STUDY REPORT

No. 147 (2005)

Post-earthquake Performance of Passive Fire Protection Systems

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The work reported here was jointly funded by Building Research Levy and the Department of Building and Housing

FUNDED BY THE BUILDING RESEARCH LEVY

ISSN: 0113-3675

Quality System Quality Endorsed Company ISO 9001 Lic 2437 Standards Australia

Preface

This is a report prepared describing research to establish a relationship between the damage caused by earthquake and the reduction in fire resistance of passive fire resistance systems.

Acknowledgments

This work was jointly funded by the Building Research Levy and the Department of Building and Housing.

A special thanks to the steering committee members whose valuable contributions and advice ensured a successful outcome of the project.

Geoff Thomas – Victoria University
Hans Gerlich – Winstone Wallboards Ltd
Hamish Ewan – Winstone Wallboards Ltd
Geoff Sharp – Holmes Consulting Group
Craig McGhie – Clendon Burns and Park Ltd
Greg Baker – BRANZ Ltd
Stuart Thurston – BRANZ Ltd
Peter Collier – BRANZ Ltd

Note

This report is intended for:

The Department of Building and Housing as a technical basis for reviewing and/or updating provisions contained in the approved document.

Other researchers considering the wider implications of fire spread after earthquakes.

POST-EARTHQUAKE PERFORMANCE OF PASSIVE FIRE PROTECTION SYSTEMS

BRANZ Study Report SR 147 **P.C.R. Collier**

REFERENCE

Collier, P.C.R. 2005. *Post-earthquake performance of passive fire protection systems.* BRANZ Study Report 147, Judgeford, Wellington.

ABSTRACT

The damage caused to passive fire protection systems by earthquake is highly variable and as a consequence the reduction in the fire resistance is similarly uncertain. This project endeavoured to quantify the resultant reduction in the fire resistance of a series of plasterboard lined lightweight timber and steel-framed walls after being subjected to simulated earthquake racking to a range of drift ratios extending above and below (+/-) the code limit. The resultant earthquake damage was shown to be a primary cause of the reduction in fire resistance when the walls were subjected to a fire resistance test. The predominant cause of the reduced fire resistance was due to flaming from gaps due to detachment of the wall linings in isolated locations resulting Integrity failures rather than Insulation failure as a result of more general failure of the exposed lining. The Integrity failures in general occurred around the perimeter of the wall specimens where the majority of the damage occurred and the detachment of the lining was directly attributable to the security of the edge detail in the simulated earthquake racking. The Insulation fire resistance was also shown to be adversely affected by the racking damage, but not to the same extent as the Integrity fire resistance, and as a consequence was not the initial failure recorded in the trials conducted. A subjective judgement of the likely reduction in fire resistance is possible by assessing the damage resulting from the racking process. The amount of reduction in fire resistance of a 60 minute plasterboard lined wall can be as high as 50% in a design level displacement cycle.

Keywords: earthquake, passive fire protection, drift ratio, plasterboard lining, fire resistance

EXECUTIVE SUMMARY

This project has shown that the post-earthquake performance of passive fire protection systems is definitely reduced when subjected to a design level earthquake. The amount of reduction in fire resistance of a 60 minute plasterboard lined wall can be as much as 50%. This is of increased importance considering that active fire protection systems such as sprinklers may have also been rendered inoperable in the earthquake event. This is a dual problem considering that a reduction in the fire resistance requirements by 50% may have been permitted because sprinklers were included as part of the fire design. The problem may be further compounded by the increased likelihood of fire outbreak due to disruption of building activities and services. Furthermore Fire Service attendance cannot be relied upon due to the certainty of multiple callouts and possible impediment/blockage of road access. Finally, egress from buildings may also be restricted by blocked exit-ways and injuries to people increasing the escape times.

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1. INTRODUCTION

Post-earthquake performance of passive fire protection systems

This research project at BRANZ studied the effect of simulated earthquake racking on the fire resistance of plasterboard lined fire resistant walls.

The role of passive fire protection (PFP) systems in accordance with NZBC Fire Safety Acceptable Solution C/AS1 (DBH, 2005) includes protecting the means of escape from a building in the event of fire, and the control of internal and external fire and smoke spread. Also, previous research referenced by Taylor (2003) has highlighted some of the implications of current fire safety design philosophies based on Fire Service response times, fire-fighting water supplies, and active fire suppression systems (especially sprinklers), which may not be viable following a major earthquake.

Although PFP systems may perform their specified function under ideal test conditions, there are concerns that an earthquake may weaken the fixing of linings to framing and hence the level of protection may be degraded post-earthquake. The likelihood of fires starting is also significantly increased by earthquake and the Fire Service is unlikely to be able to respond quickly (Botting, 1997). The integrity of the PFP systems post-earthquake is important in protecting safe paths for the egress of building occupants and delaying internal fire spread between fire cells. This is particularly so when it is also considered that egress may be slowed due to earthquake damage obstructing escape routes in buildings.

The objective of this project was to understand how earthquakes affect the functionality of PFP systems, with a view to being able to provide the Department of Building and Housing (DBH) with definitive technical guidance on the issue.

1.1 Proposed work

Undertake a literature survey on the performance of PFP systems in fire following earthquake.

Subject a selection of light timber-framed and steel-framed wall systems, which have previously been rated in fire resistance tests, to various levels of simulated earthquake racking in the laboratory.

Subject the “damaged” walls to standard fire resistance conditions and compare the fire performance of the original and earthquake damaged systems.

1.2 Outputs

After each test specimen had been racked, a damage assessment of the lining condition was recorded on a qualitative basis and compared with the drift ratio (the movement of the top of the wall divided by the height of the wall expressed as a percentage).

It was expected that a reduction in the fire resistance would occur as a function of the degree of damage sustained to the plasterboard lining in the earthquake event as simulated by the wall racking process. This resulted in a clearer understanding of the link between earthquake magnitude and the reduction in the effectiveness of fire-rated walls. It will contribute to the technical basis by which the DBH can make a decision about possible amendments to the current Approved Document for the New Zealand Building Code Safety Clauses.

2. STEERING COMMITTEE

A steering committee was formed to provide a wide base of ideas and to focus on ensuring that building features and details that may be responsible for weaknesses in buildings in the event of earthquake were considered. The following ideas and decisions are based on the discussions at a series of meetings throughout the project.

Fire engineering solutions often rely significantly on sprinkler protection in buildings and this protection is at risk in the event of an earthquake if the water supply to sprinklers is lost. In addition, the response time of the fire service may be delayed due to multiple call-outs and obstructions on the roads and within buildings. The performance of the passive fire protection (PFP) systems then becomes more important, but this protection too may also be severely damaged resulting in a much reduced fire resistance performance.

Fire resistance testing of PFP systems such as wall and floor/ceilings is based on the performance of perfect specimens; in the event of damage caused by earthquake racking this fire resistance may be considerably impaired.

2.1 The risk of fire following earthquake

The likelihood of fire occurring after earthquakes was raised and the experiences in Japan, California and New Zealand were used as examples (Roberson and Mehaffey, 2000; Cousins et al, 2003). The risk of fire following earthquake is perhaps considered to be less now than, for example, the bunsen burner scenario in the chemist shop in the Napier earthquake responsible for the fire that spread throughout the city (Sharp, 2003). Similarly in Tokyo (1923 Great Kanto earthquake) solid fuel cooking burners being knocked over in wood/paper houses were responsible for widespread fire (Cameron and James, 1998).

Given that there is a risk of fire following earthquakes, even if it is now considered a reduced risk due to improved construction, the objective of this research project was to provide guidance (in the form of test data) to the larger (and recognised) problem of the risk of fire spread post-earthquake.

It was suggested that apartment buildings represent the greatest risk in post-earthquake fires where exit-ways may be blocked by smoke/flames from failed fire resistance barriers. Fire doors may also be at risk. Doors normally held open with automatic closers (in the event of a fire alarm) may not close properly if the frame is out of alignment. Similarly, relatively stiff door/frames in racked walls may split away from walls resulting in a gap and are hence considered to be an Integrity failure as soon as a fire starts. Ceilings also represent a problem where the underside lining representing a significant proportion of the fire resistance falls away more easily than a wall lining would.

2.2 The effect of earthquake damage on the fire resistance

The specific direction of this project was to concentrate on the fire performance of gypsum plasterboard lined walls. It was proposed to simulate an earthquake by racking an isolated wall to a specified drift ratio and then subjecting it to fire resistance testing. It was proposed to do this with the wall assembled in a (braced) fire resistance test frame with a roller bearing arrangement on the top edge and suitable gaps on each side to allow the required drift. The gaps around the wall were then filled with fire resisting material before fire testing.

The magnitude of the simulated earthquakes to be applied needed to be determined. A paper by Brundson and Clark (1993) highlights the characteristics of a moderate earthquake as MM8 intensity on intermediate soils. In Wellington such an event is considered to be represented by a magnitude 6.0 to 6.5 (Richter scale) earthquake, which has a return period of approximately 140 years with a 30% probability in 50 years. According to NZS 4203 (SNZ, 1992) the maximum likely inter-storey drift of a 13 storey moment resisting frame building is 1.0 to 1.5%. This is considered a moderate earthquake likely to cause structural damage to a number of buildings of this type, in addition to extensive non-structural damage.

The question was raised whether the effect of racking was frequency dependent, in other words should a specimen be racked at the same frequency as that of the simulated earthquake or is it acceptable to cycle at a much slower frequency compatible with the jacking equipment? This led to a discussion on how best to simulate the earthquake damage under laboratory conditions and the energy-based methodology proposed by Dutta and Mander (2001) was suggested and adopted for the loading regime.

The provision of horizontal joints in linings was discussed, in relation to two sheets butting each other in an extra high location such as a stairwell. It was suggested this could be included in a racked specimen and the movement on the horizontal joint noted, before fire testing. A visit to the BRANZ structures laboratory to view an example of a recently tested racking specimen showed a horizontal joint to be unaffected by racking in spite of the perimeter fixings having significantly elongated holes in the plasterboard. The horizontal joint was formed over a nog that had been taped and stopped, and that appeared to impart sufficient strength to avoid damage to the joint.

The quality of the workmanship may have an effect on the fire resistance in the absence of any damage caused by earthquake. A study by Nyman (2002) cites a study at CSIRO (Blackmore et al, 1999) on the quality of construction workmanship and how this may affect the fire resistance. For badly constructed plasterboard systems the failure to the insulation criteria was found to occur 5 minutes earlier on average compared with standard construction walls.

Other ideas from the steering committee meetings that warranted further consideration and that were raised during the project are:

- conduct a survey of the PFP features that may be adversely affected in earthquakes
- determine the relative proportions of timber and steel construction of framed partitions
- doors in walls, in terms of resistance to racking causing the frame to become detached from the wall or if the door opens as a result of the EQ (racking) or was open to begin with
- inter-storey joint drift – is it a problem when applied to horizontal joints?
- shaft walls as applied to elevators, steel CH stud-framed walls
- inter-storey junctions in stairwells with horizontal joints on stair side and floor/ceilings on the other
- consideration of a more realistic racking regime whereby the side studs are restrained from bending, which has had the effect of concentrating the racking drift on the upper portions of the wall.

2.3 Test programme

Discussions on the preparation of a testing programme highlighted the following areas:

- The height of the test walls needed to be decided and the options were 3000 mm or 3600 mm. The important consideration was that the strain (at the fasteners) would be greater on higher walls. A height of 3000 mm was chosen for the test wall height as most damage was expected to occur around the perimeter and testing at 3000 mm was more practical.

- It was proposed that the testing be conducted on 60 minutes FRR systems using 13 mm fire-rated plasterboard.
- An experimental programme of seven racking and fire tests was proposed, initially with timber framing then steel, with the final test including a fire-rated door.
- The objective was to establish a relationship between the drift ratio and the reduction in fire resistance and find a critical value of drift ratio, where the fire resistance is reduced significantly, should it exist.

3. ADDITIONAL BACKGROUND LITERATURE

Various sources indicate that earthquake exposure does have a deleterious effect on the performance of PFP. However, the extent of the damage is as variable as the number of sources.

Taylor (2003) reports on the reliability of passive protection and highlights the main concerns as inadequately fire-protected penetrations for building services and the presence of ineffective fire and smoke doors. In a survey of office buildings in Wellington in the late 1980's (Barnes, 1997), over 24% of fire doors were removed or wedged open. Various studies (Porter et al, 2001) indicate that visible damage can be expected at drift ratios of 0.4% at which level smoke spread is expected through cracking and gaps due to dislodged stopping plaster and fire spread could occur at a drift ratio of 0.85% when the plasterboard is likely to separate from the framing. Japanese recommendations (Sekizawa et al, 2000) suggest a 50% effective reduction in fire resistance for partitions subject to a transient drift of 0.33%.

At present new buildings in New Zealand between 30 and 58 m in height typically require 45-60 minutes FRR (DBH, 2005. However, these buildings are also required to be sprinklered, which makes the situation worse should the sprinkler system be rendered inoperable in an earthquake. Taylor (2003) referenced failure rates of sprinklers in buildings in earthquakes, but there is a wide variation depending on source of data and whether it is water supply under consideration or reticulation within a building. The range of data for the reliability suggests that without redundancy, systems installed for the water supply and adequate seismic restraint on the sprinkler pipework within a building, the reliability could be as low as 0%. So the fire protection that remains might only be passive depending on how that survives.

Sharp and Buchanan (2004) report some PFP systems such as gypsum plasterboard walls are very vulnerable to earthquake damage. This can lead to a reduction in fire resistance ratings, thereby threatening the fire safety of the occupants, particularly for walls protecting escape routes. Experimental testing of timber-framed walls under lateral earthquake load indicated that the damage sustained by the wall system became significant at a drift level of 0.6%. This is where considerable deformation of the plasterboard around the nails began to occur. Such deformation would be significant enough to allow the fire cell to be compromised. The additional damage caused by further cycling with drift ratios to 1.3% may result in the loss of the majority of the fire resistance. Lightweight timber partitions are vulnerable to losing their fire resistant capability and this is especially important if the wall is protecting an escape path such as a stairwell. Following an earthquake in a building greater than about 10 stories, in which sprinklers do not operate and the walls are damaged, the occupants may be unsafe because the expected escape time is greater than the expected failure time of the fire-rated walls surrounding the escape route.

Cousins et al (2003) conclude that if passive fire resistance fails comprehensively then the risk of fire spreading through buildings and onto neighbouring buildings is increased.

3.1 An energy-based methodology for simulating earthquake damage by racking in a laboratory

The development of a realistic racking regime to simulate an earthquake event that can be replicated under laboratory conditions referred to the work by Dutta and Maunder (2001) and was based on an analysis of the energy demand and hysteretic energy absorbed by the structure. A relationship between the effective number of inelastic cycles and the period is proposed in Figure 1 based on:

$$N_c = 7T^{-1} \text{..................(1)}$$

where:

N_c = *number of effective cycles*

T = *Period*, sec*onds*

and $4 \le N_c \ge 20$

Considering a 10 storey building with a period of about 1 second the number of effective cycles required is about 7.

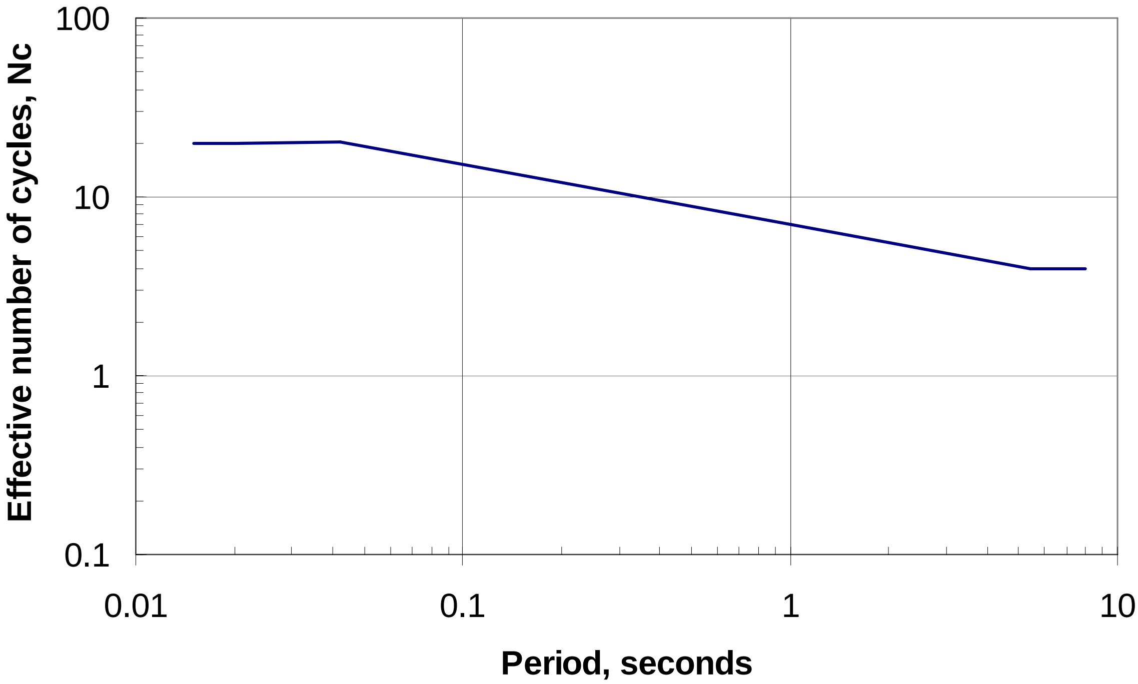

Figure 1: Effective number of inelastic cycles

A method for applying the cyclic loading is stated as:

$$N_c = \sum \left(\frac{x_i}{X_{eff}} \right)^2 \text{.....................(2)}$$

where:

x_i = *cyclic displacements*

X_{eff} = *effective displacement amplitude*

To achieve a nominal effective number of cycles of about 7 by ramping up the displacement amplitude, it is useful to combine together a number of cycles at each interval up to the desired % drift required.

For example to rack a wall to the code limit of 1.5% drift, (taking steps of 8 mm up to 48 mm which are just beyond 1.5% to allow for expected deflection of the loading frame causing slightly less deflection to be delivered, the cycling regime proposed was confirmed as follows using equation 2:

$N_c = 3 \times ((8/48)^2 + (16/48)^2 + (24/48)^2 + (32/48)^2 + (40/48)^2 + (48/48)^2) = 7.6$

Each cycle increment (in equation 2) is repeated three times making a total of 18 cycles to reach an effective number of cycles of about 7 (or between 5 and 10).

The results of similar calculations for other drifts are recorded in Table 1.

Table 1: Number of effective cycles

Drift, mm	32	40	48	56	64	72
Cycle steps	3	3	3	3	3	3
8	0.19	0.12	0.08	0.06	0.05	0.04
16	0.75	0.48	0.33	0.24	0.19	0.15
24	1.69	1.08	0.75	0.55	0.42	0.33
32	3.00	1.92	1.33	0.98	0.75	0.59
40		3.00	2.08	1.53	1.17	0.93
48			3.00	2.20	1.69	1.33
56				3.00	2.30	1.81
64					3.00	2.37
72						3.00
N_c	**5.63**	**6.60**	**7.58**	**8.57**	**9.56**	**10.56**

3.2 Framing materials

BRANZ quarterly building material survey data (BRANZ, 1999) updated by BRANZ for the period 1999-2003 was assessed to determine the framing material used for partitions as timber, steel or other material. This survey data, presented in Table 2 to Table 6, was dependent on developers/constructors voluntarily submitting information and as a consequence should be regarded only as a sample and therefore only indicative of total building activity.

Table 2: Partitions by number of storeys – new buildings

	Full years 1999-2003						
No storeys	Timber	%	Steel	%	Other	%	**Total**
1	426	78.5%	54	9.9%	63	11.6%	**543**
2	121	81.8%	15	10.1%	12	8.1%	**148**
3	16	64.0%	7.5	30.0%	1.5	6.0%	**25**
4	4.5	90.0%	0.5	10.0%	0	0.0%	**5**
5	3.5	58.3%	2.5	41.7%	0	0.0%	**6**
>5	0.5	12.5%	3.5	87.5%	0	0.0%	**4**
Total	571.5	78.2%	83	11.4%	76.5	10.5%	**731**

A comparison of the usage of timber versus steel as a partition framing material favours timber in the majority of situations. The only instances where the use of steel framing is more widespread than timber is for taller buildings in excess of five storeys for new buildings, and in the case of alterations and additions (Table 6) steel is at least on par with timber as the framing material. However, the number of buildings in the survey where steel framing is dominant is small compared with the total sample presented.

Table 3: Partition numbers by type – new buildings

	Timber	%	Steel	%	Other	%	Total
All new buildings	584	78.1%	85.5	11.4%	78.5	10.5%	748

Table 4: Partition numbers by storey height – new buildings

Storey heights	Timber	%	Steel	%	Other	%	Total
0-3m	249	82.3%	20	6.6%	33.5	11.1%	302.5
>3-5m	128	74.0%	30	17.3%	15	8.7%	173
>5m	84.5	71.9%	18	15.3%	15	12.8%	117.5
Total	461.5	77.8%	68	11.5%	63.5	10.7%	593

Table 5: Partition numbers by building type – new buildings

	Timber	%	Steel	%	Other	%	Total
Hostel	20	83.3%	1.5	6.3%	2.5	10.4%	24
Hotel/motel	22	73.3%	3	10.0%	5	16.7%	30
Hospital	10	90.9%	1	9.1%	0	0.0%	11
Education	130.5	87.6%	7	4.7%	11.5	7.7%	149
Social/cultural	51	82.9%	2	3.3%	8.5	13.8%	61.5
Retail	48.5	79.5%	8.5	13.9%	4	6.6%	61
Office/admin	64.5	83.8%	11.5	14.9%	1	1.3%	77
Warehouse	97.5	70.9%	23.5	17.1%	16.5	12.0%	137.5
Factory	73.5	73.5%	10.5	10.5%	16	16.0%	100
Farm	53	69.7%	16.5	21.7%	6.5	8.6%	76
Miscellaneous	12.5	62.5%	0.5	2.5%	7	35.0%	20
Total	583	78.0%	85.5	11.4%	78.5	10.5%	747

Table 6: Partitions by number of storeys – alterations and additions

No storeys	Timber	%	Steel	%	Other	%	Total
1	290	81.7%	30	8.5%	35	9.9%	355
2	88	88.9%	7.5	7.6%	3.5	3.5%	99
3	10	66.7%	4	26.7%	1	6.7%	15
4	4.5	45.0%	5.5	55.0%	0	0.0%	10
5	1.5	75.0%	0.5	25.0%	0	0.0%	2
>5	4.5	50.0%	4.5	50.0%	0	0.0%	9
Total	398.5	81.3%	52	10.6%	39.5	8.1%	490

3.3 Survey of current building practices

In the course of the steering committee meetings, several construction detailing aspects were raised that may be adversely affected in earthquake with the resultant damage seriously prejudicing the fire resistance. These concerns were addressed with two building site visits to evaluate how these details may be handled.

- how doors are mounted in walls, in particular the lining at door frame corners
- how horizontal joints in lining are handled in stairwells
- junctions of wall to walls and wall to ceilings, edge details
- suspended ceilings

- penetrations for services, locations/hangers
- shaft walls as applied to elevators, steel CH stud-framed walls.

Observations from the building site visits follow and the method of accommodating the various features is of course applicable to that particular building or case. In other instances, a different solution may apply.

3.3.1 Door mountings

From the observed instances the lining sheet junctions to door frames occurred in a random fashion. Door frames were rarely positioned at a multiple of 1200 mm from the last corner, so the lining would be installed from the last corner or other starting point and sheets fixed at 1200 mm intervals consistent with the sheet width or stud spacing, and when a door frame was encountered the lining would be cut to fit around it. In some instances a vertical lining joint would coincide with a door frame whereupon the vertical lining joint would continue to the ceiling. So the most frequent occurrence would be continuous lining at the two top corners of the frame, usually with a vertical joint along the top edge, and in some instances the vertical lining joint will continue vertically above the edge of the frame as shown in Figure 2.

Figure 2: Lining around door frames

3.3.2 Horizontal joints

In the stairwells, the concrete floor was supported on an 'I' beam (RSJ) with fire-rated acoustic walls installed above and below as shown in Figure 3. The acoustic wall specification for -/30/30 and STC 55 requires two layers of 13 mm standard plasterboard on each side of the frame for either timber or steel framing. In the stairwell the first layer finishes at either the concrete floor from above or the "I" beam from below; the second layer then covers the edge of the concrete and the 'I' beam forming a continuous surface. Since manufacturer specifications require that joints in double layer systems must be offset by 600 mm, there should not be any horizontal joints on the second layer close to the wall/floor junction. So the risk of earthquake damage prejudicing the fire resistance in stairwells due to the failure of horizontal joints is no worse than the lining becoming detached from other portions of the wall framing.

Figure 3: Horizontal joints between floors in stairwells

3.3.3 Lining fixing and junctions

On previous wall specimens subjected to earthquake racking tests conducted at BRANZ, the lining edges around the perimeter have been unrestrained apart from nailing. It has been observed that once the nails have torn the lining around the perimeter the lining may detach from the frame creating a passage from the fire side to the ambient side and that may be responsible for a considerable loss of fire resistance time to the Integrity criterion. So the perimeter effects may make a significant difference to the fire resistance of the racked wall specimens; therefore it is essential that the tested examples reflect actual building practice.

In the apartment buildings visited, suspended ceilings were required at an average depth of 300 mm below the top of the lining for the enclosure of services such as electrical, plumbing and sprinkler pipework. Figure 4 shows a suspended/false ceiling with coving at the wall/ceiling junction and a screw laminated joint. So the upper edges of the linings were generally concealed in the ceiling space.

Figure 4: Suspended ceiling ~300 mm below top of wall lining and junction is finished with coving strip and sheet joints are screw laminated

Internal wall corner to corner joints lining the edges were restrained in the corners by taping and stopping. Bottom to floor edges covered with skirting board as shown in Figure 5.

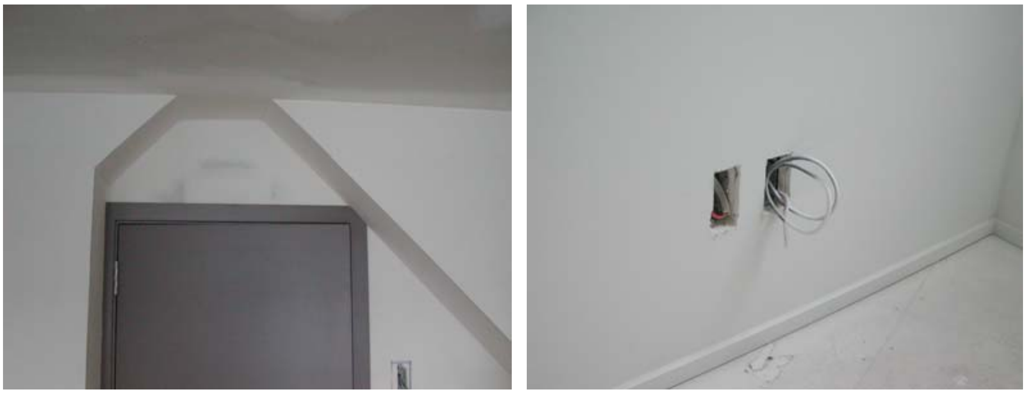

Figure 5: Corner finishing and skirting board

3.3.4 Steel frames

Figure 6 shows some examples of steel-framed partitions. Steel framing for the partitions was rigidly fixed to the structural steel members and in the event of earthquake would be racked according to the movement of the steel columns. In between structural members the top channel was fixed to the timber underside of the concrete floors or on top of concrete floors, and studs were secured in the channels with a single screw. The distance between columns for attachment of the side studs varied and in some cases was about 20 m, although 5 m was more common. This means that there could be a partition 20 m long, but it would be laterally supported by wall junctions at about 4 m intervals between units. Given the flexibility of a longer wall due to its increased length for the same amount of drift ratio, it is unlikely that it would incur more severe damage to the lining than the 3 m long walls subjected to testing in the laboratory situation.

Figure 6: Light steel frame attached to structural steel members and underside of concrete floors

3.3.5 Service penetrations

Service penetrations through fire-rated walls were generally in the ceiling space as shown in Figure 7 and sometimes in the wall cavities. It was not determined how the fire resistance of the penetrations was ensured and it was not the intention of this project to specifically determine how the fire resistance might by prejudiced in earthquake. However, the following services were observed:

- flexible hose ventilation duct
- plastic pipes, water supply
- plastic pipes, drainage
- steel pipes, sprinklers
- electrical wiring through plastic pipes in concrete.

Determination of the post-earthquake performance of the fire protected penetrations was outside the scope of this project, but the features observed are noted should further study be warranted on this aspect.

Figure 7: Penetrations above suspended ceiling

4. EXPERIMENTAL PART 1 – EARTHQUAKE RACKING TESTING

4.1 Loading frame and instrumentation

A diagrammatic representation of the racking apparatus used to simulate the earthquake exposure is shown in Figure 8. The walls for testing were constructed in a 3000 x 3000 mm fire testing frame leaving a gap around the sides and top of the wall. Gaps of 45 to 90 mm were left at each end to accommodate the 1.5 to 3% maximum drift anticipated and a gap of 140 mm on the top edge to attach a loading frame connected to a hydraulic ram to apply the racking force. Load skates were positioned at each top corner to minimise uplift and rocking of the wall. A load cell was attached to the hydraulic loading jack to monitor the load. The wall deflection was measured by a main deflection potentiometer on the top plate and six other potentiometers were used to apply corrections for:

- uplift at top corners
- horizontal movement of the bottom edge of the wall
- loading frame attachment to top plate
- distortion of fire resistance test frame.

All data was recorded in a data logger and all corrections had been applied. Hysteresis graphs are plotted in Appendix 1: Racking Test Results. The racking results are summarised in Table 8.

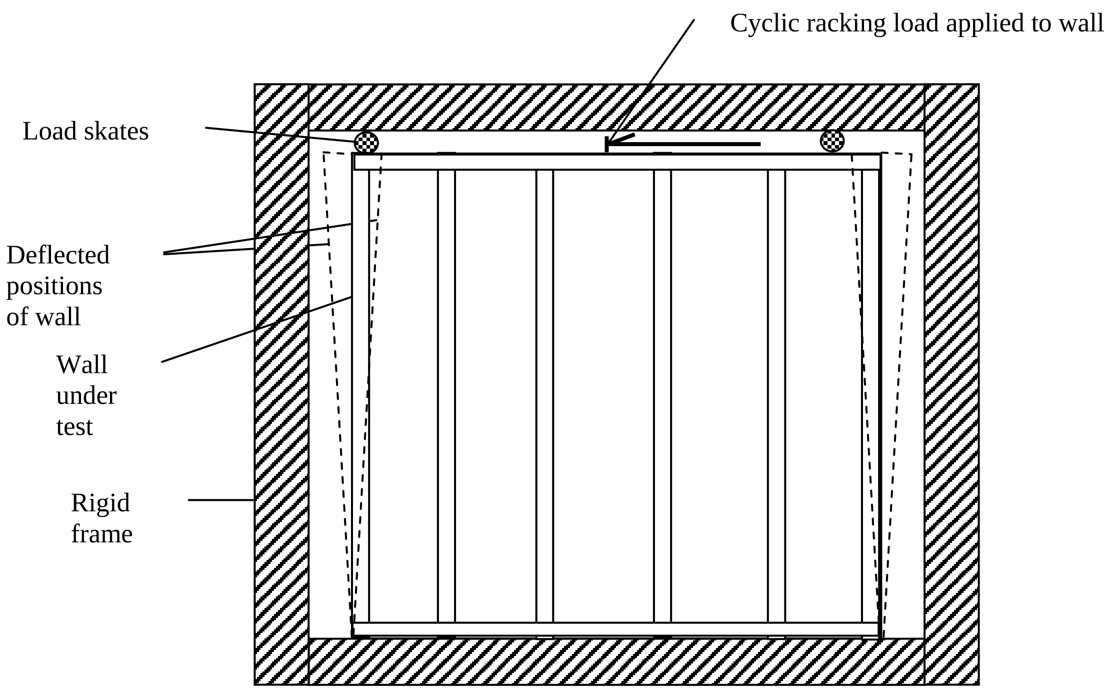

Figure 8: Racking of walls – schematic diagram

Figure 9: General arrangement of loading rig

The photographs in Figure 9 show the hydraulic jack and the frame by which the load is transferred to the wall specimen. They also show the load skates that allow horizontal movement at the top of the wall, but limit upward movement with the vertical load cells to monitor an upward movement for subsequent correction to the actual drift % that the wall sustained.

4.2 Racking philosophy

Seven racking trials with timber and steel-framed specimens were performed. The detailed results are recorded in Appendix 1.

The philosophy adopted for applying the racking displacement was based on the work of Dutta and Mander (2001) previously discussed in Section 3.1. The objective was to simulate as realistically as possible the number of cycles, displacement and energy dissipation that would be common in an earthquake to that deliverable in a laboratory situation as an experiment. In other words, subject the specimen wall to cyclic loading to cause similar damage that would be the result of an earthquake by cycling and building up to oscillations that would cause an equivalent amount of damage. The racking schedule as applied to the tested walls is set out in Table 7. For the first cycle the wall was displaced 8 mm in the first direction and then returned to zero displacement and displaced 8 mm in the opposite direction and returned to zero displacement for the completion of one cycle. This process was repeated two more times to complete the three forward and reverse cycles for the first level of 8 mm. The process was then repeated for 16 mm displacement and then for 24 mm, 32 mm and so on up to the level of drift required. The actual cycle amplitude or displacement is then corrected for movement of the wall in the frame that is not due to its deformation and also for distortion of the frame when loaded. The corrected displacement is then the actual movement of the wall and it may be slightly less than the target values in Table 7.

The intention was that the first specimen would be racked to the code limit of 1.5% drift and subjected to a fire test, and depending on the result obtained, the target drift on the next wall would be determined. The objective was to get a representative reduction in the fire resistance across a series of walls tested at a range of drift ratios to establish a trend. It was not known whether the expected drop in fire resistance would occur above or below the code limit, so an iterative approach was taken. Judgement was also exercised when the damage done to a wall was considered to be serious enough to cause a substantial reduction in fire resistance and there was nothing more to be gained by racking it to a greater drift ratio.

Table 7: Racking schedule for walls

Cycle #	Cycle amplitude, mm	Number of cycles	Equivalent drift, %*
1	±8	3	0.25
2	±16	3	0.5
3	±24	3	0.8
4	±32	3	1.1
5	±40	3	1.3
6	±48	3	1.6
7	±56	3	1.9
8	±64	3	2.1
9	±72	3	2.4
10	±80	3	2.7

* drift or drift ratio is the movement of the top of the wall divided by the height of the wall expressed as a percentage

A typical force–deflection hysteresis graph after correction for frame and restraint movement is shown in Figure 10. The force required for the initial deflection of 8 mm is 16 kN (this is a maximum) and thereafter the force required for the greater deflections actually reduces. This drop-off of the required force is typical once the fixity of the plasterboard to the frame has been broken.

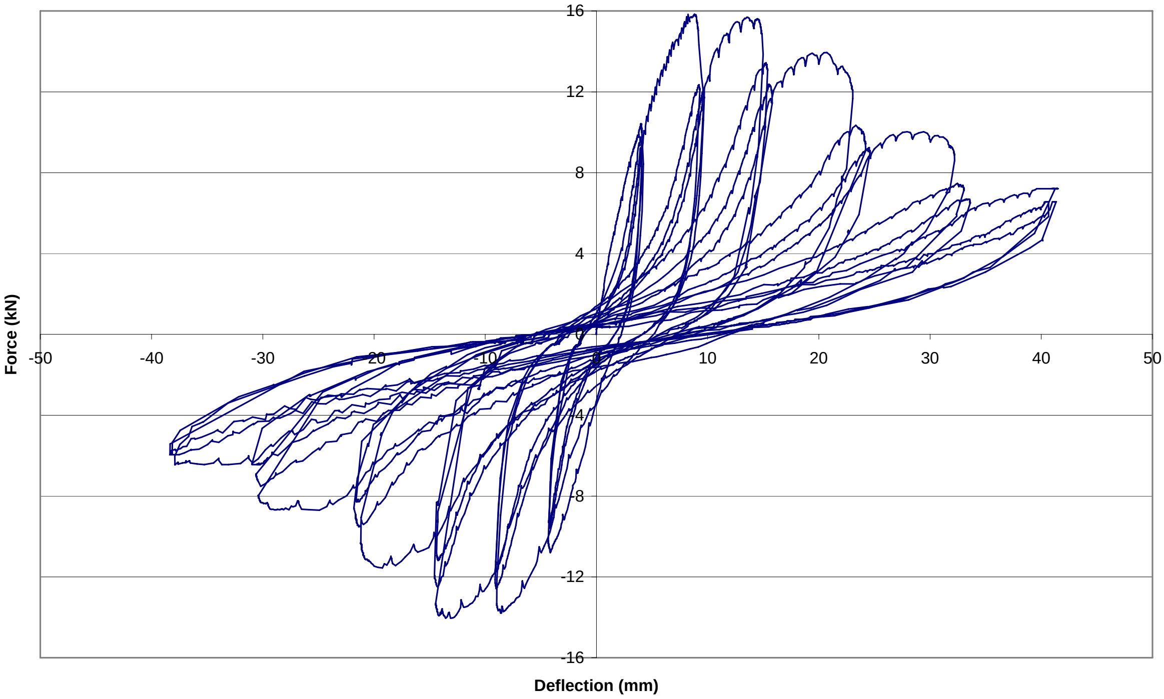

Figure 10: Typical force–deflection hysteresis graph (corrected)

4.3 Construction of walls

The test walls were either timber or steel-framed and one of the steel-framed walls contained a door.

4.3.1 Timber-framed walls

The timber studs and plates at the top and bottom were nominally 90 x 45 mm framing. The spacing between studs was nominally 600 mm between centres and was reduced slightly on the edges to accommodate the gaps between the wall and the fire test frame on each side to allow space for racking displacement. Timber nogs nominally 90 x 45 mm were fitted between the studs at nominally 800 mm centres. The heights of the walls were nominally 2850 mm high to allow space for installation of the loading frame and instrumentation. A typical construction is shown in Figure 8. The walls were lined on each face with one layer of 13 mm fire-rated paper-faced plasterboard and fixed in accordance with the manufacturer's instructions, which required nailing to the studs, nogs and plates at top and bottom.

The edge detail of the specimens evolved as the testing programme progressed; this became necessary as particular features of the behaviour of the lining in the earthquake racking process revealed various modes of failure and its consequent effect on the fire resistance. Figure 11 shows the edge detail for the five timber specimens, the top row is the side stud and top plate detail and the bottom row refers to the sill details with skirting board added for the later tests. The grey filleted corners indicate plaster stopping, but not necessarily to scale. The behaviour of the edge detail is explained in Section 5.1.1.

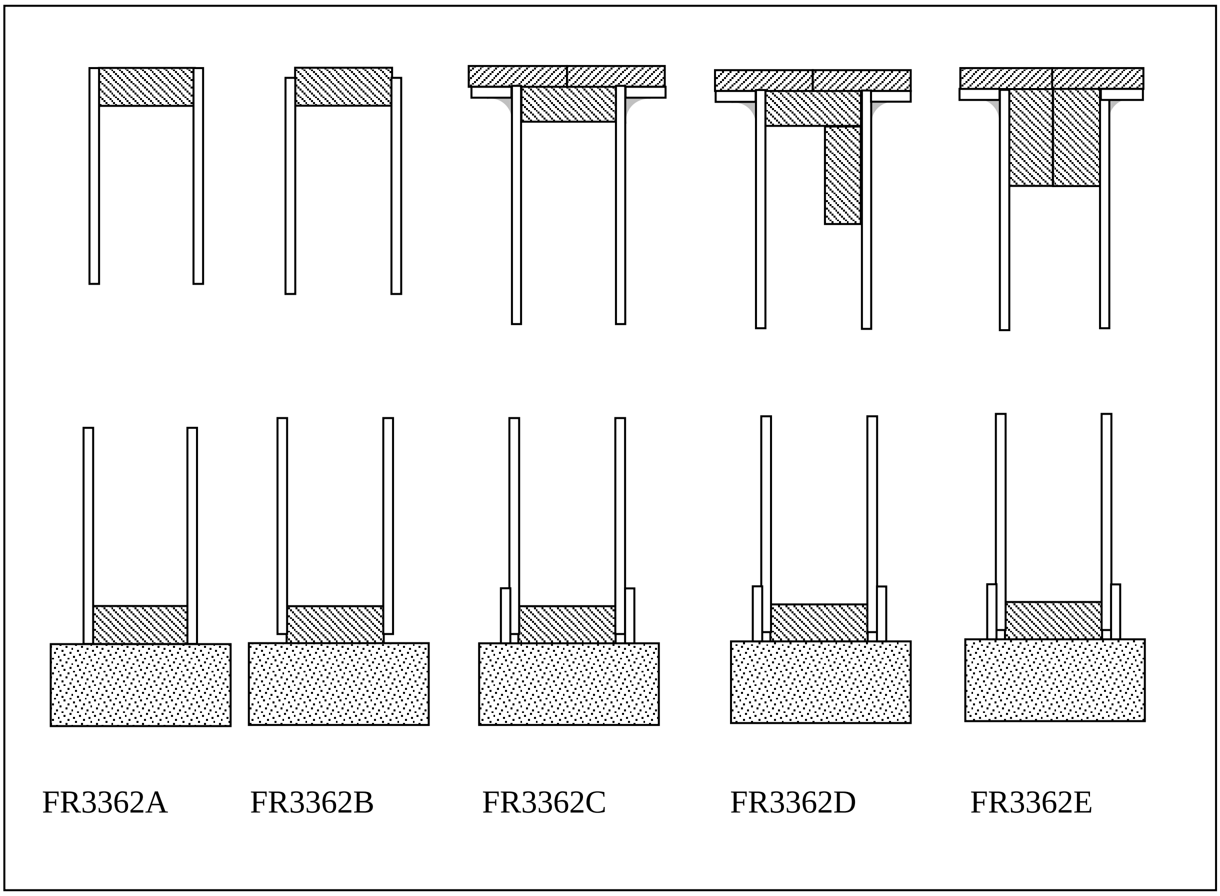

Figure 11: Cross-sections showing edge detail of timber-framed walls

4.3.2 Steel-framed walls

For the steel-framed walls, C section studs of nominal 63 x 34 x 0.5 mm dimensions at nominal 600 mm centres were fitted free floating between nominal 63 x 30 x 0.5 mm channels at the top and bottom. The walls were lined on each face with one layer of 13 mm fire-rated paper-faced plasterboard and fixed in accordance with the manufacturer's instructions.

The fixing instructions only required that the lining be fixed to the studs, so the lining was not fixed to the channels at the top or bottom. This meant that the top channel would be free to move in each direction if the loading frame was attached to it and that there would not be any racking force actually applied to the wall. To overcome this problem the side studs and top channel were contained within a rigid three-sided timber frame hinged at the top two corners as illustrated in Figure 12. The frame was constructed from two 90 x 45 mm timber members fastened together with the 90 mm dimension in the plane of the wall. The hinged joints on the two top corners were formed with offset timber lengths joined with nail plates and a 16 mm bolt that became the hinge. This allowed horizontal movement of the top section to be transferred to the side studs with minimal bending of the timber effectively simulating a steel-framed partition bounded by a rigid structure consistent with it being installed in a concrete building or between steel columns and beams.

The combined timber dimension was 90 mm compared with the steel stud depth of 63 mm. Adding the two 13 mm layers of lining, the total depth came to 89 mm, so the lining edges were effectively contained similar to that of being in a corner.

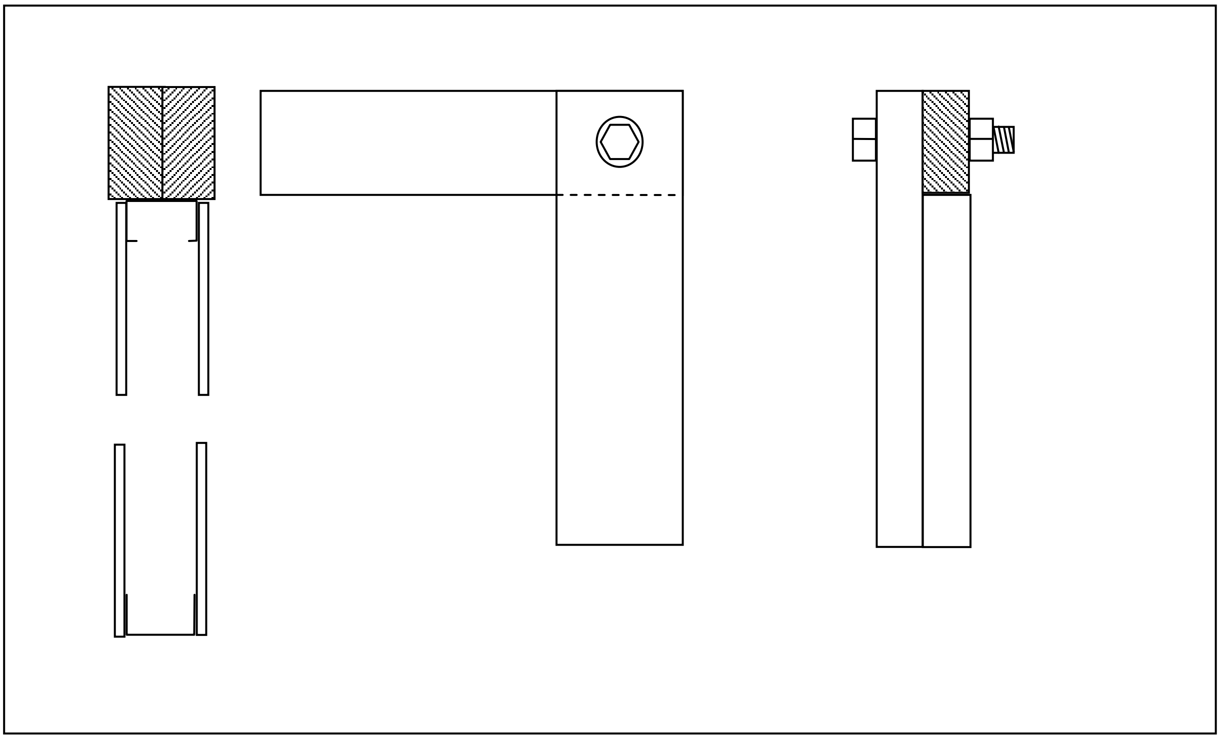

Figure 12: Cross-section and framing detail of steel-framed walls

The second steel-framed wall test included a 60 minute FRR door with a timber frame and leaf. The door was fitted in accordance with the manufacturer's instructions and the test was intended to evaluate the effect on the racking damage and then fire resistance of the additional stiffness contributed by the door assembly in the wall.

4.4 Earthquake simulation by racking

Details of the racking tests are recorded in Appendix 1 and the results are summarised in Table 8.

Table 8: Summary of racking tests phase 1

	FR3362A	FR3362B	FR3362C	FR3362D	FR3362E	FR3362F	FR3362G
% drift	-1.04, 0.95	-1.32, 1.43	-1.07, 0.84	-1.6, 1.34	-1.9, 2.5	- 1.35, 1.12	-1.35, 1.19
Lining fixing details	(1)	(2)	(3)	(3)	(3)	(4)	(4)
Framing material	Timber	Timber	Timber	Timber	Timber	Steel	Steel
Special features				L-shaped side studs	Double side studs		Included timber door
Lining detachment area mm x mm	3000 (w) x 600 (h) mm top	3000 (w) x 600 (h) mm bottom	Lining was relatively intact on framing	3000 (w) x 600 (h) mm bottom and in particular the corners	Hardly detached at all, but deformed on all 4 corners on both sides	Detached 3000 (w) x 2200 (h) at top. Bottom 800 remained attached	Detached 3000 (w) x 2200 (h) top
Lining to frame gap	7-8 mm	6 mm	~1 mm	7-8 mm	<1mm	5-10 mm	0-10 mm
Peak displacements after corrections, mm	-30.1, 27.6	-38.3, 41.5	-31.08, 24.2	-46.3, 38.8	-55.4, 77.9	-39.3, 35	-39, 34.4
Peak loads, kN -/+	-24.8, 26.8	-14, 15.8	-39.94, 34.5	-47, 50.3	-47.6, 44.6	-20.5, 18.3	-15.8, 12.9
Energy in rack, kJ -/+	2.1	2.1	7.0	10.3	12.9	6.6	2.5
Other features					Fire tested at 1.5% (45 mm) drift		

Lining fixing details:

(1) lining to edge of frame and fastened with nails 40 x 6 g at 300 mm centres etc

(2) 10 mm gap around perimeter

(3) simulated edge detail

(4) steel frame fixing details, studs are floating in channels top and bottom and the lining is only fixed to the studs.

4.4.1 Features of damage caused by racking

The edge details referred to are illustrated in Figure 11 and Figure 12.

For test FR3362A, the lining was touching the floor and was also restrained by packing at each end of the bottom plate. So the lining was prevented from moving on the bottom edge which effectively confined all damage to the upper (600 mm) wall and damage was so severe at 1% drift a decision was made to stop at 1%.

For test FR3362B, the lining was unrestrained around the entire perimeter, with a gap of 10 mm at the bottom and 22 mm top and sides. Therefore the only restraint was by the nails attaching the lining. This resulted in a more even distribution of the damage to the lining at the fixings and 1.5% drift was reached. Coincidentally or otherwise the energy required to do this was almost identical to that required for FR3362A, even though the drifts were different.

For test FR3362C, the lining was restrained on all edges to simulate junctions with a ceiling or another wall, or under a skirting board. This increased the resistance to racking significantly, but the flexibility of the side studs resulted in curvature deflection of the studs in the upper 600 to 1000 mm, contrary to what would be expected in a real building where for instance a non-load-bearing partition is fixed between concrete columns. The concrete columns would most likely remain relatively straight as would the studs attached to them. The racking cycles were stopped at approximately 1% due to excessive opening of gaps at the top corners.

For test FR3362D, the lining was attached and restrained identically to that in test FR3362C. The only modification was that the stiffness of the 90 x 45 mm side studs was increased by the addition of another 90 x 45 mm section to form an L section side plate. This considerably increased the stiffness of the side plates and the wall as a whole, but it did expose a weakness at the bottom of the side studs where there was considerable local bending of the side studs where the additional side stud ended 25 mm short of the bottom plate and this resulted in considerable damage and opening up of the plasterboard on the bottom corners. So significant was the damage that when the wall was returned to the 0% drift position there remained clear vision through the cavity.

Test FR3362E used identical restraint on the lining as in tests FR3362C and FR3362D and in addition the side studs were stiffened by being two 90 x 45's with the 90 mm dimension along the wall. This resulted in the frame being stiffer and requiring more energy to rack it and possibly less damage to the lining. The weakness in test FR3362D was eliminated by extending both side studs the full height of the wall and they remained straight throughout the test with some loosening of the plasterboard on the side studs. The top plate, which was a single 90 x 45, then became the weakest link and it buckled upwards at each end and in the process the nails ripped the plasterboard detaching for a distance of 300 to 400 mm.

A typical hysteresis plot generated from the racking of a wall through the full range of cycles was shown in Figure 10, A key indicator of the resistance of the wall would be obtained by enclosing the outer perimeter of the plot in an envelope to show the extremities of deflections and forces required. The envelopes for the timber-framed walls are plotted in Figure 13 and the area contained within and extremities of the profiles match the degree of constraint imposed by the lining edges. The locations of the absolute maximum forces (maxima and minima) indicate the point at which the resistance to racking is broken and the deflections required to do so. The magnitude of the forces is an indication of the edge restraint as described above.

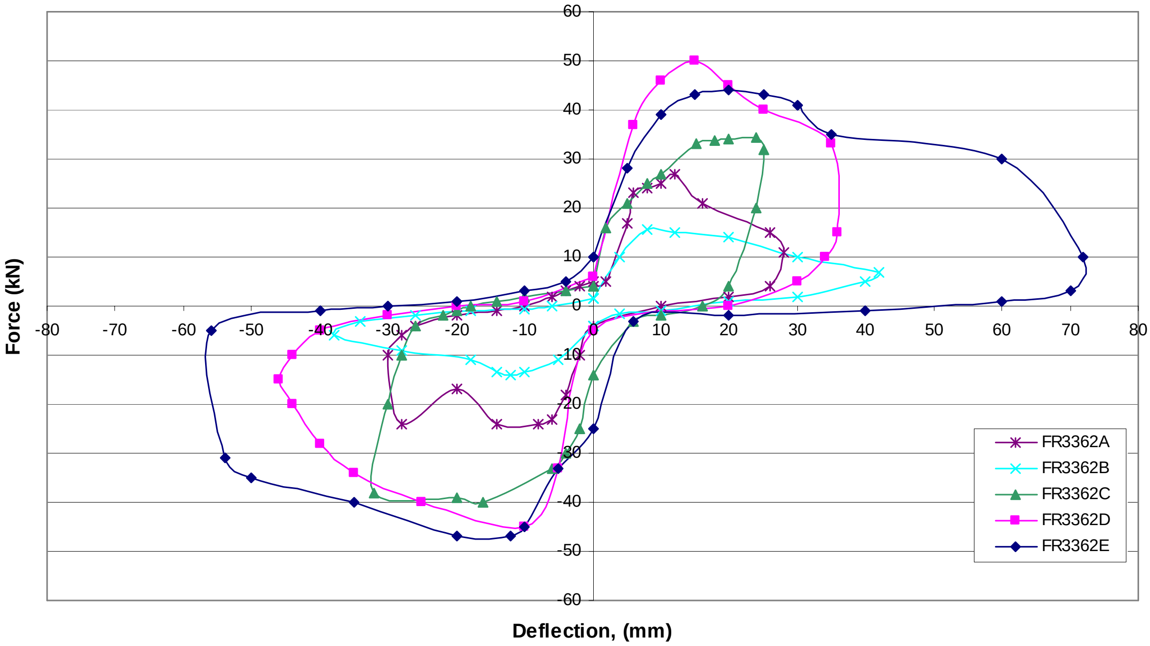

Figure 13: Deflection-force envelopes for timber-framed walls

Test FR3362F was a steel-framed wall with floating studs assembled within a hinged perimeter frame. The lining moved on the perimeter during the racking cycle process and since it was not attached at the top and bottom the two side studs provided all the resistance and this is where the detachment occurred. Detachment of the lining was greatest on the top corners and ranged from 5 to 10 mm as it was torn on the screw heads.

Test FR3362G had an identical steel frame to FR3362F with the addition of a timber door. The resultant damage to and detachment of the lining was similar to FR3362F except for around the door frame perimeter where there was also some tearing of the lining at the top corners of the frame. The door frame appeared to move relatively freely until the gaps between the door leaf and the frame closed up and then the resistance increased slightly, but not dramatically, as the door and frame was observed to rock over and lift off the sill on one side. A significant difference with a door or opening in a wall is that there is a gradual increase of the force required to generate increasing deflection. This is compared with a continuous wall where a peak force is reached beyond which a wall could be considered to be broken and increasing deflections require less force.

Figure 14 shows the hysteresis envelope for the steel-framed walls, where the only difference in the construction between the walls is the presence of a door, the flexibility imparted by the door and frame is apparent. In FR3362F, for the wall only, a break point is clearly indicated at about 20 kN and 10 mm drift and a rapid reduction beyond. In contrast for FR3362G the maximum load is 13-16 kN at a drift of about 25 mm without a marked reduction at greater deflections. So there is a greater tolerance for drift before the break point occurs on the wall with the door.

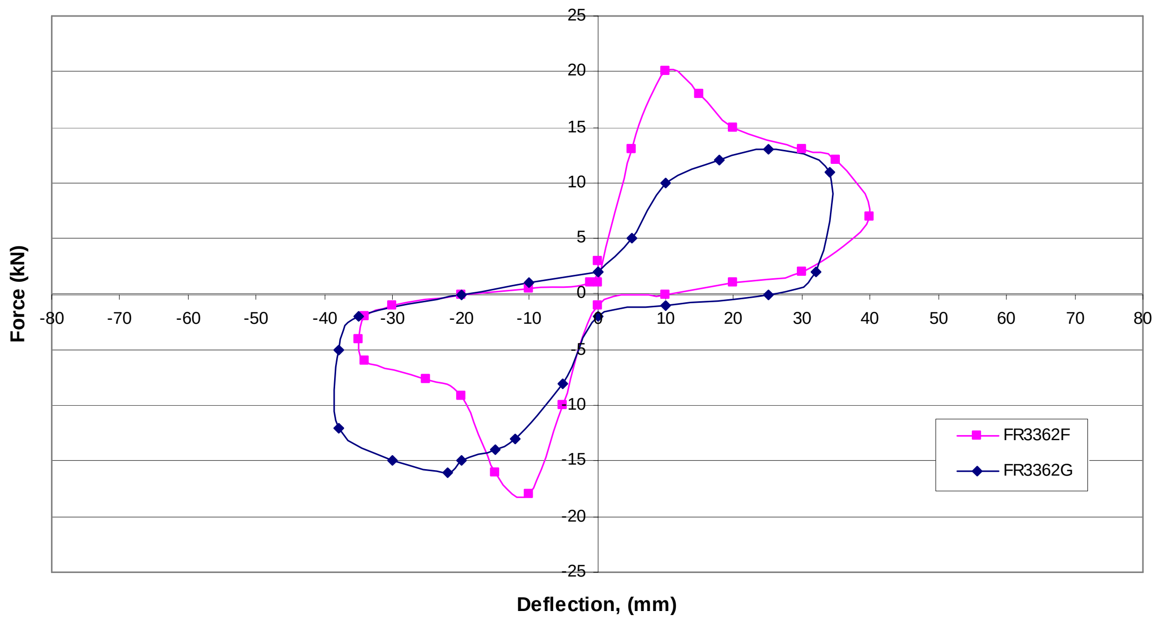

Figure 14: Deflection-force envelopes for steel-framed walls

For each sample, the energy required (force x distance) was dependent on the restraint of the plasterboard and the drift it was taken to. However, in each case once the fixing of the plasterboard had been largely broken, the force to rack the wall reduced as the displacement increased, so the energy input remained about the same for each racking cycle.

The energy absorbed in the course of racking cycles is shown in Figure 15. In the first two walls the energy required is almost identical, and this is despite the racking drifts being 1% and 1.5% respectively. A reason for this is the different way that the lining was attached and its freedom to move only being restrained by the nails. The next three timber walls show an increasing energy requirement as the restraint is increased. For the final two steel-framed walls the energy requirement is reduced particularly with the inclusion of a door opening.

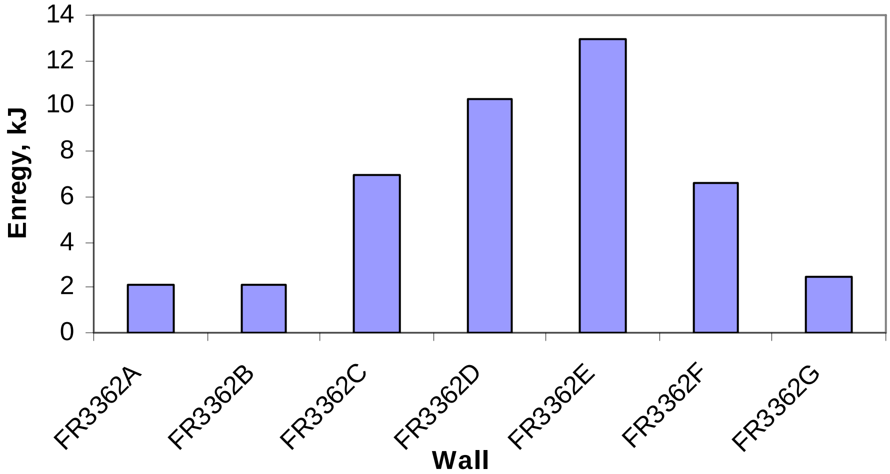

Figure 15: Energy required for racking cycles

4.4.2 Movement of door in frame

The clearances between the timber door and frame in test FR3362G were measured before the wall was racked, at the limit of each cycle and at the 0% drift position at the completion of the racking cycles. A further measurement of the clearances was taken just before the fire test. The locations of the measurement points are shown in Figure 16 and a sample of the measurements taken are summarised in Table 9.

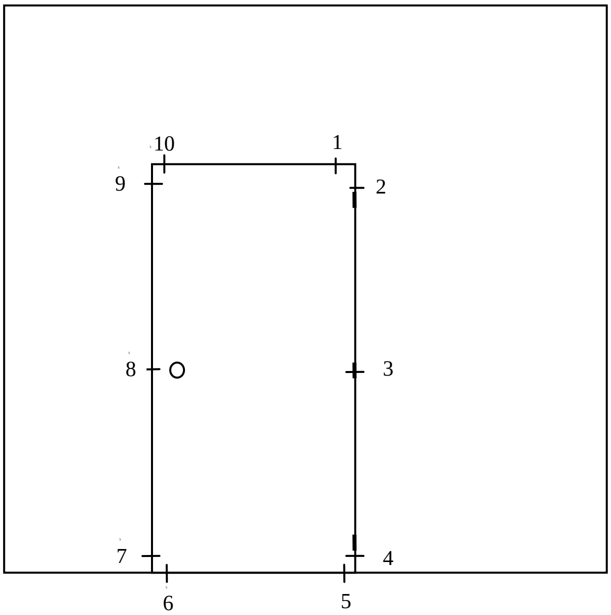

Figure 16: Fire door showing clearance measurement locations

The clearances in Table 9 refer to the original clearances before any racking had taken place and the maximum clearance is the greatest clearance measured during the racking process and is an indicator of the potential gaps that may result in a real earthquake where the door assembly does not return to its original 0% drift position. This has implications for the fire resistance of the door assembly where a large clearance in an isolated location may be responsible for a reduced fire resistance time, not an objective of this project but a useful observation about the potential reduction in fire resistance. At the conclusion of the racking when the wall was restored to 0% drift, the clearances were only marginally different from the original measurements. When set up for the fire test the clearances they again changed marginally, probably as a result of adding fire resistant packing around the perimeter of the wall.

Table 9: Door clearances in mm at various stages in racking process

Measurement location	Original clearances	Maximum recorded	Post-rack clearances	Fire test clearances
1	3.5	3.5	2.9	3.0
2	2.9	3.4	2.6	2.5
3	3.2	3.2	2.8	2.7
4	2.7	4.7	2.6	2.5
5	6.4	10.0	7.6	6.5
6	5.5	14.3	8.2	6.5
7	3.5	3.5	0.0	2.0
8	3.7	4.3	2.8	3.0
9	3.4	7.8	4.3	3.5
10	3.5	18.9	0.0	2.5

4.5 Summary of racking tests

In all of the walls subjected to racking some damage to the lining resulted. The location and severity of the damage was dependent on how the lining was fixed to the frame and the restraint around the perimeter by taping and stopping such as corner details where they were included. Once the region of weakest restraint had failed locally, generally by the lining tearing around the fixings, this relieved the load and the resistance to racking reduced significantly. The wall could then be considered broken and only minimal additional damage to the lining occurred at any other locations. Joints in the lining that had been taped and stopped performed at least equivalent to the continuous lining in the racking process. The presence of an opening such as a door did not result in any significant additional damage to the wall. In fact the door assembly added a degree of flexibility to the wall as the door leaf moved within the frame and this had the effect of spreading the load and resulting damage more evenly over the wall assembly.

In general the racking resulted in damage characterised by loosened plasterboard at the top or bottom of the wall depending on restraints around the perimeter. It was this damage that was principally responsible for the failure in the subsequent fire resistance test.

5. EXPERIMENTAL PART 2 – FIRE RESISTANCE TESTING

After the earthquake racking, the damaged walls were subjected to a fire resistance test in accordance with AS1530.4: 1997 to determine the degradation in fire resistance compared with a baseline test on an undamaged specimen. Preparation of the racked wall specimens for fire resistance testing required that the wall be secured and that the gap between the wall and the test frame at the sides and top were filled with blocking timber and ceramic fibre. It was important that any damage sustained in the racking process was preserved and that any fire preparations did not in any way repair that damage such that a better fire performance was achieved. However, materials to patch expected Integrity failures resulting in flaming were available so that a fire test could be continued and other failures recorded to extract as much data as possible on the performance.

The results of the fire tests are summarised in Table 10.

Table 10: Fire resistance tests on racked walls

Test no.	FR3362A	FR3362B	FR3362C	FR3362D	FR3362E	FR3362F	FR3362G
Nominal FR, min	60	60	60	60	60	60	60
Framing	Timber	Timber	Timber	Timber	Timber	Steel	Steel with door
Racking, % drift	-1.04, 0.95**	-1.32, 1.43	-1.07, 0.84	-1.6, 1.34	-1.9, 2.5	- 1.35, 1.12	-1.35, 1.19
Onset of char, min	23.5	22.75	24	23	23.5	23.5	23.73
Exp lining fall off, mins	46	62	65	65.5-70	59.25	47.5	55.5
Failure, mins							
Structural	NF	NF	NF	NF	NF	NF	NF
Integrity	30	34	71NF	55	20 then 44	40	36
Insulation	47	62NF*	67	64.75	59NF	51	54
Test stopped	53	62.5	69	69.5	59	54	58
Other features	Failed Integrity at top, insulation failure linked to the initial Integrity failure	Failed Integrity at bottom	Perimeter secure no Integrity failure	Failed Integrity at bottom right hand corner. Lower portions 600 to 800 mm of studs burnt away at test end	Failed Integrity at top LH corner 20 min then top RH corner at 44:30 min	Insulation failure at 51 mins indicated by scorched paper face	Door failed Integrity at 51+ min, no Insulation failure of door
Construction details, lining fixing	Lining unbounded at top and sides but in contact with sill	Lining unbounded with 10 mm gap around perimeter	Corner detail simulated at ceiling/wall, wall/wall and floor with skirting board	Corner detail simulated at ceiling/wall, wall/wall and floor with skirting board	Corner detail simulated at ceiling/wall, wall/wall and floor with skirting board		

* Insulation failure predicted to occur at 66 min by extrapolation.

** drift ratio was intended to be 1.5% but additional stiffness of the wall and movement within the frame reduced actual drift to about 1%.

Note: Baseline test (unracked) failed at 69/69/69, onset of char 24 minutes and test stopped at 69 minutes. The exposed lining remained attached to the framing at the end of test.

5.1 Analysis and discussion of fire test results

Analysis of the fire test results by comparing the reduction in the fire resistance against the % drift from racking that each wall was subjected to, does not reveal a consistent reduction with increasing drift as could be expected. Figure 17 shows the trends recorded for the Integrity and Insulation failure times for the timber-framed walls. One significant reason for the irregularity is that the edge detail was modified in the course of the five test series as summarised in Table 10. Generally the initial failure was an Integrity failure and this was directly attributable to the detachment in the lining at a particular location due to the earthquake racking. Only in one case did a wall fail first due to Insulation (FR3362C) and there was no failure due to Integrity. Significantly in this case there was no observed detachment of the lining after the racking.

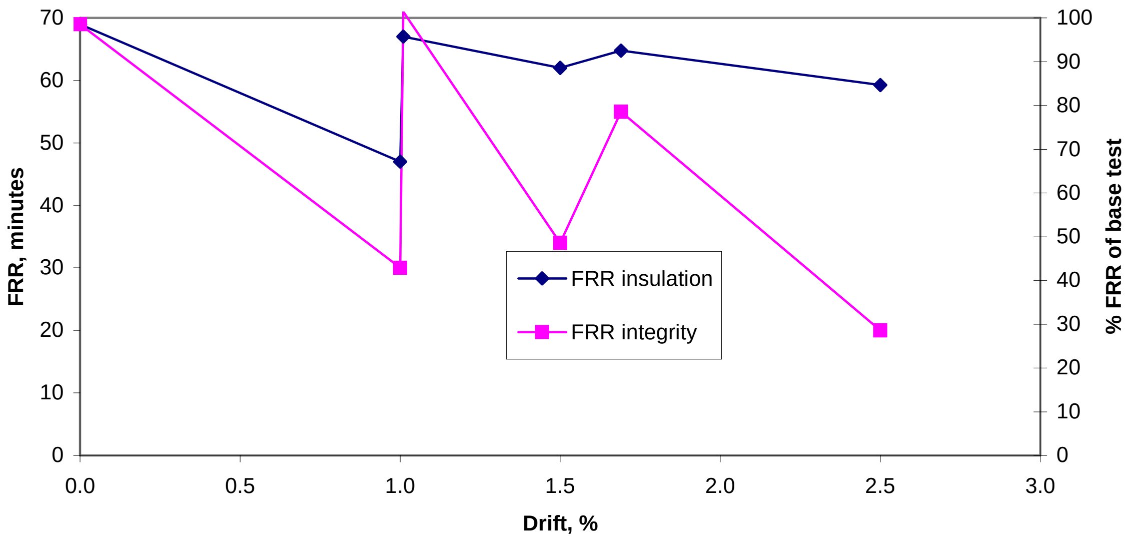

Figure 17: Effect of drift ratio on fire resistance for timber-framed walls FR3362A to FR3362E

5.1.1 Edge details on timber walls

The detailing of the lining around the edges was shown to be a significant variable affecting the outcome and the damage caused by racking then it largely determined the reduction in the fire resistance. Figure 11 illustrates the evolution of the edge detail for the wall. The top row shows the edge detail of the side and top edges and the bottom row the sill detail for the tested walls in FR3362A to E.

Considering the influence of the edge details, the tests with similar confinement of the edges were plotted independently. Unfortunately some of the graphs for the comparison included only one set of failure times in addition to the baseline test, but in the interests of performing an analysis it was necessary to separate out that particular construction detail.

In the graphs from Figure 18 to Figure 22 a downward trend is evident for both the Integrity and Insulation failures. In all cases the time to the Integrity failure criterion reduces by a greater amount compared with the Insulation failure time. This is due to the predominance of perimeter failures or detachments on the lining edges caused by the racking process resulting in the first failure, which was usually flaming from a gap constituting an Integrity failure.

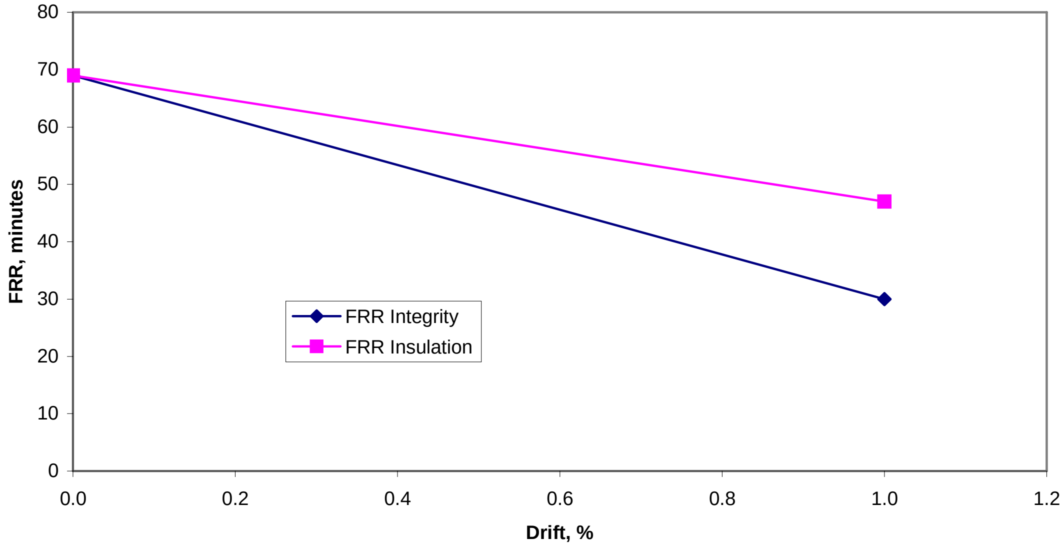

Figure 18: Effect of drift ratio on fire resistance for timber-framed walls with lining unconfined at the lining edges except on bottom sill

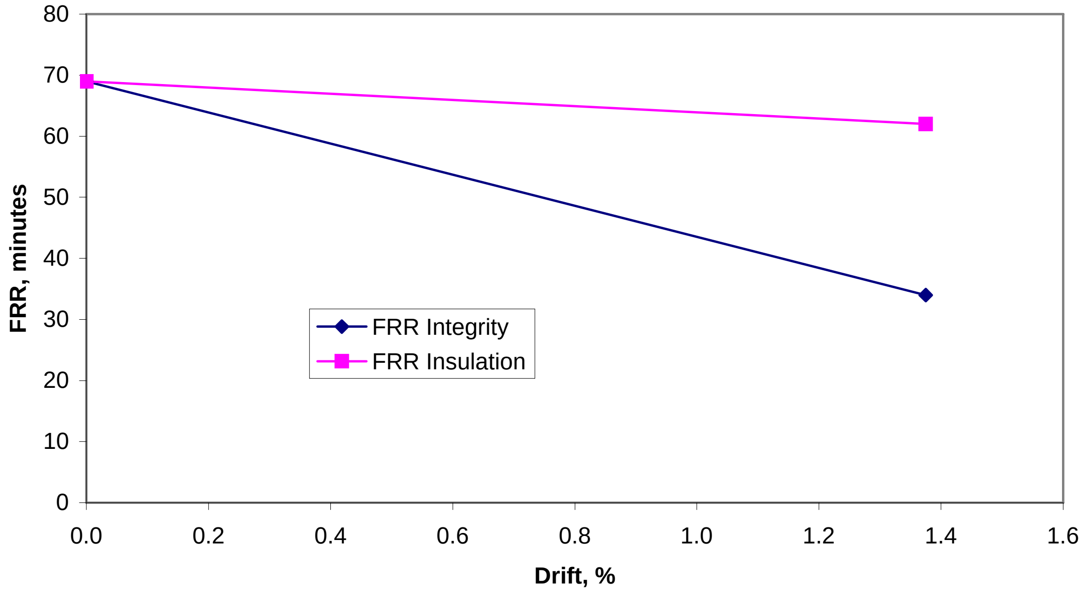

Figure 19: Effect of drift ratio on fire resistance for timber-framed walls with lining unconfined at the lining edges

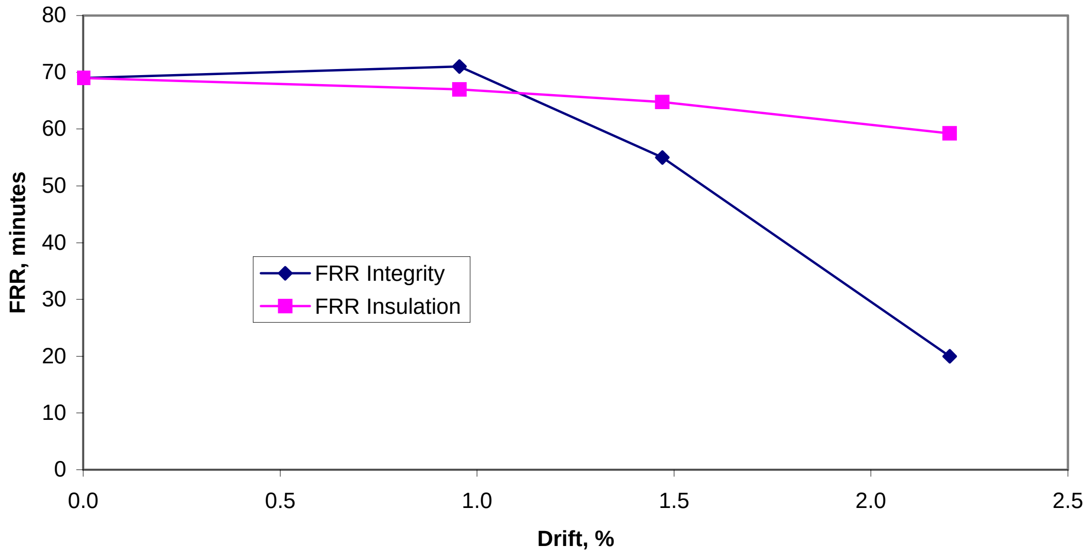

Figure 20: Effect of drift ratio on fire resistance for timber-framed walls with lining confined on all lining edges

5.1.2 Effect of residual deflection

In Figure 20 the wall that was racked to a maximum drift of 2.25% (mean of each direction) was left in a partially deflected state of 45 mm drift (1.5%) to the left when viewed from the non-exposed side. This remaining drift was to simulate the effect of the building not necessarily returning to the pre-earthquake position, which is a likely outcome. The first Integrity failure occurred on the left hand top corner at 20 minutes; this was in a location where a lining to stud gap that opened up near the end of the racking travel had not closed as completely as it otherwise would have had the wall been restored to 0% drift. Conversely on the right hand side the gap had closed up tightly for the fire test and an Integrity failure did not occur till 44 minutes.

In comparing the two Integrity failure times of 20 and 44 minutes at the two top corners (and taking an average of 32 minutes and plotting the three points on an updated version of Figure 20 as Figure 21), then the apparent discontinuity of the trend downwards is partially smoothed out. It could be surmised that that may have been the value achieved for an Integrity failure had the wall been restored to 0% drift. So if a wall remains in a distorted (drifted) state the Integrity fire resistance appears to be adversely affected if there is a larger gap remaining in a particular location than what would have been at 0% drift. The Insulation fire resistance was not affected to the same extent.

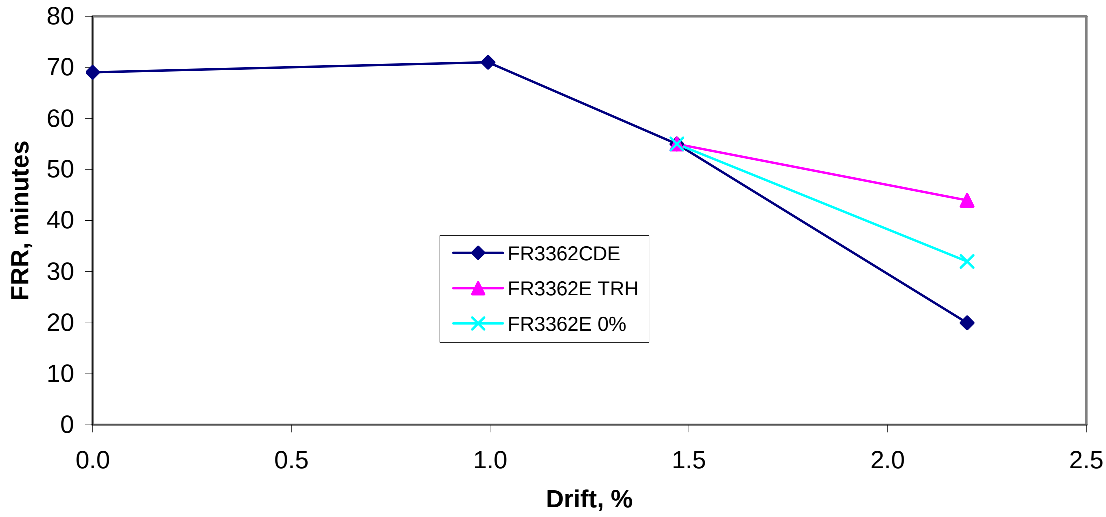

Figure 21: Supposed effect of remaining deflection on Integrity fire resistance

5.2 Fire test results on steel-framed walls

Two tests were performed on steel-framed walls and one of them included a timber door and frame fire-rated for 60 minutes. The failure times for the two walls were 40 minutes for the wall without a door and 36 minutes for the wall with a door. Each failure was an Integrity failure at either the top right hand or top left hand corner respectively. The presence of a door did not seem to make a significant difference to the fire resistance of the steel wall, the 4 minute reduction equating to 10%. The Insulation failure time increased from 51 to 54 minutes with the addition of the door to the steel wall a 5.9% increase. No Insulation failure of the door leaf occurred. The Integrity and Insulation fire resistance versus drift ratio for the two steel walls are graphed in Figure 22.

The door frame assembly failed Integrity due to flaming at the top of the door leaf at 51 minutes, but this was after the Integrity failure of the wall at 36 minutes. It is possible that the earthquake racking was responsible for some reduction in the fire resistance. But measurements taken before the fire test of the clearances around the perimeter of the leaf, particularly at the top, did not indicate any opening of gaps that would be expected to cause a problem with flaming along the top edge. Considering also the presence of intumescent strips on the door frame that are intended to expand on heat and close any gaps no explanation for what is a 60 minute fire-rated door failing at 51 minutes is apparent – this is a reduction of 15%.

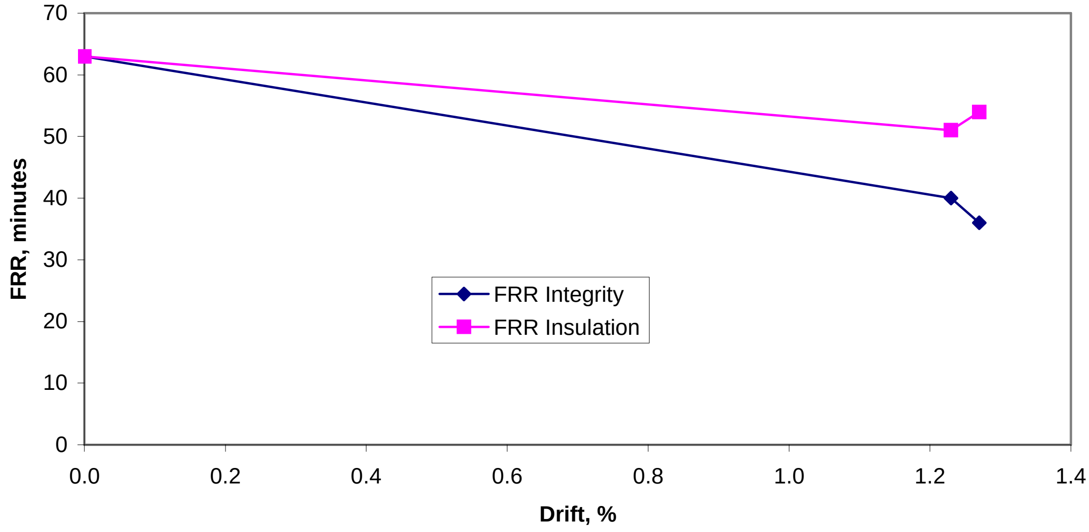

Figure 22: Effect of drift ratio on fire resistance for steel-framed walls with lining unconfined on the lining edges and not fixed to top or bottom channel

5.3 Comparison of Integrity and Insulation failures

Figure 23 and Figure 24 compare the Insulation and Integrity failures respectively. The detrimental effect of earthquake racking is more marked on the Integrity than the Insulation. Considering the tests with the confined edges (FR3362C, D and E) there appears to be a threshold beyond 1% drift that the lining is essentially broken, potentially resulting in a marked reduction in the Integrity fire resistance. This is consistent with the drop off in the racking force required at greater displacements (shown in some of the racking graphs).

The Insulation criterion does not appear to be affected to the same extent.

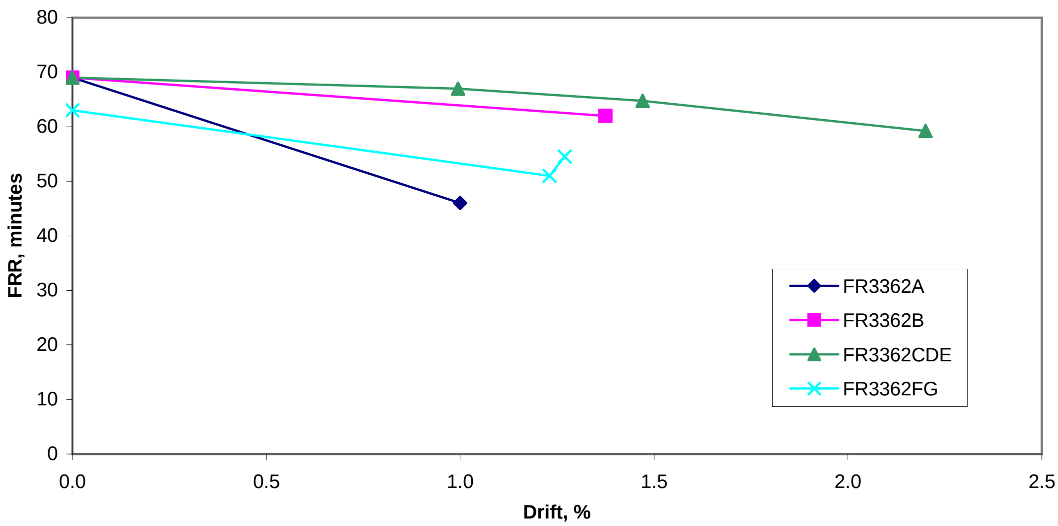

Figure 23: Comparing Insulation fire resistance of walls

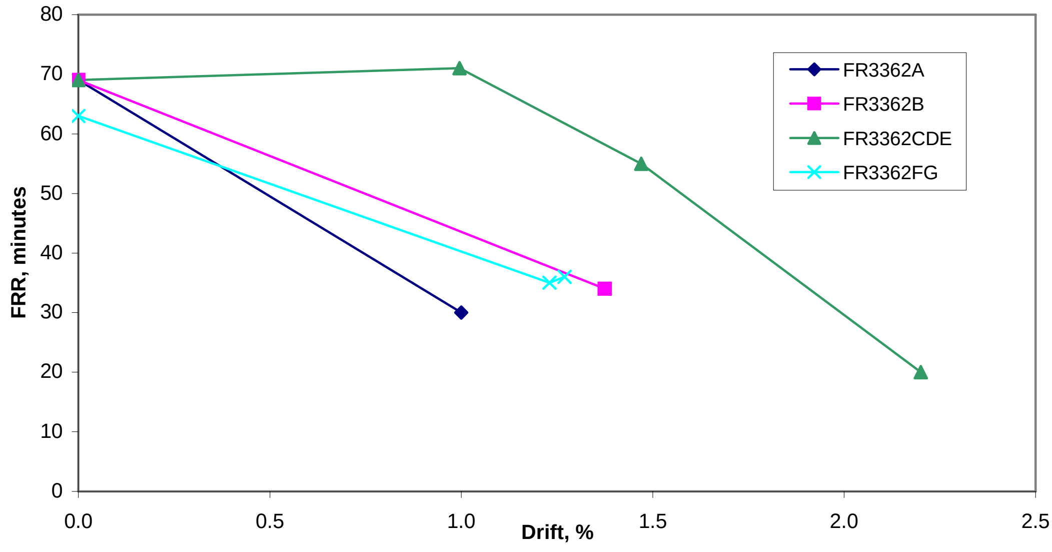

Figure 24: Comparing Integrity fire resistance of walls

Comparing the relative downward slope of fire resistance for the steel-framed tests FR3362F and FR3362G in Figure 23 and Figure 24 with the timber specimens, the loss of fire resistance is not significantly different for timber or steel-framed walls. The presence of the door did not seem to significantly affect the fire performance of the wall; while the door leaf itself is very rigid the gap between the leaf and the frame introduces flexibility to the system as a whole such that the racking damage was about the same. It is also significant that in general throughout all tests conducted the damage to the lining was greater around the perimeter due to the greater relative movement between the lining and the frame. Therefore a door frame in the middle region of a wall is unlikely to be subjected to the same level of movement. This is a likely explanation for the absence of damage to the door and frame and the similarity in performance of the wall/door test to the previous combinations.

5.4 Predictors of fire resistance reduction

To assess the mechanism of how the perceived damage to the lining of the wall may have affected the outcome of the fire resistance tests, the temperature recordings of the exposed and non-exposed linings were compared to determine whether there were trends indicating some degradation of the lining and hence overall system performance other than the recorded end result failures.

The temperature of the exposed lining measured on the cavity side is graphed in Figure 25. These temperatures are usually recorded to give an indication when the studs in a timber-framed wall begin to char and that is taken as when the temperature exceeds 300°C on the stud. For the 13 mm thick fire-rated lining used in all seven tests conducted there did not appear to be any detrimental effect at the 300°C milestone, which occurred around 23 minutes. However beyond that time there is some divergence of varying degrees indicating a degraded performance perhaps attributable to the racking damage. The most significant indicator is when the temperature spikes up several hundred °C (00’s °C) coinciding with the loss of the lining by falling off in parts or over the majority of the wall surface. It is feasible to expect that such loss of the lining was in part caused by the racking damage and since all racked tests lost some exposed lining before the baseline test, which hadn’t lost any at 69 minutes, this hypothesis is supported.

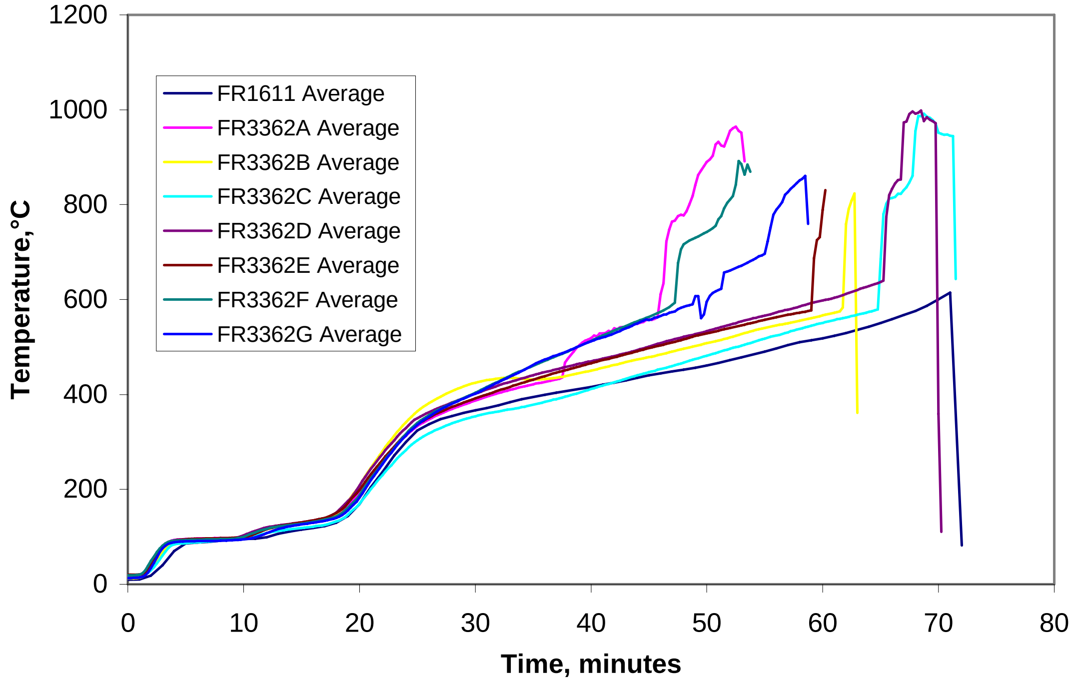

Figure 25: Temperature of exposed linings on cavity side

However in all tests the loss of some exposed lining followed the initial Integrity failure rather than preceded it, so it can be dismissed as a direct cause of the failure but it is influenced by the racking as indicated in Table 11.

Table 11: Relationship of exposed lining to Integrity and Insulation failures

Test	Baseline	FR3362A	FR3362B	FR3362C	FR3362D	FR3362E	FR3362F	FR3362G
Mean drift ratio, %	0	1.0	1.4	0.9	1.5	2.2	1.2	1.3
Loss of exp lining	69NF	46	62	65	60	59	47	50
Integrity	69	30	34	71NF	55	20*	35	36
Insulation	69	47	62NF	67	64	60NF	51	54

* tested at 1.5% drift

There also appears to be a relationship between the loss of the exposed lining and insulation failure. Comparing Figure 25 and a rapid increase in the exposed lining temperature is followed by a slower increase in the rate of rise of the non-exposed lining, but this did not always result in an Insulation failure before the test was stopped.

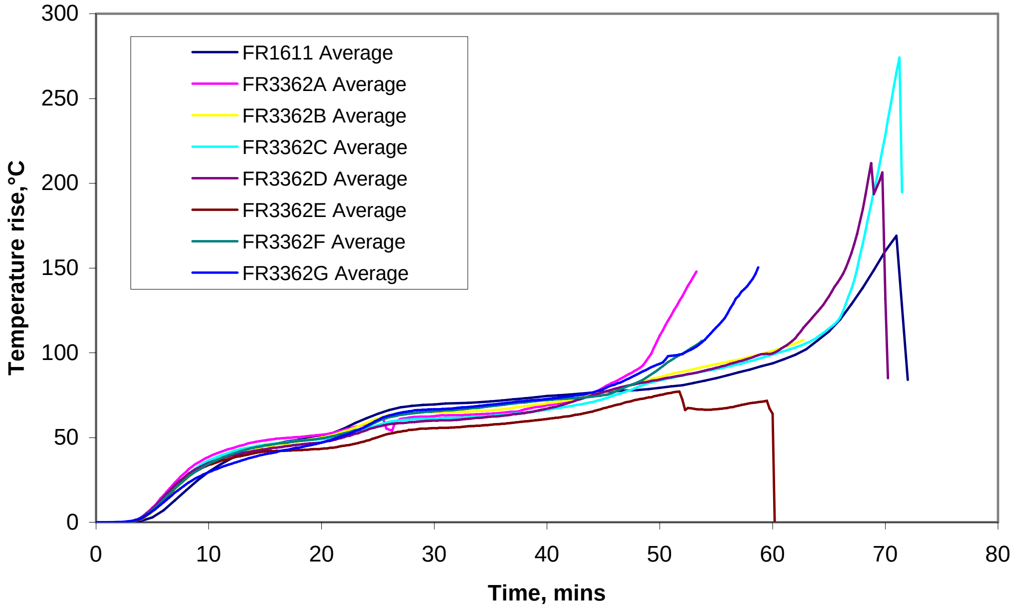

Figure 26: Insulation criterion temperature on non-exposed face of walls

6. CONCLUSIONS

The fire resistance of the seven plasterboard lined walls tested was shown to be reduced by the simulated earthquake racking. While the amount of the reduction in the fire resistance was shown to be generally related to the magnitude of the racking, other features of the attachment of the lining, in particular the finishing of the edges, determined the degree of detachment of the lining. This degree of detachment of the lining was shown to have the greatest impact on the reduction in fire resistance.

In some of the tests the walls were pushed well beyond the code limit (drift of 1.5%) without significantly more damage occurring. The treatment of the lining perimeter had a significant effect on the resistance to racking. Once the initial resistance had been overcome by increased racking displacement, the resistance decreased with very little additional damage caused. The damage sustained at that breakthrough resistance had a direct effect on the fire resistance, particularly the Integrity.

Consequent to the simulated earthquake damage various mechanisms were shown to lead to earlier fire resistance failure. The most significant deleterious effects were the localised ones such as gaps between the lining and the frame leading to Integrity failures. Damage was often confined to a localised detachment of the linings or over an area that was a weakness in the structure. It is less likely that the linings are uniformly damaged by racking as the weakest link in the system yielded first and damage was largely located in that region.

If the wall was fire tested in a deformed state rather than being restored to zero displacement this had an influence on the fire resistance. When the wall remained in a displaced position equivalent to 1.5% drift, the gaps between the lining and the frame remained more open on one side than the other and it was this open gap where the first Integrity failure occurred.

The significant factors determining the reduction in fire resistance are summarised as:

- the fire resistance is reduced as a result of damage caused by earthquake racking
- detachment of the lining from the frame and the resulting gaps are a critical factor in the initiation of Integrity failures
- the edge or corner detail of the lining is a critical factor in the magnitude of the reduction of fire resistance as a result of racking
- there is a critical point in the racking displacement in the region of 1-1.5% drift when the most significant damage to the lining occurs and beyond that point only marginally more damage is inflicted
- if the wall remains in a deformed state and there remains a greater lining to frame gap on one top corner compared to other corners then it is likely to be an earlier failure at that location than if the wall had been restored to zero displacement
- with the steel-framed wall there was less resistance to racking but the reduction in fire resistance is about the same for the same displacement
- the addition of a door caused some tearing of the lining around the corners of the door frame but this was less than the damage at the corners of wall and that is where it failed Integrity first and then at the top of the door leaf some time later
- for timber and steel-framed walls plasterboard detachment around the perimeter is the common factor
- the racking process in some cases resulted in some weakening of the lining inboard from the edges but any resultant premature loss of the exposed lining, compared with unracked lining, was not significant enough to cause an Insulation failure that preceded the Integrity failure for that wall.

This project has shown that the post-earthquake performance of PFP systems is definitely reduced when subjected to a design level earthquake. The amount of reduction in fire resistance of a 60 minute plasterboard lined wall can be as much as 50%. This is of increased importance considering that active fire protection systems such as sprinklers may have also been rendered inoperable in the earthquake event and this is a dual problem considering that a reduction in the fire resistance requirements by 50% may have been permitted because sprinklers were included as part of the fire design. The problem may be further compounded by the increased likelihood of fire outbreak due to disruption of building activities and services. Furthermore Fire Service attendance cannot be relied upon due to the certainty of multiple call-outs and possible impediment/blockage of road access. Finally egress from buildings may also be restricted by blocked exit-ways and injuries to people increasing the escape times.

While this project has identified the magnitude of the problem in relation to the fire resistance of walls, similar reductions in the performance of other PFP systems will exacerbate the problems in limiting the spread of post-earthquake fires that have been identified. So there is an ongoing need to investigate and confirm whether or not earthquake damage to other passive fire resistance systems follows the same trend. If this is shown to be the case then the risk of fire spread through buildings will be greatly increased in the event of a design level earthquake.

7. FUTURE WORK

Some of the issues raised in the course of the steering committee meetings were unresolved at the conclusion of the project:

- Behaviour of ceiling linings in racking is a concern. The underside lining represents a significant proportion of the fire resistance of floor/ceiling systems and it follows that a ceiling lining becoming detached off more easily than a wall lining would result in a greater reduction in fire resistance.
- Fire doors that normally open with automatic closers activated in the event of a fire alarm may not close properly if the frame is out of alignment following an earthquake.
- The behaviour of shaft walls as applied to elevators, in particular steel CH stud-framed walls.
- Service penetrations in walls are getting very complex with so many variables in the behaviour. Wide variability in the perception of how much these will be affected by EQ.

There is no further research planned to consider how other PFP features may be adversely affected by earthquake. In relation to the Conclusions above, the significant factors for earthquake damage determining the reduction in passive fire resistance may be applied in a qualitative manner to assess probable reductions of certain features.

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9. APPENDIX 1: RACKING TEST RESULTS

9.1 General description of test specimens

Timber frame

The test specimen in the first five trials were light timber-framed walls nominally 3000 mm high x 3000 mm wide with 90 x 45 mm timber studs at 600 mm centres with nogs at 800 mm centres. The walls were lined on each side with 13 mm GIB Fyreline® plasterboard and fixed in accordance with the manufacturer's instructions. The fire resistance rating is nominally 60 minutes. Over the course of the five trials the edge detail of the plasterboard was modified to simulate the type of detail found in practice, the variations are described in the following sections.

Steel frame

The remaining two trials were based on steel-framed walls nominally 3000 mm high x 3000 mm wide with 63 x 34 x 0.5 mm studs at 600 centres floating in 63 x 30 x 0.5 mm channels. The walls were lined on each side with 13 mm Fyreline® plasterboard and fixed in accordance with the manufacturer's instructions. The fire resistance rating was nominally 60 minutes. The sides and top plate of the wall were secured to a timber frame comprising pairs of 90 x 45 timber studs with the 90 mm dimension in the plane of the wall. The top corners were hinged and the objective was to provide a rigid perimeter for the wall to simulate installation in a concrete building where the edges of the wall are fixed to rigid members compared with the relative flexibility of the wall itself. This philosophy is based on the premise that during an earthquake in an actual building the movement/racking of the steel-framed wall will be dictated by the movement of the building itself. The second steel-framed wall had a 60 minute fire-rated door installed; this was to determine the effect of a rigid object restraining the in-plane deflection of the wall.

9.2 Results of racking test 1 FR3362A

9.2.1 Specific design features

The lining on the first specimen was fixed (extended) to the edge of the framing around the entire perimeter as is the practice in fire tests conducted at BRANZ. The objective was to rack the first specimen to 1.5% drift which is the equivalent of the code requirement for buildings greater than 30 m high.

9.2.2 Racking commentary

In the course of the racking, the bottom plate of the wall and the bottom sill/platen of the frame were moving in the direction of the racking force and movement on the top plate. Attempts were made to reduce this movement by packing the ends of the bottom plate in order to achieve the required 1.5% of drift. In packing the bottom plate the plasterboard lining was also restrained at each end and on the bottom edge. This additional restraint increased the load and movement at the top of the wall where the nails tore the lining and it became detached from the framing by up to 7-8 mm over the upper 600 to 1000 mm of the wall. Cyclic racking was suspended at 1% (corrected value) due to the damage on the upper portion of the wall as it was anticipated that this would lead to an Integrity failure in the fire test at an early stage.

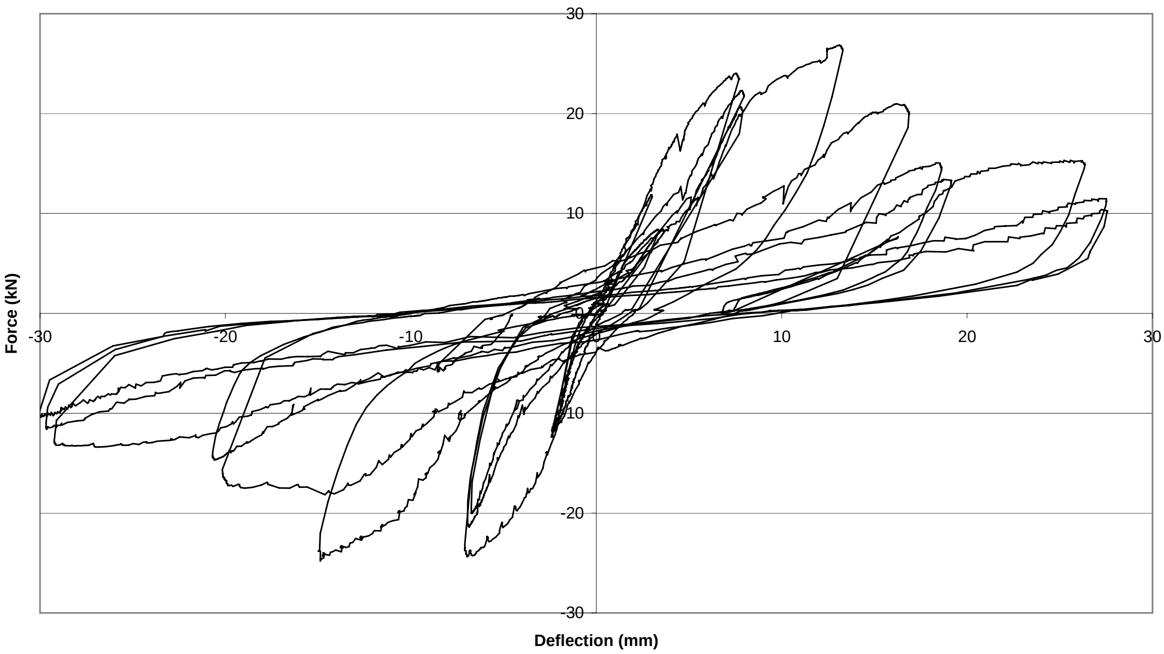

Figure 27: Racking of wall FR3362A

The hysteresis loop for wall FR3362A is shown in Figure 27. The energy expended in racking the wall was 2.1 kJ and is a measure of the resistance of the wall on the basis of the cumulative force x distance summed over the entire racking procedure.

9.2.3 Assessment of damage caused to wall

The lining had become detached over the top 600 to 1000 mm of the wall where the nails had torn the lining and it became detached from the framing by up to 7-8 mm on both sides. The nails were also bent proportionately to displacement of the lining relative to the frame. Due to the gap between the wall's timber frame and the concrete fire test frame at the two sides and the top to allow racking movement this meant the lining was relatively free to move over the frame being only restrained by the nails compared with the bottom concrete sill where the lining was also restrained by contact with the concrete. As a result the racking damage to the lining at the bottom was minimal and increased towards the top of the wall to the extent it was loose at the top thus only providing minimal resistance to racking once the higher displacement cycles had been reached as shown in Figure 27. Figure 28 shows popping of nails on an intermediate stud and tearing of the lining on a side stud. In both cases the damage is in the top 600 to 1000 mm of the wall.

Figure 28: Damage to lining in FR3362A

9.3 Results of racking test 2 FR3362B

9.3.1 Specific design features

Some changes to the attachment of the lining were made to simulate a more realistic installation. The lining was again attached in accordance with the manufacturer's instruction, the main difference compared with FR3362A being the provision of a 10 mm gap around the perimeter of the lining to the stud edge. This allowed room for the lining to be solely restrained by the nails rather than the floor or other abutments.

9.3.2 Racking commentary

In the racking process the movement of the lining over the frame around the perimeter was more even than in test FR3362A. At the conclusion of the racking, up to -1.32 to +1.43% of drift all nails had popped through the stopping around the perimeter on the bottom plate and on the side studs the nails had torn the edges over a height of 600 to 1000 mm from the bottom and at the top corners on each side. The lining on the top plate was still firmly attached. On the intermediate studs the lining was loose over the bottom 600 to 1000 mm by up to 6 mm. No visible damage by popping or cracking of the plaster was evident on stopped joints but the lining was loose in the lower regions (600 -1000 mm)

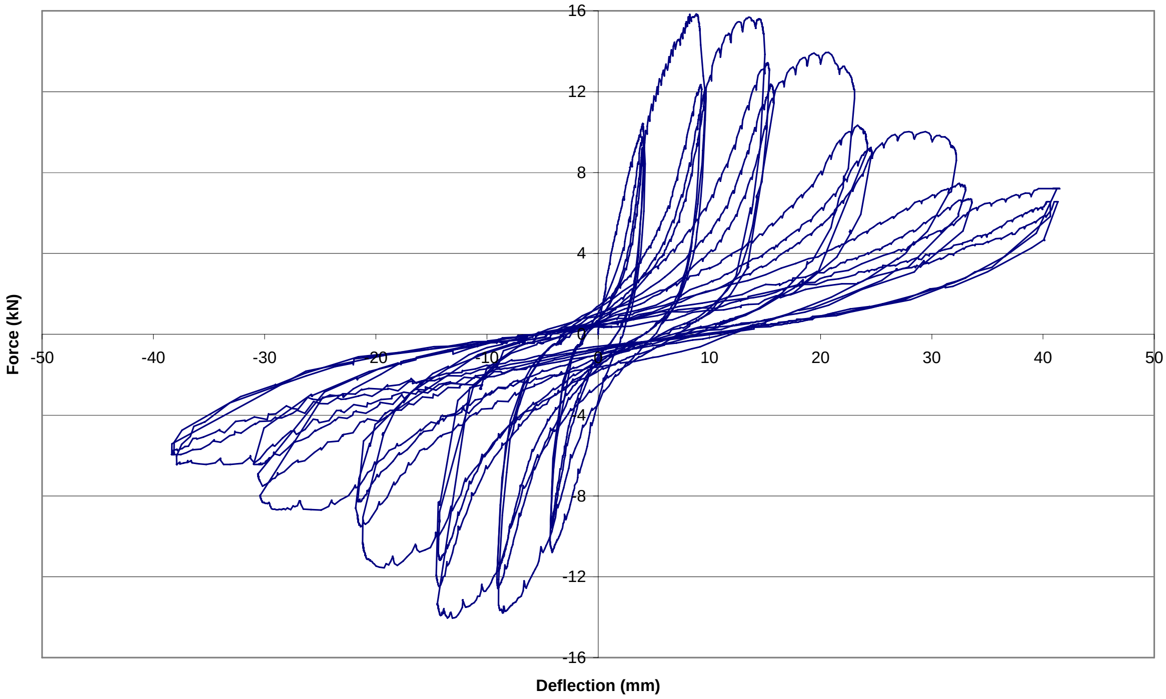

Figure 29: Racking of wall FR3362B

Figure 29 shows a graph of the hysteresis loop, a notable difference to test 1 FR3362A as graphed in Figure 27 is the reduced force required initially before the force reduces for greater drifts as the lining fixing is progressively damaged. This is a function of the degree of restraint around the perimeter where the 10 mm gap allows easier movement of the lining as only the nails are there to resist it.

The energy in racking to 1.5% was also 2.1 kJ (the same as in FR3362A) as a measure of the resistance, even though the % drift was greater, it would appear that once a certain level of damage had been sustained the resistance to racking reduces. Also whether the major failure is at the top or bottom is somewhat dependent on the overall restraint of the lining in each region and which nails tear the lining first.

9.3.3 Assessment of damage caused to wall

The damage to the lining caused was predominately at the bottom of the wall in FR3362B, as opposed to the top as in FR3362A. The bottom 600 to 1000 mm of the lining was loose and about 6 mm away from the frame on the side studs and along the bottom plate on both faces of the wall. The nails had popped and torn the edges of the lining to some extent around the entire perimeter, but damage was least at the top plate where the lining remained firmly attached to the top plate except at the two top corners. On the intermediate studs up to a height of 600 mm above the bottom the nails had popped where the board was continuous but popping was not so obvious on stopped joints. Figure 30 shows the tearing and detachment of the lining at a bottom corner at 32 mm drift and where there is no other restraint other than the nails.

Figure 30: Racking of wall FR3362B

9.4 Results of racking test 3 FR3362C

9.4.1 Specific design features

For the third racking test the edge detail was modified to simulate junctions with other walls, ceiling and floors, a more realistic situation consistent with building practice. These details were included based on the results of the first two racking tests where the perimeter of the lining became detached early on and thereafter the resistance to racking dropped appreciably. It was intended that the lining became more evenly detached over the entire surface and not just on the edges. The wall and ceiling junctions were treated as internal corners with the right angled joining of the lining nailed taped and stopped in accordance with the manufacturer's instructions. On the floor to wall junction there was a 10 mm clearance between the lining and the floor, this was then covered with 60 x 18 mm skirting board secured with 60 mm nails at 500 centres. The edge detail is shown in Figure 11.

9.4.2 Racking commentary

With the additional restraint around the perimeter the resistance to racking increased considerably. Damage was also reduced around the perimeter initially but eventually the taping and stopping on the junctions (wall to wall and wall to ceiling) was torn and gaps opened at the extreme ends of the racking travel as shown in Figure 31 . The skirting board remained attached but movement of the lining relative to it was noted with resultant evidence of nails tearing the plasterboard.

Figure 31: Bending of side plates

Racking travel was limited to ~1% (once corrected for rocking of the wall) by the 45 mm gap on each side between wall sides and the fire test frame. There were also problems with the bending of the side studs in the direction of racking travel. It was recognised that this may not be an accurate simulation of the actual phenomenon as walls in a high rise would most likely be between rigid concrete columns. The side studs had bent at the top and touched the frame limiting the displacement possible. The hysteresis graph in Figure 32 shows the considerably increased force required to reach ~1% drift consistent with the more rigid edge restraints. The energy required for racking was 7 kJ.

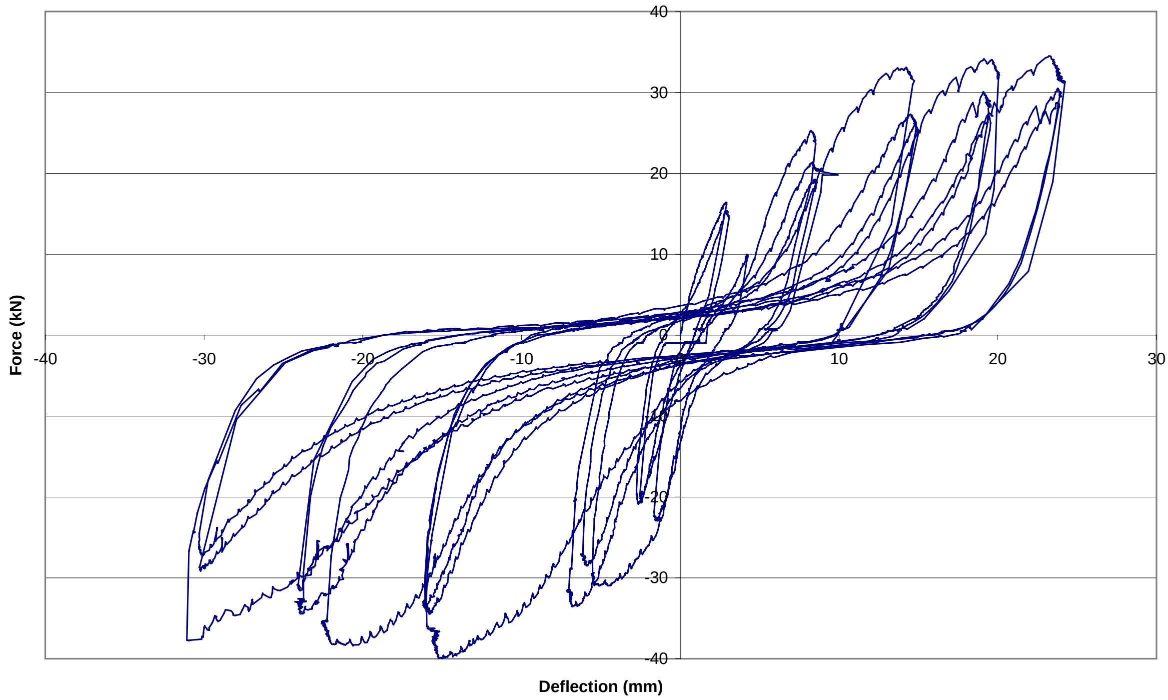

Figure 32: Racking of wall FR3362C

9.4.3 Assessment of damage caused to wall

The movement of the lining over the frame was resisted by the edge detail and that required increased racking forces to reach the required 1% drift. In the course of the racking the lining detached around the edges, and although the taping and stopping provided some resistance, cracks and tears did appear at the maximum drifts of the cycles as shown in Figure 33 where a nail is visible.

Figure 33: Lining separation in corner at maximum drift

When the wall was returned to the neutral position of 0% drift the gaps closed up, however the result of the tearing of the lining and the popping of the nails left the lining just perceptibly loose (~1 mm) around the perimeter and also on the studs adjacent to the sides. On these outer pairs of studs the nails had loosened and torn the plaster and some limited cracking of the plastered joints between lining sheets was evident in the top 600 mm of the wall.

9.5 Results of racking test 4 FR3362D

9.5.1 Specific design features

The same design as test 3 FR3362C with a modification to avoid the problem of the bending side studs. The side studs were stiffened on the inboard side with the addition of a 90 x 45 mm section making an L-shaped section stud at each side as shown in Figure 11 and increasing the gap for racking displacement on each side to 90 mm.

9.5.2 Racking commentary

The racking resistance increased accordingly (to ~50kN max for nominally 1.5% drift) and (missing word?) with the stiffer side studs the deflection at the top plate was significantly reduced. But at the bottom the side studs bent and fractured at the corners where there was a weakness because the additional side stud was cut short 25 mm. This resulted in significant popping and tearing at the wall to wall junctions and distortion/bending of the skirting board that eventually became detached from the bottom plate, but not before the nails had torn 50 mm long gouges in the plasterboard.

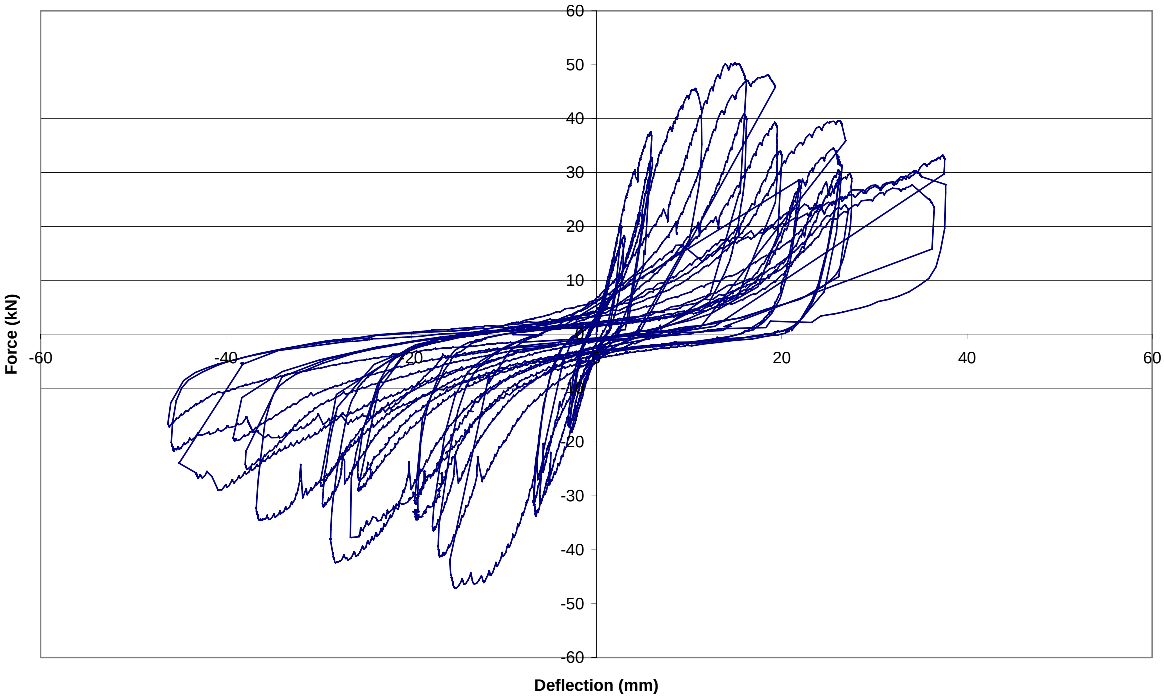

Figure 34: Racking of wall FR3362D

The racking force vs deflection is shown in Figure 34 and the energy expended in racking increased to 10.3 kJ.

On the fire exposed side the lining joint on the right hand end became detached from the stud and bowed out 135 mm at the full racking displacement with subsequent fracture of the tape and stopping on the joint shown in Figure 35. On the left bottom corner the lining had separated from the side stud.

Figure 35: Detachment of skirting board and opening at bottom corner FR3362D

9.5.3 Assessment of damage caused to wall

On returning to 0% drift the distortion in the lining at the bottom reduced, but the lining was detached 7-8 mm from three of the four central studs as well as the side studs over the bottom 600 to 1000 mm portion on both faces. Significant popping around the nail heads was observed including obvious tearing of the nails in the plaster. The upper portion of the lining remained attached to the studs, although there was some fracturing of the stopping and taping at the wall and ceiling junctions.

9.6 Results of racking test 5 FR3362E

9.6.1 Specific design features

To further stiffen the side studs, double 90 x 45 mm studs with the 90 mm dimension in the plane of the wall were used (Figure 36). Otherwise the design and fixing of the lining to the frame was identical to test 3 FR3362C and test 4 FR3362D.

Figure 36: Double plate side studs FR3362E

9.6.2 Racking commentary

The additional stiffness in the side studs by the two 90 x 45's with the 90 mm dimension in the plane of the wall contributed to greater deflection and damage on the top plate, particularly at each end of travel where it had bowed upwards (15-20 mm) over a length of 300 to 400 mm. This was in spite of the load skates at each end of the top plate to prevent uplift.

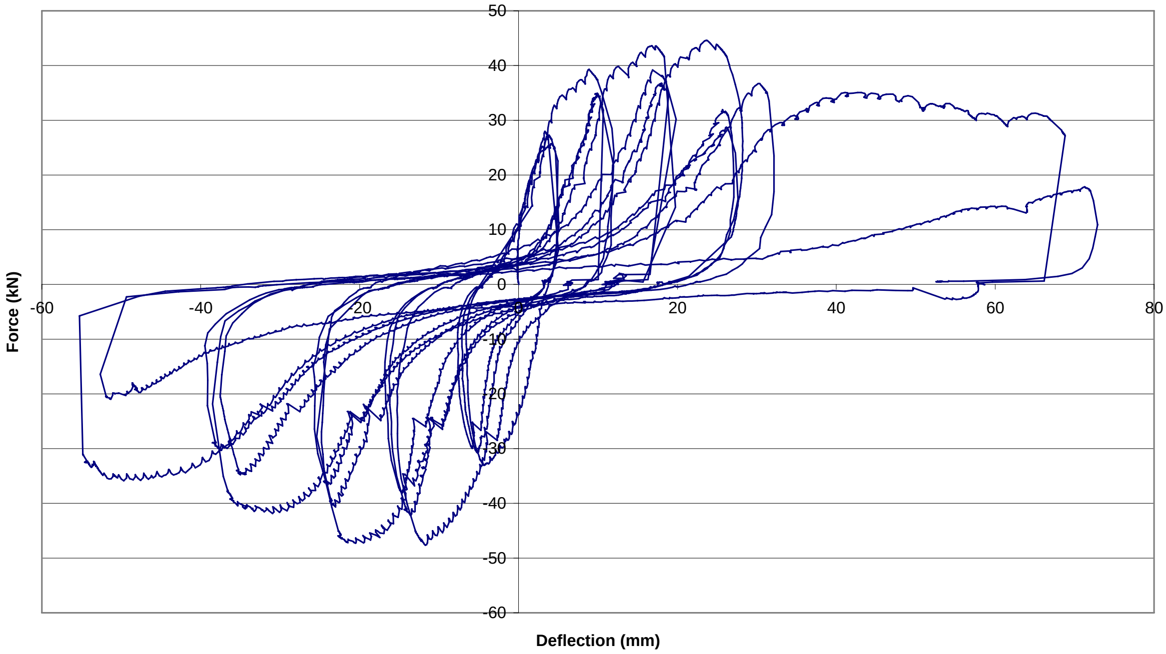

Figure 37: Racking of wall FR3362E

The adjusted racking plot is shown in Figure 37. Some adjustments were required for some practical difficulties in conducting the racking. On balance it was determined that the objective of 2.5% drift was achieved. The energy required was 12.9 kJ.

9.6.3 Assessment of damage caused to wall

On the fire side the nail connections to the double side studs had popped over the entire height. On the intermediate studs at the top and bottom regions of 300 to 600 mm, the nails had popped in some but not all locations. In the centre of the face the lining appeared to have remained firmly attached. Beneath the skirting board the lining had been torn in two places by the nails attaching the skirting board leaving two holes about 20-25 mm across and regions of bulged plasterboard were noted. It is also likely that there was more damage to the bottom edge caused by the nails attaching the lining that was obscured by the skirting board that was not visible. Damage on the corners is shown in Figure 38

On the unexposed side there appeared to be minimal damage to the lining where it was attached to the side studs, in complete contrast to the fire side. On the next from the left hand side stud the nails had slightly popped over the entire height. On the remaining studs the only nails showing any perceptible degree of popping were isolated to the top and bottom 300 mm.

Regardless of the extent of nail popping the lining remained intact over the entire frame with the greatest perceptible detachment from the frame being less than 1 mm. This contrasted with earlier racked specimens where the lining was hanging loose over large areas by up to 8 mm.

The wall was fixed at 1.5% (45 mm) drift and prepared for fire testing in the drifted condition it was not returned to 0% drift. This was to account for the realistic possibility that a building does not necessarily return to an un-deformed state after an earthquake.

Figure 38: **Damage to corners of exposed side of FR3362E**

9.7 Results of racking test 6 FR3362F

9.7.1 Specific design features

Test 6 FR3362F was a steel-framed wall with 63 x 34 x 0.5 mm thick steel studs floating in 63 x 30 x 0.5 mm thick steel channels. The top and bottom of the lining was not attached to the channels unlike the top and bottom attachment with a timber-framed wall, so the lining is only screw fixed to the central and side studs at 300 mm centres.

It was not practical to employ the same racking procedure for steel-framed walls as used for timber, as simply moving the top channel back and forth would not result in any movement of the wall as the floating top channel is neither attached to the studs or lining.

To simulate a realistic situation, the steel-framed wall was assembled inside a three side timber frame comprising pairs of 90 x 45 timber members with the 90 mm dimension in the plane of the wall. The two vertical members were hinged to a top horizontal member at the corners with bolts and gang nails creating a flexible structure. The racking force/displacement is transferred from the top plate to the steel side studs by the rigid timber side plates via the hinges. This arrangement was considered to simulate as closely as practicable the loading regime expected in a real building.

9.7.2 Racking commentary

The net result at each maximum drift, in each direction was a varying displacement proportional to the height between the lining and the side studs with the maximum at the top corners reducing to a minimal amount at the bottom corners. At the maximum drift of approximately 40 mm corresponding to 1.25%, the side studs had moved the equivalent of a stud width of 34 mm relative to the plasterboard lining, while the displacement of the plasterboard lining at the bottom of the wall was only +/-1 mm at the bottom sill. The force/displacement is graphed in Figure 39.

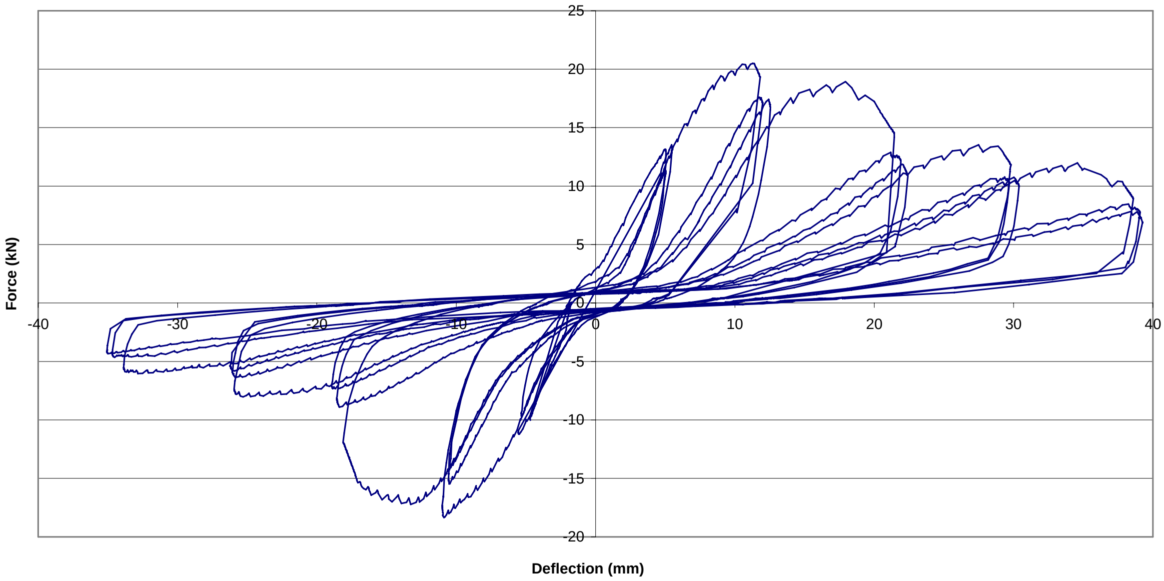

Figure 39: Racking of wall FR3362F

9.7.3 Assessment of damage caused to wall

The result was no discernible damage to the lining around the screw heads on the side studs at the bottom of the wall, but this increased considerably with height such that the lining was detached from the studs near the top and was not attached to the top channel originally.

Figure 40 shows a side stud viewed towards the top showing the increasing displacement and the screws tearing the edge of the lining. This view was typical of each of the faces and sides of the wall.

When the wall was restored to zero displacement before testing, the lining attached to each side stud on each face had detached from about 800 mm from the bottom to the top at 3000 mm. The amount of detachment varied from just being loose at 800 mm height to 5 mm on three top corners and 10 mm on the other. So it can be concluded that the lining had loosened considerably on the edges, but on the intermediate studs there was no evidence at all of the screws tearing the lining at all and this is not surprising given that the studs are floating thus not contributing to the resistance to racking. To summarise, the lining was essentially loose at the edges and was not initially attached to the top channel either.

The energy required for racking was 6.6 kJ.

Figure 40: FR3362F displacement of side studs at 40 mm drift

9.8 Results of racking test 7 FR3362G

9.8.1 Specific design features

The wall construction was identical to FR3362F but with the addition of a 60 minute fire-rated timber door and frame in the wall. The wooden door frame was attached to the steel frame with 10g 50 mm long self-tapping screws at 600 mm centres. The studs each side of the door frame were pairs of channels interlocked to form a box section. The lining was attached each side of the box section and secured into slots on the timber door frame. A channel was attached to the upper surface of the soffit frame and a floating stud fitted between it and the top channel.

9.8.2 Racking commentary

The wall and door was racked to 1.25% (40 mm), the same as FR3362F. It was assumed that the addition of the door would add stiffness to the wall but this was not apparent until the wall had moved enough to take up the clearances between the frame and the door and then the door and frame was seen to rock over and lift one side off the sill. In the process of this happening the plasterboard lining around the top of the door frame where the racking load was resisted over 800 to 900 mm height of plasterboard and effectively concentrated there instead of the full height of the wall. As a result, the damage to the plasterboard above the door was substantial where on the fire side the lining sheets joined on the studs that ran up the side of the door to the top of the wall. In this instance, the two stopped joints had split open. On the non-fire side, where the lining was continuous across the top corners of the door frame diagonal tears outwards from the corners occurred. The damage already done to the plasterboard meant that there was less resistance once the door leaf moved against the door frame and correspondingly less force was required to achieve the 1.25% drift. It is not significant that less force was required to reach a particular drift in the context of this project – it is the magnitude of the drift that is important. The force required to reach a particular drift can be a crude indicator of the damage inflicted, as in this case, the maximum load was reached at 24 mm drift and was a relatively low 15.9 kN indicating damage was done progressively as opposed to reaching a maximum at a relatively low drift and then the load required for greater drifts falls away. The energy required for racking was 2.5kJ and the load/deflection is graphed in Figure 41.

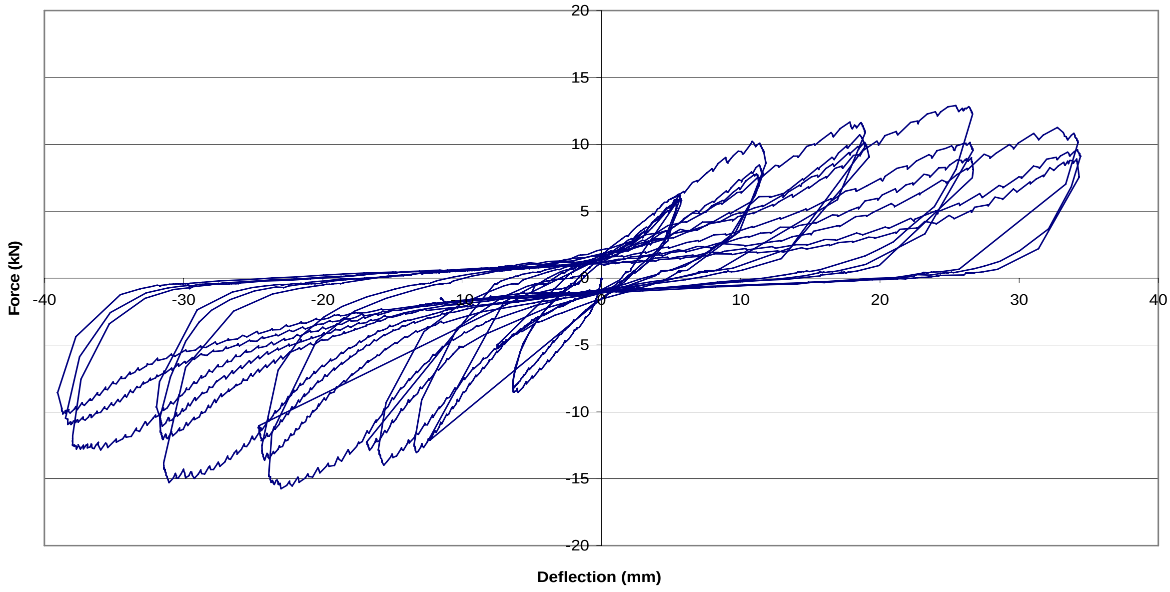

Figure 41: Racking of wall FR3362G

The movement of the door leaf in the frame was recorded before racking, at the extreme end of each racking direction and once returned to 0% drift in Table 12, the locations relate to the positions in Figure 16.

Table 12: Door to leaf clearances in mm during the racking process

Location\drift %	Pre-rack	-8	8	-16	16	-24	24	-32	32	-40	40	Post-rack
1	3.5	3.4	3.5	3.3	3.3	3.3	3.4	3.3	3.1	3.1	3.2	2.9
2	2.9	3.0	2.2	3.4	1.5	3.4	0.0	3.2	0.0	3.1	0.0	2.6
3	3.2	2.5	2.7	2.5	2.4	2.4	2.6	2.4	2.6	2.6	2.7	2.8
4	2.7	2.3	3.4	2.4	4.1	2.3	4.7	2.3	3.5	2.4	2.7	2.6
5	6.4	8.0	6.0	10.0	5.9	10.0	5.8	10.0	6.1	2.2	6.7	7.6
6	5.5	8.5	3.5	10.5	2.5	11.5	0.5	12.5	0.0	14.3	0.0	8.2
7	3.5	2.6	1.6	2.4	0.0	2.3	0.0	0.0	0.0	0.0	0.0	0.0
8	3.7	3.3	3.3	2.6	3.2	3.4	3.5	3.2	4.3	3.3	4.1	2.8
9	3.4	2.9	3.8	2.4	4.9	2.6	6.3	3.1	7.5	2.3	7.8	4.3
10	3.5	0.0	5.5	0.0	8.0	0.0	10.3	0.0	11.5	0.0	18.9	0.0

9.8.3 Assessment of damage caused to wall and door

Damage to the lining was observed on the side studs to both the fire and non-fire exposed faces. The degree of detachment of the lining on both side studs was about 10 mm at the top and reduced towards the bottom of the specimen. On the fire exposed face there was 2-3 mm detachment of the lining at the bottom. On the non-exposed face left hand side there was 10 mm detachment and on the right hand side 0-5 mm.

On the junction of the lining and the door frame there was evidence of strain in the lining that had resulted in tearing. On the fire exposed side, where there were joints in the lining running vertically above the top two corners covering the studs, the taped and stopped joints had split open as indicated in Figure 42. On the non-fire exposed side, where the lining was continuous at the corners, there were diagonal tears in the lining from the corners outwards for about 300 mm ad 45^{o} to the vertical as in Figure 43.

Figure 42: Racking of wall and door FR3362G door frame corner fire exposed side

Figure 43: Racking of wall and door FR3362G door frame corner non-fire exposed side

10. APPENDIX 2: FIRE TEST RESULTS

Fire resistance tests were conducted in accordance with AS 1530.4:1997. Descriptions of the tested specimens are in Appendix 1.

10.1 Results test 1 FR3362A

Timber frame wall.

10.1.1 Observations and commentary

Minutes:seconds Observation

4:00 On the non-exposed side there was leakage of steam and smoke from top edge of detached plasterboard.

7:00 Paper had burnt off the plasterboard on the exposed side.

8:30 Non-exposed side quite a bit of smoke coming through the top gap and black staining on the top edge packing board.

17:00 On the top left hand corner, lining had pulled away from side stud by about 15 mm with smoke exiting through gap.

19:00 Noticeable brown strip at top of centre of specimen, smoke continues to evolve from the gap and is progressively getting worse.

29:00 A plasterboard sheet strip was fitted over the top edge of the lining as flaming was established at the opening. Integrity failure was deemed to have occurred at 30 minutes.

33:00 Exposed lining remained intact, stopping plaster in place and nail holes visible.

40:30 A section of the exposed plasterboard behind the top left hand corner had fallen off. The remainder of the exposed plasterboard was intact. An additional thermocouple was fixed to the top left hand corner ~300 mm from side and top to monitor the temperature rise of the unexposed lining and this initially indicated a 73^{o}C rise.

45:30 On the exposed plasterboard behind the top right hand corner the joint in the plasterboard had opened up.

46:00 Sustained flaming was observed top left hand side, Integrity failure (>10 seconds flaming).

47:45 Excessive flaming top left hand corner had established, additional thermocouple fitted had exceeded a 180^{o}C rise indicating an Insulation failure.

50:00 Severe and sustained flaming had established on the top left hand side.

51:00 On the left hand side all lining had fallen off from top to bottom

52:00 On the right hand side all lining had fallen off from top to bottom

53:00 The test was stopped with sustained flaming on the upper left and right sides.

All lining on exposed side had fallen off at test conclusion when furnace opened.

10.1.2 Integrity

The specimen failed the Integrity criterion after 46 minutes due to flaming on the top left hand side of greater than 10 seconds.

10.1.3 Insulation

Figure 45 shows the average and maximum temperature rises on the non-exposed face of the wall. A maximum temperature rise of 180^{o}C was exceeded after 48 minutes.

10.1.4 Deflections

Deflections were recorded at approximately 15 minute intervals at the points located in Figure 44 and recorded in Table 13 and Table 14. Positive deflections are in the direction away from fire exposure.

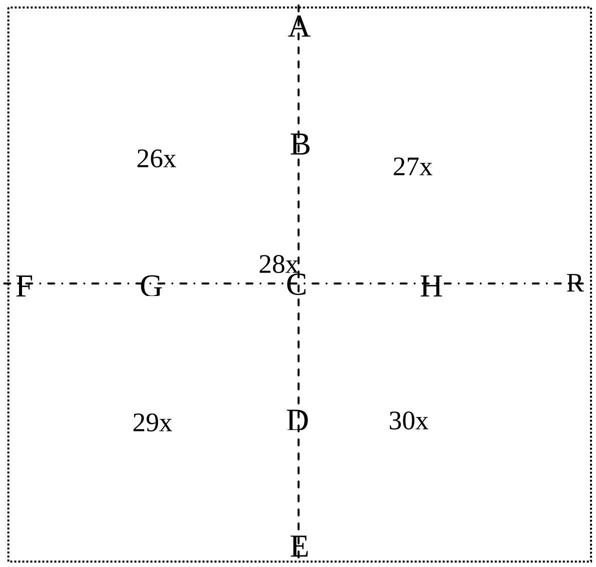

Figure 44: Deflection points and onset of char thermocouples for tests FR3362A to FR3362F

Table 13: Deflections vertical centre line of wall FR3362A

Time, mins	A	B	C	D	E
0	0	0	0	0	0
15	12	9	2	0	0
33	-2	16	10	8	1
45	-3	17	13	10	0

Table 14: Deflections of horizontal centreline of wall FR3362A

Time, mins	F	G	C	H	I
0	0	0	0	0	0
15	0	1	2	2	0
33	5	11	10	9	0
45	6	15	13	7	-4

The maximum deflection was 17 mm away from the fire, recorded at point B at 45 minutes.

10.1.5 Summary

The fire resistance in minutes achieved by the wall was as follows:

Structural adequacy	53 NF
Integrity	46
Insulation	48

10.1.6 Graphs – insulation and onset of char

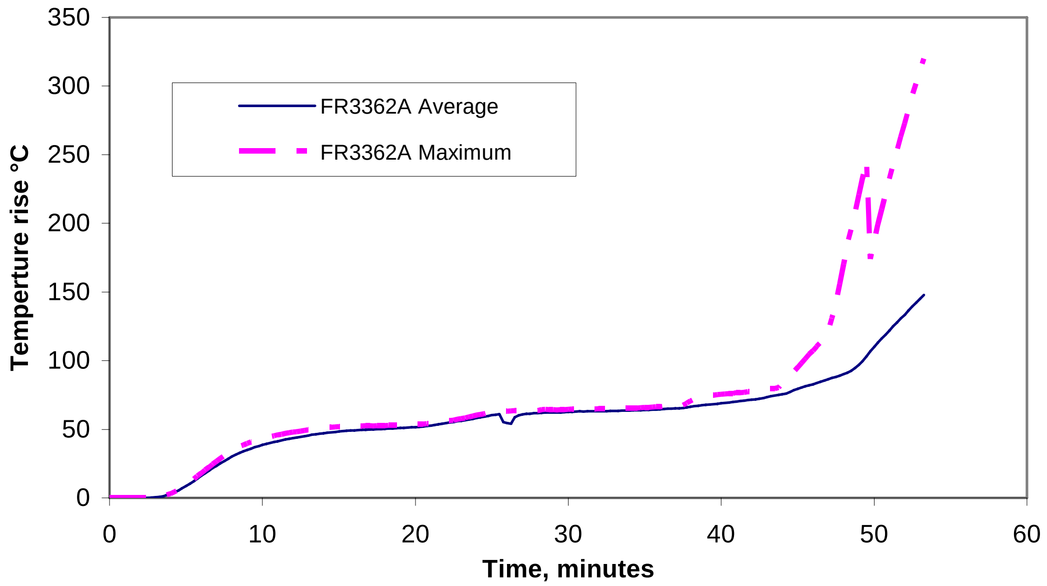

Figure 45: Insulation FR3362A

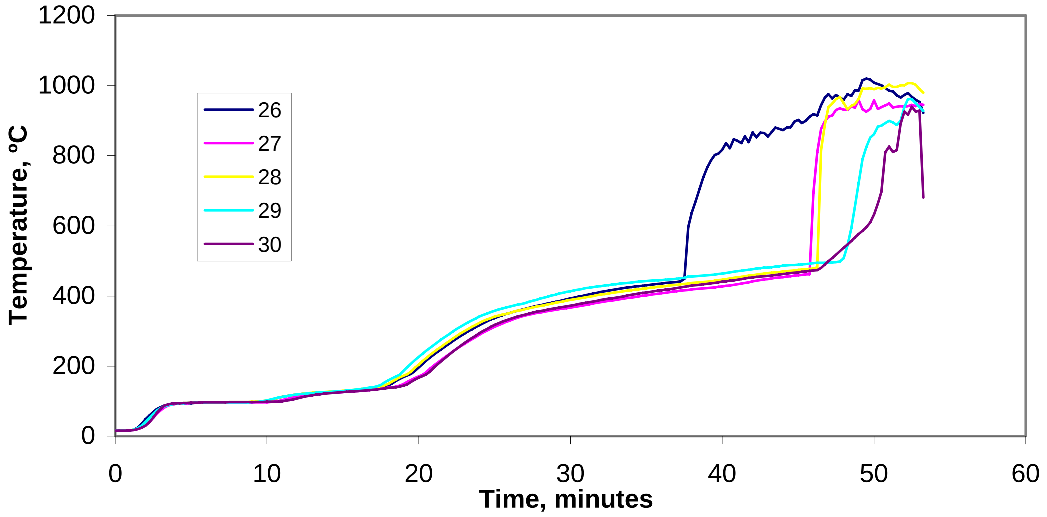

Figure 46: Onset of char FR3362A

10.1.7 Photo

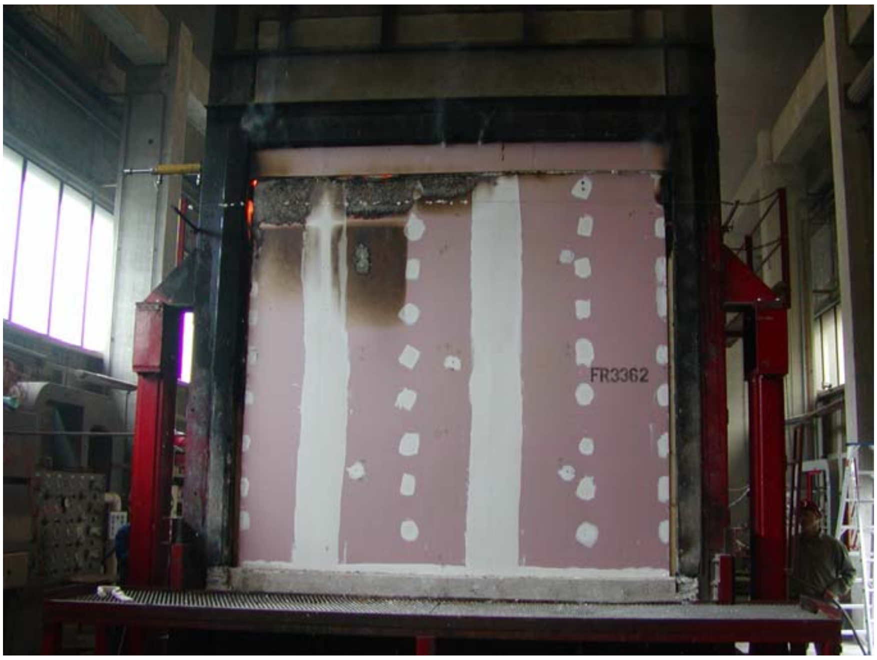

Figure 47: Non-exposed face of FR3362A at conclusion of test 53 minutes

10.2 Results test 2 FR3362B

Timber frame wall, a description of the tested specimen is in Appendix 1.

10.2.1 Observations and commentary

Minutes: seconds	Observation
0:00	The lining on each side was loose on the bottom plate with a gap of approximately 9 mm reducing to 0 mm at mid-height.
5:00	The gap between the plasterboard and the bottom plate had opened to ~30 mm.
10:00	The gap on the bottom plate had opened to 35-40 mm.
14:00	The gap on the bottom plate had opened to 40-45 mm.
21:00	Exposed face stopping had partially fallen off and the lining had a mottled type appearance.
23:00	300^{o}C was exceeded on the back of the exposed face indicating onset of char.
25:00	The gap at the bottom plate had closed to 30 mm.
32:00	The nail fixing on the exposed face remained firm but there was some flaming from the gaps/joints in the lining
34:00	Integrity failure had occurred at the bottom plate, by flaming >10 seconds at the gap previously reported. The gap was then closed with plasterboard screws and the test continued.
48:00	The exposed face was still intact, and there was considerable smoke emission on the unexposed face around the edges of the lining.
52:00	On the exposed side the lining joint at the bottom had opened to about 8 mm at mid-height and top the joint did not appear to have opened up at all. The holes had been elongated by the nail heads in the heavily racked damaged region.
53:00	There was sustained flaming on the right hand top edge, Integrity failure again but different location.
60:00	The flaming had spread all along the top edge. The exposed face lining was still intact.
62:00	The lining on the exposed face had fallen off.
62:30	Test stopped excessive flaming on top half of wall, no Insulation failure.
65:00	The furnace was opened and all of the exposed lining had fallen off. But the studs had not charred as much as in FR3362A.

10.2.2 Integrity

The specimen failed the Integrity criterion after 34 minutes due to flaming of greater than 10 seconds at the bottom plate.

10.2.3 Insulation

Figure 48 shows the average and maximum temperature rises on the non-exposed face of the wall. The test was stopped after 62 minutes without an Insulation failure.

10.2.4 Deflections

Deflections were recorded at approximately 15 minute intervals at the points located in Figure 44 and recorded in Table 15 and Table 16. Positive deflections are in the direction away from fire exposure.

Table 15: Deflections vertical centre line of wall FR3362B

Time, mins	A	B	C	D	E
0	0	0	0	0	0
15	1	1	2	0	15
30	2	9	12	8	7
45	7	15	16	13	11
60	12	22	25	18	12

Table 16: Deflections of horizontal centreline of wall FR3362B

Time, mins	F	G	C	H	I
0	0	0	0	0	0
15	0	2	2	4	3
30	1	8	12	13	4
45	1	10	16	19	4
60	1	15	25	27	3

The maximum deflection was 27 mm away from the fire, recorded at point H 60 minutes.

10.2.5 Summary

The fire resistance in minutes achieved by the wall was as follows:

Structural adequacy	62 NF
Integrity	34
Insulation	62 NF

10.2.6 Graphs – insulation and onset of char

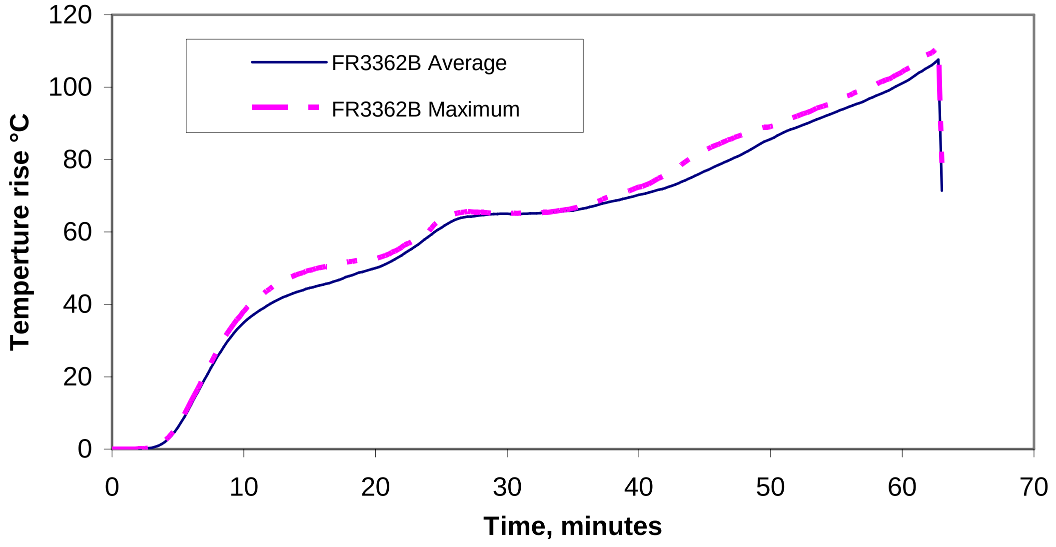

Figure 48: Insulation FR3362B

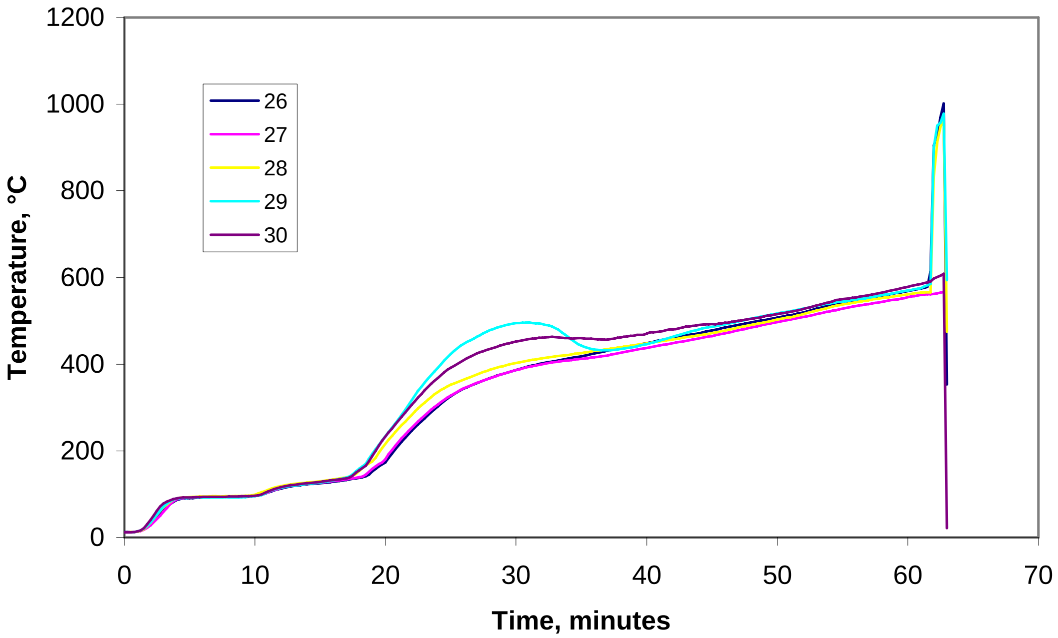

Figure 49: Onset of char FR3362B

10.2.7 Photos

Figure 50: Flaming at top edge FR3362B 60 minutes, previously failed at bottom corner 34 minutes

10.3 Results test 3 FR3362C

Timber frame wall, a description of the tested specimen is in Appendix 1.

10.3.1 Observations and commentary

Minutes: seconds Observation

Observations up to 27 minutes were similar to tests FR3362A and FR3362B.

27:00 On the exposed side deterioration of joints on top edge or around nail heads was observed, a small amount of stopping plaster remained.

37:00 On the non-exposed side some of stopping paper had disappeared on the top edge at the wall to ceiling joint.

43:00 On the exposed side some shrinkage and loss of the simulated ceiling lining at the top of the wall had exposed some timber to the fire conditions.

54:00 On the exposed side the gap at the top edge had increased to 15-20 mm wide caused by the loss of pieces of the wall to ceiling junction board.

65:00 The exposed lining had fallen off on left hand side.

67:00 Insulation failure.

69:00 The exposed lining had fallen off over entire face.

71:00 Test stopped.

10.3.2 Integrity

The specimen had not failed the Integrity criterion at 71 minutes.

10.3.3 Insulation

Figure 51 shows the average and maximum temperature rises on the non-exposed face of the wall. An average temperature rise of 140°C was exceeded after 67 minutes. A maximum temperature rise of 180°C was exceeded after 67 minutes.

10.3.4 Deflections

Deflections were recorded at approximately 15 minute intervals at the points located in Figure 44 and recorded in Table 17 and Table 18. Positive deflections are in the direction away from fire exposure.

Table 17: Deflections vertical centre line of wall FR3362C

Time, mins	A	B	C	D	E
0	0	0	0	0	0
15	-1	1	1	2	0
30	2	10	12	11	0
45	4	12	16	14	-2
60	7	17	20	17	1

Table 18: Deflections of horizontal centreline of wall FR3362C

Time, mins	F	G	C	H	I
0	0	0	0	0	0
15	1	3	1	2	0
30	2	13	12	12	1
45	2	15	16	16	2
60	3	18	20	23	3

The maximum deflection was 23 mm away from the fire, recorded at point H at 60 minutes.

10.3.5 Summary

The fire resistance in minutes achieved by the wall was as follows:

Structural adequacy	71 NF
Integrity	71 NF
Insulation	67

10.3.6 Graphs – insulation and onset of char

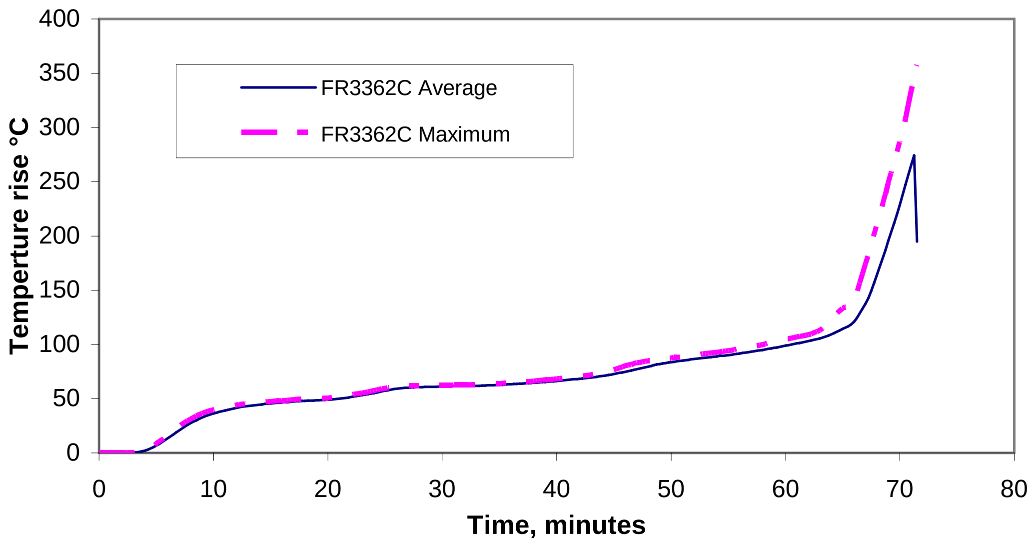

Figure 51: Insulation FR3362C

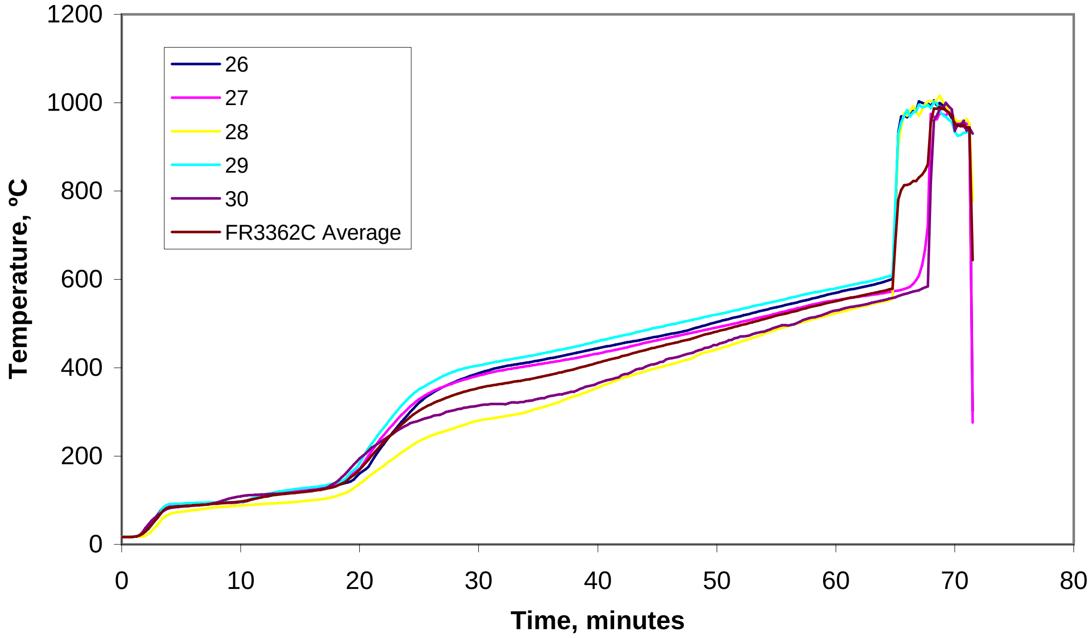

Figure 52: Onset of char FR3362C

10.3.7 Photo

Figure 53: FR3362C at 67 minutes, the time of insulation failure

10.4 Results test 4 FR3362D

Timber frame wall, a description of the tested specimen is in Appendix 1.

10.4.1 Observations and commentary

Minutes: seconds Observation

12:30 The appearance of a flickering flame in the cavity on the bottom right hand side was evident by momentary flashes and an indication that the loose plasterboard on the bottom 600 to 800 mm was providing a passage for the hot gases to enter the cavity.

19:00 The glow within the cavity continued with smoke and cooler gases being drawn into the cavity from the outside.

22:00 The exposed lining showed no additional distress around the nail heads where damage due to racking had occurred. It was also observed that there was a tendency for the lining to swell slightly and close the cracks.

24:00 On the unexposed side the skirting board fell off and the lining oscillated back and forth with puffs of smoke exiting.

51:00 Intermittent flaming from the bottom right hand corner of duration up to 2 seconds was observed, flaming within the cavity was also visible.

53:00 Intermittent flaming was observed at bottom right hand corner ~5 seconds

55:00 Integrity failure at bottom right hand corner with flaming >10 seconds, the hole was covered with plasterboard and test continued.

67:00 A temperature increase in cavity indicated the exposed lining had fallen off, sustained flaming at top edge of wall had established.

71:00 Test stopped, on opening the furnace the exposed lining had fallen off and the bottom 600-800 mm of the studs had burnt away.

10.4.2 Integrity

The specimen failed the Integrity criterion after 55 minutes due to failure of the cotton pad test and flaming greater than 10 seconds.

10.4.3 Insulation

Figure 54 shows the average and maximum temperature rises on the non-exposed face of the wall. An average temperature rise of 140^{o}C was exceeded after 65 minutes. A maximum temperature rise of 180^{o}C was exceeded after 64 minutes.

10.4.4 Deflections

Deflections were recorded at approximately 15 minute intervals at the points located in Figure 44 and recorded in Table 19 and

Table 20. Positive deflections are in the direction away from fire exposure.

Table 19: Deflections vertical centre line of wall FR3362D

Time, mins	A	B	C	D	E
0	0	0	0	0	0
15	1	2	2	3	12
30	3	9	10	8	3
45	5	14	15	11	6
60			19		

Table 20: Deflections of horizontal centreline of wall FR3362D

Time, mins	F	G	C	H	I
0	0	0	0	0	0
15	-1	2	2	2	0
30	1	10	10	10	2
45	1	14	15	15	2
60	2	15	19	18	3

The maximum deflection was 19 mm away from the fire, recorded at point C at 60 minutes.

10.4.5 Summary

The fire resistance in minutes achieved by the wall was as follows:

Structural adequacy 71 NF

Integrity 55

Insulation 64

10.4.6 Graphs – insulation and onset of char

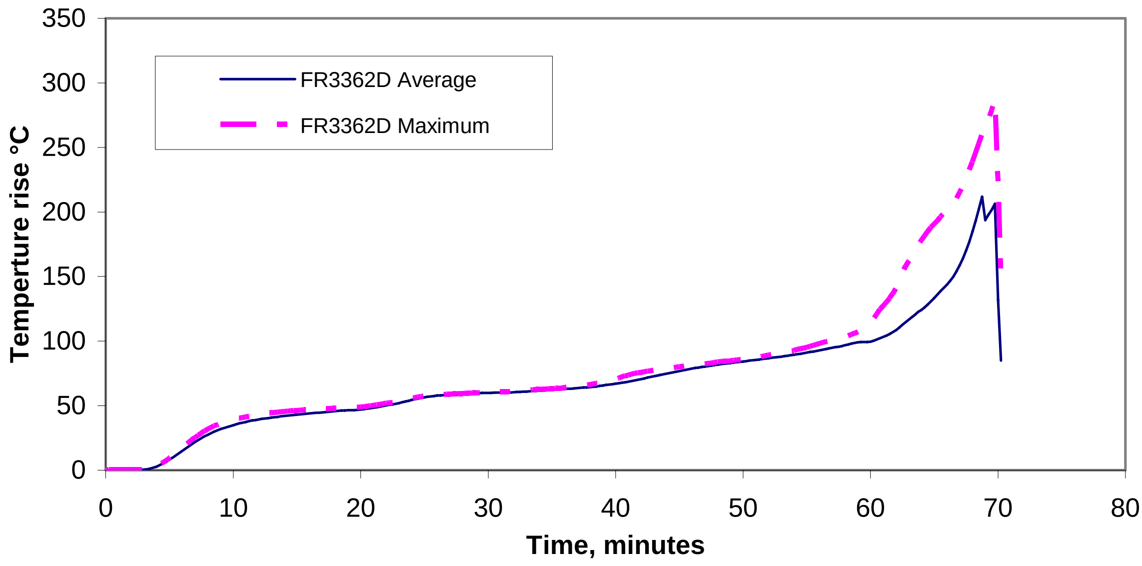

Figure 54: FR3362D insulation

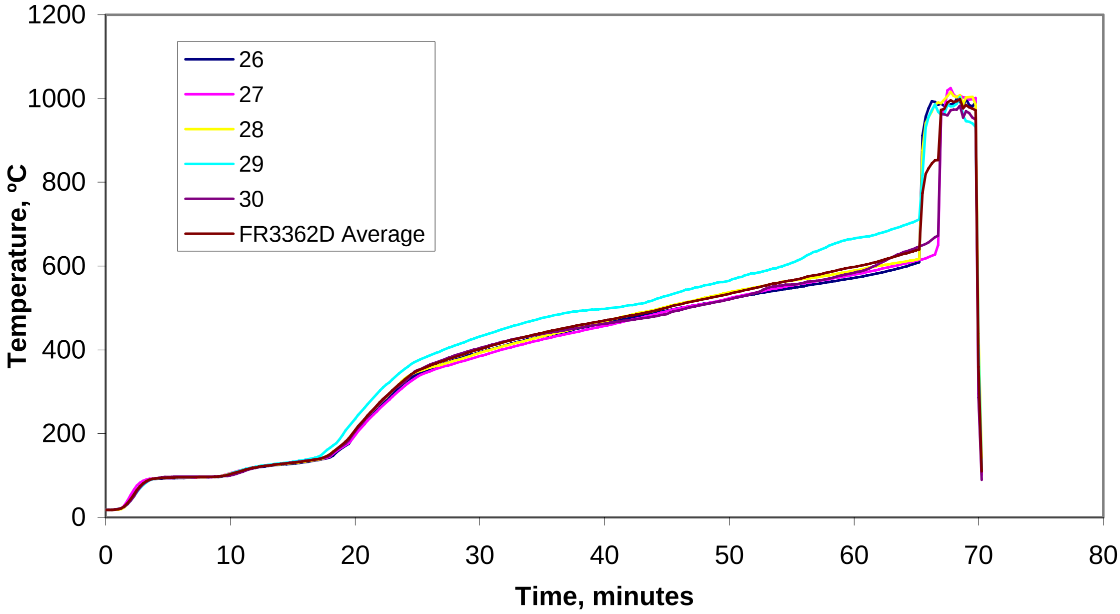

Figure 55: FR3362D onset of char

10.4.7 Photo

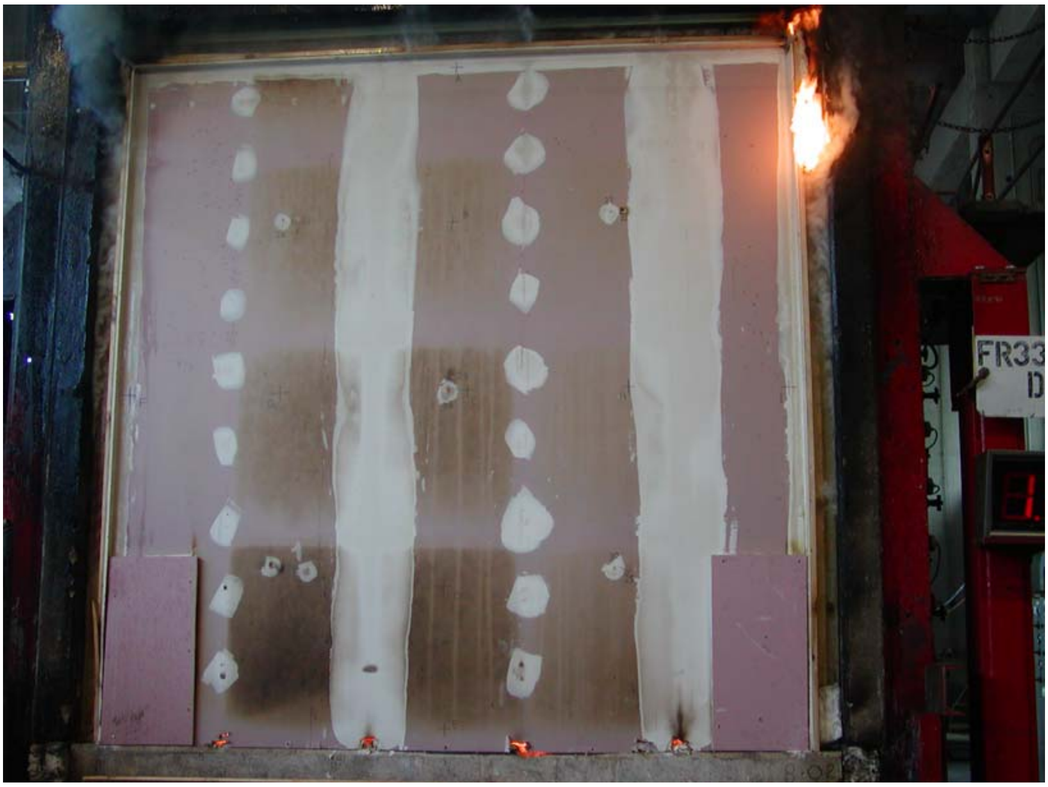

Figure 56: FR3362D at 70 minutes

10.5 Results test 5 FR3362E

Timber frame wall, a description of the tested specimen is in Appendix 1. Wall was tested with 45 mm of drift (1.5%) to the left hand side (viewed from the non-exposed side) instead of the sides being vertical at 0% drift.

10.5.1 Observations and commentary

Minutes: seconds	Observation
8:00	Smoke was exiting from the top left hand corner where the plasterboard had been damaged and was loose as a result of the racking.
14:30	At the top left hand corner there were occasional sparks from the opening where smoke was exiting from.
20:00	Integrity failure, there was sustained flaming at the top left hand corner which was covered with kaowool and the test continued.
44:30	Sustained flaming at top right hand corner was deemed to be a second Integrity failure this was covered with kaowool and the test continued.
49:00	A portion of the exposed face lining had fallen off behind the top left hand corner where the non-exposed lining was showing signs of scorching.
50:00	The remainder of the exposed lining was still intact with the exception of the top left hand corner.
59:00	Extensive flaming around the perimeter of the wall. Test was stopped.

10.5.2 Integrity

The specimen failed the Integrity criterion after 20 minutes due to flaming on the top left hand side of greater than 10 seconds. The source of the flaming was covered with kaowool and the test continued.

The specimen again failed the Integrity criterion after 44 minutes due to flaming on the top right hand side of greater than 10 seconds. The source of the flaming was covered with kaowool and the test continued.

10.5.3 Insulation

Figure 57 shows the average and maximum temperature rises on the non-exposed face of the wall. There was no insulation failure at 59 minutes.

10.5.4 Deflections

Deflections were recorded at approximately 15 minute intervals at the points located in Figure 44 and recorded in Table 21 and Table 22. Positive deflections are in the direction away from fire exposure.

Table 21: Deflections vertical centre line of wall FR3362E

Time, mins	A	B	C	D	E
0	0	0	0	0	0
15	3	2	2	1	-1
30	4	13	16	12	1
47	6	22	28	19	2

Table 22: Deflections of horizontal centreline of wall FR3362E

Time, mins	F	G	C	H	I
0	0	0	0	0	0
15	0	1	2	7	0
30	0	14	16	20	2
47	5	23	28	30	5

The maximum deflection was 30 mm away from the fire, recorded at point H at 47 minutes.

10.5.5 Summary

The fire resistance in minutes achieved by the wall was as follows:

Structural adequacy	59 NF
Integrity	20 top left hand corner, 44 top right hand corner
Insulation	59 NF

10.5.6 Graphs – insulation and onset of char

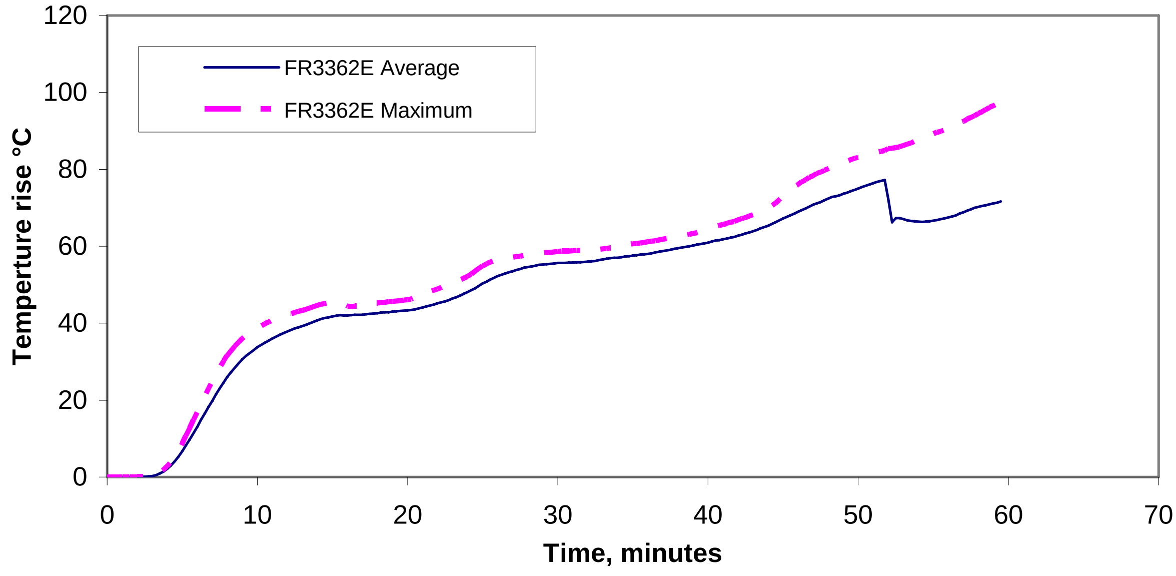

Figure 57: FR3362E insulation

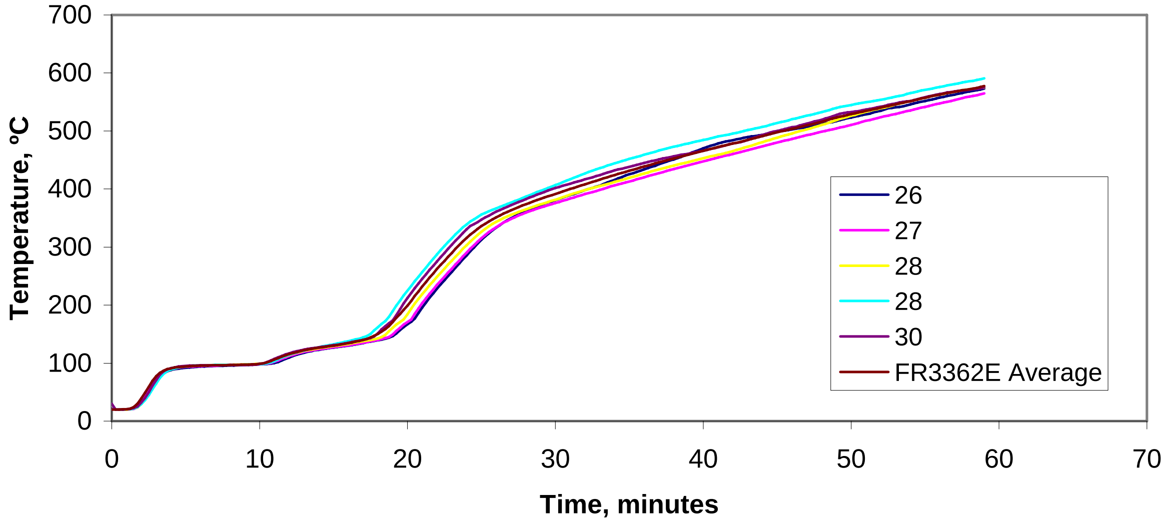

Figure 58: FR3362E onset of char

10.5.7 Photo

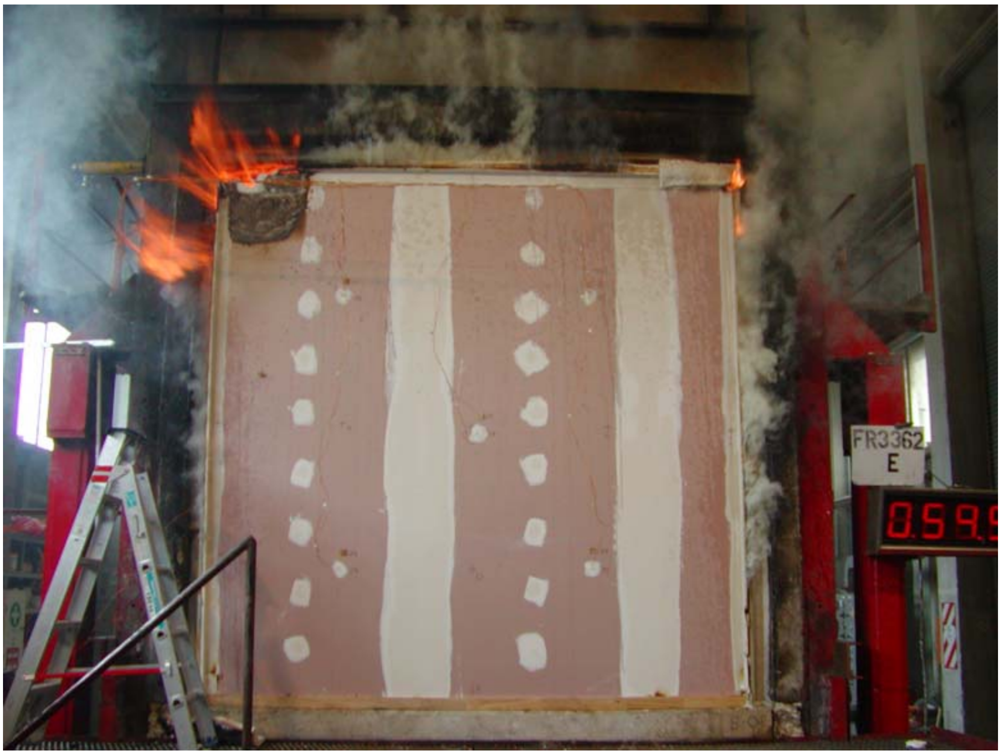

Figure 59: FR3362E end of test

10.6 Results test 6 FR3362F

Steel frame wall, a description of the tested specimen is in Appendix 1.

10.6.1 Observations and commentary

Minutes: seconds	Observation
2:00	Some smoke emitted from the gaps at the top left and right hand corners to approx 600 mm below.
4:30	On non-exposed side gaps at the top had opened up, the plasterboard had peeled back approximately 25 mm on right hand side and 10 mm on left hand side.
12:00	On the exposed side the paper facing had burnt away with no other indications of deterioration.
18:00	The gaps on the non-exposed side at the top of the lining on the non-exposed side had not changed from that observed at 4:30 when the movement of the lining had stabilised.
20:00	The exposed lining remained intact.
21:00	On the non-exposed side a steady stream of smoke was exiting from the top left and right hand corners as the paper facing was burning within cavity.
23:00	On the non-exposed side top right hand corner brown staining of the timber outer frame was observed where smoke had passed over it compared with a minimal amount of browning on the left hand top corner.
27:00	The exposed face remained intact.
31:00	Charring at the top right hand corner had progressed 200 mm downwards from the corner and 150 mm along the top. On the top left hand corner there was minimal charring of the region to 100 mm below but hot gases were exiting from the cavity. The cavity temperature in the centre of the wall is 400^{o}C +/- 10-15^{o}C.
34:00	A trial with the cotton pad test failed to ignite at 10 seconds exposure. There was also a red glow at the top right hand corner outside the specimen boundary – this was plugged with kaowool.
37:00	The top right hand corner was glowing from within the cavity but not burning.
40:00	Flaming of >10 seconds from the top right hand corner (40:35) occurred, this required a patch, Integrity failure at 40 minutes.
46:00	Flaming of >10 seconds from the top edge of the lining indicated an Integrity failure there. The top left hand corner remained intact at this stage.
51:00	Flaming had established over entire top plate and scorching of the paper face as well indicated an Insulation failure.
54:00	The test was stopped due to uncontrollable flaming. The exposed lining appeared intact before the furnace was opened. The exposed lining had fallen off completely

when the furnace was opened. The non-exposed lining was peeling back and the studs were relatively intact being only slightly buckled.

10.6.2 Integrity

The wall specimen failed the Integrity criterion after 40 minutes due to flaming on the top right hand side of greater than 10 seconds. The flaming from the detached lining on the right hand side of the wall was covered with plasterboard and the test continued.

The specimen failed the Integrity criterion after 46 minutes due to flaming along the top edge of greater than 10 seconds.

10.6.3 Insulation

Figure 60 shows the average and maximum temperature rises on the non-exposed face of the wall. The insulation criterion of failure had not been exceeded after 58 minutes.

10.6.4 Deflections

Deflections were recorded at approximately 15 minute intervals at the points located in Figure 44 and recorded in Table 23 and Table 24. Positive deflections are in the direction away from fire exposure.

Table 23: Deflections vertical centre line of wall FR3362F

Time, mins	A	B	C	D	E
0	0	0	0	0	0
15	5	1	-5	-3	0
30	8	-21	-41	-28	-1
45	22	-3	-22	-16	0

Table 24: Deflections of horizontal centreline of wall FR3362F

Time, mins	F	G	C	H	I
0	0	0	0	0	0
15	4	-5	-5	-7	0
30	0	-35	-41	-37	-3
45	7	-16	-22	-15	-3

The maximum deflection was 41 mm towards the fire, recorded at point C 30 minutes.

10.6.5 Summary

The fire resistance in minutes achieved by the wall was as follows:

Structural adequacy	54 NF
Integrity	40 on top right hand corner, 46 along top edge
Insulation	54 NF

10.6.6 Graphs – insulation and onset of char

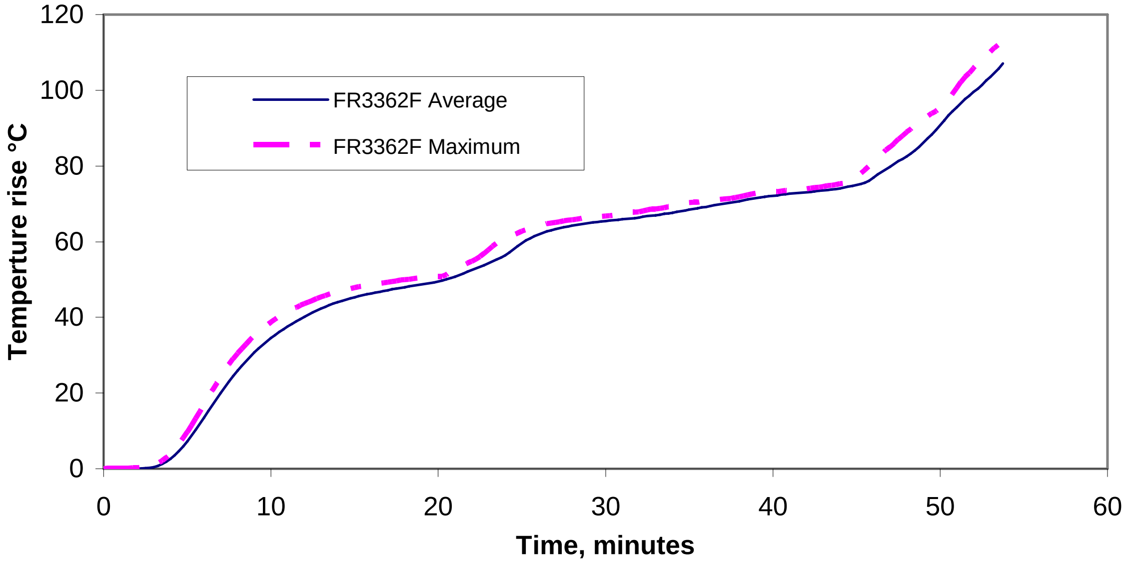

Figure 60: FR3362F insulation

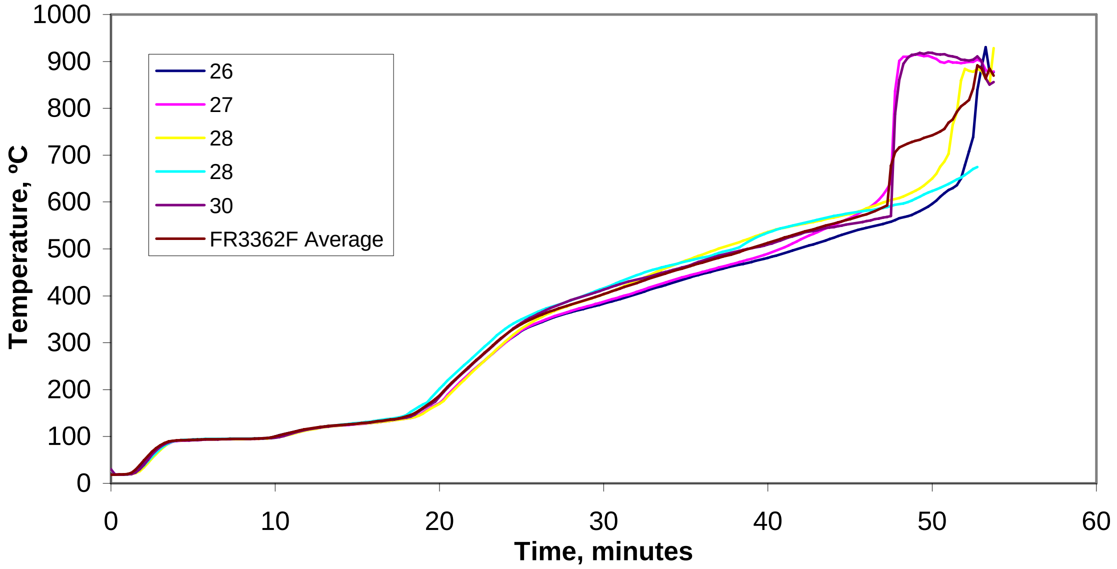

Figure 61: FR3362F temperature of exposed lining

10.6.7 Photo

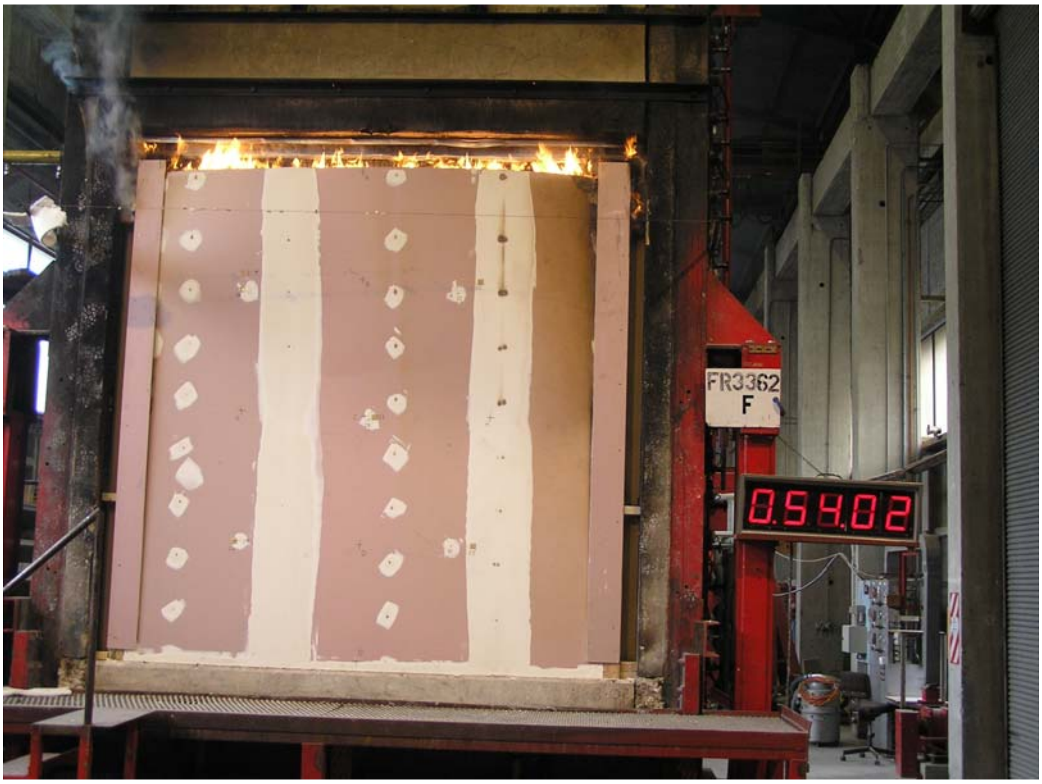

Figure 62: FR3362F at end of test

10.7 Results test 7 FR3362G

Steel frame wall with timber door, a description of the tested specimen is in Appendix 1.

10.7.1 Observations and commentary

Minutes: seconds	Observation
00:00	Test started
2:00	Smoke was issuing through top of gap between the door leaf and frame.
5:00	Smoke emission through the door assembly had stabilised, paper on the exposed face of the plasterboard had burnt off.
26:00	The exposed plasterboard remained attached. The core of the door was visible on the exposed side, the plywood facing had charred and peeled back.
33:00	The exposed face lining was still intact and the core of the door was glowing.
35:00	There was intermittent flaming top left corner of the wall < 10 seconds.
36:00	Cotton pad test ignited = Integrity failure at top left corner of wall. Gap patched with plasterboard and test continued.
39:00	The exposed face lining joint on stud at side of door frame extending above the door frame had opened 1.5 screw heads wide, but the lining remained attached.
40:00	On the exposed side lining behind the location of the top left corner, where the Integrity failure occurred at 36 minutes, a piece of 100 x 200 mm plasterboard had fallen away.
43:30	No further changes to the exposed face lining, it remained attached.
48:00	Smoke issuing from the top half perimeter of the door had increased. The deflection of the wall seemed to be restrained by the stiffness of the door frame thus reducing the deflection of the wall towards the furnace of the wall.
51:00	A red glow was observed along the top of the door with intermittent flaming, this increased to >10 seconds duration. Integrity failure of door.
54:30	The lining on the exposed face had started to peel off from the top down.
55:00	A +180°C temperature rise was recorded and deemed an Insulation failure in the same location where lining had first fallen off the back at 40 minutes.
58:00	Test stopped.

Integrity failures had occurred at top left of wall, top of door, top right of wall and then all the way down the left side, the right hand side and all along the top of the specimen where the lining had detached by 30-40 mm. The stretch marks around the door frame at the top of the door were not responsible for any failure. With the furnace open 90% of the exposed lining had fallen off and a piece 600 x 600 mm remained at the bottom between the door frame and the edge of the wall, on the narrow side. The studs were reasonably straight except the centre stud on the 1200 mm gap between the door frame and the wall edge which was slightly buckled this was the only free floating stud. All other studs were either side studs or attached to the door frame.

10.7.2 Integrity

The specimen was assessed to have failed the Integrity criterion after 35 minutes due to flaming and ignition of a cotton pad on the top left hand side. The gap was covered with plasterboard and the test continued.

The door was assessed to have failed the Integrity criterion after 50 minutes due to flaming between the top of the door and the frame.

10.7.3 Insulation

Figure 64 shows the average and maximum temperature rises on the non-exposed face of the wall. An average temperature rise of 140°C was exceeded after 57 minutes. A maximum temperature rise of 180°C was exceeded after 54 minutes.

Figure 65 shows the average and maximum temperature rises on the non-exposed face of the door. An average temperature rise of 140°C and a maximum temperature rise of 180°C were not exceeded up to 50 minutes. Recordings of door temperature were not reliable after the flaming at the top edge of the door was extinguished and the thermocouple pads were wet and thus indicating a lower temperature, so temperature readings were discontinued.

10.7.4 Deflections

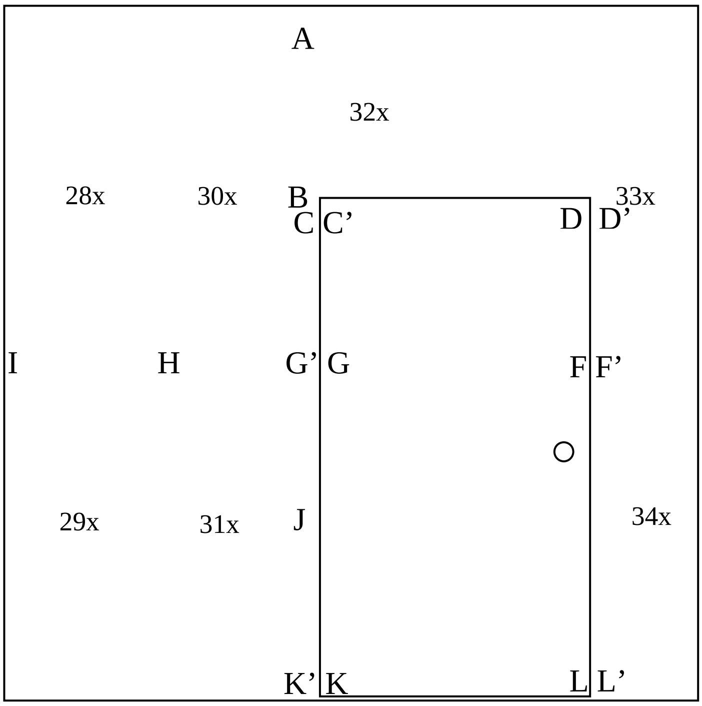

Figure 63: FR3362G deflection points and onset of char thermocouples

Deflections were recorded at approximately 15 minute intervals at the points located in Figure 63 and recorded in Table 25 to Table 28. Positive deflections are in the direction away from fire exposure.

Table 25: Deflections vertical centre line of wall FR3362G

Time, mins	A	B	G'	J	K
0	0	0	0	0	0
15	4	1	-2	-2	0
30	4	-11	-15	-12	0
45	6	-13	-18	-13	0

Table 26: Deflections of horizontal centreline of wall FR3362G

Time, mins	E	F'	G'	H	I
0	0	0	0	0	0
15	1	-1	-2	-4	-2
30	-1	-14	-15	-32	-1
45	1	-17	-18	-26	2

The maximum deflection of the wall was 32 mm towards the fire, recorded at point H 30 minutes.

Table 27: Deflections of door frame FR3362G

Time, mins	C'	D'	F'	L'	K'	G'
0	0	0	0	0	0	0
15	-2	1	-1	0	-1	-2
30	-16	-13	-14	-2	-2	-15
45	-18	-16	-17	-2	-1	-18

Table 28: Deflection of door leaf FR3362G

Time, mins	C	D	F	L	K	G
0	0	0	0	0	0	0
15	-1	-4	-5	-2	0	-3
30	-14	-18	-25	-4	0	-21
45	-17	-21	-32	-2	0	-26

Table 29: Relative deflection between the door leaf and frame

	C-C'	D-D'	F-F'	L-L'	K-K'	G-G'
0	0	0	0	0	0	0
15	1	-5	-4	-2	1	-1
30	2	-5	-11	-2	2	-6
45	1	-5	-15	0	1	-8

In Table 29 a negative relative deflection represents an opening up of a gap between the leaf and the frame.

10.7.5 Summary

The fire resistance in minutes achieved by the steel-framed wall as follows:

Structural adequacy	58 NF
Integrity	35
Insulation	54

The fire resistance in minutes achieved by the timber door was as follows:

Structural adequacy	58 NF
Integrity	50
Insulation	50 NF

10.7.6 Graphs – insulation and onset of char

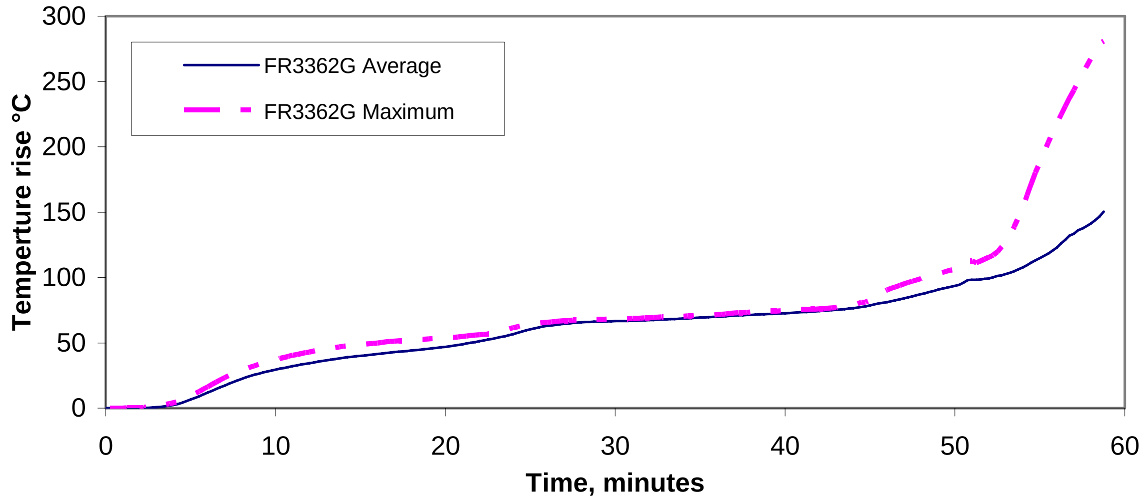

Figure 64: FR3362G insulation – wall

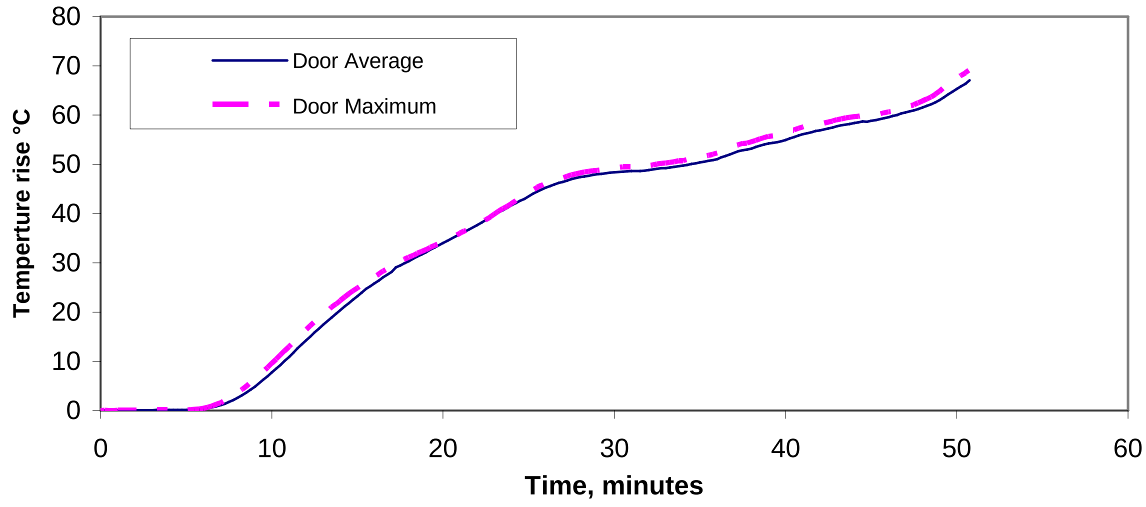

Figure 65: FR3362G insulation – door

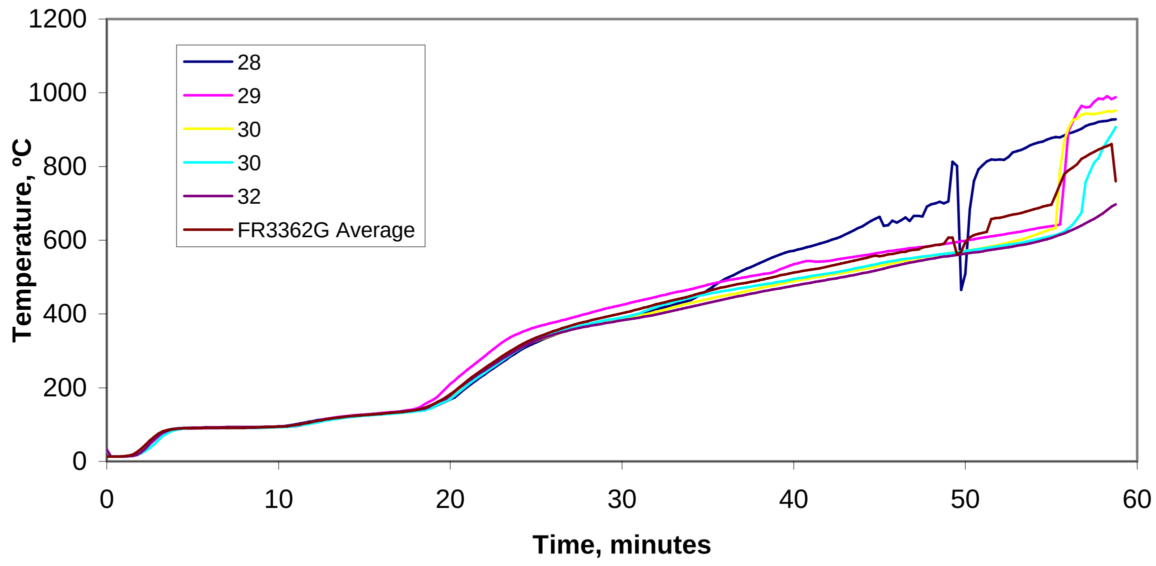

Figure 66: FR3362G onset of char

10.7.7 Photos during and after

Figure 67: FR3362G at start of test

Figure 68: FR3362G at end of test