Predicting Fire Resistance Performance of Drywall Construction Exposed to Parametric Design Fires – A Review

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ABSTRACT: This paper describes validation of a cumulative radiant energy method for predicting the time to failure of non load-bearing drywall construction exposed to realistic parametric fires. The validation uses full-scale compartment fire tests and analytical calculations. Three compartment fire tests are carried out in a room 3.6 m by 2.4 m with different arrangements of fuel load and ventilation, with walls and ceilings constructed from assemblies which have been previously tested in standard fire resistance tests. The analytical calculations use a finite difference heat transfer model developed for predicting the fire performance of cavity construction, in combination with a number of Eurocode parametric fires. We conclude that the cumulative radiant energy method can be used as a valid tool for prediction of insulation failure times of drywall assemblies, during the period of fire exposure where heat transfer is predominantly by radiation. This includes the growth period to flashover, the period of sustained ventilation-controlled burning, and the early part of the decay period.

KEY WORDS: fire resistance, wall board, cumulative radiant energy, standard furnace test.

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INTRODUCTION

FIRE RESISTANCE OF building elements has traditionally been determined using standard furnace testing. Test methods are similar around the world and generally based on ISO 834 [1] time–temperature conditions. Previous research by Jones [2] has shown qualitatively that the time to failure of building elements exposed to realistic building fires may be significantly less than implied by standard furnace testing. This is particularly applicable where modern synthetic materials are present in fires. Such materials will tend to increase both the fire growth rate and compartment temperatures, where ventilation openings and compartment geometry permit, which result in more severe exposure than the standard furnace test.

By means of fully instrumented compartment tests involving non-load bearing walls and floor/ceiling systems comprising gypsum plasterboard and fiber-cement sheet materials, research by Nyman [3] quantified the variation in performance between a building element exposed to a compartment fire and the same element exposed to a standard furnace test. A method of predicting insulation failure was proposed that estimated the time to failure in a real fire for an assembly whose performance in a standard furnace test is known. The method compares the cumulative radiant energy in a real fire with that in a standard furnace test and was found to give reasonably conservative predictions for wall systems that fail by insulation. The findings were presented by Gerlich et al. [4]. Application of the cumulative radiant energy method for predicting insulation failure was further explained by Gerlich et al. [5] using numerous time–temperature design fire curves generated from the Eurocode parametric equation [6], and applied to compartments with differing fire loads and ventilation conditions. Subsequently, finite difference computer modeling has now been undertaken by BRANZ [7] on two fire rated wall systems to test the cumulative radiant energy method of predicting insulation failure.

This paper brings together previous publications describing the compartment testing, the prediction method, its application, and the finite difference computer modeling verification. The intent is to propose that the prediction method be used by fire engineers as a verified tool for predicting insulation failures of fire compartment walls in drywall construction.

FIRE RESISTANCE RATING

The extent to which the barriers provide protection from a fire for a period of time is determined by assigning that barrier, or construction element, with a fire resistance rating (FRR). For fire compartment barriers it is most often quantified as a measure of time, usually in hours or parts of hours, in which the building element can meet certain criteria when exposed to the standard fire test. The criteria used to determine an element's FRR are stability, integrity, and insulation.

The FRR of a construction element is defined as being the time to failure, under the standard fire test (AS 1530 Part 4 [8]), when one or more of the following general failure criteria apply:

- Structural adequacy (or stability) failure – An element of construction under test is deemed to have structurally failed when collapse, excessive deflection, or significantly reduced load bearing capacity has occurred.
- Integrity failure – An element of construction under test is deemed to have an integrity failure when collapse, or the development of cracks, fissures, or other openings allow the passage of hot gases or flames through the construction element.
- Insulation failure – An element of construction under test is deemed to have an insulation failure when either the average surface temperature rise on the unexposed side of the test element exceeds 140°C, or when any point on the unexposed side exceeds a temperature rise of 180°C.

The first failure criterion does not apply to non-load bearing construction elements. In New Zealand, FRRs are assigned to construction elements in the form –/–/–, where the time, in minutes, of fire resistance to the standard fire are ordered 'structural adequacy/integrity/insulation' respectively.

TESTING FOR FIRE RESISTANCE

Full-scale furnace testing is the most common method of determining the level of fire resistance for a construction element. Fire resistance testing of building elements in New Zealand is generally carried out in accordance with AS 1530 Part 4 [8], or BS 476 Parts 20–23 [9]. The time–temperature relationship for the fire used in most furnace tests has been standardized internationally by ISO 834 [1], which defines the furnace temperature as:

$$T = 345\log_{10}(8t + 1) + T_0 \tag{1}$$

where T is the furnace gas temperature (°C); T_0 is the ambient temperature at the start of the test (°C); and t is the time from the start of the test (minutes).

Furnace tests have been undertaken over many years and although they are good comparative tests for assessing the relative performance of construction elements, the appropriateness of the standard fire as a representation of an actual fire in a modern building is questioned.

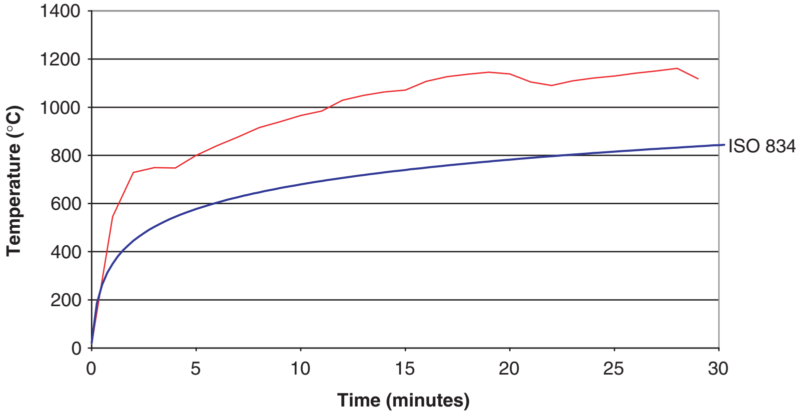

Figure 1. *More severe furnace temperatures compared with the standard temperature curve. Jones [2]. (The color version of this figure is available online.)*

As outlined by Babrauskas and Williamson [10] the origins of the standard temperature curve date back as far as 1903, with the first standard being introduced in 1917 by the American Society for Testing and Materials. The curve was originally based on furnaces burning wood fuel, modified slightly to give a faster temperature rise in the first 10 minutes, to apparently accommodate gas fired furnace temperatures. However, the approach was not based on knowledge of the intensities of building fires. The modified standard became ASTM E119 [11] in 1918, and this fire testing time–temperature regime has not significantly changed since 1918. Other countries have adopted similar standard fire test exposures.

Jones [2] undertook a pilot-scale furnace test on a nominal 60 minutes fire rated section of metal stud wall, 2 m high by 1 m wide, lined on both sides with gypsum plasterboard, exposed to time–temperature conditions more severe than the standard fire test. Integrity failure occurred at 28 minutes. Figure 1 shows the severity of the fire used in the test compared with the standard ISO 834 time–temperature curve. This test showed the significant impact of higher temperatures on the performance of the wall system. Joyeux [12] similarly observed the significantly earlier failure of fire doors when exposed to conditions more severe than the standard ISO 834 fire resistance test.

A comparison of the ISO 834 standard fire test temperatures with the real fire temperatures, in Figure 3, shows one of the limitations of trying to use existing furnaces to reproduce compartment fires – the temperatures obtained in the early stages of real fires cannot be achieved in the test furnace, particularly when modern foam plastic fuels are involved. This article does not propose any changes to the standard fire resistance testing regime, but it shows how standard fire resistance test results may be used in new ways to help fire safety design engineers.

CONSTRUCTION VARIATIONS

Another discrepancy between furnace testing and performance of fire rated elements in real buildings is found in construction differences. The size of a test specimen is limited by the size of the furnace. The specimen is commonly mounted in a fire resistant frame, which is sealed against the furnace. Restraint and boundary conditions may not be representative of installation of the construction element in a real building. For most fire rated elements the specification and quality of components and fixings are also extremely important. Manufacturers often closely supervise specimen construction and time and effort is spent ensuring the installation is to a high standard of workmanship. Such time allocated to the construction of a building element in actual construction is rare.

Deviation from manufacturer's specifications and poor workmanship will lead to a reduction in fire resistance. Blackmore [13] found that 'bad' workmanship can significantly reduce the fire resistance of gypsum plasterboard and masonry wall systems. This article shows that for real fires, differences in fire severity resulting from differences in fuel and geometry are much more significant than differences between good and bad construction methods.

COMPARTMENT FIRE TESTING

Nyman [3] carried out three compartment tests, each consisting of differing types of fire rated construction to the walls and ceiling, to obtain temperature data, and to establish failure times for assemblies exposed to fires more severe than the standard furnace test. The compartments were constructed to enable simultaneous testing of various lightweight timber and steel stud walls, a floor/ceiling system, and a fire door. Replicates of all systems had previously been exposed to an AS1530 Part 4 furnace test and detailed temperature data were available for comparison and analysis. Typical compartment test setup is shown in Figure 2 and dimensions are given in Table 1. Nine different assembly types A to I (see Table 2) were included in the tests. Compartment time–temperature history profiles were obtained and failure times were compared with standard furnace test results for identical assemblies.

Figure 2. *Typical compartment test setup. (The color version of this figure is available online.)*

Table 1. Compartment test dimensions.

	Compartment dimensions					Vent opening dimensions	
Test number	**Length (m)**	**Height (m)**	**Width (m)**	**Fuel load energy density (MJ/m^2)**	**Nominal fire resistance (minutes)**	**Height (m)**	**Width (m)**
#1	3.6	2.4	2.4	800	30	2.0	0.8
#2	3.6	2.4	2.4	1200	60	2.0	0.8
#3	3.6	2.4	2.4	800	30	2.0	1.2

Design Fires and Fuel Loads

The design fires were intended to simulate rapid growth associated with upholstered furniture, followed by a period of ventilation controlled burning. The selected fuel load energy densities (FLED) were consistent with the fire hazard categories given in the New Zealand Building Code Approved Documents. Design FLED values of 800 and 1200 MJ/m^2 were

Table 2. Compartment test assembly descriptions.

Tests reference number#	Construction element	Nominal fire resistance (minutes)	Description and nominal fire resistance
#1 #3	Assembly A	30	30 minutes light timber frame wall with gypsum plasterboard linings
#1 #3	Assembly B	30	30 minutes light timber frame wall with fiber-cement and gypsum plasterboard linings
#1 #3	Assembly C	30	30 minutes light steel frame wall with gypsum plasterboard linings
#1	Assembly D	30	30 minutes gypsum plasterboard lined ceiling on timber I-joists
#1 #3	Assembly E	60	60 minutes light timber frame wall with gypsum plasterboard lining
#2	Assembly F	60	60 minutes light timber frame wall with fiber-cement and gypsum plasterboard linings
#2	Assembly G	60	60 minutes light steel frame wall with gypsum plasterboard linings
#2	Assembly H	60	60 minutes gypsum plasterboard lined ceiling on timber I-joists
#1	Assembly I	30	30 minutes fire door

selected to ensure that failure of the assemblies would occur, enabling comparison with furnace test failure times.

All tests were intended to have similar 'fast' fire growth, but a different duration of burning. Polyurethane foam cushions with a synthetic fiber covering, in the geometry of a couch, were used to provide the initial growth expected in a fire involving upholstered furniture. The fuel was selected so that the foam cushions would take the compartment to flashover, after which burning of the wooden cribs would maintain ventilation controlled burning, until the onset of the decay phase. Untreated 'rough sawn' Radiata pine wood cribs were used for the bulk of the fuel load.

Instrumentation

Temperatures were measured within each compartment using thermocouple trees located at the room center and 100 mm from each test wall. Thermocouples were installed generally at 600, 1200, and 1800 mm from the floor. The central tree also had a thermocouple at 2400 mm, or ceiling level. Thermocouples were Type K Alumel/Chromel with crimped tips and 0.5 mm diameter glass braid insulated and sheathed thermocouple wire. Location of thermocouples within the test assemblies was consistent with placements used in previous standard furnace tests. Type K, 0.5 mm wire disc thermocouples were used, soldered to 12 mm diameter $\times$ 0.2 mm thick copper disc fitted with 30 mm square insulating pads. Insulating pads were removed for temperature measurement on the unexposed lining within the cavity. The disc thermocouples within the assemblies were generally located on the cavity side of the exposed lining, mid cavity, the cavity side of the unexposed lining, and the unexposed side of the assembly. More than 100 thermocouples were used for each compartment test.

Compartment Fire Test Results

Figure 3 gives the temperatures measured in the center of the compartments at elevations of 1200 mm, 1800 mm, and at ceiling level. Although these temperatures are reasonably representative of the compartment conditions during the fires, significant variations between thermocouple trees within the compartments were recorded. The performance of the different fire rated assemblies was analyzed using the data recorded by the thermocouple trees located nearest to the assembly. The assembly times to failure from ignition and from the start of exposure are given in Table 3. The start of exposure is defined as the time at which a rise in temperature above ambient was measured at the thermocouple tree closest to the

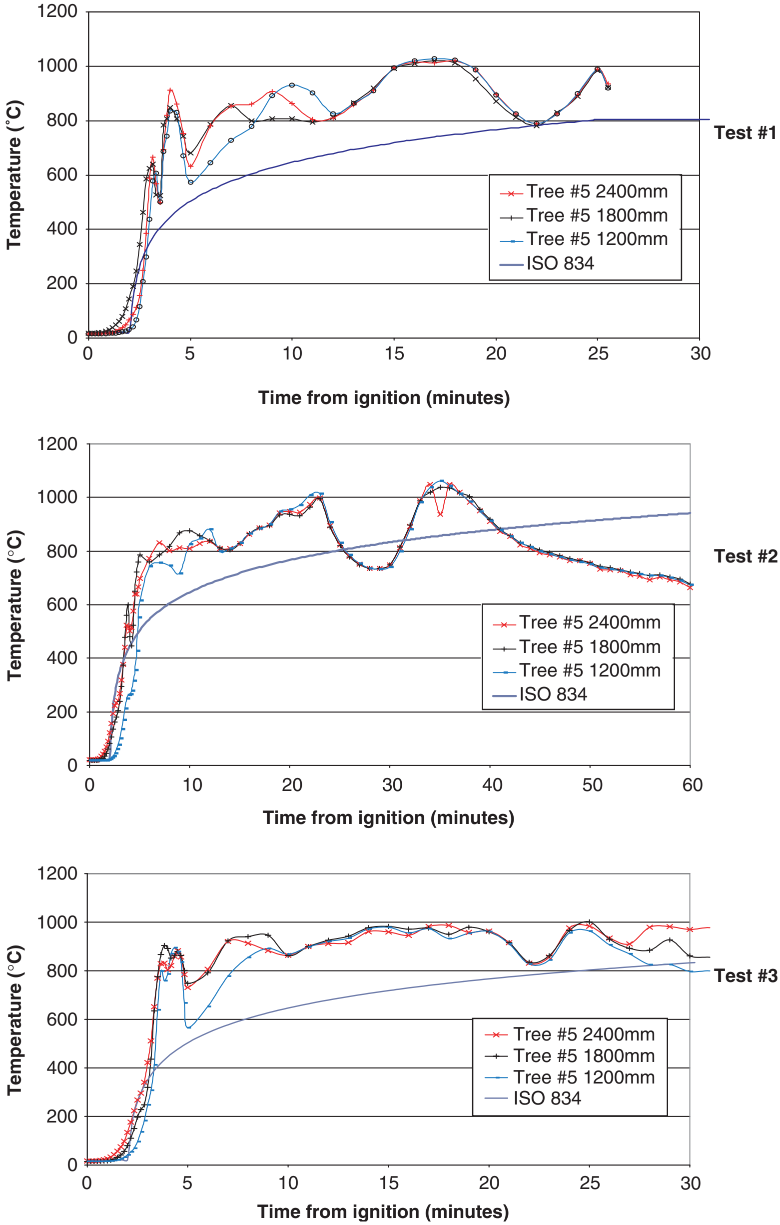

Figure 3. *Temperatures at the center of the compartment for tests #1, #2, and #3. (The color version of this figure is available online.)*

Table 3. Failure times for the tested assemblies.

Assembly reference	Test number	Time to failure in ISO 834 test (minutes)	Time to failure in compartment fire test (minutes): From ignition	From exposure	Mode of failure in compartment fire test
A	#1	42	23	21	Insulation
	#3	42	20	18	Insulation
B	#1	39	38	36	Insulation
	#3	39	26	24	Insulation
C	#1	34	21	19	Integrity
	#3	34	19	17	Integrity
D	#1	55	32	30	Structural
	#3	55	30	28	Structural
E	#2	68	53	51	Insulation
F	#2	58	57	55	Insulation
G	#2	63	37	35	Integrity
H	#2	74	–	$58 < t_{fail} < 75$ [a]	Structural
I	#1	32	22	20	Integrity

[a]Exact structural failure time was not established, and is assumed to fall in the time range indicated.

assembly being assessed. The ISO 834 test time–temperature curve is also shown on Figure 3 and as can be seen, the experimental compartment fires are generally higher in temperature.

The test results indicate that in Tests 1 and 3 integrity failure occurred (Assembly C) before any of the assemblies had failed for insulation, and well before Assembly B failed. At this stage Assembly D had undergone structural failure. Neither the integrity failures nor the structural failure resulted in a significant inflow of additional oxygen to the compartment which might have affected the radiation levels and the time to failure of the other assemblies.

Analysis

Subsequent analysis of the results in Table 3 showed that the time to failure of non-load-bearing drywall assemblies exposed to compartment fires can be predicted by a method based on the cumulative radiant energy to which the assembly is exposed. This is considered to be appropriate because the predominant mode of heat transfer in compartment fires is radiant energy ([14]). Radiant heat transfer is a function of the absolute temperature T(K) raised to the fourth power.

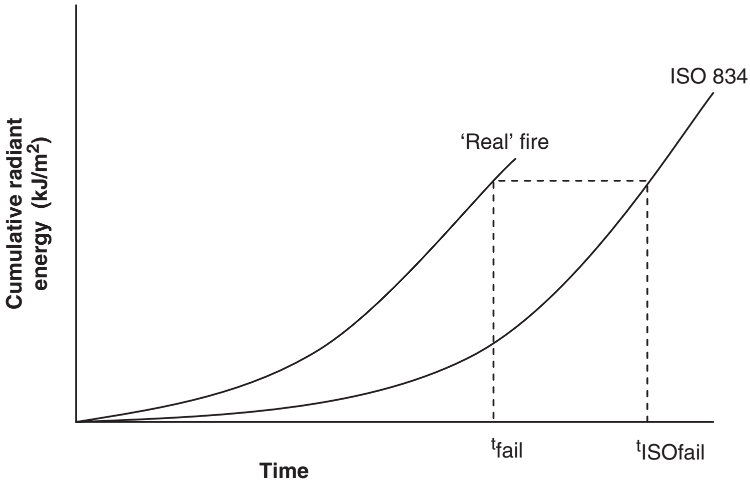

Figure 4. *Cumulative radiant energy approach for equivalent fire severity.*

The cumulative radiant energy is the area under a plot of radiant energy versus time, expressed as:

$$E = \int_0^t \dot{Q}''\,\mathrm{d}t = \varepsilon\sigma \int_0^t (T^4)\,\mathrm{d}t \quad (\mathrm{J/m^2}) \tag{2}$$

where,

- E is the cumulative radiant energy on the assembly over a period of time ($\mathrm{J/m^2}$);
- $\dot{Q}''$ is the radiant heat flux incident upon the assembly at any point in time ($\mathrm{W/m^2}$);
- ε is the emissivity (conservatively taken as 1);
- σ is the Stefan Boltzmann constant ($5.67 \times 10^{-8}\ \mathrm{W/m^2.K^4}$);
- t is the time from the start of the test (s); and
- T is the compartment gas temperature (K).

The method assumes that compartment and standard furnace fires have similar heat transfer coefficients and that convective components of heat transfer in the compartment and furnace are of equal proportion to the total energy transfer. The method is similar to the normalized heat load concept of Harmathy and Mehaffey [15] and can be applied to any time–temperature curve to predict the time to failure if performance in a standard furnace test is known. Figure 4 shows how this is achieved. The curves show the cumulative radiant heat energy to which a wall is exposed. If t_{ISOfail} is the time to failure of an assembly in the standard fire resistance test, the dotted line can be used to predict t_{fail} which is the predicted time to failure of the same assembly in the 'real' compartment fire.

Alternatively, the dotted line can be used in the other direction, so that if the desired failure time is t_{fail} the required FRR to achieve that failure time is given by t_{ISOfail}.

Figure 5 shows compartment failure times predicted for the tests compared with actual test failure times for the 9 assemblies described in Table 3. If the model were perfect all the points would fall on the 45° line. Insulation failure predictions are generally conservative (above the line), whereas predictions were non-conservative (below the line) for assemblies which failed structurally or on integrity (e.g., floor/ceiling and metal stud systems). The failure mode of each test assembly is described in greater detail by Nyman [3].

EUROCODE PARAMETRIC FIRE EQUATION

The cumulative radiant heat energy approach has been applied by Gerlich et al. [5] to time–temperature histories generated using the parametric fire equations given in Annex A of Eurocode 1 (Third Draft) [6]. The heating phase is given by Equation (3). The cooling phase is a function of fire load density amongst other variables and is described in detail in Annex A of Eurocode 1. While the equations are cumbersome, they do lend themselves to spreadsheet analysis.

$$T = 20 + 1325\left(1 - 0.324e^{-0.2t^*} - 0.204e^{-1.7t^*} - 0.472e^{-19t^*}\right) \tag{3}$$

where, T is the temperature in the fire compartment (°C);
$t^* = t \cdot \Gamma$ is a fictitious time, (h)
and,

- t is the time (h);
- Γ $= [F_v/0.04]^2/(b/1160)^2$ (–);
- b $= \sqrt{(\rho c \lambda)}$ (with limits $400 \leq b \leq 2000$) (J/(m^{2}s$^{1/2}$K));
- ρ is the density of boundary enclosure (kg/m^3);
- c is the specific heat of boundary enclosure (J/(kgK));
- λ is the thermal conductivity of boundary enclosure (W/(mK));
- F_v is the opening factor $(A_v/A_t)(h_{\mathrm{eq}})^{1/2}$ (with limits $0.02 \leq F_v \leq 0.20$) (m$^{1/2}$);
- A_v is the total area of vertical openings on all walls (m^2);
- h_{eq} is the weighted average of window heights on all walls (m); and
- A_t is the total internal surface area of enclosure (including openings) (m^2).

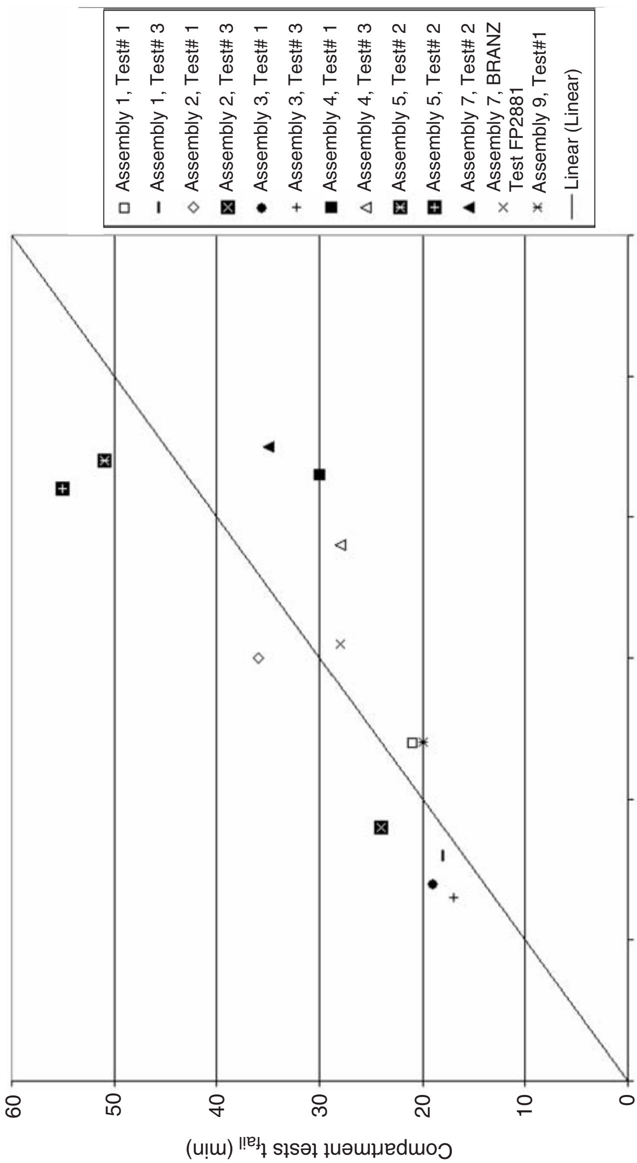

Figure 5. *Compartment tests - predicted failure time using cumulative radiant energy ves measured failure time.*

Equation (3) introduces the term gamma ‘Γ’ which includes the opening factor, F_v, and the square root of the thermal inertia of the bounding materials of the fire compartment, b. The Eurocode parametric fire becomes almost identical to the ISO 834 furnace test curve when $\Gamma = 1.0$, which occurs for a compartment with an opening factor of $0.04\,\mathrm{m}^{1/2}$ and $b = 1160\,\mathrm{J/(m^2 s^{1/2} K)}$.

There is some uncertainty as to which value of ‘b’ to use in Equation (3) for drywall construction. A compartment typical of drywall construction consists of timber or steel framed walls lined with gypsum plasterboard and a gypsum plasterboard ceiling fixed either directly to the underside of floor framing above, or to a concealed grid system under a concrete slab.

It was found that published values for the thermal properties of gypsum plasterboard would give a value of $b = 400\,\mathrm{J/(m^2 s^{1/2} K)}$, which results in compartment temperatures which are higher than those measured in tests. The BRANZFIRE [16] compartment model was used to derive a more realistic value of $b = 700\,\mathrm{J/(m^2 s^{1/2} K)}$. The justification for the higher value is thought to result from other heat losses typically experienced in compartment fires due to the presence of openings and items, such as heavy furnishings. Figure 6 shows that for the third compartment test, BRANZFIRE [16] gives a much better prediction of measured temperatures with a thermal inertia value of $b = 700\,\mathrm{J/(m^2 s^{1/2} K)}$, which was subsequently used in Equation (3) for the analysis and results.

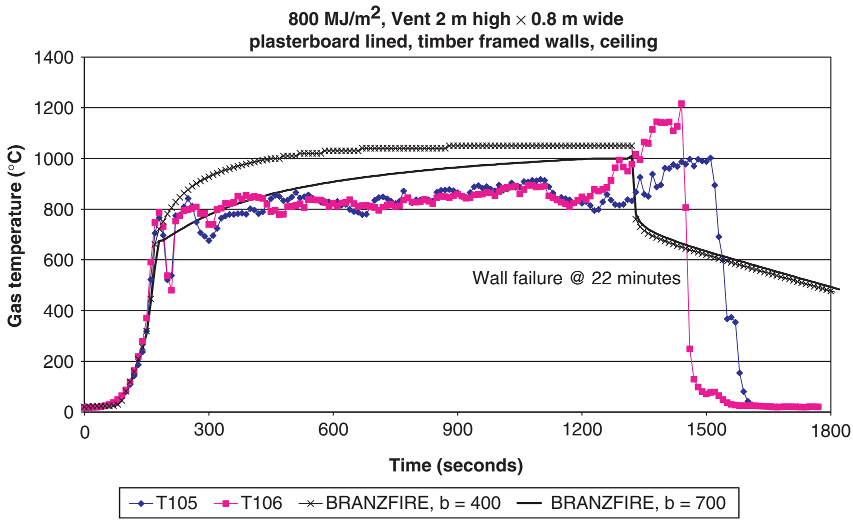

Figure 6. *Predicting compartment temperatures using BRANZFIRE2003.2 with using* $b = k\rho c = 400$ *and* $700\,\mathrm{J/(m^2 s^{1/2} K)}$*. (The color version of this figure is available online.)*

Figure 7 shows the time–temperature histories generated using the Eurocode 1 equations for compartments with opening factors ranging from 0.02 to 0.10 $m^{1/2}$ and for FLED of 400, 800, and 1200 MJ/m^2. These compartment temperatures were used to generate cumulative radiant heat energy histories by applying Equation (1). The results are shown in Figure 8 and are compared against the ISO 834 cumulative radiant heat energies. As can be seen the temperatures and cumulative radiant heat energies for the compartment tests generally lie above the ISO 834 values until after the fire has gone out.

DESIGN GUIDELINES

A design procedure has been developed to predict the time to failure in a parametric fire for an assembly which has achieved a FRR in a standard test. The design procedure involves the following steps:

- Determine relevant input data, such as geometry, compartment fuel load and thermal inertia values, and ventilation condition (opening factor)
- Compute the predicted time–temperature history for the compartment using the Eurocode parametric fire equation
- Obtain the time–temperature history for the standard ISO 834 furnace test curve (or other test curve which was used for furnace testing of the assembly)
- For each curve calculate the cumulative radiant heat energy with time
- The predicted failure time for the Eurocode curves corresponds to a cumulative radiant energy equal to that for the ISO 834 test at the time when failure actually occurred.

Using the Eurocode parametric fire equation, applied to drywall construction, the computed cumulative radiant heat values illustrated in Figure 8 were generated and compared with the cumulative radiant heat history derived from the ISO 834 time–temperature curve. For assemblies with a given furnace test result (FRR), predictions of times to failure (t_{fail}) were determined as presented in Table 4. The times to failure depend on the ventilation conditions (opening factor) and the compartment fire load density. The amount of ventilation available in a fire compartment is described in terms of the opening factor, F_v, defined previously in connection with Equation (3).

It can be seen from Table 4 that the times to failure are much less than the specified FRR, for opening factors of 0.02 or more.

The cumulative radiant heat energy concept can be also applied to determine the minimum FRR required to ensure that a safe failure time, or evacuation time, is achieved. A spreadsheet was used to establish the

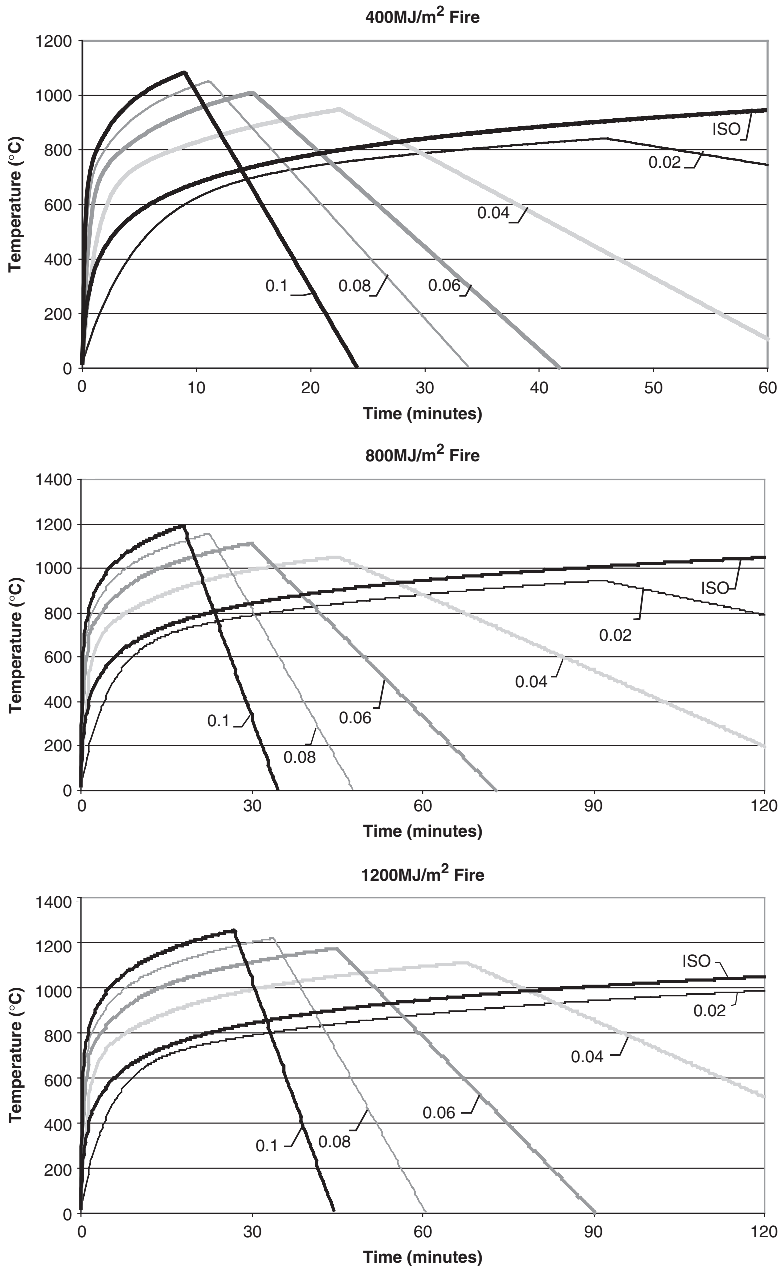

Figure 7. *ISO 834 temperatures compared with compartment time–temperature histories generated using Eurocode equations for* $b = 700\,J/m^2s^{1/2}K$ *and opening factors from 0.02 to 0.1.*

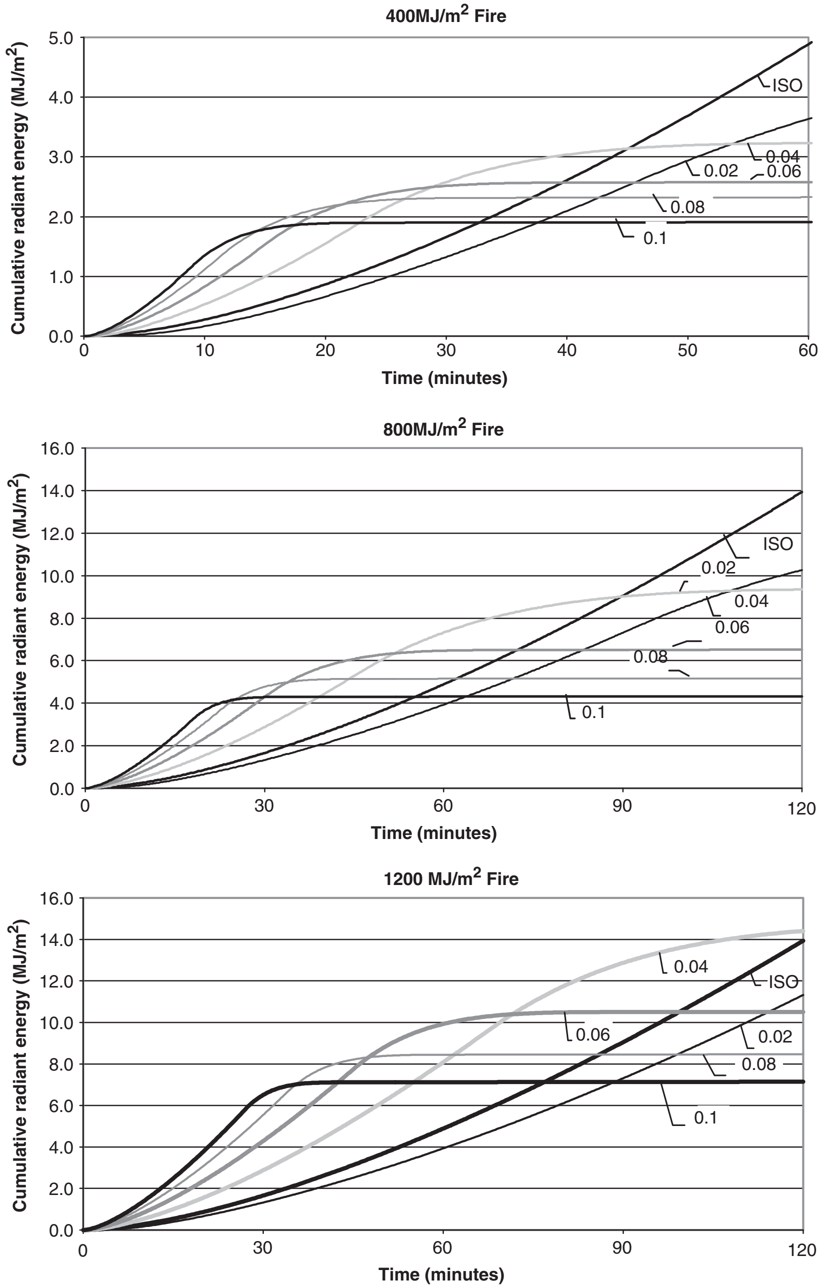

Figure 8. *ISO 834 cumulative radiant heat energy compared with energy histories generated from Figure 7 Eurocode temperatures using Equation (1).*

Table 4. Predicted times to failure (t_{fail}) in minutes for assemblies with a fire resistance rating (FRR) from a standard fire test.

	Fire load											
	400 MJ/m^2				800 MJ/m^2				1200 MJ/m^2			
	FRR				FRR				FRR			
Opening factor m$^{1/2}$	15	30	45	60	15	30	45	60	15	30	45	60
0.01	22	41	59	nf	22	40	60	80	22	40	60	80
0.02	12	24	38	nf	12	24	36	49	12	24	37	50
0.03	9	18	31	nf	9	19	28	38	9	18	28	37
0.04	7	15	28	nf	7	15	23	32	7	15	23	31
0.05	6	13	26	nf	7	13	20	28	6	13	20	27
0.06	5	12	25	nf	6	12	18	26	6	12	18	24
0.07	5	11	23	nf	5	11	16	24	5	11	16	22
0.08	5	10	23	nf	5	10	15	22	5	10	15	21
0.09	4	9	23	nf	4	9	14	22	4	9	14	19
0.1	4	9	14	22	4	9	14	22	4	9	13	18

nf = no failure. Fuel will be depleted before failure occurs.

cumulative radiant energy value reached at the times of failure for the ISO 834 standard test. Similarly, the time to achieve the same cumulative radiant energy values was also undertaken for the Eurocode parametric time–temperature curves. When the cumulative radiant energy for the ISO 834 failure is achieved by the Eurocode cumulative radiant energy assessment, that is the predicted time to failure. The actual establishing of the predicted time to failure is merely by comparing the two cumulative radiant energy spreadsheets created. These values are presented in Table 5. It can be seen that the FRR values are nearly all much larger than the required evacuation time.

FINITE DIFFERENCE MODEL EVALUATION OF RADIANT HEAT ENERGY CONCEPT

BRANZ undertook to compare the fire resistance of two fire-rated wall systems, by means of computer modeling, with a view to testing the cumulative radiant energy method. The wall systems were of timber framed construction, as follows:

- 10 mm GIB Fyreline® Board each side of the timber framing (GBT30 system [17])
- 13 mm GIB Fyreline® Board each side of the timber framing (GBT60 system [17])

Table 5. Required fire resistance rating in minutes to ensure that safe evacuation times are achieved.

	400 MJ/m²				800 MJ/m²				1200 MJ/m²			
	Evacuation times				Evacuation times				Evacuation times			
Opening factor $m^{1/2}$	15	30	45	60	15	30	45	60	15	30	45	60
0.01	10	22	34	45	10	22	34	45	10	22	34	45
0.02	19	38	50	55	19	38	56	75	19	37	55	73
0.03	25	44	52	55	25	49	71	83	25	49	72	95
0.04	30	47	52	54	30	58	75	83	30	58	85	103
0.05	33	48	52	52	35	64	76	81	35	66	92	104
0.06	35	48	52	52	38	66	76	80	39	74	94	102
0.07	37	48	52	52	42	68	75	76	42	78	93	98
0.08	38	48	50	50	48	68	74	75	45	80	92	96
0.09	39	48	50	50	48	68	73	73	48	80	92	93
0.1	40	48	49	49	50	68	72	72	51	80	88	90

Table 6. Summary of design fires used in finite difference analysis.

Design fire type	Fire load (MJ/m²)	Opening factor $m^{1/2}$	Time to peak temperature (minutes)	Time to end of decay period (minutes)
Eurocode	400	0.05	18.0	50.5
Eurocode	800	0.02	91.5	120+
Eurocode	800	0.05	36.0	97.5
Eurocode	800	0.08	22.5	48.0
Eurocode	1200	0.05	54.0	119.2

The heat transfer model used for the evaluation was FireBarrier [7]. This finite difference model has been developed by BRANZ and has been validated during its development by correlation with numerous standard fire test results of differing construction systems. The use of other heat transfer programs suitable for modeling cavity wall systems would have given similar results. Structural performance and integrity failures of the wall systems were not included in this analysis.

Each wall system was assessed against design fires including the ISO 834 standard test time–temperature fire exposure, and additionally five Eurocode [6] parametric design fire curves, for nominated fuel loads and opening factors as given in Table 6.

Baseline modeling trials for calibration purposes were conducted using the ISO 834 standard time– temperature curve to determine the cumulative

Table 7. Cumulative radiant energy at time of insulation failure in ISO 834 design fire.

Wall	Insulation failure (minutes)	Cumulative radiant energy (MJ/m^2)
GBT30	44	182
GBT60	69	364

Table 8. FireBarrier modeled performance of GBT30 compared with the cumulative radiant energy method.

			Insulation failure (min)	
Design fire type	FLED (MJ/m^2)	Opening factor ($m^{1/2}$)	FireBarrier	Cumulative radiant energy method
ISO 834	–	–	44.0	–
Eurocode	400	0.05	25.0	nf[a]
Eurocode	800	0.02	49.0	50.7
Eurocode	800	0.05	25.0	26.7
Eurocode	800	0.08	18.0	19.7
Eurocode	1200	0.05	25.0	26.7

[a]reached end of decay phase without failure.

radiant energy exposure at the time of insulation failure. The cumulative radiant energy values are shown in Table 7. Insulation failure is defined as having occurred when the unexposed ambient side of the wall construction exceeds an average temperature rise of 140°C.

These modeled results correlated very well with the actual fire resistance test results for insulation failure, which were 42–44 minutes for the GBT30 system (more than one test result available), and 69 minutes for the GBT60 system.

The expected performance of the wall systems in the Eurocode design fires was then calculated using the FireBarrier computer model and compared with the cumulative radiant energy method, based on the cumulative radiant energy shown in Table 7. The results of the comparison are given in Tables 8 and 9, for the GBT30 and GBT60 systems, respectively.

Results and Analysis of Finite Difference Modeling Comparison

Considering the 'insulation' failure criterion, close agreement is achieved between the results of the cumulative energy method and that of the finite difference modeling results, with some exceptions. Where there is a marked difference, this is indicated in the tables by the difference between a finite

Table 9. FireBarrier Modeled performance of GBT60 compared with the cumulative radiant energy method.

			Insulation failure (minutes)	
Design fire type	**Fire load (MJ/m^2)**	**Opening factor m$^{1/2}$**	**FireBarrier**	**Cumulative radiant energy method**
ISO 834	–	–	69.0	–
Eurocode	400	0.05	nf[a]	nf[a]
Eurocode	800	0.02	77.0	79.5
Eurocode	800	0.05	44.0	44.7
Eurocode	800	0.08	32.0	nf[a]
Eurocode	1200	0.05	44.0	43.0

[a]reached end of decay phase without failure.

failure time with FireBarrier and the absence of failure with the Cumulative Radiant Energy method. It is noted that the discrepancies occurred in the decay phase of the two Eurocode fires with FLED/opening factors of 400/0.05 and 800/0.08. In these cases the relatively low FLED to large opening factor ensures the fires burn out rapidly and enter the decay phase sooner than for smaller opening factors.

SUMMARY

Standard furnace testing has been used for almost a century to establish the fire resistance of building elements and is useful for comparing the performance of one product with another. However, standard furnace testing poorly represents the performance of drywall construction exposed to the range of different time–temperature conditions that can be experienced in real building fires.

Time to failure of a construction assembly may be much less than the published FRR for that assembly, especially for fires in compartments with large openings and where the temperatures in the early stages of the fire may be much higher than in the standard fire test.

Fully instrumented full-scale compartment tests have been carried out. The compartments were constructed with a range of fire rated drywall systems. Time–temperature history profiles have been obtained and compared with standard furnace test results for the same assemblies.

A prediction method has been proposed that estimates the equivalent time to failure in a real fire for an assembly whose performance in a standard furnace test is known. The method compares the cumulative radiant energy in a real fire with that in a standard furnace test.

Time–temperature and cumulative radiant heat histories have been prepared using the Eurocode parametric fires and predictions of drywall performance exposed to these design fires have been tabulated as a function of compartment fuel density and ventilation conditions. The method provides reasonably conservative predictions for 15, 30, 45, and 60 minutes fire rated systems that fail by the insulation criterion. Predictions for systems that fail structurally or by the integrity criterion are found to be non-conservative and further work in this area is recommended.

The proposed radiant energy exposure method has been further verified using finite difference computer modeling comparisons with tested wall systems.

CONCLUSIONS

The radiant energy concept proposed produces a reliable prediction of the 'insulation' fire resistance of drywall construction for design fires that differ from the ISO 834 exposure. The radiant exposure method is valid for use as a design tool, where the design fire is predominantly transferring heat to the wall construction by radiation (i.e., fast fire growth, ventilation-controlled through to early decay phase).

The conclusions drawn from this study are based on a small number of test results. It is recommended that further tests be carried out on a wider range of construction assemblies with different types of fire loads, to allow a critical review of these findings and provide more confidence to designers and code writers who wish to use them.

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