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## BEHAVIOUR OF LIGHT TIMBER-FRAMED FLOORS SUBJECTED TO FIRE ATTACK FROM ABOVE

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# BEHAVIOUR OF LIGHT TIMBER-FRAMED FLOORS SUBJECTED TO FIRE ATTACK FROM ABOVE

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## ABSTRACT

Traditional test methods for fire-resistance of floors evaluate the performance of floor/ceiling assemblies when exposed to a fire from below. This is accepted as being the most severe orientation, with little or no research having been carried out with respect to fire from above. Light timber-framed floor/ceilings in New Zealand are typically of asymmetric construction with 20 mm particleboard on the top surface of timber joists with a paper-faced gypsum plasterboard ceiling on the underside of the joists, the thickness depending on the fire-resistance rating required. The fire-resistance of the floor was expected to be quite different depending on the direction of fire exposure. For the downward direction of exposure, it is the thickness of particleboard which determines the time at which the floor joists become significantly affected by fire. However, the thickness of the particleboard is unchanged for floors with 30-120 minute fire ratings.

A fire-resistance wall furnace was adapted to enable this type of floor/ceiling construction to be exposed, from above, to a standard time-temperature curve (AS 1530 Part 4) and the fire behaviour of the floor was observed. It was determined that the fire-resistance achieved by the floor in this configuration was significantly lower than when exposed from below, for periods of exposure greater than about 30 minutes. Two non-loadbearing full-scale tests were carried out, and temperatures were measured throughout the assemblies. The effect of different types of floor covering mounted over the particleboard was also investigated in a cone calorimeter, and it was estimated that some carpets increased the fire-resistance of the floor by up to 10 minutes.

This research was intended to investigate the validity of specific requirements in the New Zealand Building Code Acceptable Solution for Spread of Fire which requires the use of a non-combustible overlay on some fire-rated floors constructed of reconstituted wood products.

## INTRODUCTION

This paper describes a research project carried out to investigate the behaviour of light timber-frame floors when exposed to fire from above. The New Zealand Building Code (NZBC) Acceptable Solution, C3/AS1 [1], addresses the possibility that fire can spread downwards into a lower firecell through a timber floor by requiring that non-combustible floor overlays are used where the fire-resistance rating of the floor is to be 60 minutes or more.

It has been suggested that the purpose of the overlay is:

a) for the protection of occupants in the firecell immediately below the firecell of fire origin

b) to ensure that occupants escaping from the firecell of fire origin have a structurally safe floor to cross
c) for the added safety of fire fighters, ensuring the floor remains serviceable for the given duration of the floor's specification.

The only rational explanation is a). In b), the occupants are not likely to be still alive and able to evacuate given the presence of a fully developed fire, and in c), fire fighters have to make their own value judgement on whether or not a burning building is safe for them to enter.

The aim of this study was therefore to determine whether the premature collapse of a fire-rated floor construction due to fire exposure from above was a valid concern, and to assess the possible application of non-combustible overlays to satisfy the NZBC Acceptable Solution, C3/AS1 paragraph 2.16.1.

In a 1972 Australian study [2], the authors concluded that fire can spread downwards through a fire rated timber floor/ceiling faster than it would in an upward direction, and that woollen carpet floor covering increased the downwards fire-resistance performance of the floor. The study considered four species of solid timber tongue-and-groove flooring; no reconstituted wood products (ie. particleboard) were included. The study discussed the observed horizontal fire spread characteristics of the bare timber boards and a variety of floor coverings. It was also considered questionable whether the penetration times observed in the furnace tests may be related to real fire conditions.

Since the Australian study, the predominant flooring material has become particleboard and floor coverings have changed somewhat in their composition.

The procedure undertaken in this research project was as follows:

1) Use the cone calorimeter to carry out a series of small scale tests on common floor coverings on a particleboard substrate to determine their relative influences on the rate of charring of the particleboard.
2) Test the floor with the covering system which provided the most protection using the BRANZ wall fire-resistance furnace, alongside a control section of floor with no covering.
3) Evaluate potential overlay products to assess the viability of such systems to increase the fire-resistance rating of the floor.

## TYPICAL TIMBER FLOOR CONSTRUCTION

A typical timber floor construction in New Zealand consists of 20 mm thick sheets of reconstituted wood products (particleboard) over timber joists of dimensions and spacing determined by the span. Ceiling linings are typically sheets of paper-faced gypsum plasterboard secured directly to the underside of the joists.

The construction of the floor used in this research followed the plasterboard manufacturer Winstone Wallboards Ltd, GBUC 60 [3] documentation for the specification and installation of a 60-minute fire-resistance rated floor/ceiling assembly, and was built in accordance with NZS 3604, [5]. The floor/ceiling assembly consisted of 20 mm timber particleboard sheet flooring over 200 x 50 mm joists at 600 mm centres with a ceiling lining of 16 mm fire-rated paper-faced gypsum plasterboard.

In the cone calorimeter, the rate of charring of the timber particleboard flooring, together with each of the common floor covering materials, was determined.

## SMALL SCALE EXPERIMENTS USING THE CONE CALORIMETER

### Method

Samples measuring 100 mm square in plan were prepared in accordance with the manufacturers specifications for each of the selected floor covering systems listed in Table 1. A typical sample would consist of the floor covering on a 100 x 100 x 20 mm block of particleboard. The samples were conditioned at 50 % relative humidity, and 23°C.

| Material | Material Composition | Backing | Underlay | Fixing |
|---|---|---|---|---|
| Carpet | 100% Wool | Polypropylene | Rubber | Nail |
| Carpet | 80% Wool / 20% Nylon | Polypropylene | Rubber | Nail |
| Carpet | 50% Wool/ 50% Polypropylene | Polypropylene | Rubber | Nail |
| Carpet | 100% Nylon | Polypropylene | Rubber | Nail |
| Carpet | 100% Polypropylene | Polypropylene | Rubber | Nail |
| Carpet | 100% Polypropylene | Foam | None | Nail |
| Vinyl | 100% Vinyl | Foam | None | Adhesive |
| Vinyl | 100% Vinyl | n/a | None | Adhesive |
| Marmolium | 100% Marmolium | n/a | None | Adhesive |

Table 1. Description of the floor covering samples selected for small-scale testing.

The samples were mounted horizontally in a cone calorimeter and exposed to an irradiance of 75 kW/m$^2$ for ten minutes, after which the test was stopped and the charred material in the centre of the sample removed. The irradiance level was set at 75 kW/m$^2$ to simulate the conditions of a fully developed post-flashover fire. Removing the charred material prevented any further charring and enabled the depth of the good material remaining to be measured. Tests were carried out in accordance with ISO 5660 [4].

### Results

The effective charring rates (mm/minute) were calculated as:

$$C_e = \left( \frac{d_o - d_f}{\Delta t} \right) \quad (1)$$

where $d_o$ and $d_f$ are the original and final depths of uncharred particleboard, and $\Delta t$ is the test duration, ie ten minutes taken from the start of the test. The effective charring rates for all floor coverings tested were calculated as above. They are shown in Figure 1 and were the average values from three replicate tests of each system.

The two predominantly wool carpets, 100% wool and the 80% wool / 20% nylon mix, both on rubber underlays, returned the lowest effective charring rates for the particleboard. As expected, the control (particleboard with no covering) recorded the highest effective charring rate.

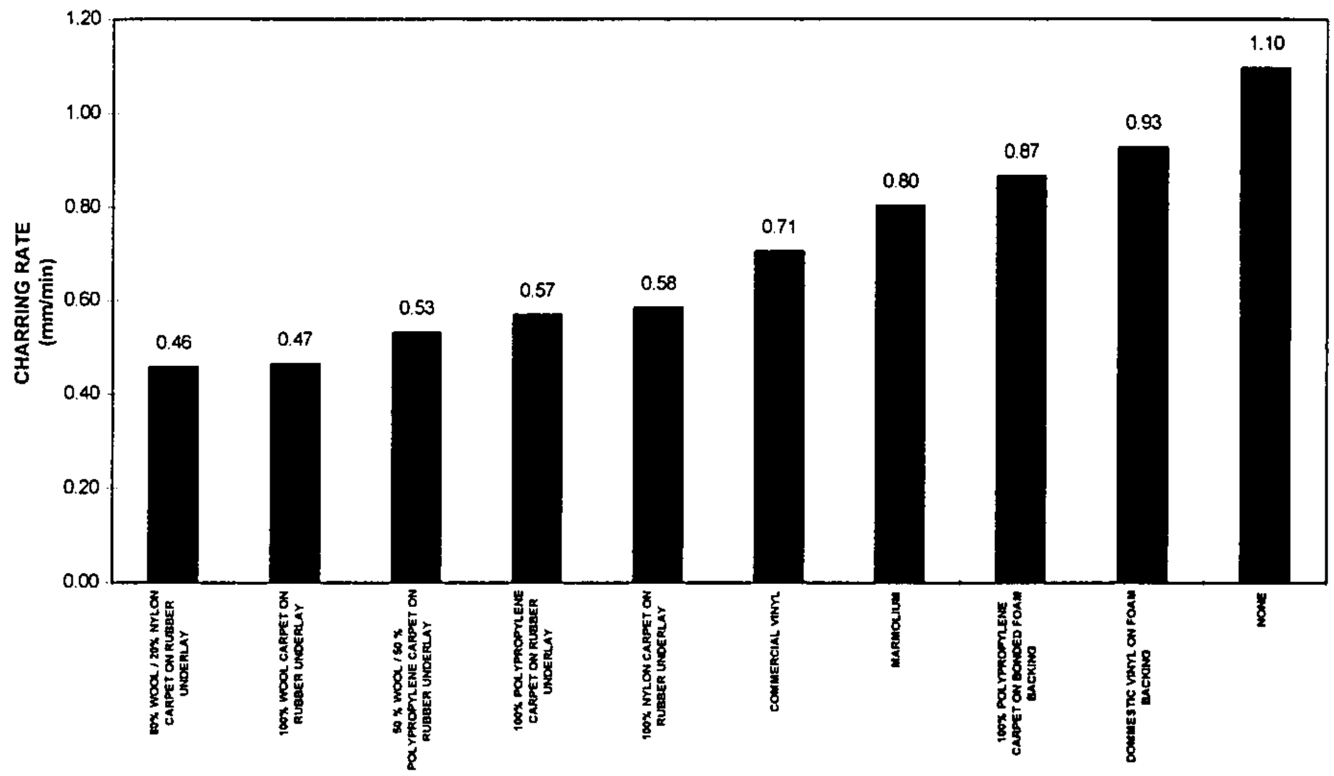


Figure 1. The effective charring rate of the particleboard under various floor coverings, measured in a cone calorimeter at 75 kW/m$^2$.

Taking both the effective charring rate and the mass loss data into account, the 100% wool carpet on rubber underlay was deemed to provide the particleboard with the highest level of protection of any of the floor coverings evaluated against fire attack from above.

## FULL-SCALE EXPERIMENTS

### Method

A fire-resistance wall furnace was adapted to enable a floor/ceiling construction to be tested. A "room" was built on the side of the furnace which enabled the timber floor structure (as described above) to be exposed to the radiant and convective heating effects representative of a standard fire-resistance test.

### Failure mechanism

First stage of failure is the complete charring of the particleboard flooring, enabling the fire to begin attacking the joists directly. It was assumed by this time that any large objects resting on the floor would either have been consumed by the fire before the particleboard failed or would be of sufficient dimensions to straddle the framework of joists and thereby be prevented from penetrating the ceiling lining sufficiently to fall into the lower fire compartment.

Second stage of failure is the collapse of the floor as a whole. In this stage the joists have been eroded by the fire to the point where they are unable to support themselves, let alone any objects being supported by them.

### Construction of the rig

An enclosure with dimensions 3.0 m wide x 1.2 m deep x 3.0 m high was attached to a 3.0 m wide x 4.0 m high furnace specimen frame, which was then mounted to the face of the BRANZ fire-resistance furnace, as shown in Figure 2. The floor was built as a removable unit in order that it could be replaced for the second test. A 1.0 m high concrete infill panel was placed across the bottom of the specimen frame, thereby raising the floor to an observable height. In both experiments, the floor was unloaded.

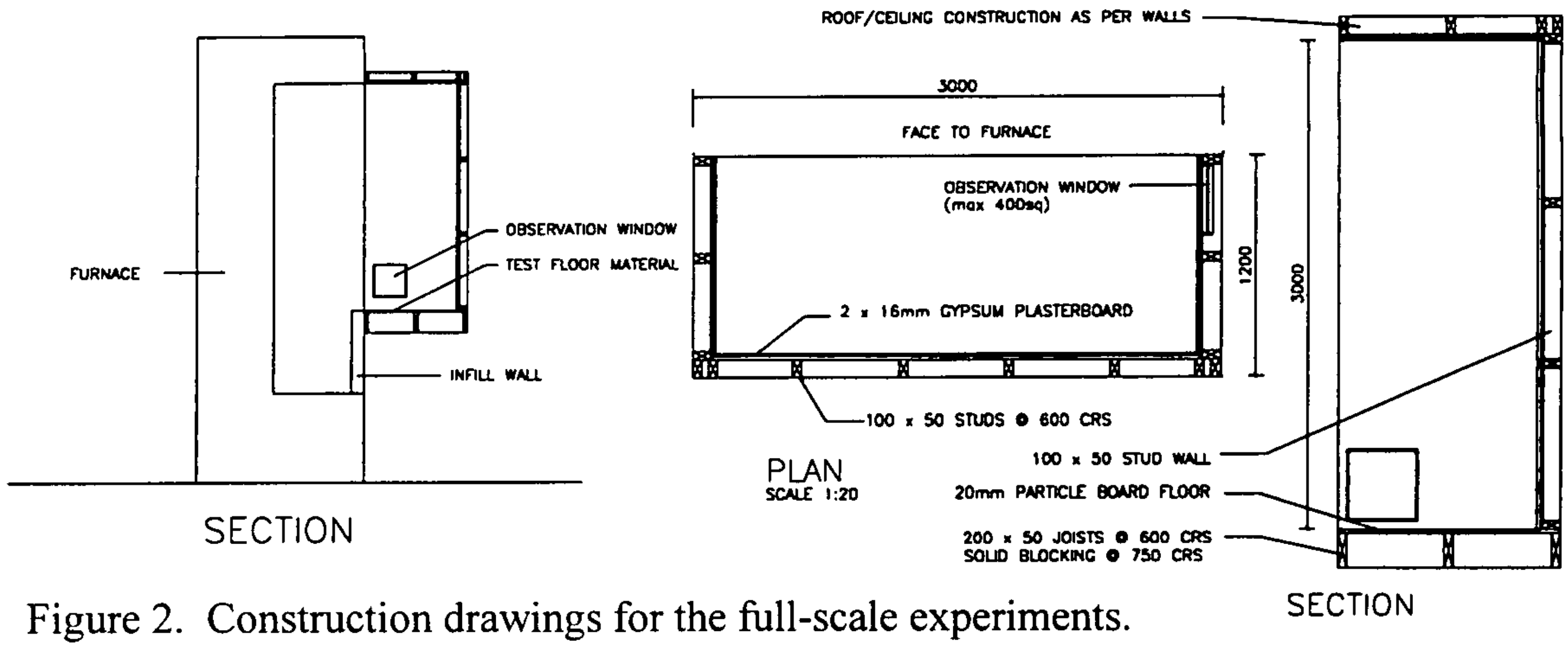


Figure 2. Construction drawings for the full-scale experiments.

## FULL-SCALE FLOOR TEST 1

### Construction

The floor was divided into two halves, each approximately 1.5 m x 1.2 m, one to investigate the performance of the floor when covered by wool carpet, and the other as a control with no floor covering. The floor joist layout effectively provided eight separate floor cavities, four in each of the two halves, as shown in Figure 3.

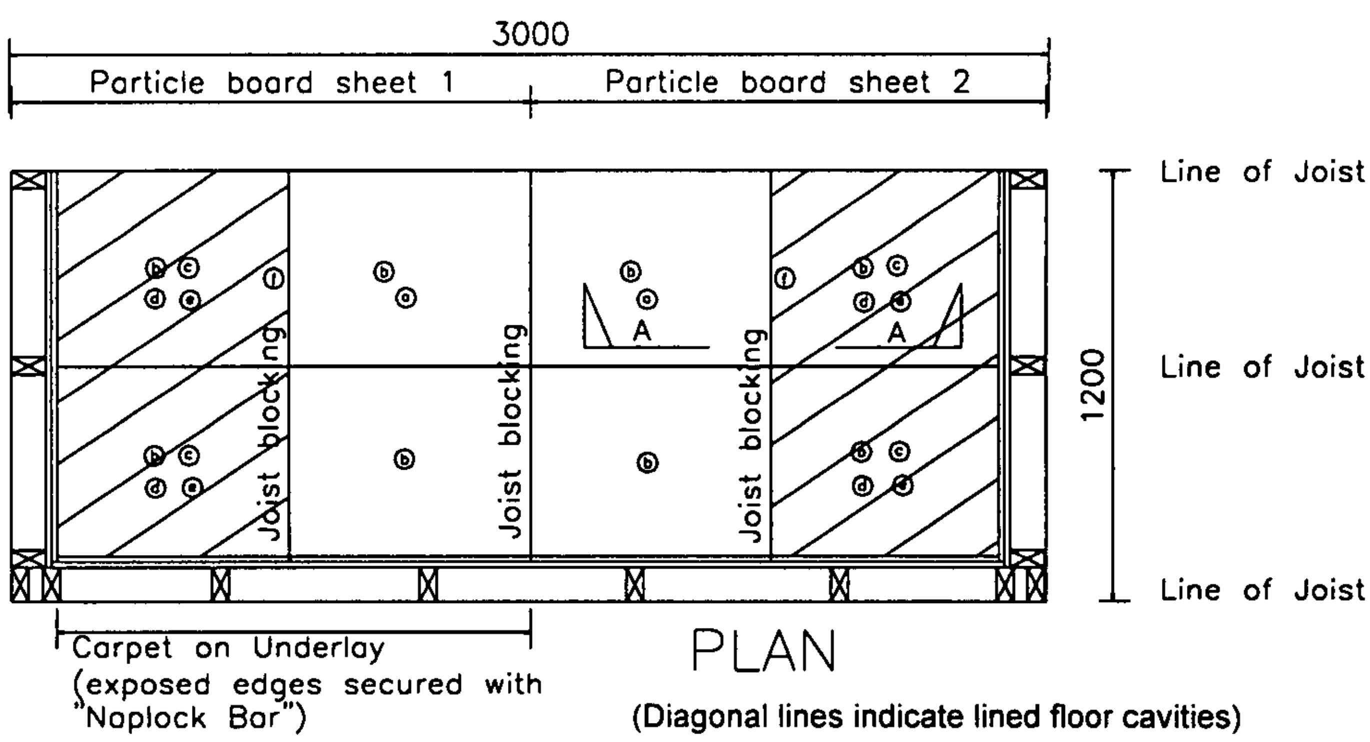


Figure 3. Floor plan for full-scale fire test 1.

The underside of the floor was lined over two adjacent joist cavities in each of the two halves, thereby providing four unique sections. Each of the four sections comprised two cavities, a front one nearest to the furnace, and a rear one farthest from the furnace, with instrumentation located in each cavity, as shown in Figure 4.

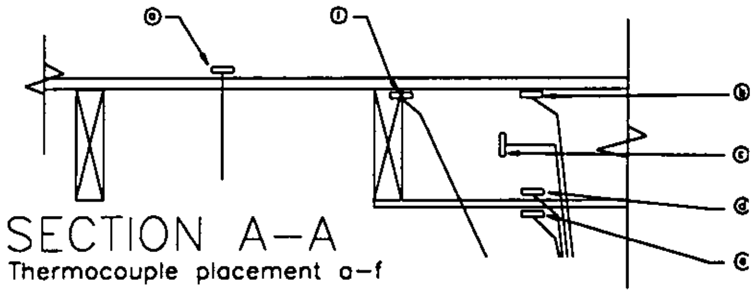


Figure 4. Floor section identifying location of thermocouples, full-scale test 1.

**Control of the furnace**

The furnace temperature was controlled as closely as possible to the test standard AS1530 Part 4 [6], as shown in Figure 7. Furnace pressure was controlled to maintain zero pressure at 900 mm above the floor of the test specimen thereby giving a negative pressure (-9 Pa) at the floor.

**Results**

After 38 minutes, the control section (uncovered particleboard) collapsed, with all the particleboard having completely charred through. Stopping the test at this point enabled the depth of charring under the carpet-covered section to be assessed. The depth of uncharred material remaining under the carpet section ranged between 6 - 7 mm.

The most informative temperature recordings were those taken from thermocouples attached directly to the underside of the particleboard floor. Any measurement in excess of 300°C was taken to indicate that the char front had reached the thermocouple on the underside of the particleboard. After 38 minutes, the average temperature recorded on the underside of the uncovered section of floor was 334°C, while beneath the carpet-covered section, the temperature only averaged 94°C.

Interestingly, there was no appreciable difference in the temperatures recorded within the floor cavities between those with and those without the ceiling lining. Initially it was considered that the lined cavities would result in higher internal temperatures and therefore lead to the particleboard charring at a faster rate, but this was not the case. Only minor variations existed, with the lined sections generally recording slightly higher temperatures.

As the test was stopped when the particleboard first collapsed, no data was recorded on how the lined and unlined cavities might have influenced the performance of the joists within those sections.

## FULL-SCALE FLOOR TEST 2

**Construction**

In this test, additional information was sought in the knowledge that fire can spread down through a timber floor within the nominal 60-minute fire-resistance time. Here, three potential overlays were evaluated and, for comparison, a control section of uncovered particleboard was included. In the floor cavity within the control section a dummy joist was included to provide information on the charring rate of the floor structural members. The overlays considered in the second full-scale fire test are given in Table 2.

| Overlay (trade names) | Material composition | Thickness (mm) | Density ($kg/m^3$) |
|---|---|---|---|
| Promatect H | Calcium silicate board | 12.0 | 958 |
| Fyreline | Paper-faced gypsum plasterboard | 12.5 | 784 |
| Villaboard | Fibre cement board | 6.0 | 1383 |

Table 2. Fire test 2, overlay product information.

The underside of the floor was lined with a continuous sheet of 16 mm fire-rated paper-faced gypsum plasterboard, in accordance with Winstone Wallboards Ltd Specification GBUC 60 [3]. This is a 60-minute fire-rated floor/ceiling system (the same lining as used in Test 1). The arrangement is shown in Figure 5, and thermocouple locations in Figure 6.

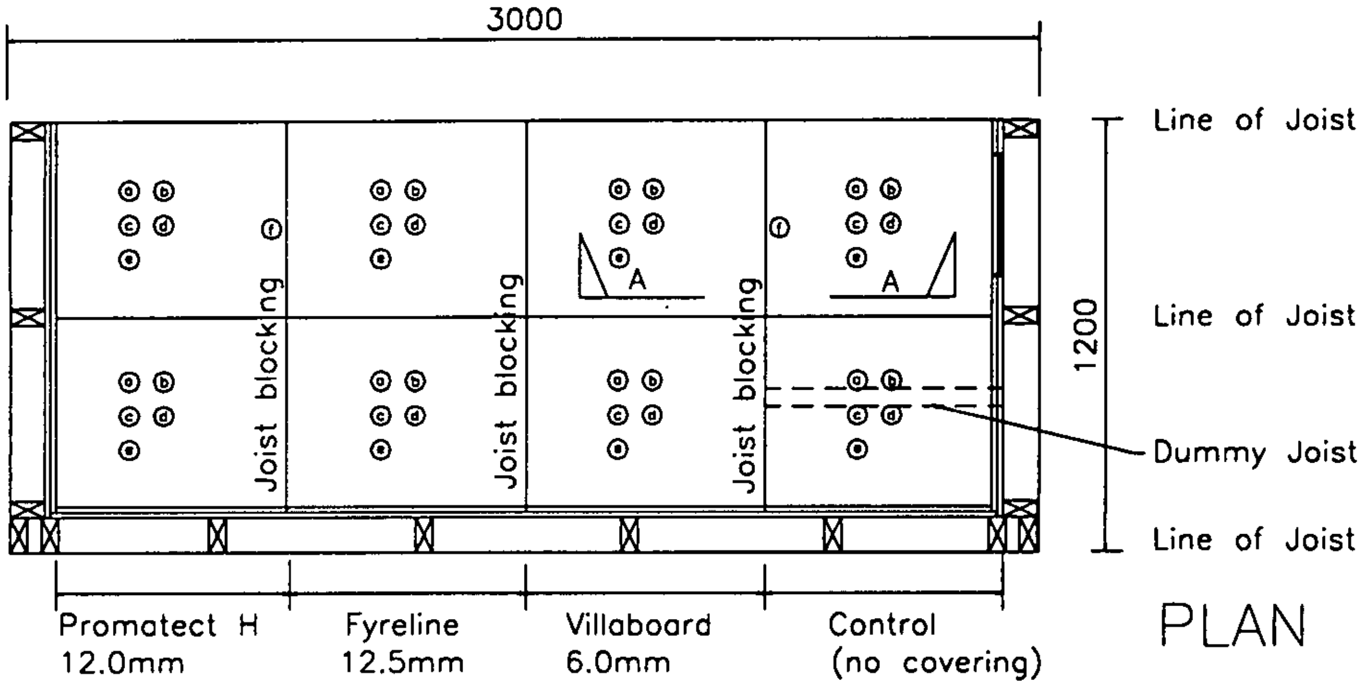


Figure 5. Floor plan for full-scale test 2.

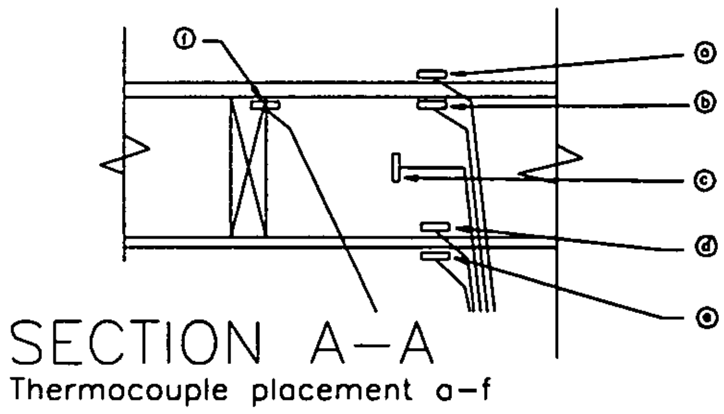


Figure 6. Floor section identifying location of thermocouples, full-scale test 2.

**Control of the furnace**

The furnace temperature was controlled as closely as possible to the test standard AS1530 Part 4 [6], as shown in Figure 7. Furnace pressure was controlled to maintain zero pressure at 900 mm above the floor of the test specimen.

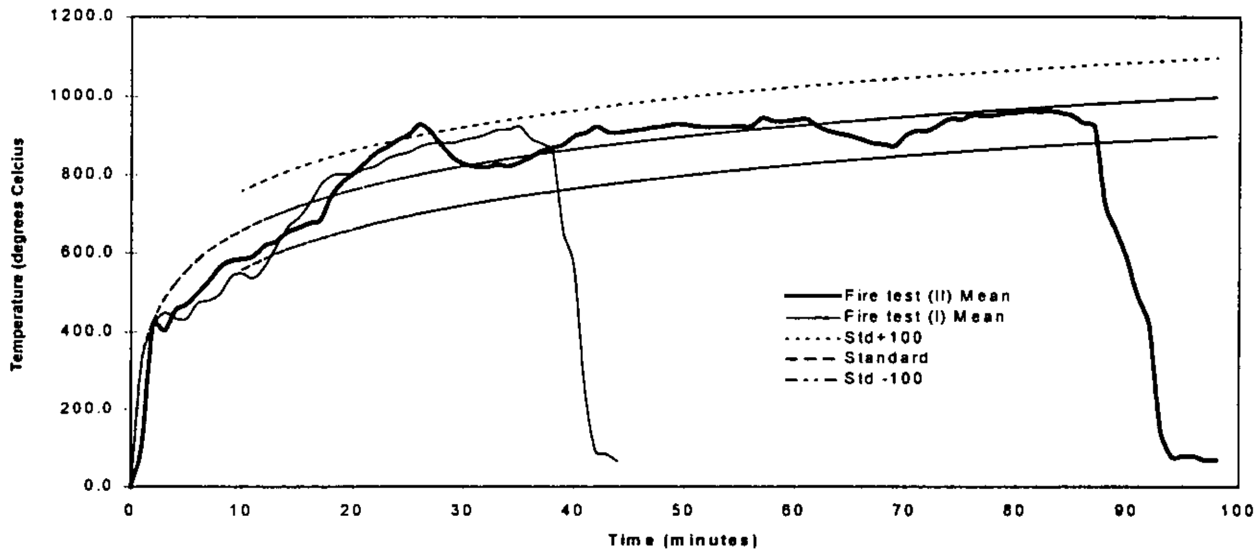


Figure 7. Furnace time temperature curves fire tests 1 and 2.

**Results**

The particleboard control section completely charred through within 34 minutes. This was earlier than the 38 minutes recorded for Test 1. At this time large cracks had formed in the fibre-cement board, allowing the fire to directly attack the particleboard beneath. Similarly, the calcium silicate board was subject to cracking, causing the particleboard beneath to degrade at a higher rate than expected. The calcium silicate board performed better than the fibre-cement board, recording a minimum time of 60 minutes before the underside of the particleboard beneath reached 300°C. Of the three overlay products the fire-rated gypsum plasterboard provided the highest level of fire protection.

While it may be possible to improve the performance of these overlays through better design of the fastening systems, another variable, that of the thickness of the overlays, was not included in the experiment.

It should be noted, however, that only the calcium silicate board is classified as "non-combustible" and therefore complies fully with the requirements of the NZBC Acceptable Solution for use as a floor overlay.

In Table 3, the time in minutes from the beginning of the test is identified for the thermocouples located on the underside of the particleboard to record 300 °C, averaged for each overlay product.

| Thickness (mm) | Overlay Product | Time to 300 °C (min) |
|---|---|---|
| 12.5 | Fire-rated gypsum plasterboard | 84 |
| 12.0 | Calcium silicate board | 64 |
| 6.0 | Fibre cement board | 49 |
| 0.0 | Control (no overlay) | 34 |

Table 3. Time for particleboard to completely char when protected by overlays, results from fire test 2.

**Degradation of the floor joists**

This is the second stage of failure, where fire has entered the floor cavity and is able to attack the joists directly, leading to the collapse of the floor/ceiling structure as a whole.

Once the fire had entered the floor cavity, degradation of the joists occurred rapidly. Figure 8 illustrates the data collected from thermocouples located within the 200 x 50 mm dummy joist in the section without a protective floor covering. The fire began attacking the joist directly from approximately 34 minutes into the test.

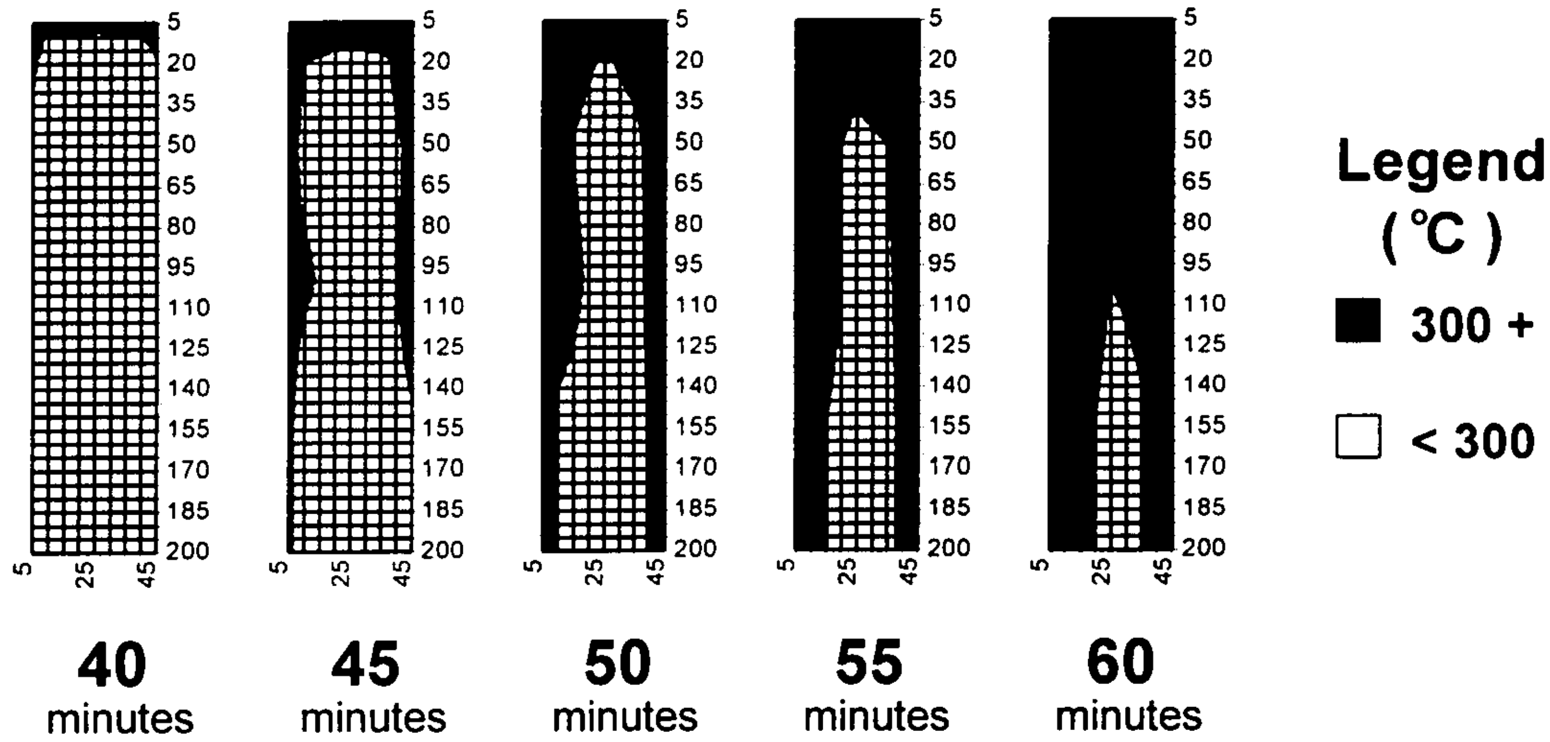


Figure 8. Charring front profile over time for the dummy joist.

In this test the floor was not loaded, with the joists subject only to the dead load of the components of the floor/ceiling. It is apparent from Figure 8 that within 60 minutes the cross-sectional area of the joist had been reduced to approximately 10% of its original area and hence marginal material remained to secure the fixings.

Further assessment of data in this format could be used to estimate the time for a joist to be reduced by fire to its limit state dimensions, and therefore to determine the time to failure in terms of its design load capacity.

## CORRELATION BETWEEN SMALL-SCALE AND FULL-SCALE EXPERIMENTS

A further series of cone calorimeter tests were carried out to provide the data necessary for comparison with that from the full-scale test of the overlays. In achieving a correlation between the two sets of test data, a method is proposed for estimating the performance of an overlay material on a 20 mm particleboard substrata at full scale based on the small-scale cone calorimeter test.

Thermocouples located on the underside of the particleboard recorded the back face temperature as in the full-scale test. An irradiance of 75 kW/m$^2$ was used, as in the earlier cone calorimeter tests. The tests were stopped when the rate of heat release reached a stable plateau, and the temperature recorded on the underside exceeded 300°C. The particleboard was assumed to be completely charred through when the temperature recorded on the back face reached 300°C. The effective charring rate figures (mm/minute) were calculated as:

$$C_{cc} = \left( \frac{d_o}{\Delta t_{300}} \right) \qquad (2)$$

where $\Delta t_{300}$ is the time for the back face temperature to read 300°C, measured from the start of the test. The effective charring rates for the particleboard in the full-scale test were calculated using the same method. The correlation between the cone calorimeter results and those from the full-scale test is illustrated in Figure 9.

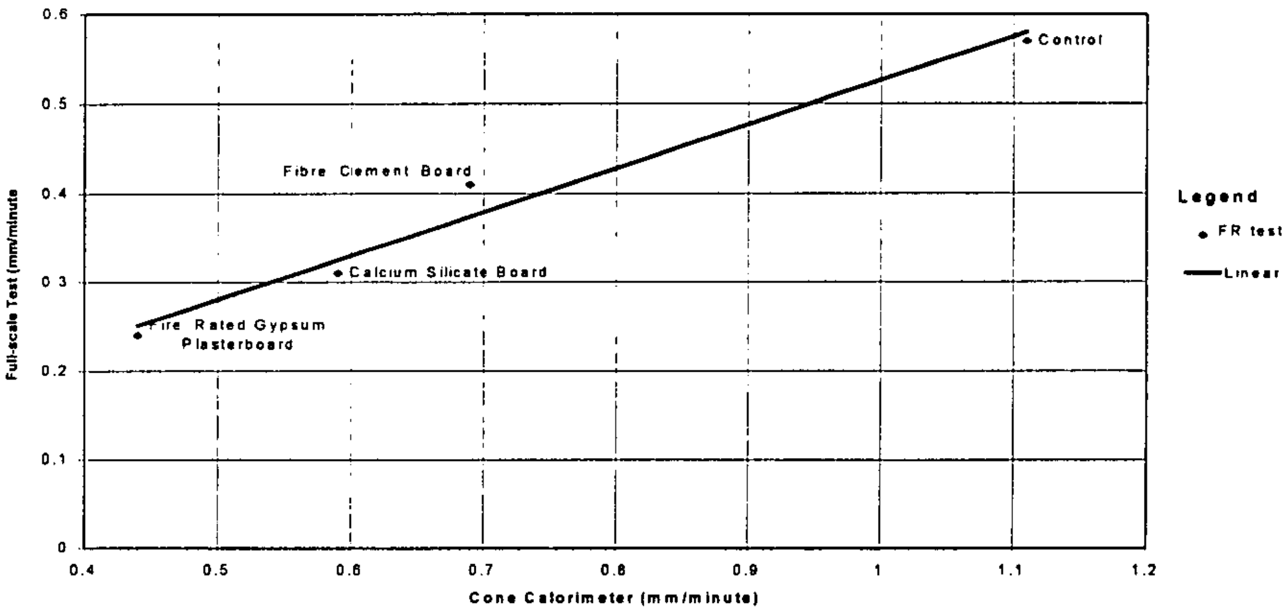


Figure 9. Correlation between the effective charring rates determined from the cone calorimeter and the full-scale tests.

The equation of the best fit line in Figure 9 allows the effective charring rate for the full-scale fire-resistance test $C_{fr}$ (mm/min) to be estimated from the results of small-scale cone calorimeter tests. The equation of the best fit line is:

$$C_{fr} = 0.49 \times C_{cc} + 0.04 \qquad (3)$$

Using the $C_{fr}$ value it is possible to determine what depth of particleboard $D_{ph}$ is necessary to prevent the fire from attacking the joists within the time specified by the required fire-resistance rating $R_t$ (min) for the floor.

$$D_{ph} = R_t C_{fr} \quad \text{(only valid for } D_{ph} \leq 20\,\text{mm)} \qquad (4)$$

It is therefore proposed that if the value obtained for $D_{ph}$ is less than the original thickness of particleboard, then it constitutes an "acceptable solution". If however the value of $D_{ph}$ is greater than 20 mm, an alternative overlay system is required.

Using the above procedure, the depth of uncharred particleboard remaining beneath the carpet section in the first full-scale test after 38 minutes was calculated to be 6.4 mm. This concurs well with the results from test 1. Measurements taken of the remaining depth of uncharred particleboard ranged between 6 and 7 mm.

Alternatively it may be desired to vary the thickness of the particleboard floor instead of using an overlay. In the second full-scale fire test, the control section was instrumented with thermocouples located on the top and bottom surfaces of the 20 mm thick particleboard. Charring was deemed to occur when the temperature recorded at a thermocouple exceeded 300°C. From the start of the test, it was 8 minutes before the top thermocouple recorded 300°C and the bottom thermocouple recorded the same temperature at 34 minutes. Taking the initial delay of 8 minutes into account, the rate of charring for the 20 mm particleboard is calculated to be 0.77 mm/minute.

Therefore, to predict the minimum thickness of particleboard required to achieve the specified $R_t$, in the absence of an overlay, equation (5) is proposed.

$$D_{pb} = 0.77(R_t - 8) \quad (5)$$

## CONCLUSIONS

There exists potential for fire to spread downward through unprotected timber floors. The performance of a floor is independent of the performance of the ceiling lining. Observations of the two full-scale fire tests suggested that for periods of exposure greater than 30 minutes, the fire-resistance of the floor was significantly lower than when exposed to fire from below. For the downward direction of exposure, it is the thickness of the particleboard which determines the time at which the floor joists become significantly affected by fire.

In order to improve the downward fire-resistance performance of a conventional timber floor, overlays offer a potential solution. More development is required regarding the specification of overlays in terms of appropriate applications and fastening systems.

The overlays do not necessarily have to be "non-combustible" to achieve the required fire protection of the flooring beneath.

In summary, the following provisions are proposed:

- For floor systems requiring a fire-resistance rating of 30 minutes or less, an overlay is not required.
- For floor systems requiring a fire-resistance rating between 30 - 60 minutes, an overlay may be needed.
- For floor systems requiring a fire-resistance rating of 60 minutes or more, an overlay is required if the floor is to perform as an effective barrier to fire from above for the full fire-resistance period.

A simple method has been described which utilises the results from small-scale cone calorimeter tests to estimate the fire-resistance performance achieved at full scale for floor coverings/overlays. It should be noted, however, that the small scale of the cone calorimeter test specimens minimises any problems such as cracking, which may be caused through differences in the expansion rates between the overlay and the particleboard substrate when fastened to each other.

The research described in this paper makes reference to the requirements within the NZBC Acceptable Solutions and the presently accepted test methods on which they have been based. In the provisions proposed above, the assumption is made that these test methods are valid. In future research it is intended to conduct a full-scale room fire experiment using a specified fire load rather than using the fire-resistance furnace. This will allow comparisons to be drawn and, if necessary, alterations made to the correlation with the small-scale results as carried out in this paper.

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