a measure of fire resistance can provide a consistent and arguably fair basis for comparing the fire resistances of alternative wall constructions. The proviso for consistency and fairness is the selection of wood with an elastic modulus with a low COV which is easy because of the availability of wood grading machines that measure elastic modulus. In other types of construction, for example concrete, as many as 20 tests are required to establish a fair measure of compression strength. There is considerable variation in the 20 measurements. The second lowest measurement (the five percentile value) is adopted as the fair measure.

THE CUMULATIVE PROBABILITY DISTRIBUTION OF FAILURE TIMES OF WALLS SUBJECTED TO STANDARD FIRES AND REAL LOADS

It is desirable to know the variation of failure times for walls exposed to standard fires and loads with realistic COVs. It is also desirable to know the variation of failure times resulting from the removal of the controls on the selection of studs used to minimize the COV of the elastic modulus of wood discussed in the previous section; that is, when the only control is the selection of studs from one strength grade. The low variation in failure times for walls exposed to standard fires and with specific controls on loads and studs does not demonstrate the reliability of fire resistance provided by walls. For example, if the statistically expected failure time for a wall was 1.0 h and the COVs in failure times created by standard fires and real loads was 0.25, significant failure times would range between 30 and 90 min. The large size of this variation would demonstrate irrationality of designing on the basis of fire ratings which imply that standard tests can ensure that walls can prevent the spread of fire for some definite period. It would be more rational to require walls to prevent fire spread within some small probability of failure for the required period of time.

As for the previous section, standard fire was considered to be deterministic. The same assumptions and properties for gypsum board were adopted. The same independent random parameters were adopted for the specific heat and conductivity. The COV for the density of wood to strength grade F8-AS1720.1 was deduced [30] from measurements to be 0.10 and that value was adopted. In the wall furnace experiments [14,20], loads were shared by three studs. The COV for the average density of three studs, each with a COV of 0.10, can be shown to be approximately 0.06. Similarly from measurements [30], the COV for the average elastic modulus of three studs was deduced as 0.07. The same COV was also adopted for the tensile and compression strengths because their values had little effect on the time-to-failure.

From structural design loads given in the loading code, AS1170.1, and an estimated mean arbitrary-point-in-time live load of 1.0 kPa, it can be shown that the ratio between live and dead loads for the studs in a lower story wall in a two-story residential building is approximately 40%. The live load in a fire should be taken as an arbitrary-point-in-time value, that is a typical value, because only one extreme event should be considered at one time [4]. In this evaluation, the extreme event is the fire. Considering more than one extreme event is far too conservative. A lognormal probability distribution with a COV of 0.7 was adopted for the live load [23]. A lognormal distribution with a COV of 0.1 [23] was adopted for dead load.

The probability distributions for all independent random variables was lognormal, unless otherwise mentioned.

One hundred simulations were undertaken. In all of the simulations, the mode of failure was structural collapse. The resulting cumulative probability distribution is shown as the dashed line in Figure 10. The plot from Figure 9 is repeated for comparison. The COV computed for the dashed line was 0.12. It can be seen that despite an expected failure time of 60 min, the time of failure is significant at 50 min when realistic loads and wood mechanical properties are considered. However, the variation in failure times is not so large as to make specification of fire resistance periods without some control on failure probability, meaningless.

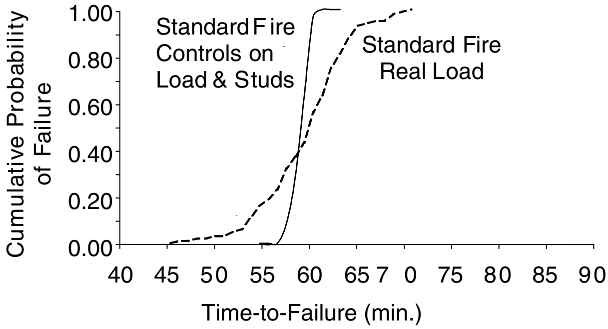

Figure 10. *Comparison of the cumulative probabilities of failure with time for wood-framed wall with a realistic variation in mechanical properties and loads, subjected to standard fire [16].*

THE CUMULATIVE PROBABILITY DISTRIBUTION OF FAILURE TIMES OF WALLS SUBJECTED TO REAL FIRES AND REAL LOADS

Advances in fire safety engineering should be focusing on, where possible, real fire scenarios. Insights to the failure of wood-framed walls in real fire scenarios were sought. The simulations in the previous section were repeated except the standard fire was replaced with a real fire model [18]. The model gives the fire temperature as a function of the basic variables of ventilation, fuel quantity and heat loss through wall, floor and ceiling boundaries. An enclosure size of 3.0 m height and a floor plan of 5.0×4.0 m was adopted. Variation in the enclosure dimensions was not considered because it is believed that enclosures can be built accurately, with little variation to the dimensions intended. Furthermore, variations between enclosures in a building is an architectural choice which is subjective and is thus difficult to define. The aim in the simulations described in this section was to investigate probability of failure for a given enclosure. All live load was assumed to be cellulosic fuel. For similar reasons given in the previous section of this paper, an arbitrary-point-in-time live load of 1.0 kPa was adopted instead of normal design values. Assuming that the load of 1.0 kPa on the floor comprises mainly furniture, it can be shown that the average fuel per unit area over the entire interior surface area of the enclosure, as required by the model, is approximately $20\,\mathrm{kg\,m^{-3}}$. Not all fuel is burnt in a fire. A burning efficiency of 50% was assumed and thus the fuel load that was assumed to be thoroughly burnt was $10\,\mathrm{kg\,m^{-3}}$. The resulting plot for fire gas temperature versus time is given in Figure 11. The probability distribution and COV for the fuel was the same one adopted for the live load – lognormal and 0.7, respectively.

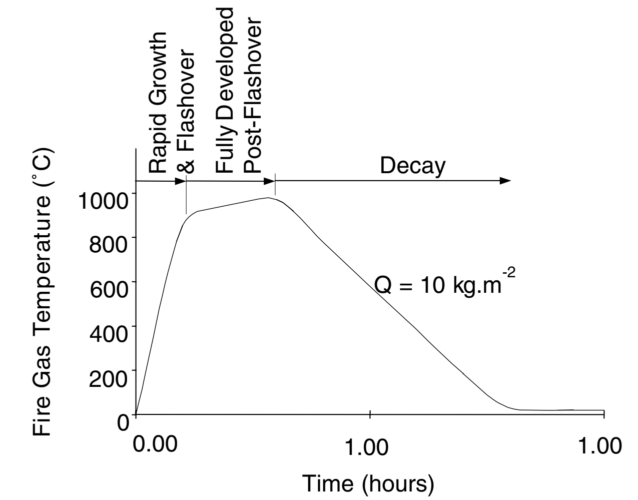

Figure 11. *Real fire severity used in evaluation.*

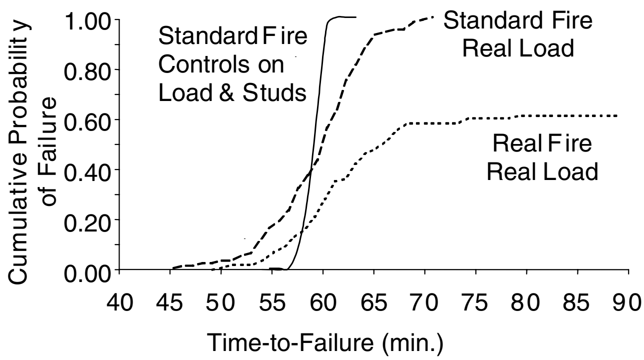

Figure 12. *Comparison of the cumulative probabilities of failure with a realistic variation in mechanical properties and loads, subjected to real fire.*

The cumulative probability plot for the wall with real load and subjected to real fire is shown in Figure 12. One hundred simulations were undertaken and, in all of these, the mode of failure was structural collapse. The previous plots in Figures 9 and 10 are repeated for comparison. The COV for the failure time for the wall with real load subjected to real fire was 0.12. The probability of failure was not significant until 55 min which was less than 60 min for the wall experiment in standard test conditions, but more than the 50 min for the standard fire exposure with real load. The case involving realistic fire and load shows that the probability of eventual fire spread is limited and by no means definite as is the case for standard fires. This conclusion is largely due to the nature of the probability of realistic events which are not definite; that is, not deterministic.

A summary of all data and results that have been discussed in this paper is given in Table A-1.

CONCLUSIONS

A probability of failure model has been developed to aid the application of new performance-based fire safety regulations to wood-framed wall construction. Evaluations have been undertaken and support its validity. Applications have estimated coefficients of variation, COVs for thermal and mechanical properties of materials in wood-framed walls in fire. Unlike mechanical properties of wood, which are highly variable, the thermal properties appear to be remarkably consistent. For a given density, the COVs of the thermal properties of timber appear to be approximately 0.02 compared with the COVs for mechanical properties which range between 0.15 and 0.40. The reason for the consistency of thermal properties of timber appears to be the dependency of the properties on the constituents of wood, which are consistent; namely, cellulose and lignin. The thermal properties appear to have little dependence on growth characteristics such as knots and splits which are responsible for the high variability of mechanical properties in wood. The practical implication of the low variation thermal properties is that standard fire tests on loadbearing wood-framed walls can be made consistent and fair if studs are selected within a narrow range of elastic moduli.

Walls made from wood, which is randomly selected from graded supplies (Grade F8 [30,32]), leads to a significant coefficient of variation in the time-to-failure of 0.12. However, this variation is moderate because probability analysis has shown that walls, which are constructed in accordance with building regulations, will have fire resistance levels that are not significantly less than intended.

Advances in fire safety engineering should be focusing on, where possible, real fire scenarios. Insights to real fire scenarios have been given. Walls in real fire have some maximum probability of failure, less than 1, independent of time. That is, in reality and contrary to what may be assumed from standard fires, the occurrence of fire does not necessarily lead to walls collapsing. For the application demonstrated in this paper, the variation of failure times, for those walls which failed, was similar to the variation failure times for the walls in standard fire. Further investigation is required to establish the variability of failure times of walls in real fire compared with failure times in standard fires in general.

Future research should be undertaken to increase the speed of the probability of failure model with the use of efficient numerical routines such as importance sampling functions to make probability analysis more convenient.

Due to the extensiveness of service penetrations and the suspected poor control of their fire resistance, particularly during construction, surveys and research into the reduction of the times of failure due to service penetrations in walls and other construction details should also be undertaken.

NOMENCLATURE

c	specific heat ($\mathrm{J\,kg^{-1}\,C^{-1}}$)
c_i	coefficient for the ith term in the polynomial expression for determining $\beta_{y/x_{20}}$
b_i	exponent of the ith term in the polynomial expression for determining $\beta_{y/x_{20}}$
C	confidence level
COV	coefficient of variation
CPF	cumulative probability function
FOSM	first order second moment method
k	thermal conductivity ($\mathrm{W\,m^{-1}\,K^{-1}}$)
k_g	thermal conductivity of gas ($\mathrm{W\,m^{-1}K^{-1}}$)
k_s	thermal conductivity of solid ($\mathrm{W\,m^{-1}\,K^{-1}}$)
N	required number of simulations
p_f	probability of failure
p_i	probability of failure in failure mode i independent of other modes of failure.
$R^*_{x_{20}}$	a random number between 0 and 1 used to generate $\alpha'_x$and hence x_{20}
x_{20}	value of independent random variable x at 20°C
$\bar{x}$	expected value of independent random variable x
$\bar{x}_{20}$	expected value of random variable at a temperature of 20°C
y_{20}	value of dependent random variable y at 20°C
α'_x	random parameter with a mean of 1.00
α_y	random parameter for variable y, including both the independent and dependent characteristics
α'_y	random parameter for the independent characteristics of variable y
$\beta_{y/x_{20}}$	parameter for dependence on the value generated for x_{20}
ρ	density ($\mathrm{kg\,m^{-3}}$)
π_g	proportion of total volume of material occupied by gas
π_s	proportion of total volume of material occupied by solid

APPENDIX: SUMMARY OF PROPERTIES AND OTHER DATA

This appendix summarizes data, in Table A-1 and Figures A1–A7, that was used in the research described in this paper.

Table A-1. Summary of values adopted for random variables.

		COV of α' (random parameters)		
Variable	**Mean at 20°C**	**Standard Fire Controlled Loads and Properties**	**Standard Fire Real Loads Real Properties**	**Real Fire Real Loads Real Properties**
Fire variables				
Temperature		0.0	0.0	0.0
Emissivity	0.60	0.0	0.0	0.0
Fuel	$10\,\text{kg m}^{-2}$	NA	NA	as for live load
Enclosure = H × B × D (m^3)	3.0 × 5.0 × 4.0	NA	NA	0
Opening = H × B (m^2)	1.2 × 2.0	NA	NA	0
Thermal Properties of Wood				
Density, ρ	$470\,\text{kg m}^{-3}$ *Figure A-1	0.03	0.06	0.06
Specific heat	Figure A-2	0.02	0.02	0.02
Conductivity	$(0.4 + 0.6\alpha_\rho) \times k(T)$ $k(T)$ in Figure A-3	0.02	0.02	0.02
Thermal Properties of Gypsum Board				
Density	810(kg m^{-3}) *Figure A-1	0.02	0.02	0.02
Specific heat	Figure A-2	0.02	0.02	0.02
Conductivity	$(0.1 + 0.9\alpha_\rho)$ *k in Figure A-3	0.02	0.02	0.02
Mechanical Properties of Timber				
Compression strength	24 MPa *F_c in Figure A-5	0.013	0.07	0.07
Tensile strength	24 MPa, *F_t in Figure A-4	0.013	0.07	0.07
Elastic modulus	7400 MPa *E in (Figure A-6 or Figure A-7)	0.013	0.07	0.07
Structural Loads				
Dead load	5.67 (kN/stud)	0	0.10	0.10
Live load	2.33 (kN/stud)	0	0.70	0.70
Total load	8.00 (kN/stud)	0	0.25	0.25

Notes: NA means not applicable, H = height (m); B = breadth (m); D = depth (m).

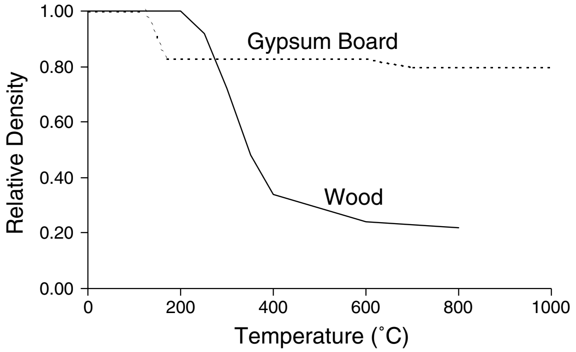

Figure A-1. *Relative densities of gypsum board [33] and wood [25] with temperature.*

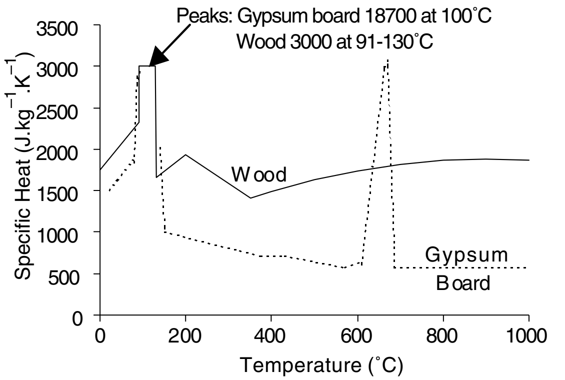

Figure A-2. *Specific heats of gypsum board [34] and wood [25] with temperature.*

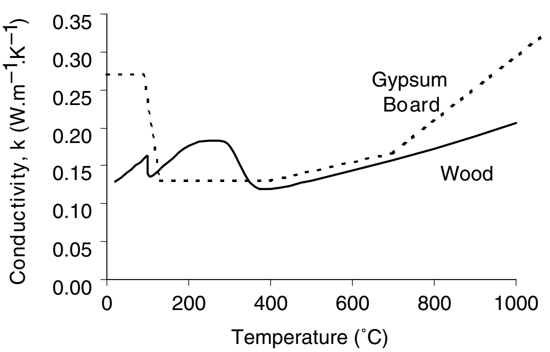

Figure A-3. *Conductivities of gypsum board [33,14] and wood [25] with temperature.*

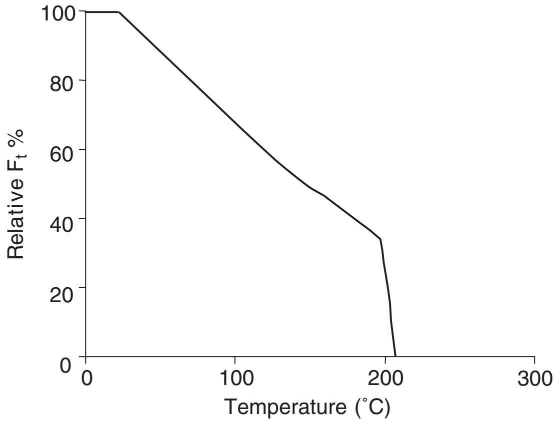

Figure A-4. *Relative tensile strength of timber vs. temperature [12].*

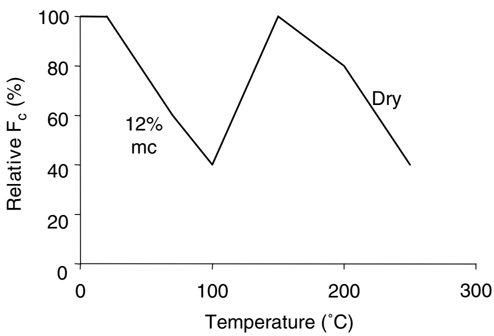

Figure A-5. *Relative compression strength of timber vs. temperature [26].*

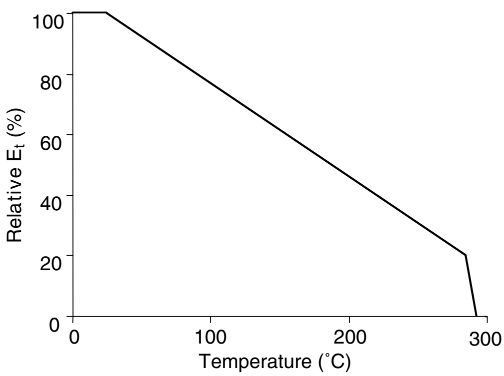

Figure A-6. *Relative elastic modulus of timber in tension vs. temperature [21].*

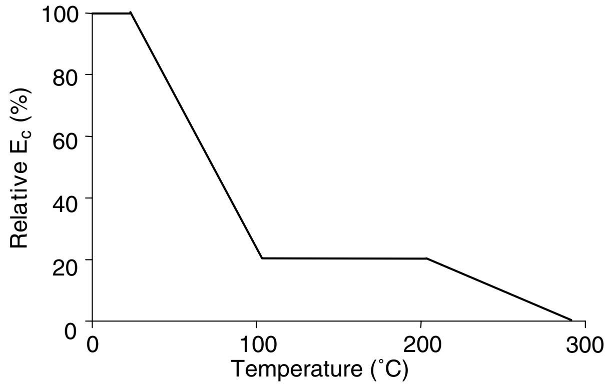

Figure A-7. *Relative elastic modulus of timber in compression vs. temperature [26].*

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