Structural Fire Design: The Role of Time Equivalence

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ABSTRACT

This paper describes the process of designing structures for fire resistance, emphasizing the importance of using realistic design fires. The concept of equivalent fire severity is described and illustrated with a number of examples. Equivalent fire severity is useful where standard fire resistance test results are available, but time equivalent formulae may be very inaccurate beyond the range of data for which they were calibrated. It is much more accurate to perform structural fire resistance calculations from first principles.

KEYWORDS: Fire, structure, severity, time equivalence, steel, concrete, wood.

INTRODUCTION

The move towards performance based codes has forced a re-assessment of structural design for fire. In the days of prescriptive codes, design of structural members was little more than simply providing an assembly that met the code requirement for 30, 60, or 90 minutes fire resistance rating, using laboratory or proprietary listings. New calculation methods are now available, which create opportunities but raise a number of problems, as discussed in this paper.

OBJECTIVES

The main objectives of any fire safety design are to provide life safety in the building of origin, to prevent the fire spreading, and to protect property. These objectives are spelled out clearly in performance based codes which vary somewhat from country to country. The New Zealand requirements are described by Buchanan [3]. To assist in meeting these objectives, structural members must perform two functions; they need integrity and insulation to contain fires, and structural stability to prevent structural collapse.

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Containment is necessary to prevent spread of fire to other firecells on the same floor, fire spread to other stories of the same building, and fire spread to other buildings. Structural collapse must be prevented where occupants or fire fighters remain inside the building, where collapse would cause fire spread, or where property protection is required.

The most straightforward design criterion is for each firecell to be designed to resist a complete burnout. That will meet all of the objectives stated above. In theory, design can be for a lesser fire exposure if property protection is not considered important, and rescue and evacuation can take place in a shorter time, or if fire fighter intervention is expected to suppress the fire before burnout. The decision on this must be made by code writers in different countries. This paper will concentrate on design for a complete burnout of the firecell of origin.
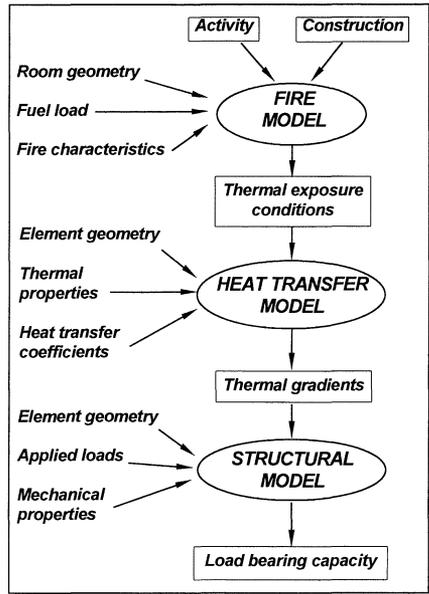

FIGURE 1. Flow chart for structural fire design.

DESIGN METHODS

The traditional method of structural design for fire is to use results of full scale fire tests (or a listing based on test results) to provide the fire resistance rating prescribed by the building code. Full scale fire tests use a standard time temperature curve, based on ISO 834 or ASTM E119 standards, with minor differences from country to country,

The other end of the spectrum is a full calculation design, using a fire model to predict likely temperatures in the firecell for the duration of the fire, a thermal model to predict the temperatures in the exposed member, and a structural model to predict the load carrying capacity of the structure throughout the fire. The structural model is not necessary for non load bearing elements. Even with such calculation methods, some full size fire resistance tests are still necessary to assess integrity of construction and to calibrate the thermal and structural models.

A compromise between these two methods is to use knowledge of the fire load and ventilation to characterize the expected fire as an equivalent time of exposure to the standard test fire. This enables an assessment of expected fire severity to be used with the results of standard fire resistance tests. These methods are discussed in more detail below.

FULL CALCULATION DESIGN

The full calculation design method has three important components, the fire model the thermal model and the structural model, as shown in Figure 1 with the required input.

Fire Model

The fire model requires the derivation of a time temperature curve for the expected fuel load and ventilation in the firecell. The most commonly used time-temperature curves are the Swedish curves developed by Magnusson and Thelandersson [10] which give temperatures for various combinations of fuel load and ventilation, as shown in Figure 2. These curves are useful, but some of the underlying assumptions have been questioned [14]. The COMPF-2 computer program [1] calculates compartment temperatures from a heat balance assuming that the firecell is a well mixed single zone reactor, with heat release rate governed either by the available ventilation or by the fuel surface area. Both the Swedish curves and COMPF-2 take the wall and ceiling construction into account to assess the heat loss by conduction into the materials, resulting in higher temperatures in well insulated compartments.

These and other models have some severe limitations, including the following important factors which will be included in a model to be developed at the University of Canterbury. The surface area to volume ratio of charring fuel, or the surface area of liquid fuel, has a major impact on whether the fire is ventilation or fuel bed controlled, and this can change during the fire. COMPF-2 has the option of "pessimizing" the pyrolysis rate, to give the maximum possible rate of heat release at each time step, resulting in time temperature curves of the shape shown in Figure 3, with a very steep decay phase after all of the fuel has burned. The figures in brackets are the opening factor ($m^{0.5}$) and the fuel load (MJ/m^2 floor area), respectively.

COMPF-2 also allows for fuel controlled burning, for the special cases of wood cribs and sticks, which produces a wide range of curves as shown in Figure 4, for various stick sizes. Other more realistic fuels need to be considered, both in the burning phase and the decay phase of the fire.
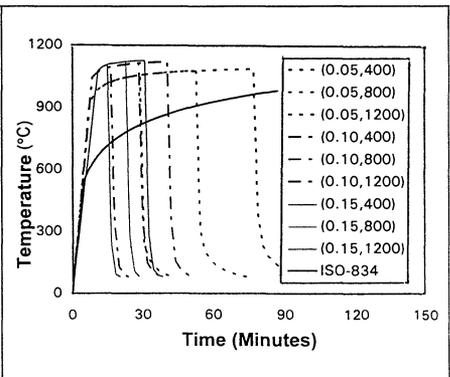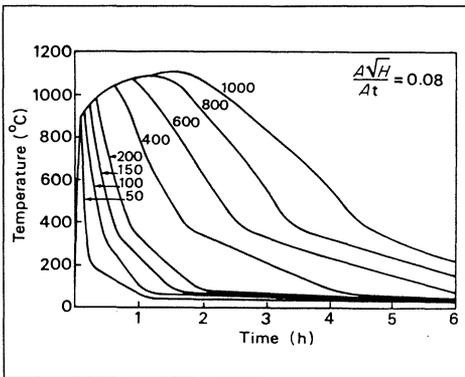

FIGURE 2. Swedish time temperature curves.

FIGURE 3. Time temperature curves from COMPF-2 assuming pessimized pyrolysis.

Many high fire loads such as solid wood products or bulk paper have low rates of heat release because of the low surface area exposed to radiation. Magnusson and Thelandersson showed that the temperatures at the end of the fire can be important for some types of structures, but their curves were more like a cooling phase after all the fuel had been burned. Figure 5 shows how the decay phase temperatures can change, assuming a constant rate of pyrolysis until two thirds of the fuel is consumed, followed by a linear or parabolic (time squared) decrease in the rate of pyrolysis. Exposure of steel and concrete members to these curves shows that there is very little difference for concrete, but the dotted decay curves reduce the equivalent fire severity for steel members by over 10% as shown by Thomas [14]. The difference between steel and concrete results from the much larger thermal mass and high thermal conductivity in steel structures.
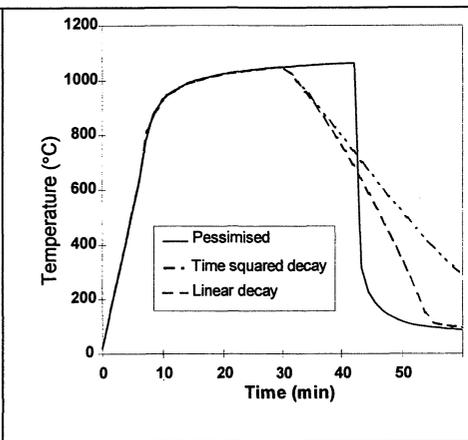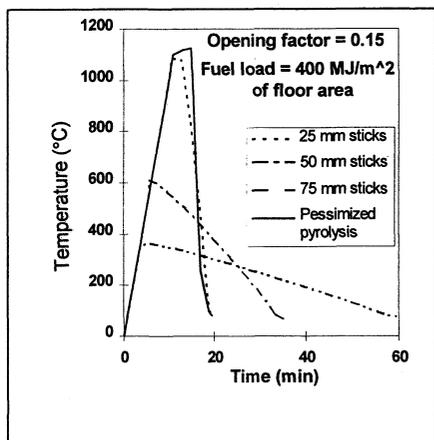

FIGURE 4. Time temperature curves from COMPF-2 for different stick sizes.   **FIGURE 5. Time temperature curves from COMPF-2 for different decay rates.**

The aspect ratio of the compartment is important. Recent tests in a long compartment with only one opening by Kirby *et al.* [8] show how a fire can burn progressively from the window end, with large horizontal variations in temperature. This might be quite different with more than one opening, especially if a blowing wind could cause cross ventilation. Ceiling openings will also have a major impact on burning rates, but have not been properly included in any current models.

Another important parameter is the percentage of pyrolysates burned inside the compartment. For highly ventilation controlled fires a significant amount of the fuel leaves the compartment unburned, either burning in flames outside the openings, or remaining in smoke. Programs such as COMPF-2 require a guess of this percentage which is difficult to estimate.

Thermal Model

Temperatures in structural assemblies exposed to fire can be calculated by a range of methods. Simple hand calculations are available assuming one dimensional heat transfer or a lumped mass system. Computer based finite element or finite difference methods can use a fine mesh to calculate thermal gradients throughout a cross section. Problems include finding accurate

temperature dependent thermal properties of materials and calculating convective and radiative heat transfer at surfaces and within cavities. Specific fire engineering programs are available, such as TASEF [13] and heat transfer modules of commercial finite element stress analysis programs can also be used. None of these programs include the effects of moisture movement in materials such as wood, gypsum plaster or concrete.

Structural Model

In theory, structural design for fire is just a matter of following normal structural design procedures under cold conditions, making allowance for the elevated temperatures. Simple hand methods can be used where the structure is simple and the elevated temperature is well defined or uniform over the cross section. This becomes more complicated where there are steep temperature gradients, flexural continuity or axial restraint, and there is time dependent behaviour such as creep. Moisture can affect mechanical properties of some materials such as wood and concrete. It is difficult to obtain accurate mechanical properties for some materials at elevated temperatures. None of the models allow for spalling of concrete or degradation of applied fire protection.

Despite these difficulties, a number of special programs and commercial stress analysis programs have been used successfully to predict structural behaviour in fire, taking into account the expected loads on the structure at the time of the fire. Loads at the time of the fire may be quite different from design loads before (or after) the fire. Thomas [14] has described a finite element structural model for light timber frame structures.

TIME EQUIVALENCE

The time equivalence concept is used to relate the expected real fire exposure to the standard test fire, to allow the use of published fire resistance ratings. Early attempts at time equivalence compared the area under time temperature curves as described by Drysdale [6], where the real fire shown in Figure 6 is considered to have equivalent severity t_e to the standard fire if the areas A_1 and A_2 above the reference temperature are equal.
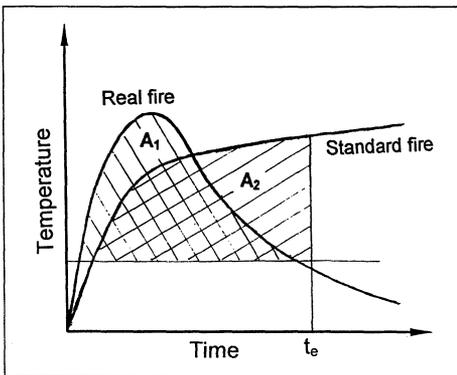

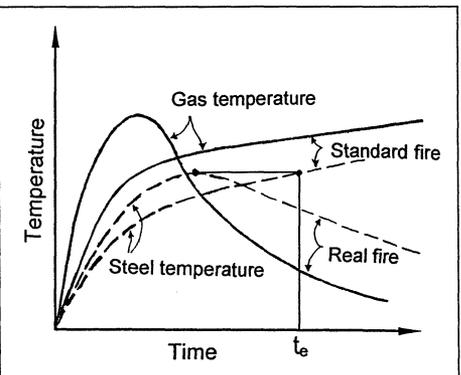FIGURE 6. Equivalent fire severity on equal area basis.

FIGURE 7. Equivalent fire severity on temperature basis.

The equal area concept has little theoretical significance because the units of area are not meaningful. This concept can give a very poor comparison of heat transfer for fires with different shaped time temperature curves, because heat transfer from fully developed fires is mostly by radiation, the balance by convection. Radiative heat transfer is proportional to the fourth power of the absolute temperature, so heat transfer in a short hot fire may be much greater than in a long cool fire, even if both have equal areas under the time temperature curves.
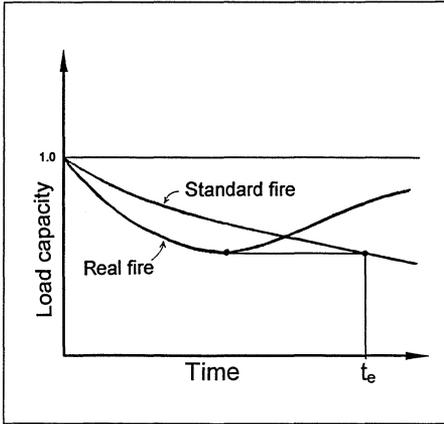
A more realistic concept, used by Law [9], Pettersson *et al.* [12] and others, is to define the equivalent fire severity as the time of exposure to the standard fire that would result in the same maximum temperature in a protected steel member as would occur in a complete burnout of the firecell. This concept is shown in Figure 7.

Alternatively, the equivalent fire severity is the time of exposure to the standard fire that would result in the load bearing capacity being the minimum occurring in a complete burnout of the firecell. This concept is shown schematically in Figure 8.

FIGURE 8. Equivalent fire severity on load capacity basis.

Formulae

The most widely used time equivalent formula is that published by the CIB W14 group [5] based on the size of vertical window openings and the fuel load. Horizontal roof openings are not included. The equivalent time of exposure to an ISO-834 test t_e (min.) is given by:

$$t_e = cwQ_f \tag{1}$$

where: Q_f is the fuel load (MJ/m^2 of floor area)
$\quad c$ is a parameter to account for different compartment linings (min m$^{2.25}$/ MJ)
$\quad w$ is the ventilation factor (m$^{-0.25}$) given by:

$$w = A_f \Big/ \left(A_w A_t H_v^{1/2} \right)^{1/2} \tag{2}$$

where: A_f is the floor area of the compartment (m^2)
$\quad A_w$ is the total window area (m^2)
$\quad A_t$ is the total area of the bounding surfaces of the compartment (m^2)
$\quad H_v$ is the height of the windows (m)

The CIB formula has a limitation of only being valid for compartments with vertical openings in the walls. This formula was later modified and incorporated into the Eurocode [7] as:

$$t_e = k_b\, w\, Q_f \tag{3}$$

where k_b (min m^2/ MJ) replaces c and the ventilation factor w is altered to allow for horizontal roof openings, given by:

$$w = \left(\frac{6.0}{H_c}\right)^{0.3}\left[0.62 + \frac{90(0.4 - \alpha_v)^4}{1 + b_v\alpha_h}\right] > 0.5 \tag{4}$$

where: H_c is the compartment height (m)

$$\alpha_v = A_v/A_f \qquad 0.05 \le \alpha_v \le 0.25 \tag{5}$$
$$\alpha_h = A_h/A_f \qquad \alpha_h \le 0.20 \tag{6}$$
$$b_v = 12.5\ (1 + 10\ \alpha_v - \alpha_v^2) \tag{7}$$

A_f is the floor area of the compartment (m^2)
A_v is the area of vertical openings (m^2)
A_h is the area of horizontal openings (m^2)

This formula, known as the Eurocode formula, is used in the structural Eurocodes and also in the German Standard DIN 18230. The derivation of the Eurocode formula has never been published. It is understood (Schneider, pers. com.) to have come from an empirical analysis of calculated steel temperatures in a large number of simulated fires computed by the German program "Multi Room Fire Code" (MRFC). An important difference from the CIB formula is that the equivalent time is now independent of opening height, but depends on the ceiling height of the compartment.

Values of the terms c and k_b are given in Table 1, where they depends on the compartment materials (roughly inversely proportional to the thermal inertia of the materials). The "general" case is that recommended for compartments with unknown materials. Note that the term c in the CIB formula has slightly different dimensions, and different numerical values to k_b in the Eurocode formula, because of the different ventilation factors.

Source	Formula	$\sqrt{k\rho c}$			
		>2500	720 - 2500	<720	General
CIB W14 [5]	CIB	.05	.07	.09	.10
Eurocode [7]	Eurocode	.04	.055	.07	.07
FEDG [4]	Eurocode	.045	.055	.08	.067
Kirby et al.[8]	Eurocode	.05	.07	.09	

k = thermal conductivity (W/mK) ρ = density (kg/m^3) c = specific heat (J/kg K)
TABLE 1. Values of c or k_b used in the time equivalent formulae

The values used in the examples in this paper are those given in the Fire Engineering Design Guide (FEDG) [4], also used in the New Zealand Building Code [11]. These values are slightly higher than those used in the Eurocode, based on recommendations of Barnett [2]. The bottom line of Table 1 shows the values recommended by Kirby et al. [8] after tests on large scale compartments with wood cribs showed that both the CIB and Eurocode formulae underestimate the fire severity, which could lead to unsafe designs.

Problems

There are a number of concerns about the use of time equivalent formulae. These are empirical formulae developed by regression analysis using the results of a selected number of tests or calculations. They have been developed for a certain range of structural steel sizes and thicknesses of insulation, but may not be appropriate beyond this range. They are not applicable to unprotected steel. Some of the data points in the regression may be for heavily protected steel members where maximum temperatures are far below those that would cause failure. It will be shown later how the equations are very poor for short hot fires. The time equivalent formulae are often used for other materials such as concrete or wood structures, but very little is known about their accuracy for these materials.

A major shortcoming of this method is that it ignores the effect of applied load on the structural member. A member with low stresses at the time of the fire has far more fire resistance than a highly stressed member. The critical design actions for most structures are load combinations involving snow, wind, earthquake, or extreme live loads, which are unlikely to be present at the time of a fire, giving increased fire resistance. A recent study by Thomas [14] based on the examples below, has shown that the linear dependence on fuel load is not accurate when using design fires produced from COMPF-2. When the fuel load doubles, the equivalent fire severity is less than double.

There is considerable debate about the ventilation factor. The ventilation factor in the CIB formula was based on many tests on very small compartments reported by Law [9], but did not allow for horizontal openings in the ceiling. The Eurocode formula gives similar results for typical small buildings, but the reason for dependence on the height of the firecell, not the height of the window opening, and the derivation of the ceiling opening component has not been published. Neither of these formulae has been verified for large or tall compartments.

Examples

Calculations for typical steel and concrete members show that the time equivalent formulae are unsafe in many cases. Results are given below for the following calculation procedure:

1. Select a structural member.
2. Estimate temperatures in the member exposed to the standard fire (by calculation or test).
3. Select a range of design fires.
4. Calculate temperatures in the member when exposed to each of the design fires.
5. Compare the time to maximum temperature with the standard fire exposure to obtain the equivalent fire severity as shown in Figure 7.
To use the more accurate method including the effects of load capacity:
6. Calculate the load carrying capacity throughout the standard fire.
7. Calculate the load carrying capacity throughout each of the design fires.
8. Compare the time to minimum load with the standard fire exposure to obtain the equivalent fire severity as shown in Figure 8.

This procedure was carried out for a range of members. The design fires are shown in Figure 3 obtained from calculations using a room 5 x 5 metres and 3 metres high, with three different

sizes of window opening. The fuel load varied from 100 to 1200 MJ/m^2 of floor area. The fire was assumed to be ventilation controlled throughout, using the pessimized pyrolysis rate to give maximum temperatures for the given ventilation, with 70% of the pyrolysates burned inside the room.

Temperatures within each member were calculated using TASEF. The concrete slab was 150mm thick with 20mm dia. reinforcing bars at 300mm centres and 20mm cover as shown in Figure 9. The concrete wall was 100mm thick with 20mm dia. reinforcing bars at 300mm centres placed centrally. The steel beam was a 360mm deep I-beam weighing 57kg/m, supporting a concrete slab and protected on three sides by a box of 16mm gypsum plasterboard. The steel column was a nominal 250mm deep universal column section protected on all four sides by a box of 16mm gypsum plasterboard as shown in Figure 10. The critical steel temperature for the steel and concrete members was taken as 500°C.
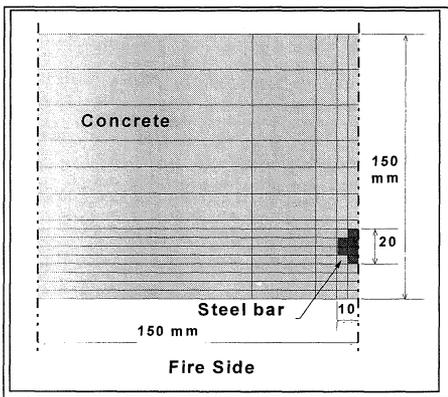

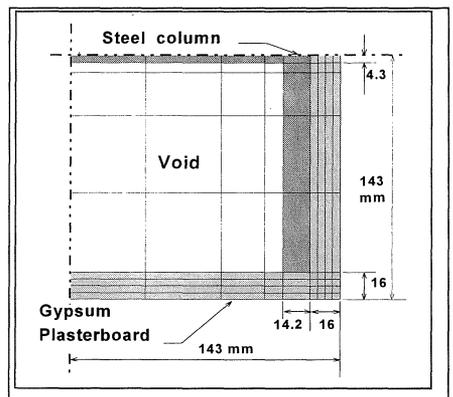FIGURE 9. Finite element grid for reinforced concrete floor.

FIGURE 10. Finite element grid for protected steel column (one quarter).

Figure 11 shows the results for the concrete floor slab and wall. The x-axis shows the equivalent fire severity calculated in accordance with the procedure described above, for the fires shown in Figure 3. The y-axis shows the equivalent fire severity from the Eurocode formula. If the formula was exact, all of the data points would be on the dotted 45° line. The solid line is a linear regression through the origin. The Eurocode formula underpredicts the fire severity in most cases, except for long duration fires.

Figure 12 is a similar graph for the steel members. It can be seen that the Eurocode formula is much worse for these steel members, particularly at the lower end of fire ratings. The formula severely underestimates the effect of hot short fires where there is very high radiant heat transfer to the structure.
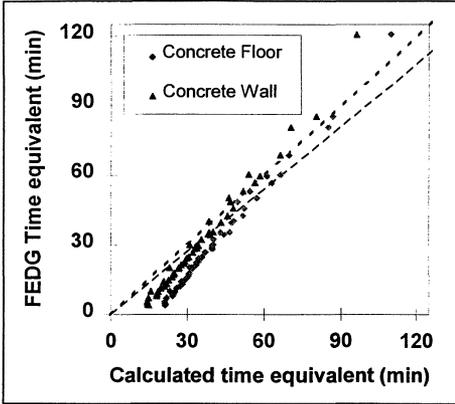
FIGURE 11. Comparison of calculated time equivalent with Eurocode formula for concrete members.
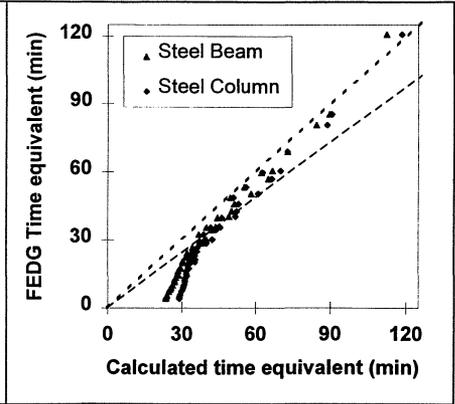

FIGURE 12. Comparison of calculated time equivalent with Eurocode formula for steel members.

Similar results are shown in Figures 13 and 14 for light timber framed walls and floors protected by gypsum plasterboard panels, where the Eurocode formula is very unconservative for floor joists and shows a lot of scatter for structural behaviour of walls. Figures 11, 12 and 13 were obtained by using steps 1 to 5 of the procedure described above. Figure 14 required the use of steps 1 to 8.
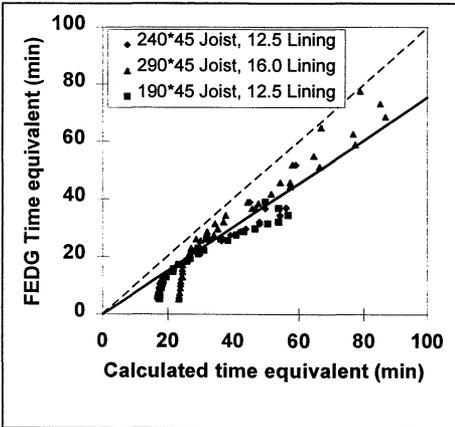

FIGURE 13. Comparison of calculated time equivalent with Eurocode formula for insulation failure of timber joist floors.
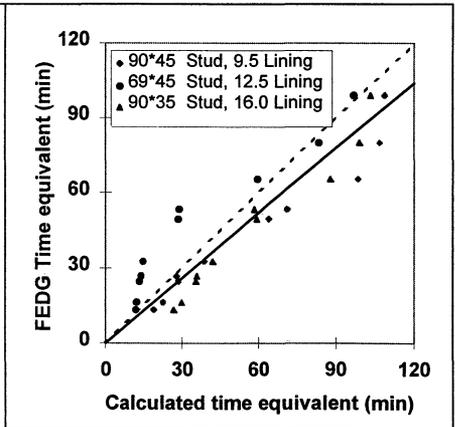

FIGURE 14. Comparison of calculated time equivalent with Eurocode formula for structural failure of light timber walls.

SAFETY FACTORS

Safety factors have been widely used in engineering design, in order to avoid failures. A more modern approach is to base design on characteristic values which represent extreme values rather than expected values of load and resistance, with partial safety factors (or load and resistance factors) to give a certain probability of failure. Robust probabilistic design methods for structures exposed to fires are not yet available, but it has become accepted to cut safety factors to minimum levels, on the basis that a severe fire is an extremely unlikely event, the design fire is based on the 80%ile or 90%ile fuel load and structural loads for fire are the "arbitrary-point-in-time" loads expected at the time of the fire. However, the smaller the safety factor, the more important to have accurate predictive equations without the unsafe bias shown in Figures 11 to 13. There is so much scatter in fire engineering predictions that an appropriate safety factor should be used with calculations, especially when using approximate methods such as time equivalence.

When time equivalent formulae are used in building codes, they should be made conservative for two reasons; to avoid unsafe designs, and to encourage the use of more accurate fire engineering design procedures.

CONCLUSIONS

- Computational tools are available for structural fire design from first principles, for structural members of any material exposed to real fires.

- Time equivalent formulae have provided a useful but rather crude method of comparing real fire exposure with standard test fires.

- Time equivalent formulae have been developed for protected steel members exposed to certain real fires, but are shown to be unsafe for some other types of fires and other materials.

- When used in building codes, time equivalent formulae should be made very conservative, to avoid unsafe designs, and to encourage the use of more accurate fire engineering design procedures.

- Design from first principles using realistic design fires is the recommended method of designing structures for fire resistance.

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