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LIGHT TIMBER-FRAMED WALLS EXPOSED TO COMPARTMENT FIRES

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SUMMARY

The objective of this project was to determine the equivalent time of exposure (to the ISO-834 standard fire), for a number of light timber-framed wall assemblies exposed to a range of time temperature curves characteristic of compartment fires.

This analysis considered only the thermal behavior of the walls. Load bearing performance will be the subject of the next phase of the study.

The overall method was as follows.

(1) The data from four full-scale ISO-834 wall tests were used to calibrate a finite element model of the wall assembly developed using the TASEF program. Subsequently the model was validated using test on walls with different layouts.

(2) A set of characteristic time-temperature curves for compartment fires was developed using the computer program COMPF-2, a post-flashover compartment fire model.

(3) The finite element models of the walls developed in Step 1 were subjected to the time temperature curves developed in Step 2.

(4) The temperatures within the wall assembly found in Step 3 were compared with the measured temperatures from Step 1 to obtain the equivalent time of exposure for each time temperature curve.

(5) The equivalent time of fire exposure from Step 4 was compared with the CIB formula for time equivalence used for steel structures.

INTRODUCTION

Previous work by the principal author [1] on the feasibility of multistorey light timber-framed buildings highlighted the need for fire engineering design of load bearing timber-framed walls. To promote the use of light timber-framing in multi-unit residential or motel-hotel type buildings, a simple formula for the design of fire resistant light timber-framed walls is highly desirable. Collier[2] has developed a design method for light timber-framed walls exposed to the ISO-834 standard test, but the authors are aware of no previous studies considering real compartment fires.

A widely used formula[3] is available to relate the equivalent time exposure of protected steel members to a compartment fire to exposure to a furnace test. The concept of equivalent time is described in Schleich[4]. This formula depends on the ventilation parameters of the compartment and the fuel load and is given by:

$$t_e = cwQ_f \qquad (1)$$

where:

t_e is the equivalent time of exposure to an ISO-834 test (minutes).

c is a parameter to account for different compartment linings. It is roughly inversely proportional to the square root of the thermal inertia of the compartment linings. The thermal inertia is the product of density, specific heat capacity and thermal conductivity of the lining material.

Q_f is the fuel load (MJ/m^2)

w is the ventilation factor

$$w = A_f(A_w A_t H^{1/2})^{1/2}$$

where:

A_f is the floor area of the compartment (m^2)

A_w is the total window area (m^2)

A_t is the total area of the bounding surfaces of the compartment (m^2)

H is the height of the windows (m)

The paper attempts to show whether this formula is valid for the thermal behavior of light timber-framed walls clad with gypsum plasterboard.

Throughout this paper values for the time equivalent calculated using the Equation 1 are referred to as "calculated" values, and those predicted using the computer models are referred to as "predicted" values.

Modelling of Furnace Tests Using TASEF

TASEF is a two dimensional finite element, heat transfer program developed by the Swedish National Testing Institute[5]. It is specifically designed to predict heat transfer through materials subject to fire exposure. The program uses a forward difference time integration scheme. It can model voids or cavities within an assembly, but cannot model mass transfer or ablation of materials. Mass transfer, particularly of water, does occur in light timber-framed walls, but has little effect at temperatures over about 120 °C. Ablation of gypsum plasterboard, which occurs at temperatures over 1000 °C, is erosion of the exposed surface, reducing the thickness of the board.

The model was calibrated using four furnace test results. The results were supplied by the Building Research Association of New Zealand (BRANZ), who operates the only full-size fire test furnace in New Zealand.

Each test specimen consisted of one layer of gypsum plasterboard nailed to each side of timber studs spaced at 600 mm centres. The walls were 3.0 m square and subjected to the ISO-834 standard fire test. The four tests are outlined in Table 1.

Table 1. Parameters of Furnace Test Results Used for Model Calibration

Test Number	Lining Thickness	Stud Size (mm)
FR1582A	9.5 mm each side	69*45
FR1582B	9.5 mm each side	90*45
FR1611	12.5 mm each side	69*45
FR1777	16 mm each side	90*35

The positions referred to in the text are shown in Figure 1. Positions 2, 3, 4 and 5 are thermocouple locations. The output from these thermocouples was used in the calibration of the model.

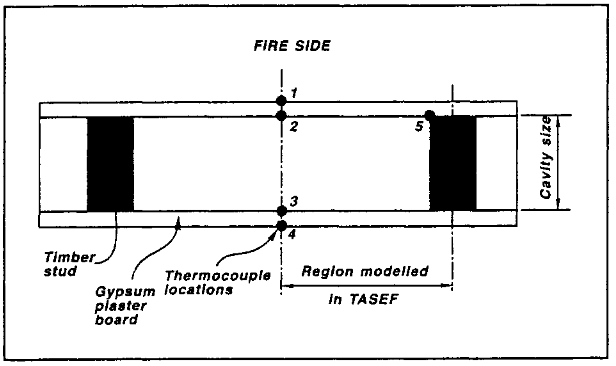

Figure 1. Positions in Test Wall Referred to in Text.

Thermal Properties of Wood and Gypsum Plasterboard

Values of thermal conductivity for wood and gypsum plasterboard are shown in Figure 2. The values for wood are those derived by Fredlund[6], but doubled between 60 °C and 120 °C to allow for the increase in conductivity due to moisture movement in the wood. The values for gypsum plasterboard were those measured by Mehaffey *et. al.*[7] for type X (glass fibre reinforced) board.

Figure 3 shows the values of enthalpy used for wood and gypsum plasterboard. The values used for wood are derived using Janssens[8] and assuming:

(i) Wood density is 450 kg/m³ at 12% moisture content

(ii) Moisture is evaporated between 100 and 120 °C

(iii) All steam is lost to the system after the moisture is evaporated. Some moisture remains in the wood, but the amount is difficult to determine and so is ignored.

(iv) Initial density is used to calculate the enthalpy throughout the temperature range.

The values used for gypsum plasterboard are based on the values of Andersson and Jansson[9] values. Enthalpy is the summation of the product of specific heat and temperature. Enthalpy rather than specific heat is used to avoid the sharp peaks that occur in the specific heat for both materials at about 100 °C due to the

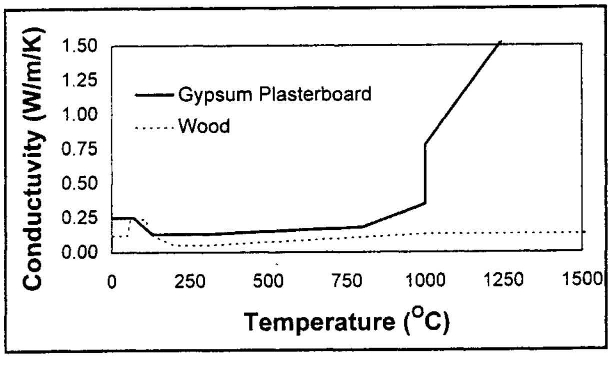

Figure 2. Thermal Conductivity Values for Wood and Gypsum Plasterboard.

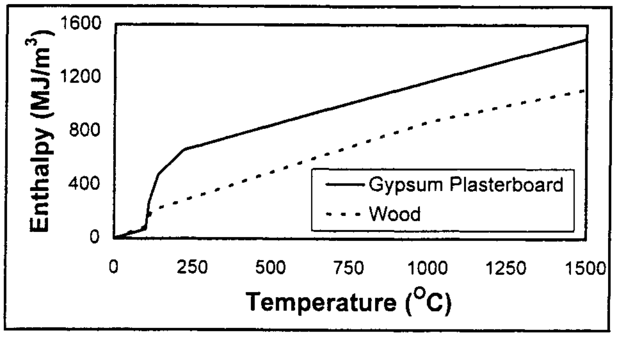

Figure 3. Enthalpy Values for Wood and Gypsum Plasterboard.

evaporation of moisture. Using an input with large discontinuities in slope can lead to numerical instabilities in a finite element model.

Heat Transfer Coefficients Used in the Model

As shown in Figure 1, there are five boundaries in the model between solid material and gases:

(i) between the fire and the lining on the fire side of the wall

(ii) between the lining on the fire side of the assembly and the interior cavity

(iii) between the lining on the ambient side of the assembly and the interior cavity

(iv) between the stud and the interior cavity

(v) between the lining on the ambient side of the wall and the ambient air

The heat transfer at these boundaries is governed by:

$$q = \varepsilon\sigma(T_g^4 - T_s^4) + \beta(T_g - T_s)^\gamma \qquad (2)$$

Where:

q is the rate of heat transfer (kW/m^2)

ε is the resultant emissivity of the gas and the boundary (dimensionless)

σ is the Stefan-Boltzmann constant ($5.67*10-8\ W/m^2K^4$)

β is the convection coefficient ($W/m^2K^{4/3}$)

γ is the convection power, usually 1.33

T_g is the gas temperature (K)

T_s is the surface temperature (K)

The values used for these boundaries in the finite element model are shown in Table 2.

The values for the coefficients in Table 2 were found by varying the values within a reasonable range in order to give a good correlation with temperature profiles recorded in test. The starting range was found by a combination of a literature survey and calculation using generally accepted principles of heat transfer. A sensitivity study showed that varying these parameters one at a time had little effect on the temperature within the assembly. This process is described at length in Thomas[10].

Table 2. Heat Transfer Coefficients for Furnace Model

Position	ε	β	γ
Fire side of wall	0.8	1.00	1.33
Lining, fire side of cavity	0.6	1.00	1.33
Lining, ambient side of cavity	0.6	1.00	1.33
Stud, in cavity	0.6	1.00	1.33
Ambient side of wall	0.6	2.20	1.33

Calibration with Test Data

The resulting correlation for one test is illustrated in Figure 4. The position numbers refer to those in Figure 1. The heavy lines are results from the furnace tests, the lighter lines, the model.

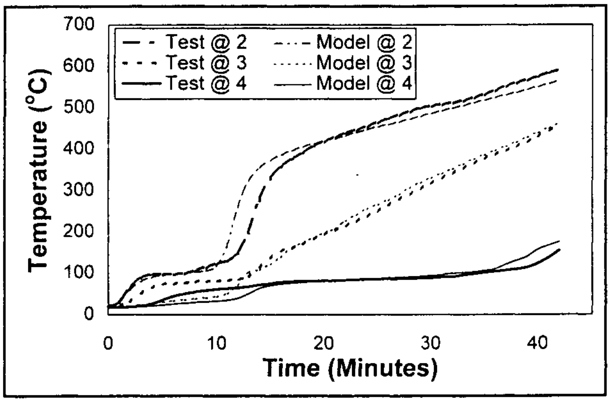

Figure 4. Comparison of Furnace Test Results with TASEF Model.

The discrepancy at positions 3 and 4 at temperatures below 100 °C is due to mass transfer not being modelled. The side of the cavity farthest from the fire is heated by moisture condensing on it and hence releasing energy, after being evaporated from the lining on the fire side of the cavity. As this energy input from the condensation of the moisture is equal to that required later to evaporate it again, the overall effect at high temperatures is negligible. This can be seen as the lines rejoin. The temperature at position 2 drops off for the model at high temperatures, because ablation of the gypsum plasterboard has not been modelled. Ablation has the effect of reducing the resistance to heat flow of the lining, and hence the temperatures through the assembly will increase at a faster rate than modelled. Ablation is more significant for thinner linings as a higher proportion of the thickness is lost.

Validation with Test Data

After the model was calibrated, it was validated by running the model for different wall layouts and different time-temperature curves and comparing the results with data from furnace tests. The correlation between model and tests was very good.

Compartment Fire Modelling Using COMPF-2

COMPF-2 is a computer based post-flashover compartment fire model developed by Babrauskas[11]. It assumes the compartment is a single well-mixed zone, with no significant temperature variation. Inputs are compartment geometry, window geometry, fuel load, fuel geometry and thermal properties of the bounding surfaces. The temperature is then derived by solving a heat balance at each time step.

Description of Input

For this project a room of 5.0 m by 5.0 m by 3.0 m high was chosen, as shown in Figure 5.

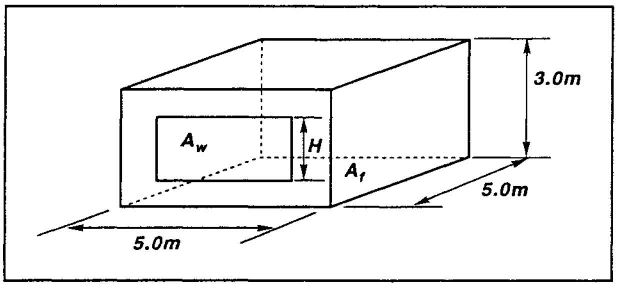

Figure 5. Layout of Compartment Used in COMPF-2 Model.

A range of seven fuel loads of 100, 200, 300, 400, 500, 600, 800 and 1200 (MJ/m^2) of floor area were used. The values of 400,800 and 1200 MJ/m^2 are specified in the *New Zealand Building Code*[12]. The value for a motel-hotel type building, likely to be built in light timber framing, is usually around 300-400 MJ/m^2. The opening factor is given by:

$$V = A_w H^{1/2} / A_t \qquad (3)$$

where:

V is the opening factor

A_w is the window area (m^2)

H is the window height (m)

A_t is the total area of the bounding surfaces of the compartment (m^2)

Six window sizes were used as shown in Table 3. The larger window sizes would consist of multiple windows in several walls.

Effect of Fuel Geometry

In COMPF-2 the fuel pyrolysis rate is determined using one of three subroutines. One is for a hydrocarbon fuel fire. Another is for wood cribs or wood sticks. In the third subroutine, the pyrolysis rate is pessimised. This option is described later.

The crib subroutine utilizes Nilsson's formulas for crib fires[13]. This subroutine results in the fuel geometry having a significant effect on the time-temperature curve of the fire for fuel-bed controlled fires. A stick fire is controlled by this subroutine, but without the crib porosity limiting the pyrolysis rate.

If a fire is fuel surface controlled, the temperatures will be lower than for a ventilation controlled fire (everything else being equal), and increasing the ventilation will lower the temperatures. If the fire is ventilation controlled, increasing the ventilation will increase the temperatures, resulting in a more severe, but shorter duration fire.

The effect of fuel geometry is highlighted in Figure 6, for a compartment with a fuel load of 800 MJ/m^2 and a ventilation factor of 0.10.

In this project, the third option in COMPF-2 was used, that is pessimising the fuel pyrolysis rate. Pessimising can be thought of as "analogous to, but the inverse of optimization"[14]. In this process, the pyrolysis rate is continuously adjusted to give the highest possible temperature at each time step, producing the most severe fire for a defined ventilation and fuel load. It can be seen in Figure 6 that the pessimised

Table 3. Window Parameters

WINDOW			Opening Factor
Height (m)	Width (m)	Area (m^2)	($m^{1/2}$)
1.0	2.75	2.75	0.025
1.5	3.00	4.50	0.050
2.0	3.00	6.00	0.077
2.0	4.00	8.00	0.103
2.0	5.00	10.00	0.129
2.0	6.00	12.00	0.154

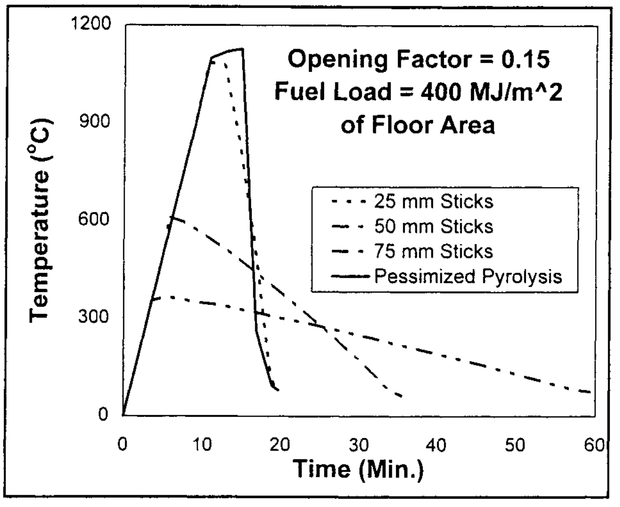

Figure 6. Effect of Fuel Geometry on the Time-Temperature Curve.

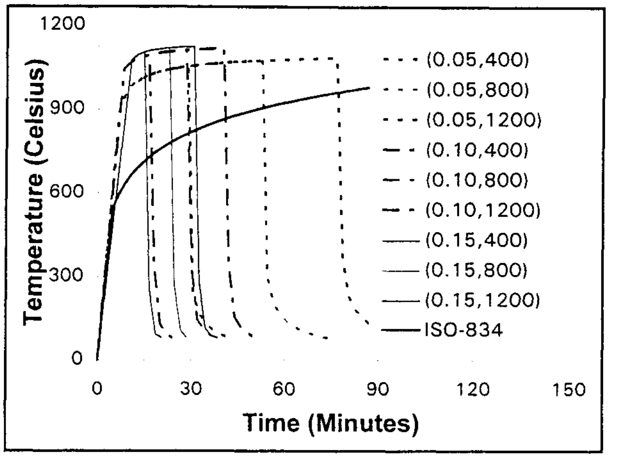

Figure 7. Families of Time Temperature Curves Input to TASEF.

fire produces higher temperatures for a longer time than the crib or stick fire, with a very rapid decay phase. Figure 7 shows three families of curves produced for three ventilation factors and three fire loads. The pairs in the key are for the opening factor ($m^{1/2}$) and the fuel load (MJ/m^2) of floor area respectively. The ISO-834 standard fire test curve is also shown in Figure 7, producing temperatures considerably lower than the COMPF-2 output.

These curves vary from the widely used Swedish curves[15], in that the decay phase is much shorter, as is the overall duration of the fire. COMPF-2 was chosen over the Swedish curves because it has a more rigorous approach to calculating the compartment temperature, rather than assuming a heat release rate that produces temperatures that compare well with some experiments.

The initial rate of temperature rise in Figures 6 and 7 was obtained by assuming a constant initial rate of temperature rise of 100 °C per minute. This was required because the COMPF-2 is a post-flashover compartment fire model, in which the output starts at a high temperature at a time of zero. During the cooling phase COMPF-2 terminates when the compartment temperature drops below 80 °C, hence it is assumed that the compartment cools to 20 °C over 30 minutes.

Combining Models

The time-temperature curves found above for the four different wall assemblies were input into the TASEF finite element model of the wall assemblies to predict behavior of the walls exposed to compartment fires. The heat transfer coefficients were altered at the fire side of the wall and are given in Table 4. A higher value for emissivity was used than for the furnace because of the differing emission characteristics of the furnace and a compartment fire. The convection coefficient, β is also higher as the air flow in a burning compartment is more turbulent and not well defined.

Comparison of Heat Transfer in TASEF and COMPF-2

As COMPF-2 uses a heat balance to calculate temperatures, the thermal properties of the wall need to be input. COMPF-2 assumes a solid homogeneous wall, so the properties of the gypsum plasterboard had to be modified to mimic those of an equivalent solid wall. This was done by altering the density to be a weighted average of

Table 4. Heat Transfer Coefficients for Compartment Fire Model

Position	ε	β	γ
Fire side	1.0	5.00	1.33
Lining, fire side of cavity	0.6	1.00	1.33
Lining, ambient side of cavity	0.6	1.00	1.33
Stud, in cavity	0.6	1.00	1.33
Ambient side of wall	0.6	2.20	1.33

density over the thickness of the wall. The conductivity was multiplied by a factor equal to the width of the cavity over the total thickness of both linings. The increase in thermal conductivity of the gypsum plasterboard at temperatures greater than 300 °C was ignored. Figure 8 shows temperatures on each side of the wall assembly from the COMPF-2 output compared with the TASEF results for the same wall, modelled using the COMPF-2 time-temperature curve as input data. It can be seen that these modifications produced very good results.

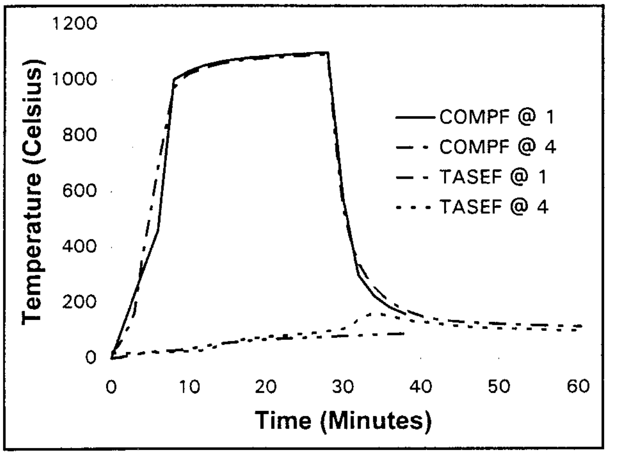

Figure 8. Comparison of Wall Temperatures from TASEF and COMPF-2.

TIME EQUIVALENCE

The equivalent time of fire severity for an assembly is described below with reference to Figure 9.

For the purposes of this paper, the equivalent time is the time at which the maximum temperature at a characteristic location in a wall exposed to a real compartment fire is reached in a standard furnace test. An alternative means of determining equivalent fire severity is the time at which another parameter, such as load bearing capacity, reaches a minimum. In this study the two characteristic locations are at position 5 (Figure 1), where charring of the timber would first occur, and position 4, on the ambient side, where an insulation failure would occur. It can be seen in Figure 9 that the equivalent time, when the maxi-

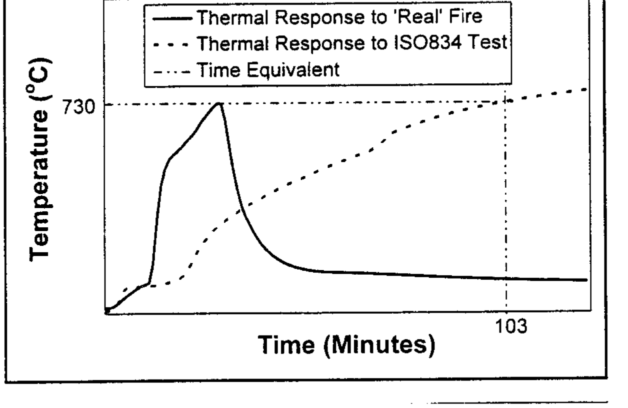

Figure 9. Definition of Time Equivalence.

mum temperature of 730 °C is reached, is approximately 103 minutes for the charring criterion at point 4.

Results

The maximum temperature values for the insulation and charring criteria were recorded and an equivalent time deduced from the furnace tests results. Values for time equivalents were calculated using Equation 1 with c = .09, the recommended value for lightweight linings. Not all combinations of fuel load and ventilation produced valid results because some predicted time equivalents were beyond the duration of the fire tests.

The values found using the computer models were then plotted against the values found using Equation 1 for the insulation and charring criteria, as shown in Figures 10 and 11.

The lower line represents a linear regression of the results. The correlation coefficient is 0.88 for the charring criteria and 0.82 for the insulation criterion.

The correlation between the two methods seems reasonable, with a linear dependence. Equation 1 predicts the trend of the results, but consistently underestimates the values. The scatter in the data is comparable with the data used to correlate the original CIB expression[16].

As the term c in Equation 1 is poorly defined, it may be appropriate to alter this value in order to produce the appropriate equations for the two criteria given here. The correlation for the insulation criteria is the better of the two. The study is currently being extended to consider structural behaviour.

Conclusions

(1) TASEF can be used to model thermal behaviour of light timber-framed walls.

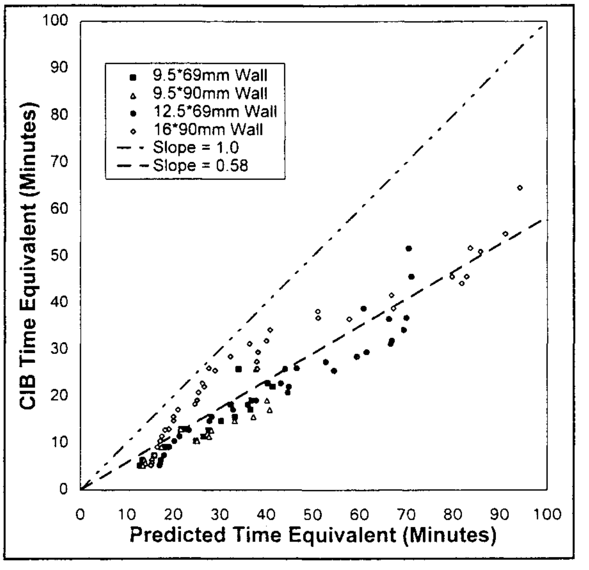

Figure 10. CIB Time Equivalent vs. Computer Prediction of Time Equivalent For Charring Criterion.

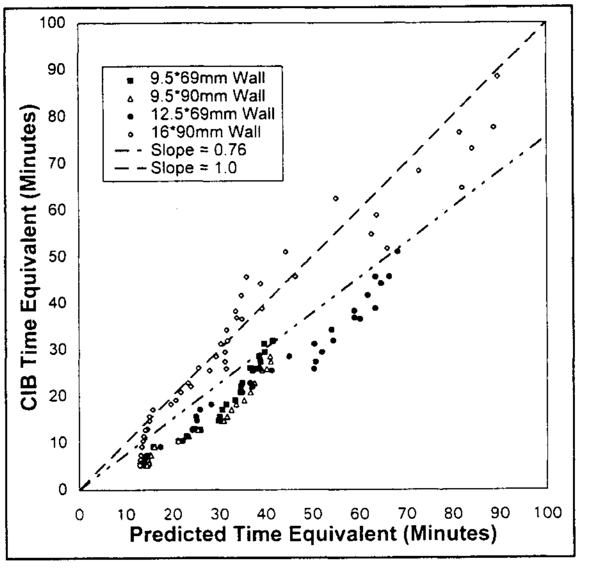

Figure 11. CIB Time Equivalent vs. Computer Prediction of Time Equivalent For Insulation Criterion.

(2) A cavity wall can be modelled as a solid homogeneous wall for use in post-flashover compartment fire models such as COMPF-2 by modifying the thermal properties.

(3) Post-flashover fIre temperatures from COMPF-2 are highly dependent on fuel geometry. This problem is avoided by assuming pessimised pyrolysis which gives very hot short duration fires.

(4) The CIB time equivalent formula consistently underestimates the equivalent fire severity of light timber-framed walls, when considering thermal behaviour. This may not be the case for structural behaviour which will be considered in due course.

ACKNOWLEDGMENTS

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