Post Earthquake Fire in Tall Buildings and the New Zealand Building Code

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POST EARTHQUAKE FIRE IN TALL BUILDINGS AND THE NEW ZEALAND BUILDING CODE

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Abstract

This report examines the factors involved in determining the fire safety in tall buildings following an earthquake, and assesses the risk to occupants in such an event for a building designed to the Acceptable Solutions of the New Zealand Building Code.

The development of performance based design requirements for fire is reviewed, with particular reference to the New Zealand Building Code. The usual philosophy of such building codes is that they should consider all potential events that could lead to an unsatisfactory level of risk. The Acceptable Solutions of the New Zealand Code provide non-mandatory prescriptive design options for compliance. The section on fire safety does not specifically consider the impact of post- earthquake fire in the determining fire safety provisions. Of particular concern is the high probability of failure of active and passive fire safety systems observed in earthquake events throughout the world.

The Acceptable Solution is also widely used as a base document for setting the safety level for alternative designs. Unfortunately it contains many provisions that lack the consistency, transparency and technical validation to give practitioners confidence that its use will guarantee satisfactory performance.

In this report, a case study building designed to the Acceptable Solution is assessed for life safety following an earthquake, and the probability of loss of life in event of a fire is found to be significant. Failures of the sprinkler system and the passive protection to the stairs are identified as the principal contributors to the unsatisfactory performance, and recommendations are made for improving their reliability.

Recommendations are made to improve the post-earthquake reliability of fire safety systems and to amend the New Zealand Building Code Acceptable Solution to include the consideration of earthquake vulnerability of systems and utilities. Recommendations are also made to strengthen the technical basis of the Acceptable Solution.

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Table of Contents

List of Figures.

List of Tables.

1. Introduction.

1.1 Objective

The objective of this report is to identify key factors affecting the fire safety of tall buildings after an earthquake, with particular reference to the requirements of the New Zealand Building Code.

1.2 Background

Major earthquakes in urban areas have often been followed by significant conflagrations that have been difficult to control and have resulted in extensive damage to property. Major contributing factors have been identified as accidental ignition due to earthquake shaking, external fire spread through vegetation and inadequate building separation, earthquake damage to building's fire safety systems, loss of water supplies for fire suppression, and the lack of intervention by fire fighters due inadequate resources and obstructed access to the site of the fires.

Similarly, occupants within buildings may be subject to increased risk of loss of life due to potential damage or failure of the building's active and passive fire safety features, possible obstruction of exitways due to damage to the building's fixtures and fittings, and reduced likelihood of external intervention. Tall buildings can be considered as especially vulnerable due to increased escape path lengths, limited escape options, high occupancy loads, a high level of reliance on active fire control systems and communication systems, and often a dependency on external intervention to facilitate fire suppression and/or escape of occupants. Of particular concern is the uncontrolled fire growth that can occur when sprinkler systems become inoperative due to system damage or lack of water.

Trade-off provisions allowing reductions in passive fire systems where sprinklers are installed have been increasingly incorporated in prescriptive codes since the 1970s. There is little doubt that sprinklers are the most effective form of fire protection available. However there is a danger that an unacceptable reliance may be placed on these seismically vulnerable systems, which could leave the building occupants with little protection from fire after a significant earthquake.

Performance based building codes give designers the flexibility to use increasingly sophisticated active fire safety systems, and to properly assess the risk associated with reductions in the passive fire separations. The probability of occurrence of fire after earthquake will be low, but for a tall building in particular the consequence may be disastrous. It is obvious therefore that fire after earthquake is a design scenario that should be properly addressed in any performance based design in locations where significant earthquakes can occur.

1.3 Method

The project consists of a literature review, a review of current design practice and a risk assessment.

The literature review covers previous work on post earthquake fire design. It also considers summarised case studies of previous earthquake events, which are used to identify the vulnerability of active and passive fire safety systems, the probability of ignition and fire growth, and the reliability of external intervention.

A review is given of current New Zealand Building Code provisions for fire, including a summary of the requirements of the prescriptive Acceptable Solution for active and passive systems required for tall buildings.

A risk assessment is carried out on a typical office building designed to the Acceptable Solution to the New Zealand Building Code. Although the New Zealand Building Code is a performance document, the Acceptable Solution is a non-mandatory, prescriptive means of meeting the code performance requirements, and includes significant trade-off reductions in passive fire separations due to active systems installed in the building. The risk assessment endeavours to measure the effect of different levels of earthquake damage on the available escape times from the building.

1.4 Outputs

The outputs from the project consist of recommendations on building code provisions for the design of tall buildings to ensure an acceptable level of risk from a post-earthquake fire. Areas where further research is needed are also identified.

1.5 Sprinkler reliability

Some commentators have assessed the reliability of sprinkler systems in normal service as less than 90%, although New Zealand statistics are generally much better than this. The system reliability is likely to be much reduced after an earthquake. When trade-offs have been used to reduce the rating of the passive fire separations, the level of performance of these elements will be critical to maintain life safety. The conclusions of this report will be of assistance in assessing the implications of sprinkler reliability.

1.6 Other extreme events

While this report is limited to fire following an earthquake, it is suggested that many of the underlying principles and findings may be relevant to other low probability extreme events. Recent high profile disasters have highlighted the possibility of an increasing occurrence of malicious intervention, resulting in fire events well outside the normal design fire scenarios. Examples would be the vulnerability of active fire systems to sabotage and vandalism, and the possibility of extraordinary levels of fire load due to terrorism or the use of explosives or accelerants. Clearly the dependence on a single means of protection designed for a “typical “ fire event may no longer be appropriate considering the potentially extreme consequences of such events.

1.7 Outline of report.

The remainder of this report comprises the following sections.

2. Review of non-earthquake fire design issues for tall buildings.
3. Review of the effect of earthquake on building fire safety
4. Literature review of fire after earthquake

5. Discussion on performance codes for general (non-earthquake related) fire design
6. Review of New Zealand regulatory requirements, with emphasis on fire and earthquake.
7. A review of the prescriptive New Zealand Acceptable Solution for fire design.
8. Assessment of the reliability of critical fire safety systems, in both normal and post-earthquake situations.
9. A risk assessment of post-earthquake fire on a tall office building designed to the Acceptable Solutions.
10 Conclusion of the report
11 Recommendations.

2. Fire safety in tall buildings

2.1 Introduction.

The level of fire safety in a building is the result of a complex interaction of many factors including the ignition, fire growth, spread of smoke and fire, the active and passive fire protection features in the building, the behaviour of the building occupants, and the response of the fire service. The level of safety needs to be addressed for a particular use, which will determine the fire load potential of the building contents and the number, ages and physical and mental ability of the building occupants.

Some types of building may, by nature of their location, construction, layout or use, present special considerations not found in more conventional buildings. Tall buildings are one such category.

Tall buildings are defined, for the purpose of this report, as buildings with an escape height of 25 metres or more. This is the height at which sprinkler protection becomes mandatory for all uses under the New Zealand Building Code Acceptable Solution C/AS1 (BIA, 2000). This is close to the 75 feet (22.5 metres) height that defines a High-Rise Building in NFPA 101®, Life Safety Code® (NFPA 2000).

2.2 Fire development and growth.

Fire development and growth is primarily a function of the fire load and characteristics of the building contents, and the construction, dimensions and ventilation of the spaces within the building. Fire and smoke spread beyond the room of fire origin is determined by the developed size of the fire, the fire resistance and integrity of the fire separations between rooms, and the presence of any suppression systems.

2.3 Performance requirements

Performance requirements for fire safety in the New Zealand Building Code are to provide adequate means of escape, to facilitate fire-fighting operations, and to protect adjacent buildings from the effects of fire. Generally the prevention of fire spread within a building is only required between household (i.e. sleeping) units and to protect means of escape.

2.4 Fire design philosophy.

The general features of a fire design philosophy should include measures to:

- control ignition
- control fire growth
- control internal fire and smoke spread to allow time for escape
- control external fire spread for duration of the fire
- provide adequate means of escape
- facilitate fire service operations
- prevent structural collapse for complete burnout of the fire.

These will generally be achieved by a combination of systems as appropriate to each building, which may include:

Management systems to;

- limit fire load and accidental ignition
- ensure that all fire safety features are properly managed and maintained
- provide for and facilitate safe and speedy evacuation

Passive fire protection systems, including internal compartmentation, external wall construction and structural fire protection to;

- limit fire and smoke spread within the building,
- limit fire spread beyond the building
- maintain structural integrity.
- provide adequate, appropriately located, protected means of escape.
- facilitate fire fighting operations.

Active fire protection systems to:

- control fire growth and spread (sprinklers).
- control smoke spread (smoke control, pressurisation).
- give adequate warning of fire .

Fire service intervention to:

- Assist escape.
- Protect other property.

Table 2.1 shows how a fire may develop progressively if not controlled. It indicates appropriate systems that, if installed, may prevent or increase the time required for the fire to progress to the next stage. The table is adapted for a similar table in Sekizawa et al. (2000).

2.5 Tall buildings.

Statistics suggest that tall buildings have a low risk of fire per square metre of floor area (Hall, 1997). However the small numbers of tall building fires that do occur often have significant social impact on the local economy and emergency services.

There are a number of special features that make tall buildings worthy of special consideration. Caldwell (1997) identified the following particular risks.

- Restrictions on effective fire service intervention. This includes inability of fire fighters to effectively carry out fire fighting or rescue operations from outside the building, and delays reaching the seat of the fire from inside the building. This latter is due to the inaccessibility of the upper floors and the logistics of deploying sufficient personnel and equipment to carry out an adequate rescue or fire fighting operation.
- Delays in escape due to limited number of escape routes, queuing at stairways, and extended escape routes lengths from upper floors.
- The effect of natural phenomena on fire and smoke movement. This includes wind forces as well as the potentially significant "stack" effect, which can cause large air movements due to convective currents.

Phase	Description	Transition threshold to next phase	Means of detection	Action to prevent transition	Life safety
Incipient	Heating of fuel	Ignition	Smell, Smoke detectors	Extinguishers, Hose reel.	
Initial growth	Flaming combustion	Not controlled by occupants	Smoke detectors	Extinguishers, Hose reel.	
Growth A (Plume)	Fire threatens occupants of fire room. Smoke spread to other rooms	Tenability of fire room. Tenability of other rooms.	Heat detectors Smoke detectors	Sprinklers. Smoke control systems, barriers	Evacuate fire room. Evacuate building.
Growth B (Radiation Feedback)	Rapid temperature increase due to radiation feedback	Flashover		Fire Brigade action.	
Fully developed	Full fire room involvement	FRR of fire room barriers		Fire Brigade action.	
Fire spread to adjacent rooms		FRR failure of barriers		Fire Brigade action.	
Fire spread to other floors, stairs.		FRR failure of external walls in integrity or insulation		Fire Brigade action.	
Fire spread to adjacent buildings	External flames or critical radiation levels	FRR failure of structure		Fire Brigade action.	
Structural failure	Collapse				

Table 2.1: Fire development phases.

- Possible high concentration of fuel and occupant loads compared with low-rise buildings, which leads to potentially larger fires and more persons at risk.
- Mixed tenancies and uses with different configurations, which may require complex, interactive fire safety systems
- Sophisticated building services often serving many floors. These may require shared service shafts and ducting that require careful treatment to protect the services from fire damage and to prevent fire or smoke migrating between firecells.

These issues require different and additional design considerations, which may include complex integrated systems, to achieve an equivalent level of fire safety to that of low-rise buildings. However the incorporation of sophisticated fire safety features does not guarantee safety. Zicherman (1992) reported on a number of specific concerns identified from case studies. These include:

- Earthquake damage to sprinkler systems in the Loma Prieta Earthquake caused significant water damage. If fire had occurred following the earthquake, the damaged sprinkler system and the reduced passive fire protection due to trade-offs may have caused loss of the building.
- Compartmentation is important to control fire spread. Tall buildings are at much greater risk from post-flashover fires than low-rise buildings. Isolation of the area of fire origin significantly improves the chances of safe evacuation and successful fire service intervention.
- Exterior façade design must consider the potential for vertical fire spread between floors as occurred in the First Interstate Bank fire in Los Angeles (Morris, 1990).
- Smoke spread, exacerbated by the stack effect, may occur through inadequately sealed service ducts. In the Las Vegas MGM fire (Best and Demers, 1982) this caused fatalities due to smoke inhalation many floors above the floor of fire origin.
- Management systems also become relatively more important, as human response to fire cues is more critical in tall buildings. The margins of safety are generally less, and occupants are therefore at greater risk if evacuation

procedures are inadequate. Good emergency planning is critical in ensuring effective, rapid escape.

One aspect of tall building fire safety that is undergoing further development in the US is the use of elevators for evacuation. Jennings (2000) reports that current elevator recall systems continue to fail, putting fire fighters at risk. This has led to a shift from pressurisation of stairwells to pressurisation of elevator shafts and lobbies, and refuge areas. This has potential to allow full use of elevators during evacuation, including provision for persons with disabilities. However appropriate management systems, communication and training will continue to be a crucial element for successful implementation of elevator evacuation.

2.6 System reliability and redundancy.

The principal aim of the fire safety systems in tall buildings must be to control fire and smoke spread to allow sufficient time for safe evacuation of the building and to facilitate fire fighting operations. It is generally accepted that the installation of sprinklers coupled with adequate compartmentation is the most effective way to limit fire growth and minimise property damage. Prescriptive code options in New Zealand and the USA require sprinklers for tall buildings. However the introduction of performance codes allows designers to select other options provided the performance requirements can be met. If sprinklers are not installed, a higher level of performance is demanded from the passive fire separations to prevent the fully developed fire spreading to other floors and to protect egress routes.

The presence of sprinklers does not guarantee fire safety in all situations. All systems have a finite probability of failure. In addition many sophisticated safety systems have an effectiveness and reliability that is difficult to assess in a real fire situation. The design of pressurisation systems for instance is very dependent on design assumptions and the integrity of the associated passive enclosures. And passive fire separations are known to be vulnerable to often unauthorised service penetrations, and ineffective door closers. And all systems, active and passive, will only perform to expectation if they are regularly inspected and maintained.

It is also seen as appropriate to make some allowance for unforseen events. This could include fires in unexpected locations. For instance Hall (1997) noted that some 10.6% of reported fire in tall apartment buildings in the US between 1985 and 1995 occurred in egress routes. Other potentially disastrous scenarios could include unexpectedly large fire loads, arson, and system damage due to vandalism or earthquake.

In view of the complexity in assessing the worst likely effect of fire in a tall building, and the high risk of loss of life if the systems fail, it is recommended that design systems should incorporate a degree of conservatism. This should be by way of redundancy, diversity and independence of the fire safety systems, as discussed further in Section 5.6 of this report. Most current prescriptive codes for tall buildings will include a wide range of active and passive systems. The New Zealand Code Acceptable Solutions are typical in this respect, with the range of required systems increasing with the building height (Refer Section 7.4 of this report). This is consistent with the philosophy noted above of providing a high level of redundancy and independence of protection systems to allow for finite system reliability, design uncertainties and unforseen events.

3. Effect of earthquake on building fire safety.

3.1 Introduction.

History has demonstrated that large earthquakes can have a devastating effect on the built environment. As well as damage to buildings and their contents, effects may include uncontrolled urban fire spread, and disruption to communications, transport and services such as water supply and electric power. This can result in a number of potential impacts on building fire safety. These effects are examined in terms of the critical factors that determine the extent of damage, current building code requirements, and observations and statistical analysis based on recent earthquakes.

3.2 Potential effects on building fire safety

There are a number of potential effects of earthquake on tall buildings that need to be considered to fully address the earthquakes impact of fire safety. These include;

- Accidental ignition, possibly in more than one location, due to damage to gas or electrical services or appliances.
- Fire and smoke spread due to damaged passive protection and building services, non-operation of suppression and control systems, and lack of water supply for fire fighting.
- Delayed evacuation due to damage and obstruction in escape routes, loss of lighting, and inoperative alarm systems
- Lack of fire service intervention to control fire spread and facilitate escape.

3.3 Principal variables determining damage

In any particular case, the principal variables that determine the extent of damage to the fire safety systems are as follows;

- Earthquake intensity. This is a measure of the ground shaking at the site. The measurement scale used in New Zealand is the Modified Mercalli (MM)

Intensity Scale, which is a subjective assessment of the likely effects on people, fittings, structures and the environment. The currently used version of the scale was adopted in 1992 (Study Group of NZNSEE, 1992), and a suggested revised version to include modern ductile buildings (Dowrick, 1996) is reproduced in Appendix A of this report. Earthquake damage to modern buildings may be expected to occur from intensity MM6.

- Subsoil Properties. The dynamic properties of the subsoil can have a significant influence on the response of a building to an earthquake. For instance stiff buildings on strong subsoils and flexible buildings on weak subsoils may both exhibit a greater response than for an intermediate soil type. In addition some soils have potential for liquefaction (loss of soil strength due to pore water pressure), which can result in foundation failure.
- Ground conditions will also have an effect on the seismic reliability of buried services (water, gas, oil etc.), which may fail due to ground dislocation in a significant event.
- Building Type. The configuration and structural characteristics of a building will have a significant effect on it dynamic properties. Stiff shear wall type buildings and more flexible frame buildings will respond very differently to any particular earthquake. Flexible buildings will be subject to greater deflections, and non-structural elements such as wall and glazing will be at risk unless they are separated from the structure. Stiff buildings will be subject to greater accelerations and may result in larger loads on equipment, fixtures and fittings and their fixings.
- Building Age. The understanding of earthquakes and building response has developed significantly over the last few decades. Building codes requirements have shown an important change of emphasis from designing for a minimal level of lateral load strength to detailing to achieve robust energy absorbing elements for ductile post-elastic deformations. In New Zealand, requirements to consider earthquakes in design first appeared in 1935, and it was not until 1976 that proper consideration of ductility was incorporated. It is therefore likely that many pre-1976 buildings will perform well below the level expected from current design methods.

3.4 Structural damage

For modern buildings, significant structural damage should occur only at high earthquake intensity levels. Dowrick (1996) suggests that some buildings may exhibit structural damage from MM9. Most modern buildings should not collapse in a MM12 event, although heavy damage would generally be expected. However lesser levels of structural damage may have implications on fire safety. Significant cracking or movement may allow smoke penetration through walls and slabs, and dislodge fire resistant coatings from structural elements. Damage to stairs may hinder evacuation from the building.

3.5 Non- structural damage

Brunsdon and Clark (2000) suggest that current New Zealand design requirements for ductile frame structures offer only limited protection to building parts and contents, even in a moderate earthquake. Fragile elements and unsecured contents may exhibit damage as low as intensity MM7.

Walls, partitions and external glazing are vulnerable to damage in a moderate earthquake due to the loads applied as the building deflects. Fire separations may suffer significant cracking and loose their fire integrity. The loss of exterior glazing will change the ventilation factors for a fire compartment and may allow development of larger fires than anticipated in the design.

Fire stopping in seismic joints and services penetrations may be dislodged and become ineffective.

Services ducts may be broken or dislocated allowing passage of smoke.

Dislocation of fixtures and fittings such as ceiling systems and shelving are well documented, and can cause injury and delay evacuation. Toppling and sudden mobility of furniture and equipment is also a common hazard.

3.6 Active systems damage.

Equipment without back-up power will be vulnerable to failure of the urban supply.

Detectors, circuits and panels on alarm and control systems may become damaged or dislodged by impact if not adequately secured.

Sprinkler systems are subject to damage from inertia loads on the suspended pipework, movement across seismic joints, and impact with suspended ceilings. Reserve water supply tanks are vulnerable if not adequately secured.

Smoke detectors are vulnerable to dust dislodged during earthquake motion and may become unreliable.

Mechanical systems such as smoke control and pressurisation may become ineffective due to dislocation of ductwork and equipment or loss of electric power.

3.7 Lifelines system damage.

In-ground reticulated services may be damaged by ground movement or dislocation, or by the failure of the supply system pumps, reservoirs etc.

Electric power supplies may fail due to damage to cabling, reticulation system or equipment. Network communication systems may face similar problems.

Transport systems may be significantly disrupted due to ground movement, resulting in damage to roading, airport runways, embankments and reclaimed land and rail tracks, structural failure to bridges, terminals and control buildings, and loss of communication systems.

These factors will have a major effect on the ability of rescue, fire fighting and medical personnel to gain access and operate effectively in areas with major damage.

3.8 Earthquake loss prediction.

Prediction of damage caused by earthquakes has, until recently, concentrated on macro-scale considerations for use in insurance loss exposure and for planning mitigation of disruption to lifelines and utilities. The assessments are typically based on data from observed earthquakes, and any assessment of building systems is usually generic in nature. The data is analysed to identify different categories of building to enable meaningful loss prediction for specific communities. Examples of such projects include Rojahn and Sharpe (1985) and Thiel (1996) in the US, and Shephard et al. (2002) in New Zealand.

While these investigations recognised the threat of fire in the post-earthquake environment, they generally considered only those earthquake effects that could contribute to potential urban conflagration, principally loss of water supply and unavailability of fire service intervention. Little attempt was made to predict damage to specific building elements and systems, and the impact of such damage on life safety.

Following the 1994 Northridge earthquake in the US, the need for a more detailed examination of the performance of non-structural components was recognised, and a seminar was held to identify the principal issues and initiate further research and more detailed reporting procedures for reconnaissance teams. (Rojahn, 1998).

The increasing availability of information on performance of individual elements has encouraged moves in the US and Japan to develop damage assessment methods for individual buildings based on the vulnerability of the particular elements and systems in the building. This is consistent with the move to performance evaluation for building design, allowing due consideration to be given to the individual characteristics of each building rather than being limited to global assessment categories.

Porter and Scawthorn (1998) considered the post-earthquake reliability of critical equipment systems in the San Francisco Bay Area. Their paper included a comparative analysis of risk of loss of life and property damage in a typical high-rise building with unbraced and retrofitted sprinkler systems. A cost/benefit analysis of the retrofit was included.

Porter et al. (2001) have also developed a wider performance evaluation model that considers both active and passive systems. This incorporates the results of considerable testing to predict the fragility of wood framed partitions and glazing to imposed deformations. The method does not directly consider post-earthquake fire safety, but the vulnerability of sprinkler systems, switch gear and generators are all included for individual consideration. The method provides a probabilistic determination of direct repair costs and loss-of-use costs as well as giving quantified damage level estimates for comparison with performance based design objectives.

Sekizawa et al. (2000) are developing a similar method that extends to prediction of post-earthquake fire spread in the building. The procedure is principally based on analysis of observed damage, ignition and fire spread fire in recent earthquakes in Japan. It includes a simplified model of structural response to predict the earthquake actions on individual building element.

3.9 Damage levels.

The general extent of damage in more recent earthquakes has been well documented, and an extensive summary prepared by Botting (1998) details the fire safety implications of these reports. They generally show a wide variation in the extent of damage observed for any particular earthquake event. In the absence of information about the seismic characteristics of the individual building or the seismic design of the building elements it is difficult to use the data to make any useful prediction of system damage for specific buildings.

Case studies of past earthquakes have however been a catalyst for more extensive testing and modelling of non-structural building elements to enable better damage prediction, and proper performance assessment to meet building code requirements. This has included work by Porter et al. (2001) on drywall construction, glazing and ceilings, and Beattie (2000 and 2001) and Shelton et al. (2002) on building parts and services.

A particular concern with the performance of non-structural elements is coordination of the design and detailing to achieve the required performance. Often the systems are designed and installed by contractors who have neither the ability nor the contractual responsibility to review the seismic performance of the systems they are installing. Beattie (2000) highlighted this concern following a number of audits of building services. Feeney (2001) raises the same concerns in relation to passive fire protection to structural elements.

3.10 Review of principal fire safety elements

This review provides general comment on the relative vulnerability of specific elements with particular reference to buildings designed to current earthquake codes.

a. Sprinkler systems.
   Sprinkler systems have proved to be vulnerable in many past earthquakes. Principal damage scenarios are lack of restraint to the system pipework and damage to heads due to impact with ceilings (Gates amd McGavin, 1998). Current codes should require a high level of earthquake security due to the life safety issues involved. However both Fleming (1998) and Beattie (2000 and 2001) found that current provisions were inadequate.

b. Water supply.
   Water supply is again a crucial element in post- earthquake fire safety, both for sprinkler protection and to allow intervention by building occupants and fire fighters. Loss of supply has been a significant element in the post-fire conflagrations in a number of earthquakes. Todd et al. (1994) recorded failure of the water supply due to widespread damage in the 1994 Northridge earthquake. However the risk of fire development in an individual building can be significantly reduced if a robust reserve water supply is provided to supplement the urban reticulation. (Harmsworth, 2001).

The vulnerability of the reticulated water supply is outside the control of the building owner, and is dictated largely by the ground conditions and the age and condition of the system. It is also evident that a temporary failure in supply or even a moderate reduction in mains pressure can have critical implication for a tall building. In addition the supply is likely to be unreliable for a number of weeks as the mains are repaired and reactivated. (Brunsdon and Clark, 2000)

Where supply tanks and pumping equipment are provided within buildings it is important that these are adequately restrained. Pipework must also be designed and detailed for earthquake actions, and provision must be made to allow for anticipated movement at seismic joints.

c. Non- structural fire separations

Damage to non-structural partitions is a function of the racking loads imposed by the deflections of the building. Damage is therefore more likely in flexible framed buildings, unless the partitions are separated from the structure to allow differential movement, and may occur in moderate earthquakes situations (Brunsdon and Clark, 2000). Smoke transmission can be expected once cracking of the lining material occurs, and fire spread becomes possible when the linings separate from the framing.

Glazing in partitions is vulnerable values unless separations are provided between the glass and the surrounding structure.

The fire integrity of partitions may also be compromised by impact of dislodged fittings and equipment.

Any separation or movement joints that are required to maintain fire integrity must be detailed to allow the full anticipated seismic movement. This movement can be considerable, particularly for seismic joints between tall buildings (James and Buchanan, 2000).

d. Automatic alarm systems.

Automatic alarm systems have be found to be vulnerable in an earthquake, in particular from secondary effect such as activation due to dust, short circuits following ceiling collapse, and water damage from failed pipework or sprinkler systems. Control equipment and cabling may be damaged if not adequately restrained, or by impact from falling fittings or equipment.

Botting and Buchanan (2000) found little reported damage to the alarm or detection systems in the buildings assessed in their report. However even undamaged systems were often rendered ineffective in communicating with the fire service due to significant problems with radio and telephone links.

a. Building services.

Papers by Beattie (2000and 2001) and Shelton et al.(2002) have highlighted current concerns about the adequacy of design and detailing guidance for building services. In particular the prescriptive code requirements for restraint of major items of plant including generators, pumps, boilers, heat exchangers do not appear to match the probable earthquake response. Similarly pipework and ducting systems are often not adequately restrained, and are prone to damage due to differential movement, vibration, and impact at wall, floor and ceiling penetrations.

The principal concerns are:

- The potential for smoke and/or fire spread through damaged ducting, services shafts and penetrations. In addition dampers may fail to operate due to damage or detector malfunction.
- The failure of mechanical services such as smoke control and safe path pressurisation. This may be due to power failure, detector activation malfunction or system damage.

3.11 Post-earthquake ignition potential.

Post earthquake ignition sources identified from past earthquakes are reviewed by Botting(1998). Scawthorn (1992) discusses ignition sources and predicts post earthquake ignition rates for typical high rise buildings for different earthquake intensities.

Immediately following the earthquake event, the principal ignition sources are overturning of electrical appliances, short-circuiting of electrical equipment, gas leakage from damaged equipment and pipework and leakage of flammable fluids (including fuels for emergency generators etc.). Spillage of chemicals may also be a potential ignition source in buildings where they are utilised or stored.

Another major concern is the high potential for ignition as electricity and gas supplies are restored some time after the earthquake. Leaking gas and damaged electrical appliances were identified as initiating a greater than normal incidence of fires in the days following the Kobe and Northridge earthquakes.

Arson, vandalism, and use of candles and makeshift cooking appliances by unauthorised occupants have also been identified as potential ignition sources in the days following the earthquake (Williamson, 1999 and Scawthorn et al., 1998).

3.12 Post-earthquake escape from buildings.

Escape times from a post-earthquake fire may be adversely affected in a number of ways by earthquake damage, depending on the intensity of the event and the vulnerability of systems in the particular building. These effects may include;

- Failure of fire detection systems to alert occupants
- Loss of lighting.
- Loss of visibility due to smoke invasion.
- Obstruction of escape routes by falling ceilings, displaced fittings, damaged doors.
- Structural damage to stairs.

In addition the escape routes may be threatened by smoke and fire spread earlier than anticipated in design due to the failure of sprinkler systems, smoke control systems and passive protection. The end result may be a considerable reduction in the safety margin for escape due to a longer required time to evacuate the building and a shorter time before conditions become untenable.

The use of elevators for evacuation in tall buildings has much potential, and is in attracting increasing attention particularly in the US. (Jennings, 2000). However the safe and effective use of elevators and the necessary associated smoke control systems is dependent on a continuing, robust power supply and an operational detector and communication system.

Occupant behaviour is extremely unpredictable in an earthquake event, with the magnitude of the earthquake being the principal determining factor. Murakani and Durkin (1988) have reported on a number of studies in Japan and the US, and find that behaviour in low intensity events are similar to fire events, with typical activities including assisting and protecting others and waiting for instructions. However in high intensity events any immediate activity will be impossible, and panic may occur.

In Japan there is a high awareness of the potential for post-earthquake fire, due to previous events and extensive training. This is not the case in New Zealand, where the failure of fire alarm and communication systems may delay occupant awareness of a developing fire. Building occupants are generally advised not to attempt to leave the building during the earthquake due to the hazards from falling building elements and glass. However it is considered likely the occupants will endeavour to evacuate the building as soon as possible, thereby reducing the risk exposure to a post-earthquake fire.

3.13 Intervention.

Significant earthquakes in urban areas can result is a large number of ignitions. Where the local fire services have inadequate resources to control the fires in the early stages there is a risk of a major conflagration. (Sekizawa, 1997).

In addition intervention can be significantly delayed or rendered ineffective by:

- Damage to emergency facilities, plant and operations centres
- Loss of communication with emergency services.
- Limited vehicle access due to damage and obstruction of transport routes.
- Failure of water supplies.

It is therefore inappropriate to assume any external assistance from trained personnel to assist with evacuation or fire fighting is any particular building. This will be particularly important where building evacuation planning includes “defend in place” options or the controlled use of elevators.

3.14 Conclusion

Current building code provisions do not appear to make adequate provision for the seismic design of life safety systems. In addition the individual systems are often designed by subcontractors without the technical ability to properly assess the required earthquake response of the system.

Sprinkler protection is without a doubt the most effective method of controlling fire in tall buildings. Unfortunately sprinkler systems have been shown to be vulnerable in past earthquakes, due to both system damage and water supply failure.

Smoke control and pressurisation are usually dependent on the external power supply. It is inappropriate to rely on their operation after a significant earthquake.

It is therefore important that adequate passive systems be provided. These must be designed to accommodate earthquake effects without damage and to provide a fire and smoke separation that survives for sufficient time to allow safe evacuation of the building.

4. Fire after earthquake : literature review

4.1 Introduction

Botting (1998) reviewed the available literature on over 40 major earthquakes and carried out a comprehensive analysis of the impact of post-earthquake fire on the buildings and the urban environment. The paper contains a detailed description of 15 selected events where significant fires occurred, and an extensive reference list. Botting and Buchanan (2000) contains a summary analysis of the findings including ignition sources, fire spread, damage to buildings, communication systems, fire protection systems and water supply, and impediment to fire service operations. Suggested mitigation measures are also included.

Although many countries have in the past experienced the disaster of a post-earthquake fire, it is only in recent times that the issue has received significant attention. Even after the large urban fires following the 1906 San Francisco and 1923 Tokyo earthquakes, Japan was the only country to immediately initiate research to address the problem. (Scawthorn, 1992).

The initial focus of attention on post-earthquake fire was on fire spread in high-density low-rise urban areas with little in-built fire resistance. This represented the major risk, to the predominant building stock at the time. However the literature and research on the topic has broadened and changed emphasis over time as a reflection of changes to the built environment and building performance philosophy. These include;

- Increased use of sprinkler protection.
- The increasing number of high rise buildings.
- The move to performance based building codes.

4.2 Urban fire spread

In 1986, Scawthorn (1986) reported that urban conflagration following earthquakes had caused the largest single losses due to earthquake in the United States and Japan. Urban fire spread was therefore one of the earliest topics addressed, with endeavours to find methodologies for estimating potential fire losses due to urban conflagrations. Moran (1958) identified the principal issues as;

- Importance of emergency planning
- Building design for fire protection
- Communications
- Post earthquake building inspections
- Cut-out valves to gas supplies
- Water supply vulnerability.

Methodologies for measuring urban fire spread were being introduced in Japan from the 1960s and in the United States from 1980. Initially these were based on analysis of observed events, but later studies have become broader and more sophisticated, and based more on the principles of fire engineering. Recent papers, including one by Thomas et al. (2002) demonstrate the continuing work in this field, principally for lifelines planning and loss estimation.

However the Wellington Lifelines Group (WLG, 2002) has noted that the models are very dependent on variable situational circumstances, such as wind speed and direction, and can only therefore give accurate fire spread predictions for specific limited scenarios.

The same report identified a general lack of integrated response procedures by the fire service and utility organizations, which could result in inappropriate and inefficient use of available resources in preventing urban fire spread.

4.3 Tall buildings

The largest property losses due to post- earthquake fire are likely to continue to be due to conflagration in low or medium- rise buildings predominantly of timber construction, in high-density urban areas (WLG, 2002). However post-earthquake fires in tall buildings have the potential for unacceptable loss of life if adequate time is not available for evacuation.

Scawthorn (1992) discussed specific issues related to tall buildings. These included;

- Potential for multiple ignitions, from electrical, gas, fuel or chemical sources.
- Fire spread due to damaged passive systems and glazing
- Fire spread between buildings due to uncontrolled fire growth and lack of fire service intervention.
- Damage to detection and suppression systems.

Botting and Buchanan (2000) highlighted the need for proper coordination between the fire and seismic design, to ensure that all active and passive systems, all potential ignition sources and all escape routes are designed to have adequate seismic performance and restraint.

4.4 Sprinkler system performance

Seismic bracing became a requirement for sprinkler installations following the 1933 Long Beach earthquake (Botting and Buchanan, 2000). Scawthorn et al (1988) reported that sprinkler bracing was generally effective, but only a small proportion of the building stock was sprinkler protected at that time. However in 1992, Scawthorn (1992) noted the vulnerability of tall buildings in the event of a sprinkler system failure, and highlighted the observed low reliability of urban water supplies.

Fleming (1998) reporting on the Northridge earthquake recorded the failure of some systems due to inadequate seismic bracing. He noted that the systems had been subject to earthquake accelerations far exceeding code requirements. Reporting on the same earthquake, Gates and McGavin (1998) observed that much damage to sprinkler systems occurred due to differential movement where the sprinkler heads penetrated the suspended ceilings. Consequential water damage was significant.

Although sprinkler installations have a high reliability, especially in Australia and New Zealand, (Marryatt, 1988), some commentators (Robertson (2001) and Botting and Buchanan (2000)) have expressed concerns at over-reliance on sprinkler systems, especially in association with trade-off reductions in passive protection. Barnes (1997) highlighted the futility of providing passive protection to compensate for a sprinkler system failure unless the protection had a sufficient fire resistance to contain the resulting uncontrolled fire.

Harmsworth (2001) discussed the vulnerability of municipal water supplies, and suggested that the provision of a small reserve water supply tank can significantly increase the reliability of the sprinkler system, without significant cost.

The Wellington Lifelines Group (WLG, 2001) noted the historic reduction in requirements for fire separation between buildings, based on improved detection and suppression systems and fire service response. This suggests that more recent buildings may be more vulnerable to post-earthquake fire spread following sprinkler system damage. However this may be offset by the anticipated lower earthquake damage levels in these buildings.

4.5 Performance codes.

The general international trend towards performance codes has initiated a more rigorous examination of the risk assessment aspects of post-earthquake fire. Traditional prescriptive codes generally reflected historic events, and were considered to provide an adequate margin of safety to perform to an acceptable level in a low probability event such as post earthquake fire. However the concept of performance based codes requires each potential event to be considered specifically. This can be either through a full probabilistic analysis, or at least through a prescriptive option that allows for the probability of adverse earthquake effects on the fire safety systems.

Robertson and Mehaffey (2000) proposed a two level design for sprinkler protected buildings. The first design level assumes the fire protection systems are fully operational. The second assumes failure or impairment of the fire safety systems and uses a design fire of reduced size (heat release rate) depending on the assessed system reliability and the required performance level of the building after the event (i.e. fully operational, operational, life safe). For life safety, the principal criterion is the reliability of the water supply. For property protection the principal considerations become building vulnerability (construction, environment, protection features) and fire service response. A minimum reduced design fire 0.25 is recommended to limit inappropriate reliance on vulnerable systems.

Sekizawa et al. (2000) have described a probabilistic method currently under development to assess post-earthquake fire spread within a building. The method is based on observed damage in a number of locations, principally from the 1995 Kobe earthquake. The input to the analysis is the building geometry, construction type, fire safety systems, fire load density and growth rate, and earthquake peak ground acceleration. The model computes the probability of ignition, active system failure, passive system failure, and intervention to calculate the probability of fire spread. Output is in the form of an expected fire spread area. Life safety issues are not specifically considered.

Feeney (2001) carried out a risk analysis on sprinkler effectiveness in multi-level steel framed buildings. The principal aim of the report was to consider the probability of structural failure. In its consideration of post-earthquake fire, the report utilised available statistical data on probability of earthquake occurrence, fire ignition, sprinkler operation, sprinkler control of the fire, and integrity of passive fire protection to determine the probability of an “adverse effect” on the structure. The report found that the probability of structural failure due to fire is less than that for other required design loadings. However as consideration of life safety is not specifically addressed, the reports conclusions are not directly relevant to this report.. The probability of loss of life is likely to be much greater than the probability of structural collapse, and the number of persons potentially at risk in a tall building will give significant weighting to the consequence of the event.

4.6 Risk scenarios.

The literature identifies a number of possible post- earthquake scenarios that present different critical elements in the assessment of risk of loss of life.

Scawthorn (1992) focuses on the problem simultaneous ignitions during the earthquake. Due to the likely degradation of fire systems these may lead to uncontrolled fire that may threaten persons endeavouring to leave the building. In addition evacuation may be impeded by obstructions and damage caused by the earthquake.

Robertson and Mehaffey (2000) conclude that most risk is caused by persons returning to damaged buildings with damaged fire safety systems, and note the potential for ignition when gas or electrical systems are restored, or due to earthquake after-shocks.

Williamson (1999) highlights the need for fire professionals to be included in post-earthquake inspection teams. Buildings that are assessed as structurally adequate for reoccupation may still have severely impaired fire safety systems. He poses the scenario of homeless persons re-entering a damaged building with inadequate water supply, and the risk of resultant out-of–control fires, including potential fire spread through damaged external walls to adjacent buildings.

Scawthorn et al. (1998) discusses the problem of arson that often follows earthquake. Unauthorised entry and occupation to buildings by vagrants significantly increases the likelihood of ignition. Even with adequate water supplies, vacant and damaged buildings make fire fighting dangerous and difficult.

5. Performance codes for fire design

5.1 General

Performance based fire design is currently being adopted by many countries to replace the traditional prescriptive design methods. However there is no common perception on how performance requirements should be quantified, and the methodology adopted by different countries shows considerable diversity. A summary of the approaches adopted has recently been published by Beller et al.(2002).

Traditional codes contained specific requirements detailing how buildings were to be constructed. They were largely based on the subjective assessment of statistical data, and we often amended reactively in response to historic events without any analysis of the risk of reoccurrence of such events. There was an implied assumption that the margins of safety in the prescriptive solutions were adequate to provide for occasional extreme events and for occasional system reliability failures. However the margins were not quantified, and a wide variation was likely.

Performance based design requires the statement of clear performance objectives. Compliance with these objectives may then be checked using either a prescriptive solution set out in the code documents or by a fire engineering design. The use of fire engineering design allows the designer to determine a solution that is appropriate to a particular building, taking account of the specific features and requirements of the project.

It is evident that any fire engineering analysis requires adequate and authoritative data and design tools to enable an assessment of the building's performance for comparison with code requirements. As the adoption of performance based codes gathered pace, it soon became evident that there was little international agreement on the appropriate link between qualitative performance objectives and the quantitative analysis results. In addition there were insufficient comprehensive, robust, generally accepted techniques of modelling fire behaviour to have any confidence that performance could be properly measured. These restraints are discussed more fully in the following sections.

5.2 Quantifying performance regulations

There is no generally accepted policy on whether quantified values should be included in the building regulations. (Beller et al. 2002). Some countries regard the regulations as purely a statement of public policy, which should be independent of the changing knowledge and design methods. Other countries include quantitative requirements in the regulations, while some use reference to other quantitative documents to be used as verification methods.

The purpose of the performance design is to assess the building performance against the qualitative performance expectations in the code. At some point in the process the performance must be quantified to enable this assessment. Otherwise the fire engineer and the approving authority are required to reach their own subjective interpretation of the policy statement, which may or may not reflect society's expectations. This could not only lead to considerable difficulty in achieving approval of particular designs, but could also make either or both parties vulnerable to legal challenge and liability.

In addition it is known that the acceptable measure of risk is not constant for all situations, and is related to a number of social perceptions. Wolski (2001) identified the factors involved and discusses the importance of risk perception in determining acceptable levels of risk in various situations. For loss of life in fire the most important perceptions are the severity of the risk (number of persons involved) and the controllability (who controls the risk?). For instance, the loss of ten lives in a single event in a high-rise building is perceived to be less acceptable than the loss of ten lives in individual house fires.

5.3 Demonstrating compliance.

Most performance codes allow compliance to be established either by use of a prescriptive "acceptable solution" or using fire engineering design. Fire engineering design may be used to compare the proposed solution with alternative options, or to measure performance in absolute terms. However there is a clear need for prescriptive solutions to have a sound technical basis if they are to achieve satisfy performance requirements (Custer and Ashe, 2002). This is particularly important where the prescriptive solution is to be used as a guide to assess alternative solutions.

Most buildings are likely to designed using prescriptive codes for reasons that include familiarity, ease of implementation and design economy (Averill 1998). Performance design has significant design costs and may also require negotiation with the approving authority. However significant costs savings can be achieved in system installation on appropriate projects.

Often a simple comparative assessment using a limited number of design fire scenarios will be adequate for assessing the equivalence of different system components. However for major or innovative projects, there are potential advantages in measuring performance of complete system in absolute terms. This would require a full probabilistic risk analysis as described below.

5.4 Probabilistic risk analysis

The basis of any comprehensive fire engineered design must be a probabilistic risk analysis of potential fire scenarios to determine within an acceptable probability whether the performance objectives have been met.

The key factors in determining risk have been identified be Meacham (2001) as

- Fire Hazard Assessment
- Consequence Identification and Valuation
- Risk Characterisation
- Forming Judgement on the Likelihood of Occurrence
- Uncertainty, Variability and Indeterminacy

The risk assessment procedure therefore consists of the predicting the probability of occurrence of an appropriate number of fire scenarios and the effect of these on the building and its occupants, taking account of the reliability of the system and building elements, and the uncertainty of the assumptions used in the analysis.

5.5 Design scenarios

For the simple consideration of alternative fire system options, examination of a limited number of fire scenarios may be adequate to confirm comparative levels of performance

However for significant projects, and to get a meaningful overall measure of performance and the full benefit of an engineered solution, the risk analysis must include consideration of all fire event scenarios that could have a significant contribution to the total measured risk. Rare events with high consequences should be considered as well as frequent events with less potential for performance failure.

The design scenarios must allow for the reliability of systems as well as the uncertainties in the analysis and design assumptions. System failures do occur, and the output effects from real fires can exceed those from deign fires, and these factors must be incorporated in the analysis.

5.6 System redundancy.

While the probabilistic risk analysis enables the reliability of the total interacting fire safety system to be assessed, most authorities agree that complete reliance on a single system is unwise and inappropriate.

The principal concern for modern tall buildings must be the significant use of system trade offs. While there is little doubt that sprinklers are the most effective form of fire protection available, there is a danger that an unacceptable reliance on the sprinkler system could leave the building occupants with severely reduced passive protection in the event of a system failure. This is of particular relevance in post earthquake fire where sprinkler systems are known to be seismically vulnerable.

Simenko(2002) promotes the “defence in depth” philosophy to limit reliance on a single system, noting that a single component failure can compromise the whole system. He advocates designs that include redundancy, diversity and independence of systems, including defences against human error.

Bukowski (1997) notes that many significant fires involve a series of failures that contribute to the event, and it is important to consider worst-case scenarios to set extreme boundaries for performance. He reports that the U S Department of Energy requires that one part of the fire hazard analysis for their facilities is to assume both that the automatic systems fail and that the fire department does not respond. While this represents an extreme case, which may not be appropriate for many buildings, the general philosophy of considering a system failure will ensure that inappropriate reliance is not placed on a single fire protection measure.

The NFPA Life Safety Code (NFPA, 2000) sets out a number of design scenarios it recommends for a performance based design. These include consideration of the independent failure of each fire safety system. These scenarios may not be required only if the approving authority believes that “…. the level of reliability of the system <u>and</u> the design performance in the absence of the system are acceptable.”

5.7 State of the art.

The reluctance in many countries to including formal quantitative performance in the regulations is largely a reflection of the state of the art of fire engineering, both in terms of design methodology and performance assessment.

In the 1996 Australian Fire Engineering Guidelines (FCRCL,1996), probabilistic analysis methods were recommended as a useful method for comparison of the performance of various fire safety systems. However use of the method on an absolute basis was not recommended as a measure of estimated losses against acceptable community expectations. This concern reflected the significant technical and social issues still to be resolved.

Custer and Meacham (1997) identified specific constraining factors that include the variation in methodology available, the lack of data, the lack of credible analysis and design tools, and the relationship of the methodology to the regulatory performance requirements. While there were a number of useful design guides available (Buchanan 1995 and SFPE, 1995), there was no generally accepted framework for fire analysis and design.

By the year 2002, Johnson (2002) was able to comment on the good progress achieved in design, analysis and technology over the previous five years. However he identified design fires and human behaviour in egress as key elements for further research in the area of modelling input data. He also noted that significant challenges still remained in the policy, regulatory, approval and accreditation areas.

Harrington and Puchovsky (2002) expressed concerns that many of the current calculation methods and models are prone to inappropriate use without an understanding of the assumptions, purpose or limitations of the model, resulting in erroneous output.

Johnson (2002) also highlighted the need for comprehensive risk/cost models. Absolute safety cannot be achieved, so the code must ensure that the risk perceptions and values of society are reflected in the performance requirements.

5.8 Economic considerations

Averill (1998) examined the private and social cost implications. He suggested that most buildings would continue to be designed using prescriptive designs for a number of reasons including design familiarity and simplicity, economy of the approval process and ease of implementation. Performance based designs can have significant design costs and may require negotiation with the approving authority. Costs of construction, maintenance and system management are also likely to be lower where standard systems of known performance are utilised.

In many cases the engineered performance based designs will be based on a competitive quote, and both the design process and the engineered solution are likely to be a bottom line performance for the particular building. This could lead to different fire safety levels for otherwise similar buildings, and have significant implications on the future use and operation of the building. Averill identified potential external costs associated with this aspect of design, which could reduce the net saving to society. These include issues of loss and liability, and could lead to increased insurance, property transaction and regulatory costs if there is a perceived need to determine and verify the risk level for each individual building. The impact of these externalities may not become evident for some time.

5.9 Conclusion

In spite of recent progress in fire engineering, there are still significant challenges remaining to achieve universally accepted design methodologies and performance measures. However with many countries now moving to develop performance-based codes, it is anticipated that there will be continuing rapid development over the next few years to a point where an authoritative and generally accepted design methodology will be available.

It is likely that performance based design can achieve significant cost savings in many situations. However it is important that the implementation process takes account of the long term costs to society and future owners as well as the immediate cost of system installation.

6.0 New Zealand regulatory requirements.

6.1 The Building Act 1991

The Building Act 1991 (New Zealand Government, 1991) is the national regulatory document for building control in New Zealand. The Building Act establishes a hierarchy of documents to define and demonstrate compliance with the requirements of the Act. These are shown in Figure 6.1.

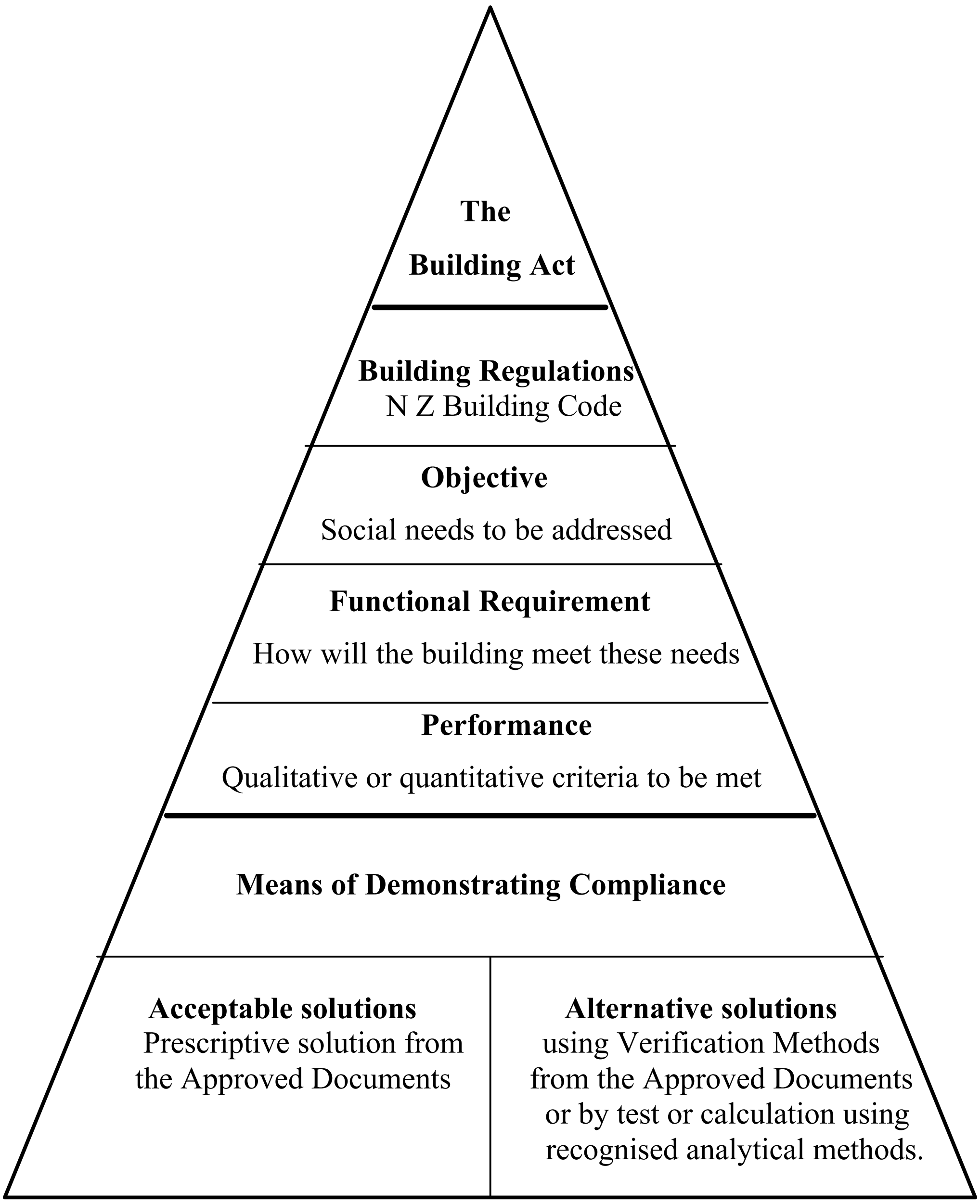


Figure 6.1 : The New Zealand Building Act : Hierarchy of documents

As shown in Figure 6.1, the hierarchy of documents is

- The Building Act 1991
- The Building Regulations 1992 (New Zealand Government, 1992)
- The New Zealand Building Code Handbook and Approved Documents (BIA, 1992 and 2000).

The Act establishes the Building Industry Authority (BIA) as the statutory authority responsible for administration of the Act. The BIA's duties include advising on amendments to the building code, and approving documents for establishing compliance.

Section 6 of the Act includes the requirement that, "in determining the extent to which matters……..shall be under control, due regard shall be had to the national costs and benefits of any control…..." This provision gives the BIA the discretion to consider economic matters in determining an acceptable appropriate performance level to meet code provisions. .

Section 49 of the Act authorises the BIA to prepare or approve, in whole or in part, and subject to any modifications it considers necessary, any document for use in establishing compliance with the building code. This allows the BIA to amend any documents which it considers to be not relevant to, or to exceed the performance requirements of the code.

Section 44 of the Act sets provisions for the continuing safe use of buildings by way of regular inspection, maintenance and reporting of building systems. This includes systems of particular relevance to this report such as sprinkler systems, warning devices, automatic fire doors, lifts, mechanical ventilation and pressurisation systems, and means of escape from fire.

6.2 The Building Regulations 1992.

The Building Regulations 1992 include the Building Code as Schedule 1. This is a performance-based document, which sets out a hierarchy of requirements for each element of building performance. These are:

- Objective
- Functional Requirement
- Performance

Appendices B and C of this report contain the New Zealand Building Code clauses for fire safety and structural design.

The building owner is free to use any materials, components or construction methods which can be shown to meet the relevant performance criteria of the code.

6.3 The New Zealand Building Code Handbook and Approved Documents

The Code Handbook and Approved Documents detail general options for demonstrating compliance with code provisions. These include use of Acceptable Solutions, or the preparation by the building owner of an Alternative Solution.

Acceptable Solutions contain detailed prescriptive requirements, which the regulatory authority is bound to accept as meeting the performance standards of the Building Code. These are set out in the Approved Documents for each element of the building work. The Acceptable Solutions may also be used as guidelines to assess the performance level of any Alternative Solution proposed for the building.

Alternative Solutions use materials, components or construction methods that differ from the Acceptable Solutions. It is the responsibility of the building owner to supply the regulatory authority with sufficient evidence for the authority to believe " on reasonable grounds" that the performance objectives will be met.

Verification Methods given in the Approved Documents provide approved means of demonstrating that an Alternative Solution will provide a satisfactory level of performance. This may be by appropriate testing or by calculation using accepted methods of analysis

In addition the Handbook lists default procedures for the inspection and maintenance of building systems to ensure continuing satisfactory performance.

6.4 Fire design

The design of buildings for fire is included in clauses C1 to C4 of the Building Code. The clauses are;
Clause C1 : Outbreak of Fire
Clause C2 : Means of Escape
Clause C3 : Spread of Fire
Clause C4 : Structural Stability during Fire
The clauses are reproduced in Appendix B of this report.

The general objective of these provisions is to safeguard people from injury or illness while escaping from a fire or during fire fighting operations, and to and to protect household units and other property from the effects of fire.

It should be noted that the objectives include for protection of adjacent *household units* and *other property* (defined as land or buildings or part thereof which are not held under the same allotment, or not held under the same ownership - and includes any road). The code does not provide for protection of the owners property, and any such provision will be at the owner's request.

In addition the Building Code includes three other clauses relevant to building fire safety;
Clause F6 : Lighting for Emergency
Clause F7 : Warning Systems
Clause F8 : Signs

An Acceptable Solution giving prescriptive requirements for each clause is contained in the Approved Documents. These include reference to New Zealand Standards for fire safety systems and test methods for fire related properties.

There is no verification method for fire design in the Approved Documents. This can be seen as a reflection of the "state of the art" of performance based fire engineering, as discussed in section 5 of this report.

6.5 Structural design.

The requirements for structural design of buildings are covered in Clause B1 : Structure.

The objective of this provision is safeguard people from injury or loss of amenity caused by structural behaviour, and to protect other property from damage. The clause is reproduced in full in Appendix C of this report.

In contrast to fire design, Clause B1: Structure has a prescriptive Acceptable Solution for minor buildings and building elements only. All major buildings require engineering design to the appropriate Verification Method given in the code. This includes reference to the New Zealand Code of Practice for General Structural Design and Design Loadings for Buildings (The Loading Code), NZS 4203:1992 (SNZ, 1992), and to various engineering material design codes and standards. The Loading Code has a section on the seismic design of building parts. This includes requirements for connections of permanent services equipment, but not for the equipment itself.

Seismic design of fire protection equipment is generally covered by the New Zealand Standard Specification for Seismic Resistance of Engineering Systems in Buildings, NZS 4219:1983 (SNZ, 1983). This standard includes provision to design fire protection systems for earthquake loads, and to design other systems to minimise potential ignition sources and damage that could affect egress or fire fighting. Seismic design of sprinkler systems is included in New Zealand Standard for Fire Sprinkler Systems, NZS 4541:1996 (SNZ, 1996). Both these standards refer back to the

Loading Code NZS 4203 for design actions, and both also allow alternative prescriptive design options.

The previous Loading Code referenced in NZS 4219 is now obsolete, and the current code is significantly different in many respects. The two documents are no longer compatible, and there is considerable uncertainty on appropriate design load derivations. In addition recent research indicates that the prescriptive design options will often be exceeded. Botting and Buchanan (1998) give a detailed summary of the current unsatisfactory situation.

A new draft of NZS 4219 has been prepared which addresses some of these concerns (Beattie, 2001). However this document is now on hold pending the completion of a new Loading Code. This should ensure that the documents are compatible and consistent in their requirements. Unfortunately however it is likely that the adoption of the amended document may be some time away.

The current Loading Code has two levels of earthquake loading, one for the assessment of potential injury or loss of life due to structural failure (the ultimate limit state), and one for loss of amenity due to earthquake shaking (the serviceability limit state). The earthquake event specified for the serviceability limit state is only one sixth of the shaking intensity required for ultimate limit state design. This represents a relatively small earthquake of about ten years return period.

The Loading Code lists fire as one of the physical conditions to be considered in assessing building stability. It gives load combinations and safety factors for structural design to be used in fire emergency situations. The material design standards contain sections on fire design, which give basic simple relationships to relate material properties to fire temperature. Where appropriate, reference may be made to more detailed presentations (Buchanan, 2001b, SFPE ,1995), or to the references listed in the standards.

6.6 The Fire Service Act 1975

The Fire Service Act (New Zealand Government, (1975) requires the New Zealand Fire Service to ensure that the owner of any significant building makes provision for an evacuation scheme to the approval of the Fire Service. The scheme is to include the appointment of building and floor wardens, trial evacuations at prescribed intervals, monitoring of means of escape, and special provision for specific occupant groups (elderly, disabled etc.) where appropriate to the building function. The evacuation time and procedure is to be to the approval of the Fire Service.

6.7 Discussion

The Acceptable Solution for fire design does not mention post-earthquake damage to fire safety systems as a consideration in fire in design. There is a presumption that, if the fire safety systems are designed for the earthquake loadings as required in the structural sections of the code, the risk of not meeting the code performance is insignificant. However the confusing and contradictory requirements in the system design standards cast some doubt on this assumption. There is also some confusion regarding the required performance levels for the systems. This concern is examined further in the following section.

It is also evident that, in the absence of a quantified verification method for fire design, the Acceptable Solution will be used as a measure of alternative designs. It is therefore important that the Acceptable Solution has a sound technical basis, such that it can be shown to provide solutions that meet the performance criteria of the code. Otherwise its use as part of performance based design philosophy is clearly inappropriate.

7. Fire design to the New Zealand Acceptable Solutions.

7.1 General

The Acceptable Solution for fire design C/AS1:2000 (BIA : 2000) contains prescriptive measures for fire safety in buildings. Sections include:

- Introduction
- Occupant numbers and purpose groups
- Means of escape
- Requirements for firecells
- Fire resistance ratings
- Control of internal fire and smoke spread
- Control of external fire spread
- Fire fighting
- Outbreak of fire

Many of the requirements of the Acceptable Solution are by way of reference to other code sections and to prescriptive New Zealand standards for alarm and detection systems, emergency lighting, and fire performance testing.

7.2 Fire resistance ratings

The Acceptable Solution uses two systems for fire rating building elements, depending on their application. These are designated as F (firecell) ratings and S (structural) ratings.

F ratings apply to elements required to protect building occupants during evacuation and fire fighting. The F rating are assessed on the likely time required to evacuate the building, and are based on the escape height and whether a sprinkler system is installed to control fire growth.

S ratings apply to elements required to maintain structural stability for protection of other property. The ratings are based on the burn-out time of the firecells. The ratings given in the document are obtained from a modified Eurocode expression (Eurocode, 1966), which includes consideration of firecell dimensions, thermal properties and ventilation, whether the fire cell is sprinklered, and its fire loads.

7.3 Trade-offs

Trade-offs are provisions in prescriptive codes, which allow reductions in passive fire ratings (or relaxation in other requirements) if active systems are installed. Most trade-off provisions relate to sprinkler systems, and these have been increasingly incorporated in prescriptive codes since the 1970s. Barnes (1997) summarised the history of sprinkler trade-offs in New Zealand and compared the provisions with codes in Australia, Canada and the US (UBC). Robertson (2001) notes that there approximately 60 identifiable trade-offs or relaxations in current Canadian codes.

The New Zealand Acceptable Solution has been further revised since Barnes' report, and has extended the requirement for mandatory sprinklers to additional building types (especially residential buildings) with corresponding trade-off reductions in passive system requirements.

A summary of some of the trade-offs in the Acceptable Solution are as follows. Where sprinklers are fitted;

- Reduced total width of escape routes (one exit discounted without sprinklers).
- Longer permissible escape routes (100% increase)
- No holding capacity required for protected paths
- Less fire separation required to external escape routes (50% reduction)
- Increased permissible escape height for single stair (150% increase)
- Unlimited firecell areas
- Reduced structural fire endurance rating (S rating).(50%)
- Reduced fire rating for firecell elements (F rating) (50%)
- Non- insulated glazing allowed in fire separations
- Non-insulated glazing allowed in safe paths
- No smoke separations required in vertical safe paths
- Longer corridors permitted without separation (50% increase)
- Increased areas of hidden roof and ceiling space

- Reduction in interior surface finish fire spread requirements
- Increased allowable unprotected area in external walls (100% increase)
- Reduced length required for wing walls or return walls (50%)
- Vertical fire spread from lower roof may be ignored.
- Vertical fire spread from lower levels of same building may be ignored.

In addition there are further trade offs available for other active systems. These include;

- Longer permissible escape routes (with heat or smoke detectors)
- Increased area of intermediate floors (with smoke control system)
- Low hazard activities permitted in safe paths (with smoke detectors)
- Reduction in smoke control capacity of some doors (with pressurisation)

Also of note is the amended allowable received radiation at boundaries, which has been increased above normally accepted values based on the likelihood of fire service intervention.

As can be seen from the above summary, there are some significant concessions allowed, particularly in sprinklered buildings. This is, in part, a reflection of the excellent record of sprinkler performance in Australia and New Zealand. (Marryatt, 1988).

7.4 Tall buildings.

Requirements for fire safety systems for firecells are given in Tables 4.1/1 to 4.1/5 of the Acceptable Solutions and are included in Appendix D of this report.

The following is a summary of the general requirements of the Acceptable Solutions for buildings over 25 metres height.
All buildings are to include the following features;

- Sprinkler protection.
- Manual call points.

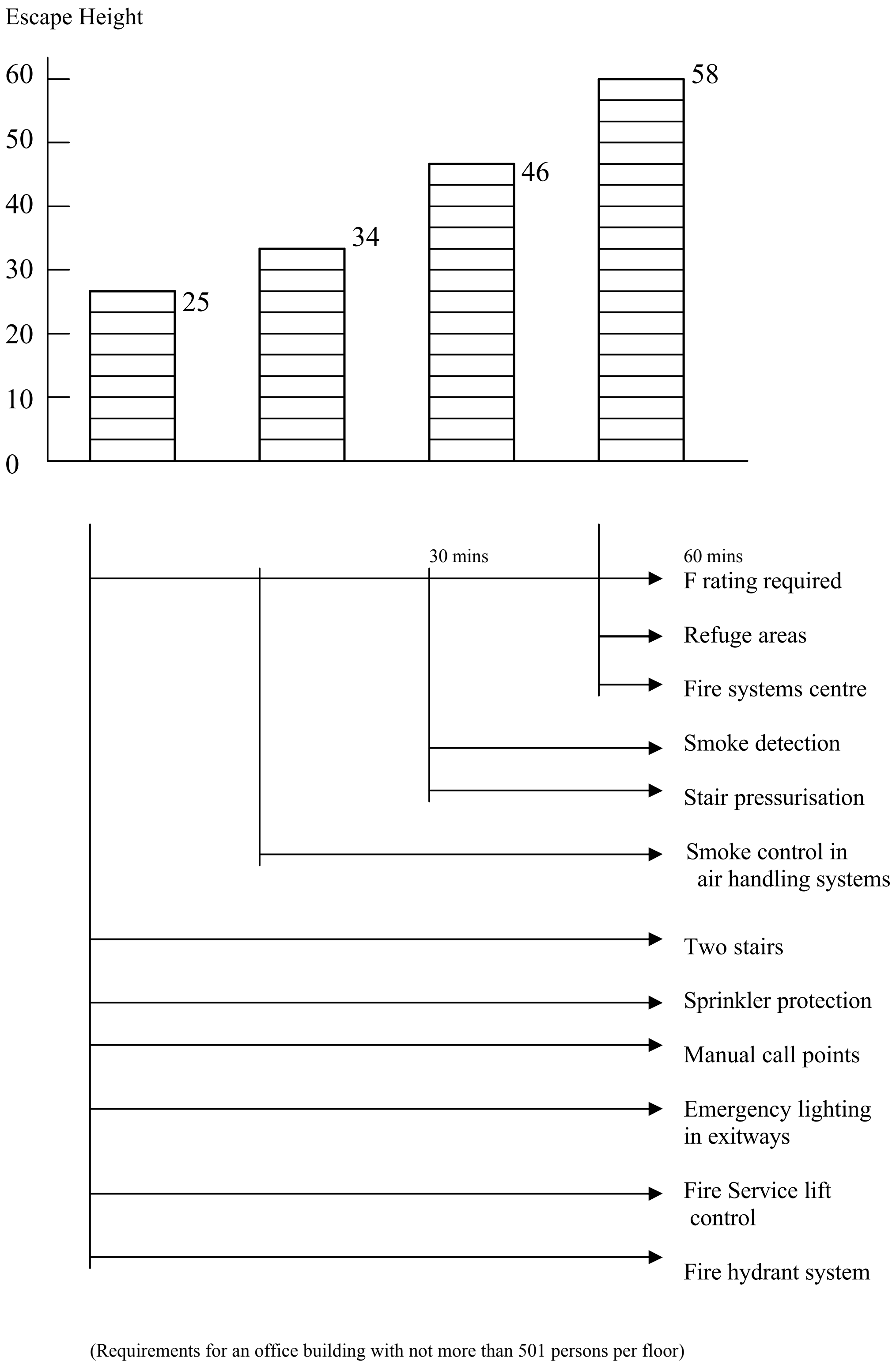


Figure 7.1 : Fire safety system requirements

New Zealand Building Code Acceptable Solutions

- At least two means of escape.
- An F rating of 30 minutes, increasing to 60 minutes at 58 metre height.
- Fire Service lift control.
- Emergency lighting in exitways.
- A fire hydrant system.

In addition, all office, commercial and storage type uses are to have;

- Smoke detectors if over 46 metres height.
- Safe path pressurisation if over 46 metres height
- Smoke control in air handling systems if over 34 metres height
- Refuge areas at every third floor in safe paths if over 58 metres height
- Fire system centres for Fire Service control if over 58 metres

These requirements are for office buildings with less than 501 persons per floor, and are summarised in Figure 7.1.

Requirements for multi-unit apartments buildings are similar. All require smoke detectors and all apartments are to open onto a safe path.

7.5 Post–earthquake performance of fire safety systems

The Acceptable Solution for fire does not mention post-earthquake damage to fire safety systems as a consideration in fire in design. There is a presumption that, if the fire safety systems are designed for the earthquake loadings specified elsewhere in the code, the risk of not meeting the code performance for post earthquake fire is insignificant.

As noted in section 6, requirements for earthquake design of fire safety systems are contained in NZS 4203, NZS 4541 and NZS 4219. NZS 4219 (SNZ, 1983) requires the building designer to consider the effect of earthquake on fire protection systems, public utilities, non-structural elements and other potential hazards as they relate to protection of life and property and safe egress from the building. However, as noted in section 6.5, there is confusion regarding application of the requirements due to code changes and inconsistencies.

There is also uncertainty about the required level of earthquake loading for fire protection systems. The wording of the Building Code performance requirements would suggest that the serviceability limit state is appropriate for design of fire safety systems. Unfortunately, as noted previously, this would provide a very limited level of protection, even in a moderate earthquake.

Clearly the potential failure of fire protection systems is a life safety consideration, and the BIA has recognised this ambiguity in design requirements. They have published an opinion (BIA, 1993) that these systems should be designed for a load midway between the ultimate limit state and the serviceability limit state. This compromise would significantly improve the reliability of the systems, but it is not a requirement of the approved documents and therefore cannot be required for compliance.

And even where prescriptive load options are given they have been shown to be inadequate to ensure survival of the systems in a design earthquake. (Beattie, 2000 and Botting and Buchanan, 1998).

In addition to requirements for requirements for seismic restraint, the New Zealand Standard for Automatic Fire Sprinkler Systems, NZS 4541:1996 (SNZ, 1996) also contains a provision to increase the reliability of water supply for sprinkler systems in the earthquake prone areas. All systems in areas with moderate seismic activity are to have two independent water supplies, of which one shall be independent of the town main reticulation. However the BIA, as part of their approval of NZS 4541 as a means of compliance, have deleted this provision. In the worst case this could result in a building being dependent on both a fully operational external water and electric power supply for reliable sprinkler operation. The adoption by the BIA of this minimum standard water supply for sprinkler systems assumes a high level of earthquake reliability for the utility systems. All evidence suggests that this assumption is not realistic, but no guidance is given on how the designer is to address the potential vulnerability of these systems.

7.6 Document Status

The lack of a verification method for fire safety design leaves the regulatory authority in the difficult position of having to measure the building performance in fire against an unquantified requirement. The generally accepted default procedure is to assess the performance against the prescriptive Acceptable Solution. However this gives no indication of the true level of safety or assurance against failure. There are also a number of apparent inconsistencies in the Acceptable Solution, and the absence of the technical background material makes it difficult to assess the applicability of the requirements to any specific situation.

In addition, the cost/benefit consideration from section 6 of the Building Act has been presented as justification for some recent amendments to the Acceptable Solutions. In some of cases the benefit of the changes appears arguable. And as the actual cost/benefit calculations have not been made available, no useful quantitative information about performance can be inferred.

There is therefore some understandable resistance from some fire engineers to reference their designs to the acceptable solutions, an approach which they see as unnecessarily restrictive. However the BIA have made the following pertinent observations in a recent formal determination (BIA, 2002).

a. *Some acceptable solutions cover the worst case so that in less extreme cases they may be modified and the resulting alternative solutions will still comply with the code.*
b. *Usually, however, when there is non- compliance with one provision of the acceptable solution it will be necessary to add some other provision to compensate for that in order to comply with the building code.*

In the same determination, the BIA reported a New Zealand High Court decision, that held that BIA was entitled to use the Acceptable Solution as a "guideline or benchmark" to compliance.

These precedents appear to support the use of the Acceptable Solution as a measure of performance for alternative designs, at least until quantified performance criteria are incorporated in the code.

A study group was established in 1989 by the Australian Fire Code Reform Centre to develop and validate risk assessment models for cost effective fire safety design. In a recent review of the group's recommendations (Custer and Ashe, 2002) the establishment of a technical basis for prescriptive requirements was identified as an important factor if they are to be linked in a meaningful way to performance objectives. This process would remove the uncertainty currently surrounding the performance and cost effectiveness of the prescriptive solutions. This is particularly relevant when the Acceptable Solution is the only quantified performance criteria given in the code.

7.7 Discussion

It is evident that tall buildings designed to these prescriptive requirements depend on a number of both active and passive systems for life safety and property protection. It is also evident that many of these systems are susceptible to damage in a major earthquake, and that many depend on vulnerable external utilities (water supply, power, communications) for proper functioning. The apparent assumption in the Acceptable Solution of adequate reliability of the safety systems may be inappropriate.

As detailed above the Acceptable Solution incorporates many trade off relaxations, particularly in sprinklered buildings. There is little doubt that sprinklers are the most effective form of fire protection available. However there is a danger that an unacceptable reliance may be placed on seismically vulnerable systems, which could leave the building occupants with little protection from fire after a significant earthquake. As noted by Barnes (1997), a 50% trade off reduction in the rating of a fire separation could reduce its safety factor from a respectable 2.0 to a close to failure situation should the sprinkler system fail to operate.

In addition the fire resistant barriers themselves may well be prone to damage due to inadequate design requirements for limits on earthquake deflections.

In view of the earthquake prone environment found in many parts of New Zealand, it would seem appropriate that post-earthquake fire should be included as part of a comprehensive multi-scenario risk assessment of fire safety. This would allow the contribution of the possible seismic event to the overall fire risk to be properly quantified and assessed. The potentially high consequences of a post earthquake fire, particularly in tall buildings, make it a scenario that should not be ignored. While the current state of the art makes a full absolute performance analysis unrealistic, the methodology can still be used to compare a design against the Acceptable Solutions or an alternative solution.

However the uncertainty of the level of performance of design to the Acceptable Solution will continue until its technical validity has be demonstrated.

8. Reliability of fire safety systems – before and after earthquake.

8.1 Introduction.

Most modern seismic building codes contain some provision for seismic restraint of building fittings and equipment, and appropriate separation of non-structural elements that are vulnerable to earthquake damage. However a number of recent reports have indicated that an appropriate level of performance is not always being achieved. The reasons for this include inadequate code provisions, lack of design coordination between building and equipment designers, and poor or inappropriate detailing.

This section of the report considers specifically the systems and utilities that make the major contribution to fire safety in a modern tall building, and endeavours to quantify the reliability for use in a risk analysis in the following section of this report. The systems to be reviewed are;

- Sprinkler system reticulation
- Sprinkler system water supply
- Smoke control systems
- Passive protection.

Alarm systems may become ineffective during an earthquake due to non-activation or false alarm activation. However it is suggested that people are likely to evacuate the damaged building as quickly as possible, and will be alert and aware of the potential fire risk. For the purpose of the risk analysis, it is assumed that the absence of reliable alarms will not materially affect the life safety of building occupants. However it is obviously important that damaged buildings should not be re-occupied until the alarm systems are confirmed as operational.

The following sections discuss the normal operational reliability of the systems as well as the degradation anticipated after an earthquake.

8.2 Sprinkler system reticulation.

The issue of the reliability of sprinkler systems in normal operational situations has been the focus of considerable discussion, with reliabilities as low as 81% found in some studies (Budnick, 2001). 95% confidence limits recommended by Budnick for commercial use in the US are in the range 88.1 to 98.1 %. However Feeney (2001) has argued that systems in Australia and New Zealand have a significantly higher reliability, and recommends a failure probability of 99.83%. This figure, which includes an allowance for system isolation for alteration or maintenance, is consistent with previous research by Marryat (1988), and is justified mainly due to the additional self-monitoring features and the high level of inspection and testing required in these countries. The Australian guideline document (FCRCL, 1996) recommends 99% for flashover fires and 95% for non-flashover situations.

Experience in the US indicates that most sprinkler systems remained intact in recent earthquakes, and that seismic bracing where installed was generally effective. However some bracing failures were reported in the Northridge earthquake (Fleming, 1998) and, as previously noted, current prescriptive standards do not make adequate provision for seismic restraint of sprinkler systems. Both Fleming (1998) in the US, and Beattie (2000) in New Zealand noted that the systems were subject to seismic accelerations significantly greater than the required design values. The New Zealand Sprinkler Code NZS 4541:1996 (SNZ, 1996) permits a default value of 1.0g for design. This is considerably less that the values of over 3g obtained by modelling buildings to the current New Zealand code, and measured in recent California earthquakes (Shelton et al. 2002). The provision is clearly inadequate in some situations.

Porter and Scawthorn (1998) determined a 2% (approx.) probability of failure for a retrofitted system in San Francisco for a 0.4g PGA earthquake (equiv to a 475 return period event). For an unbraced system the probability of failure rose to 50%. These probabilities were based on observed median failure acceleration of 2.6g for braced systems compared with 0.72g for unbraced.

Robertson and Mehaffey (2000) used a reliability index of 80 – 100% for post-earthquake system reliability in their performance-based assessment. This value assumes a water supply designed to a significantly higher seismic loading such that it is not a significantly contributing failure element.

Feeney (2001) adopted a probability of failure of 40% for a design level earthquake in his risk assessment for a NZ building. This figure takes account of concerns regarding design and installation as expressed above.

8.3 Sprinkler system water supply.

Under normal conditions, municipal water supplies are highly reliable. Feeney (2001) analysed water supply data from Auckland and Melbourne to derive an annual probability of 99.992% that water will be available at the normal pressure and flow rate. Reliability of supply to the sprinkler system will significantly increase for independent dual supply systems.

However experience in many earthquakes has demonstrated that municipal water supplies have a high probability of failure during an earthquake. Of the fifteen significant earthquakes reported in Botting and Buchanan (2000), only one appears to have no reported major damage to water supplies. Two recent New Zealand reports (Brunsdon and Clark, 2000 and Christchurch Lifelines Group, 1997) identified a high vulnerability in the local water supplies to a "moderate" seismic event (150 year return period, assessed as MM8).

And while a number of modern tall buildings will have a secondary supply, this may itself be dependent on the reliability and adequate restraint of a number of other elements including pumps, supply tanks, control panels and emergency power supply.

Robertson and Mehaffey (2000) suggest post-earthquake reliability levels for sprinkler systems that vary from up to 80% for water from a reliable on-site pumped storage (designed to operate under the design level earthquake) to between 0% to 35% for a municipal supply considered at risk (under the design level earthquake).

Feeney (2002) has recommended reliability levels of 54% for a dual system with seismic designed primary water supply (Type A supply to NZS 4541:1996 (SNZ, 1996)) reducing to 1% for a system dependent on the municipal supply and/or electric booster pumps. (Type C supply to NZS 4541:1996).

8.4 Smoke control systems

FCRCL (1996) reported that the probability of successful functioning of smoke management systems may be less than 50%, and noted that the more complex the systems the lower the reliability. Klote and Milke (1992) estimated the mean life before failure of commissioned systems as varying from 116 months for a system with 3 fans and no other components to 3 months for a system with 5 fans and 54 other components. Even with stringent inspection and maintenance procedures are in place, these figures must be of concern, particularly when the presence of the system is used to trade off for smoke separations. Obviously systems should be kept as simple as possible. For the simple system of not more than three fans and no other components, Klote and Milke estimate a reliability of 97% before commissioning.

Inspection and testing of mechanical systems in New Zealand is carried out by Independently Qualified Persons (IQPs) registered by the territorial authorities. The procedures for inspection and testing are submitted for approval as part of the building consent application. Usually the default procedures from the Building Handbook are specified, but extended and more detailed provisions are often submitted for sophisticated systems. However it is evident that in some cases the IQP is not familiar with the operational requirements of the system, and do not use the approved procedures for testing. This may have significant implication on the reliability of the system.

Dixon (1999) noted that the effective performance of smoke control systems is dependent on accurate data on building leakage. Any damage to doors and enclosures may significantly reduce the level of performance.

Where the systems do not have an emergency power supply, they are vulnerable to the loss of reticulated supply in an earthquake. The NZ Building Code Acceptable Solution requires emergency supply for crowd and some sleeping activities only, and then only for buildings over 58 metres height.

Feeney (2001) researched the New Zealand situation and has estimated the probability that power will be available after a design earthquake as 10%.

Botting (1998) reports loss of electric supply over significant areas in most the earthquakes reviewed. Brunsdon and Clark (2000) and Christchurch Lifelines Group (1997) predict short-term power outages in New Zealand locations under the 150 year (approx) return period “moderate” earthquake.

8.5 Passive protection.

The main concern in the reliability of passive protection is the presence of inadequately fire- protected penetrations for building services and the presence of ineffective fire and smoke doors. Barnes (1997) reports on a survey of Wellington NZ office buildings carried out in the late 1980s, that found that over 24% of fire doors were removed or wedged open. It is considered that the increased awareness of fire safety issues, more effective automatic closers, the introduction magnetic hold-open devices, and the more rigorous inspection procedures introduced by recent legislation will have significantly reduced this number. The Australian design guide (FCRCL, 1996) suggests a reliability of 95% for separations with no openings reducing to 90% for openings with automatic closers. This implies a 5% probability that the door closers will not operate successfully.

Damage to non-structural enclosures in earthquake results from forced deflections imposed on the elements as the building deflects. The performance will depend on the flexibility of the building as well as the details of the enclosure panels, such as aspect ratio, presence of doors and penetrations, and degree of edge restraint from the main structure. The maximum permissible drift ratios in the NZ Loading Code (SNZ, 1992) are 0.015 to 0.020 (depending on height) for the ultimate limit state and 0.0025 for the serviceability limit state.

Tests quoted by Porter et al. (2001) indicate that visible damage can be expected at a drift ratio of 0.004. Although this is not the ultimate drift that the panels can sustain it represents the value at which smoke spread could be expected through cracking and gaps due to dislodged stopping plaster. Fire spread could occur at a drift ratio of 0.0085 when the plasterboard is likely to separate from the framing. Sekizawa et al.

(2000) quotes Japanese recommendations of a 50% reduction in effective fire resistance for partitions subject to a transient drift of .0033.

Brunsdon and Clark (2000) analysed a typical modern New Zealand concrete frame building subject to a “moderate” earthquake and found maximum drift ratios of 0.0042, implying a value under ultimate design level load of 0.0073.

It can be seen that smoke penetration may be expected in partitions in flexible buildings after a moderate earthquake, and the fire integrity will be lost at drift ratios well below ultimate load deflections unless the partitions are separated from the structure. Successful structural separation depends on properly designed and detailed, high performance, fire resistant seismic joints (James and Buchanan, 2000).

8.6 Passive protection – real fire reliability

Fire testing of elements is traditionally carried out in standard furnaces using the ISO 834 or equivalent standard time-temperature curve. This has the advantage inherent in an internationally recognised standard test procedure, which allows comparison of fire tests carried out in many different locations.

The ISO 834 test dates back to the 1930s, and is based on cellulose fuels. The significant change in the type of materials used today, especially modern plastics, have called into question the validity of the ISO 834 test. The specific concern to be addressed is whether an element tested to a certain rating will achieve that rating in a real fire. As the standard test ratings are typically used in calculations of, for instance, safe escape times, it is imperative that the test designations are realistic.

Recent publications by Jones (2001) and Nyman (2002) have reported on furnace tests with more realistic time-temperature curves and found that assemblies can fail at a time considerably less than the standard test rating. Some compartment tests based on upholstered furniture fires showed times to failure of less than 50% of the times predicted by standard fire exposure tests. Based on his test results, Nyman has proposed a relationship for time-to-failure for non-load bearing walls based on the cumulative radiant energy reaching the wall.

9. Risk assessment

9.1 Objective.

To identify key issues affecting the post- earthquake fire safety of tall buildings.

To examine the level of protection from post- earthquake fire provided in a tall building designed to the Acceptable Solution of the New Zealand Building Code.

9.2 Philosophy

A rigorous analysis of post earthquake fire risk is a complex, multi-variable problem. Earthquake damage may significantly affect many of the typical fire scenario parameters including probability of ignition and fire growth, probability of intervention, the reliability of the active and passive fire safety systems, and the ease of evacuation.

The analysis must also consider the probability of an earthquake of given intensity and estimate the probability of damage to the various systems. Simplistic assessments based on general fire statistics, including risk ranking (Gretner, FSES, etc.) are therefore not appropriate. However a comprehensive probabilistic risk analysis is outside the scope of this report, and is probably not justified in terms of the current knowledge of likely damage levels.

The aim of this section of the report is to carry out a simple analysis for a number of representative fire scenarios for a typical case study building. The scenarios include a range of damage levels due to a “moderate” and a “design level” earthquake event.

This analysis will obviously not give a comprehensive or an absolute measure of the increased risk to life safety due to fire following an earthquake. However it presents a comparison of the effect of earthquake damage on fire safety systems for some typical scenarios in the case study building.

9.3 Method

- To estimate the likely earthquake damage to fire safety systems in the case study building.
- To assess the resulting fire growth and fire and smoke spread for typical design fires at different floors of the building.
- To assess the implications on life safety of occupants.

9.4 Procedure

For the case study building, the procedure is as follows.

- Select a typical design fire consistent with the buildings use.
- Select three fire locations at the near the bottom, top, and mid height of the building.
- Select a number of design scenarios to include combinations of potential damage to fire safety systems.
- Compute the time to loss of tenability for critical locations for each scenario, and the available safe exit time for occupants at risk.
- Compute the required safe egress time for each floor for each scenario.
- Compare the available safe egress time with the required safe egress time to determine the number of occupants at risk. Derive the average number of occupants at risk for all floors for each scenario.
- Estimate the probability of each scenario for a moderate and a design level earthquake, and determine the number of occupants at risk.

9.5 Case study building,

The case study building is an office building designed and built in the late 1980s. The earthquake design is comparable with current earthquake code requirements, and the fire safety systems provided are generally equivalent or better than current requirements. For the purpose of this case study, the fire safety systems are assumed to be those of the Acceptable Solutions (BIA, 2000).

This building was selected because it is typical of the size, use, configuration and structural characteristics of tall office buildings likely to be constructed in New Zealand in the near future. Apartment and other residential buildings have significantly different fire safety system requirements, requiring a generally higher level of protection. They also have more compartmentation, and are therefore more complicated to analyse for fire and smoke spread. However there are few apartment building of comparable height in New Zealand.

The case study building consists of a 20 storey tower with a three storey podium structure, including one level of basement. The tower is symmetrical and regular, of plan dimensions 36 m x 26 m. Storey height is 3.6 m at ground floor and 3.42 m typically. The podium is 55 m x 50 m, and is seismically separated from the tower. The structure is of reinforced concrete with precast concrete floors, precast concrete beams and cast-in-place concrete columns. Earthquake loads are resisted by the reinforced concrete peripheral frames. This means that the building is relatively flexible compared with a building using structural shear walls as the principal earthquake resisting system.

The tower has a centrally located service core, which includes two precast concrete stairs and five lifts. The walls to the core are timber framed with plasterboard linings. External cladding is glazed curtain wall. The main floor area is assumed to be a single open plan office area. The podium has additional stairs independent of the main core.

A typical floor plan is shown in Figure 9.1.

The initial design for the building derived a predicted first mode period of some 2.5 seconds. Earthquake design to the New Zealand Loading Code (SNZ, 1992) specifies a 450 year return period earthquake (MM 8.5 approx.), for which the predicted maximum inter-storey deflection is calculated as 28mm. This is well within the allowable deflection of 51 mm specified in the Loading Code. An equivalent shear wall building could be expected to have a period of some 1 second and a maximum inter-storey deflection of less than 12 mm.

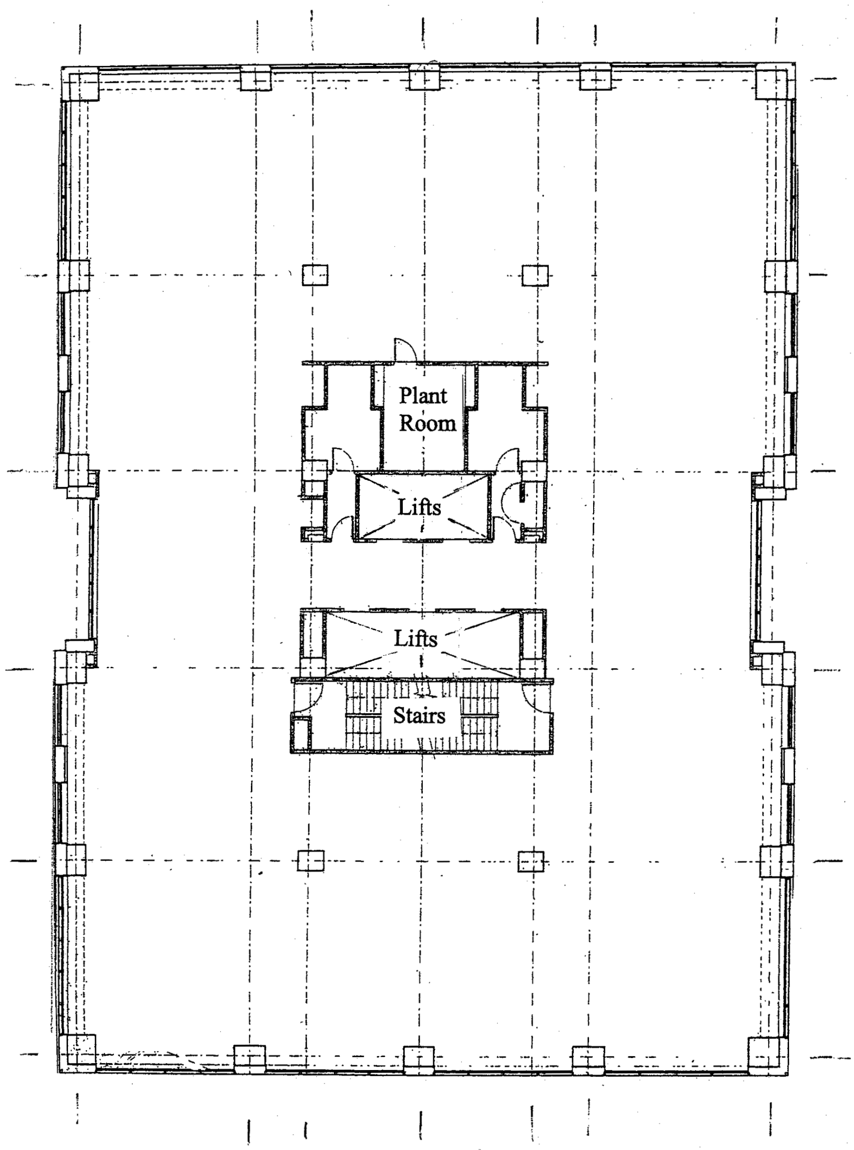


Figure 9.1 : Case study building : typical floor plan.

The mechanical services in the building include;

- Separate air-handling units on each floor, with ducted supply, and with return air via the ceiling plenum.
- Fan assisted vertical supply and spill air ducts serving the air-handling units on all floors.
- A separate fan-assisted toilet ventilation duct serving all floors
- Pressurisation units to both stairs.

- Fire dampers fitted to ducts at all fire separations (floors) and at the top of the lift and stair shafts.
- Smoke detector activation of all fire dampers.

The fire safety systems assumed for the analysis (and as required by the Acceptable Solutions) are as follows;

- Two safe path stairs.
- Automatic fire sprinkler system.
- Automatic smoke detection system with manual call points.
- Smoke control in air handling systems.
- Pressurisation in safe paths.
- Fire Service control of lifts.
- Emergency lighting in exitways.
- Fire hydrant system.
- Refuge areas in stairs.
- Fire systems centre.
- Fire rating of floors, and protected shafts (F rating) : 60 minutes.
- Fire rating of primary structure (S rating) : 180 minutes.

Note that the external walls of the tower are some 9 metres from adjacent properties and do not require fire resistant cladding materials.
Smoke control is achieved by plant shutdown, and activation of stair pressurisation units and fire dampers (limited smoke control only) on alarm activation.

The Acceptable Solution recommend a design Fire Load Energy Density (FLED) of 800 MJ/m^2 for general office use, and a design occupant density of 0.1 person/m^2 of occupied floor area. These values are used in the design.

9.6 Modelling.

The building is modelled for fire growth and fire and smoke spread using the BRANZFIRE Version 2002.7 computer programme (BRANZ, 2002). This is a multi-compartment (up to 10 room) zone model that accommodates multiple vents, and multiple burning objects. It aims to predict various fire characteristics in the upper and lower layers, including temperature, species concentration, plume and vent flows, layer interface height, fractional effective dose, visibility, and sprinkler/ detector activation. It also includes provision for mechanical ventilation, flame spread and fire growth models for room lining materials, and glass fracture prediction.

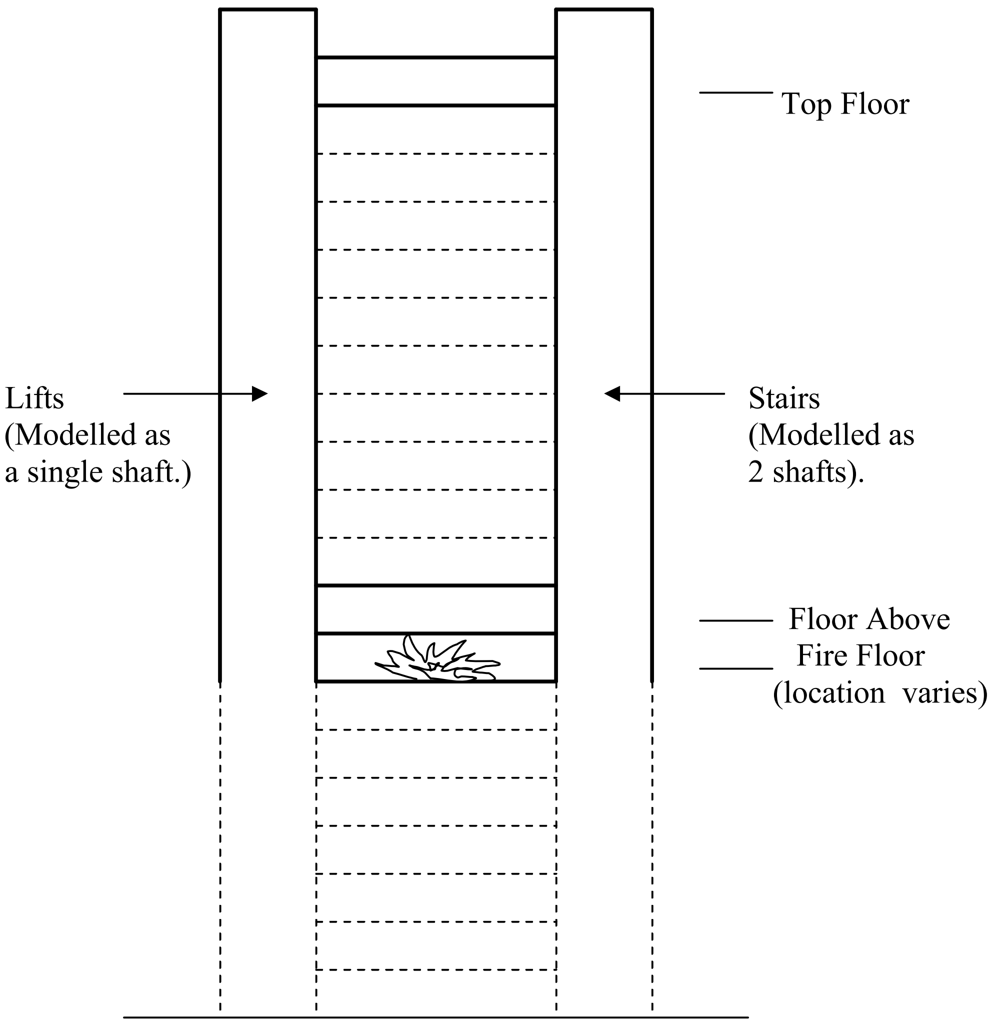
The building is modelled with floors as separate individual compartments, and each stair and the lift shaft modelled as a separate full height shaft. The various compartments are connected with vertical and horizontal vents to adjacent compartments and to the outside as appropriate. Vents are calculated to include normal construction leakage as well as damage to separations and services, possible open doors, and glass breakage as appropriate to the scenario being modelled.

The ceiling space in each floor is a return air plenum for the ventilation system. Each floor is modelled as full height, but smoke detector and sprinkler activation are separately modelled to reflect their location at the lower ceiling level.

In order to work within the limitation of the software it is necessary to make some simplifying assumptions to the physical model of the building. Preliminary modelling of various smoke spread mechanisms was carried out to confirm that the assumptions would still achieve realistic results, and an endeavour has been made to keep these conservative (in terms of not significantly overestimating hazard). The assumptions are as follows;

- Critical locations for tenability are the stairs, the fire floor, the floor above the fire floor (due to inter-floor leakage), and the top floor of the building (due principally to smoke transfer via the lift shaft).
- Leakage from other floors and from the lift and stair shafts may be modelled as if to the outside, with appropriate adjustment to leakage areas to reflect the restriction to the flow due to the enclosure.

The resulting model is shown diagrammatically in Figure 9.2.



Note : Solid lines show extent of modelled spaces.
Leakage paths, openings and glazing not shown.

Figure 9.2 Case study building : analysis model.

Other assumptions relevant to the modelling are as follows:.

- The lift and stairs are modelled as single zone rooms.
- Except where open doors are modelled, both stairs will have the same tenability conditions.
- The stack effect is ignored. It is acknowledged that this may have a significant effect on smoke movement. However the stack effect is principally driven by the ambient temperature difference between internal and external spaces, and may encourage or suppress smoke movement into the shafts depending on the

location of the fire room. As this assessment is a comparison of specific scenarios, it is valid to ignore this effect.

- Glass in the external walls to the fire floor will progressively fall out between the programme predicted fracture time and flashover.
- Fire dampers have fail-safe closure mechanisms, but allow a 2% smoke penetration in fire mode.

Basic calculations for the modelling input, and a typical input printout are presented in Appendix E.

9.7 Design Fires.

The initial design fire is a two-panel computer workstation taken from the NIST fire test records. This has a growth rate between fast and medium to a peak Heat Release Rate of 1800 kW after 280 secs. as shown in Figure 9.3. This design fire is used where sprinklers are operational, as noted below.

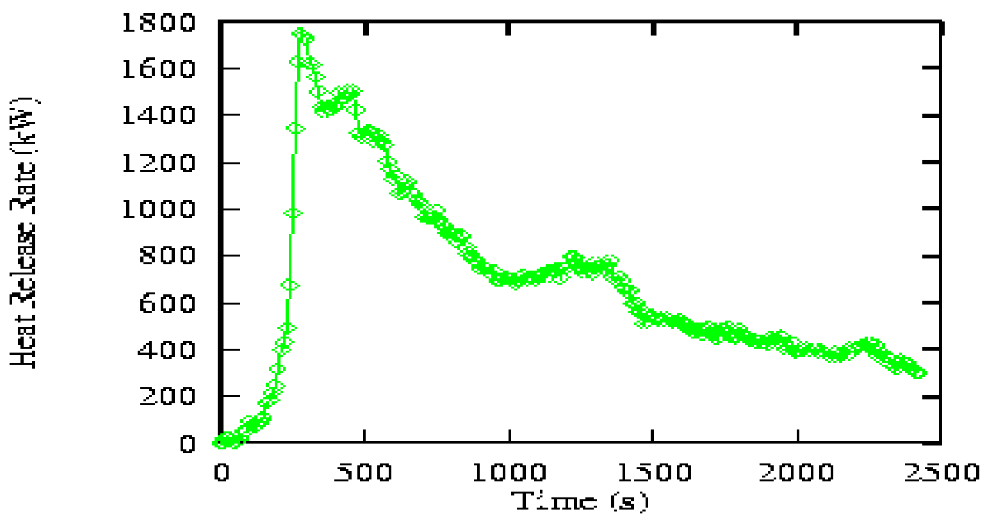


Figure 9.3 : NIST workstation fire.

For uncontrolled fires (when sprinklers do not operate), fire spread throughout the compartment is modelled using the FREEBURN subroutine from the FPETOOL software (Deal, 1994). Similar workstations were assumed at approx 3 metre centres and the rate of fire spread due to radiation was modelled, assuming the initial burning object was adjacent to the centre of an exterior wall. The resulting composite fire was found to closely match a t^2 fire growth curve of fire intensity coefficient $\propto = .019$, as shown in Figure 9.4. This fire is used to model the uncontrolled fire up to flashover, when the full FLED of 800 MJ/m^2 becomes involved.

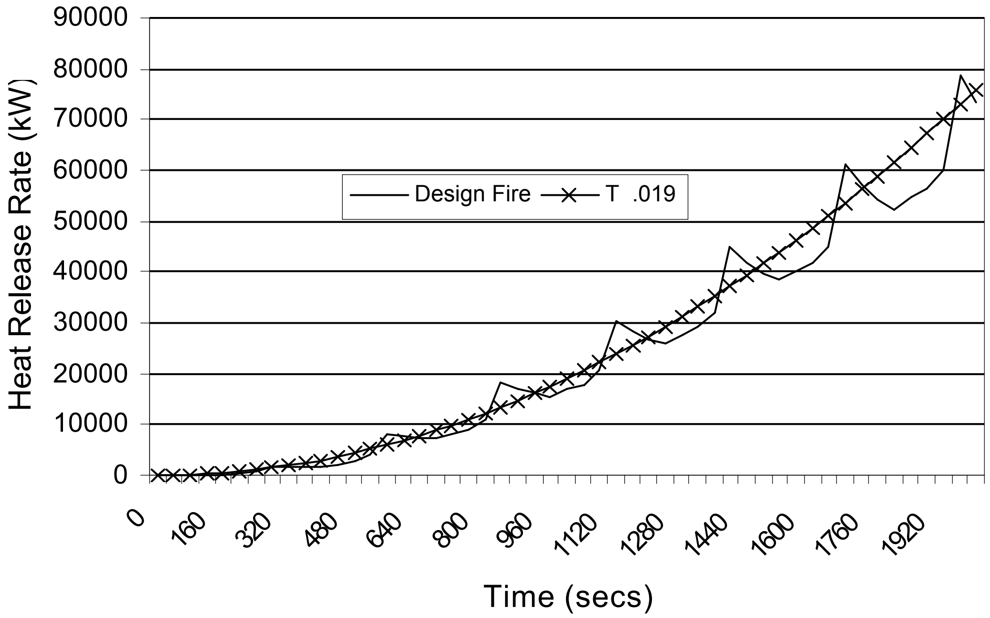


Figure 9.4 : Combined design fire

The FREEBURN analysis indicated that ignition of the nearest adjacent workstations occurred at approximately the same time as predicted sprinkler activation. It was therefore considered reasonable to limit the sprinkler controlled fire load to burnout of the single workstation, using the fire curve in Figure 9.3.

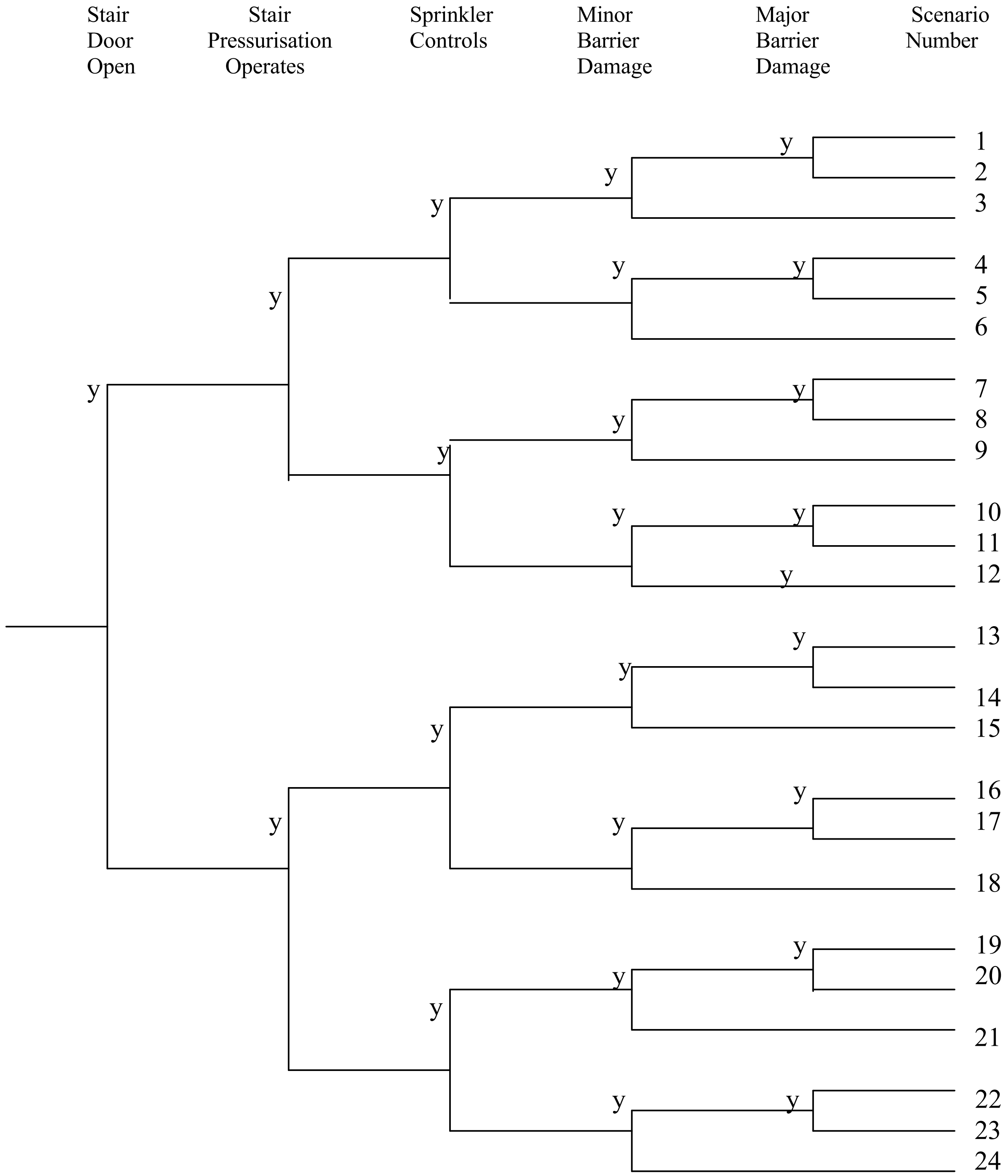


Figure 9.5 : Design scenario event tree

9.8 Design scenarios

The event tree in Figure 9.5 identifies the design scenarios considered.

The “open doors” scenario assumes the door to one stair and one elevator door are open on the fire floor only. For the elevator door, it is assumed that the lift car is located at the fire floor.

The “moderate barrier damage” scenario reflects limited joint cracking and some loosening of fixings in the framed walls, allowing limited smoke penetration. The “major barrier damage” scenario assumes separation of the lining from the framing at the joints, and also assumes the failure of 33% of the external glazing at each floor. The figure of 33% is considered a realistic minimum. Generally the increased early ventilation will increase the time to loss of tenability.

It should be noted that this structure is relatively flexible, because earthquake loads are resisted by frame action. The timber framed stair and lift enclosures will therefore be subject to significant damage before any cracking is likely occur in the floor slabs.

This section of the analysis assumes that the fire has developed to a sufficient size to activate the sprinkler system. The likelihood of Fire Service intervention at this stage in a seismic event is considered unlikely, and has been ignored. Even where vehicular access is possibly, it is unlikely that the Fire Service will have the capability or resources to assist with the potentially large number of fire incidents after a significant earthquake.

9.9 Tenability considerations

The BRANZFIRE model calculates and reports a number of critical tenability criteria including FED radiation, FED narcotic gasses, smoke obscuration, and convective heat, all at a specified monitoring height. Tenability is typically assessed at a reference height of 2 metres (Buchanan, 2001a). The critical design criteria for this case study are found to be upper layer convective heat (60^{o}C max) and smoke obscuration on the fire floor, and upper layer smoke obscuration on other floors. The critical value for smoke obscuration is taken as 10 metre visibility (Buchanan, 2001a), which is equivalent to an Optical Density of 0.13.

For the stairs, which were modelled as single zones, smoke obscuration was again the critical criteria, and the same limiting values were adopted. The single zone model may underestimate the smoke spread from the shafts at the upper levels, but is probably conservative for tenability in the shaft as a whole.

Bryan (1995) reported on a British study where 64% of the subjects continued to move through smoke with a visibility of only 4 metres. However walking speeds will be significantly reduced at this visibility (Klote and Milke, 1992), and people are likely to be more cautious on stairs than on level routes. It s also noted that the smoke obscuration values from BRANZFIRE are for free burning situations, and higher soot yields will occur after flashover. The value of 10 metre visibility is therefore considered a reasonable design criteria.

When considering the tenability of stairs, the following assumptions have been made.

- Emergency lighting will continue to operate.
- Where they have a choice, occupants will always avoid a stair with reduced visibility.
- Where barriers are not damaged, smoke will only enter the stair when the upper layer lowers to the door head level.
- The stairs below the fire floor will remain tenable at all times.
- Pressurised stairs will prevent leakage around the doors and open door flow for the controlled fire only (this should represent the usual design case for the system). Leakage will occur for the uncontrolled fire.

9.10 Modelling results

A number of BRANZFIRE simulations were run at three different levels in the building. Table 9.1 shows representative results from all simulations. Simulations were generally run to 3000 secs. (50 minutes).

Glass Fracture :	9.7 mins (180^o C approx.)
Flashover (uncontrolled fire);	19.3 to 20 mins.
Sprinkler activation;	4.8 mins.
Smoke Detector Activation;	1.9 mins.

Tenability Location	Sprinkler controlled fire scenarios			Uncontrolled fire scenarios			
	Door Open	Mod. Damage	Major Damage	Door Open	Door Closed	Mod. Damage	Major Damage
	Time to untenability (mins)			Time to untenability (mins)			
Fire Floor	6.2	6.3	6.4	5.6	5.5	5.6	5.7
Floor Above	*	*	*	29.5	*	24.5	*
Top Floor	*	*	17.1	21.7	26.5	21.5	9.9
	Time to OD at 0.13 m^{-1} (mins)			Time to OD at 0.13 m^{-1} (mins)			
Stair with open door[a]	14.4	14.0	10.9	7.3	N/A	8.4	8.4
Stair with closed door[a]	40	33.6	11.0	22.2	24.3	10.0	8.5

* indicates no loss of tenability at 50 minutes.

[a] the open/closed door is located on the fire floor.

Table 9.1 : Untenability times from case study modelling.

It can be seen that:

- The untenability time of the fire room is longer for the controlled fire, but otherwise shows little variation between scenarios. The fire is not ventilation controlled at loss of tenability, and the smoke layer has lowered 2.2 metres to before sprinkler activation.
- For other floors, the available egress time is determined by the untenability time of the escape stairs. The untenability time is shorter for an open door to the stair, and decreases with increasing damage to the stair walls.

- The top floor untenability time is a function of smoke movement through the shafts. The untenability time decreases with open doors and/or increasing damage to the shaft walls.
- The floor immediately above the fire floor is not critical. Untenability times again depended on smoke movement from the shafts.

The model output is used to estimate tenability times for other scenarios not specifically modelled. For instance the stair tenability for both stair doors open is assumed to be the same as the "open stair" in modelled case, and the tenability times for other stair locations was interpolated from the three locations modelled.

The BRANZFIRE model also measures the Equivalent Fire Resistance Rating within the fire enclosure, in accordance with the cumulative radiant energy method (Nyman, 2002). This allows a comparison of the actual fire exposure with the standard tests (ISO 834 and equivalent) used in the NZ Building Code. For the case study building, the equivalent thermal exposure time measured by model was in all cases less than the actual time after ignition. This is a reflection of the moderate fire growth.

9.11 Earthquake scenarios and damage probability

It is evident from previous seismic events that earthquakes of a lesser magnitude than the "design" earthquake can cause significant damage in new buildings. The term "moderate" earthquake has been used for earthquakes in the range upper MMVII to lower MMVIII (MM 8.0), (Brunsdon and Clark, 2000). These events are more frequent than the "design' event, and, as observed at Northridge and Loma Prieta, they can cause significant failure of fire safety systems.

The moderate earthquake event has also been used for lifeline vulnerability assessment (Christchurch Lifelines Group, 1997) as it represents a seismic intensity for which urban water supply, power supply and communications systems have been seen to demonstrate a significant probability of failure.

It should be noted that there is some disagreement on an appropriate seismic hazard model for some seismically active areas in New Zealand, and the return periods, peak ground acceleration and felt intensities given in Table 9.2 must therefore be taken as indicative only.

For this study the probability of each of the damage scenarios presented in Table 9.1 above is to be assessed for a “moderate’ earthquake (150 year return period) and a “design” earthquake (450 year return period) to obtain an overall comparative risk index. The expected damage ratios are listed in Table 9.2, and their derivation is discussed below.

Damage probability	Earthquake		
	None	Moderate	Design
Earthquake return period	NA	150	450
Approx. intensity	NA	MM8	MM8.5
Approx. peak ground acceleration	NA	0.25g	0.37g
Max. inter-storey deflection	NA	15mm	28mm
Probability of open door at fire floor	0.05	0.05	0.1
Probability of pressurisation system operating.	0.97	0.3	0.1
Probability of sprinkler control	0.99	0.1	0.01
Probability of mod. barrier damage	0.05	0.7	0.25
Probability of major barrier damage	0	0.1	0.7

Table 9.2 : Earthquake damage probability

The values quoted have been assessed using engineering judgement based on the material given in section 8 of this report. They are as follows.

- Probability of open door – Australian Fire Engineering Guidelines (FCRCL,1996), (refer this report section 8.5). The increased probability at the major damage stage is to reflect that deformation of the walls may prevent doors closing completely.
- Probability of pressurisation system operating (this report section 8.4) - An initial reliability of 0.97 is based on data from Klote and Milke (1992). The reduced post earthquake figures are based on the probability of the electric power supply failure using data from Feeney (2001) and by inference from Christchurch Lifelines Group (1997) for the moderate earthquake. Note that

these figures do not include the effect of barrier damage, which is considered separately.

- Probability of sprinkler control (this report section 8.2 and 8.3) – A pre-earthquake reliability of 0.99 is taken from FCRCL (1996). Post earthquake probability is primarily determined by the reliability of the external water and electricity supplies. This report has assumed an installation to the minimum requirements of the Acceptable Solution (BIA, 2000). This is a single town main supply with electric booster pump. Feeney (2001) assesses the probability of failure in a design earthquake as 0.99. This figure includes consideration of sprinkler pipework integrity as well as water and power supply vulnerability assessed for a New Zealand urban area. The probability of failure of 0.90 for a "moderate" earthquake reflects the high vulnerability of the water and power supplies as identified in New Zealand reports (Brunsdon and Clark, 2000, and Christchurch Lifelines Group, 1997).
- Probability of barrier damage (this report section 8.5) – Pre-earthquake probability of failure from FCRCL (1996). Post-earthquake values are inferred from date by Porter et al (2001), Sekizawa et al.(2000) and the NZ Loading Code (SNZ, 1992). It is noted that the deflection expected at "moderate" earthquake level (15 mm) is well in excess of the recommended deflections (8 to 13 mm) from the above references for loss of serviceability due to cracking. However the deflection at "design" earthquake level exactly matches Porter et al figure of 28 mm for "significant" damage.

From Table 9.2 and its derivation it can be seen that;

- The barriers are subject to significant loss of integrity in a moderate earthquake. The extent of barrier damage is primarily a function of the inter-storey earthquake deflection, which varies with the storey height above ground. The deflection used here is the maximum deflection and is representative of the lower few floors. This value is considered appropriate, as these floors are the high-risk fire locations for loss of tenability in the stairs.
- The post-earthquake performance of the sprinkler and pressurisations systems is dominated by the vulnerability of the external water and/or power supplies. This is independent of the floor location.

Emergency lighting as required by the Acceptable Solutions consists of robust, independent battery powered units, and is considered to remain operational during evacuation. It is acknowledged that effective lighting is critical for effective evacuation.

Earthquakes of greater intensity than the design earthquake are of course possible, but with decreasing probability of occurrence. A significant concern with larger earthquakes is the potential damage to the stairs, possibly trapping occupants in the building. This consideration is outside the scope of this project, but highlights the importance of adequate design and detailing of stairs to ensure that they survive at least the design earthquake.

9.12 Required safe egress time.

The required time to evacuate the building in a typical fire emergency situation has been assessed using the method of Nelson and MacLennan (1995). The speed of evacuation is generally controlled by the capacity of the stair. Calculations are included in Appendix F. Table 9.3 is a summary of the calculation results.

Location	Time of travel	
	1 stair available	2 stairs available
Max. travel time to stair entry	3.7 min	3.4 min
Exit flow in stairs	47.9 person/min	95.8 person/min.
Time to travel one flight	0.31 min	0.31 min
Time to evacuate floor (ignoring queuing)	1.67 min	0.84 min
Time from lowest stair to final exit	0.5 min	0.5 min
Total time to evacuate building	35.9 min	19.9 min

Table 9.3 : Required safe egress time summary.

There are a number of issues that differentiate post-earthquake design scenarios from those envisaged in the typical fire evacuation situation. These include;

- Damage to alarm systems may delay cues and initiation of action.
- The duration of earthquake shaking will vary. Earthquake shaking from a major fault may exceed one minute duration, and it is unlikely that any occupant response will be possible during this time.

- Damage to ceilings, stairs, doors and partitions may reduce travel speeds.
- Normal evacuation management may fail due to communication system damage, leading to possible congestion and queuing at vulnerable locations.

However it is assumed for this analysis that occupants will endeavour to leave the building as soon as possible after shaking ceases. The adopted pre-movement time of 3 minutes is based on 2 minutes for earthquake duration and 1 minute for occupant decision and investigation time.

The total evacuation time is dictated by the capacity of the stairs, and queuing is likely to occur at the entry points to the stair on each floor. In the absence of an operational management system, the time to evacuate any given floor will be heavily dependent on the hierarchy of use of the stair. For this analysis it is assumed that persons already in the stair will take dominance over those waiting at other floors. This will mean that, once the stairs are full, the building will empty progressively from the top floor down.

The obvious exception to this must be the fire floor, unless this is situated in the top few levels. However it seems reasonable to assume that the occupants of this level will have an earlier awareness and an increased motivation of self preservation the will enable them to enter the stair before conditions on the floor become untenable.

9.13 Number of occupants at risk.

The tenability times determined in 9.11 and the required safe egress times from 9.12 above are compared to determine the number of persons at risk for a fire on each floor for each scenario.

Consideration of the tenability times shows that, if evacuation of the fire floor takes some precedence over other floors, the safe escape from the building is determined by the tenability of the stairs. The procedure for determining the occupants at risk is therefore as follows.

For a given floor and scenario, determine;

- The number of occupants on the fire floor and all floors above.
- The time to loss of tenability of the stair/stairs at the fire floor.

- The number of occupants in the upper floors that cannot evacuate to below the fire floor in this time.
- The average number of occupants for all floors for each scenario.

The calculation basis and spreadsheet printout are given in Appendix G of this report.

For each selected earthquake, the damage probabilities detailed in Table 9.2 above are then applied to each scenario to determine an average number of persons at risk for that earthquake. The results are shown in the top line of Table 9.4.

To consider possible means of reducing the risk, additional computations were carried out with enhanced systems as follows.

- Sprinkler reliability of 80%, as recommended by Robertson and Mehaffey, (2000).
- Barrier reliability of 90%, assumed achievable with proper seismic joint detailing (FCRCL, 1996).

Results are shown in lines 2 and 3 of Table 9.4.

A typical spreadsheet calculation printout is included in Appendix H of this report.

Design Criteria	Number of Occupants at risk		
	No earthquake.	Moderate earthquake	Design earthquake
Design to Acceptable Solutions	0.2	216	335
Enhanced sprinkler reliability (80%)	NA	66	195
Enhanced barrier integrity (90%)	NA	30	38

Table 9. 4 : Number of occupants at risk

For each earthquake case, the number of occupants shown in Table 9.4 is the number of persons unable to evacuate to below the fire floor before the stairs become untenable, based on the average for a fire on any floor of the building. The Table shows that;

- For a total building occupancy of 1600 persons, the number at risk is significant in both scenarios considered.
- The risk of loss of life may be significantly reduced by improved post-earthquake reliability of the sprinkler and stair enclosures.

9.14 Absolute risk

This analysis has used a simplified fire spread model and single design fire. While this should give a reasonable comparison of performance for the various scenarios, it cannot be considered as sufficiently rigorous and comprehensive to give an authoritative measure of risk in absolute terms. However, as our scenarios are based on realistic assumptions and likely events, it may be instructive to consider our results against current opinion on quantifying acceptable risk.

Using our results, an approximate absolute risk can be calculated using assumed figures for the probability of "serious ignition" (ignitions that cannot be suppressed by building occupants) from Scawthorn (1995). Results are shown in Table 9.5.

	Mod. earthquake	Design earthquake
Annual probability of earthquake (P1)	0.0067	0.0020
Probability of "serious ignition" (P2)	0.027	0.037
Probability building is occupied (P3)	0.24	0.24
Combined probability P' = (P1xP2xP3)	4.34 $\times 10^{-5}$	1.78 $\times 10^{-5}$
Number of occupants at risk (N)	216	335
Probability of loss of life per Person per year. (P'/N)	2.0 $\times 10^{-7}$	5.3 $\times 10^{-8}$

Table 9.5 : Absolute risk.

Porter and Scawthorn (1998) list a number of recommended values for "tolerable" risk for loss of life.
These include;

- US Government agencies, for general environmental hazards ; 1 in 1,000,000 chance of untimely death in a lifetime (1.4 $\times 10^{-8}$ per person per year for 70 year expected life).
- FEMA (US). 2. 8 $\times 10^{-7}$ per person per year due to earthquake induced collapse in an engineered building.

Other authorities include the severity of the event (expressed as the number of fatalities) as one of the determining criteria for acceptable probability. These include;

- UK draft fire safety code DD240 (BSI, 1997), which suggests 5 $x10^{-8}$ per person per year for multiple deaths (greater than 100 persons at risk).
- Helm (1996) provides a graphical relationship (Figure 9.6) for tolerable risk due to natural and technological disasters. Results from Table 9.5 are plotted on Helm's chart in Figure 9.6.

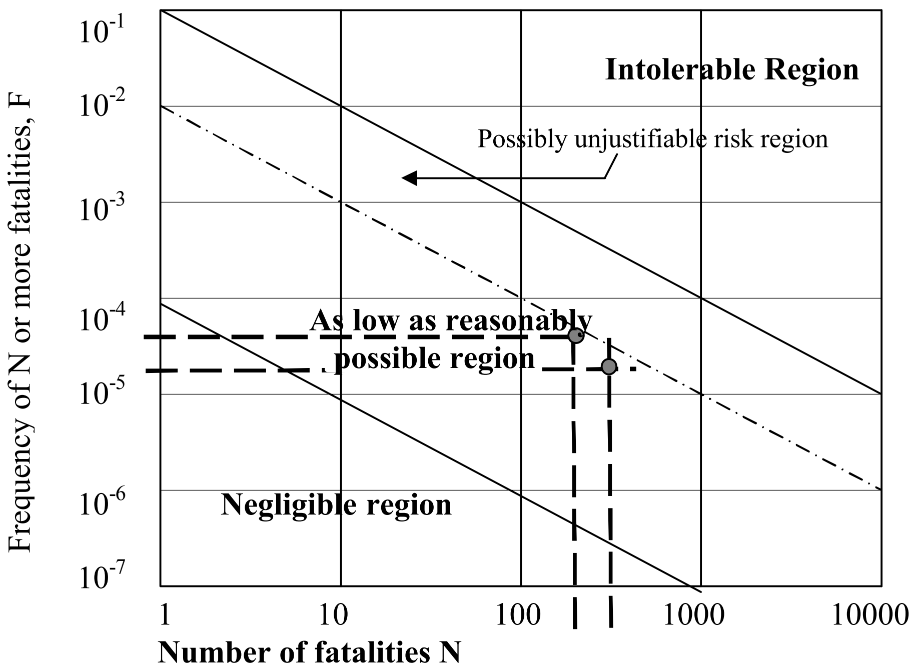


Figure 9.6 Tolerable risk as a function of severity

(after Helm,1996)

As this analysis includes a comparison of different scenarios it is appropriate to compare results with an authority that includes the event severity. Both our scenarios exceed the recommended UK draft recommendations. On the Helm chart, the results fall within the region where the risk is tolerable only if the cost of risk reduction would exceed the improvement gained. The moderate earthquake plot in particular is close to the region identified as "tolerable" only if risk reduction is impracticable or grossly disproportionate to the improvement gained."

Table 9.5 indicates that;

- The moderate earthquake presents a greater risk of loss of life due to its greater frequency.
- Both scenarios pose a significant risk of loss of life, and would be unacceptable to most authorities without detailed justification that further risk reduction is economically impracticable. Note that any meaningful cost/benefit analysis will need to be building specific to properly assess the cost and benefits of risk reduction.

9.15 Conclusions

The following conclusions can be drawn for the case study building for the scenario of fire following an earthquake.

- Occupants are exposed to a significant risk of loss of life, which would require cost/benefit justification for acceptance by most authorities reviewed above.
- The moderate earthquake presents a greater annual risk of loss of life due to its more frequent occurrence.
- Integrity of stair enclosures is the most significant factor in ensuring adequate available evacuation time. Although the deflections of the building comply with code limitations for both ultimate and serviceability limit states, the seismic degradation of the enclosures is considerable.
- Sprinkler control may not maintain tenability in the stairs in the event of enclosure damage.
- Stair pressurisation is not effective once enclosures are damaged.

These conclusions are assessed from a model that includes the specific structural characteristics, size, layout, fire load, mechanical system and ventilation of the case study building. They will not necessarily apply to other building. In addition there are features that were considered adequate in this building that may be of major importance in other situations, and should generally be included in the risk assessment. These are:

- Effective emergency lighting in the stairs.
- Effective smoke control in air handling systems.

- Adequate fire resistance of stair enclosures for “real’ fire exposure.

Our analysis indicates that the “moderate” earthquake presents the larger annual risk to loss of life, due to its more frequent occurrence. However it should be noted that larger earthquakes would result in increasing damage to fittings, fixtures and elements, which will cause obstruction and delays in evacuation.

10. Conclusions

10.1 General

Earthquakes in seismically active areas can significantly reduce the reliability of fire safety systems in buildings, and significantly increase the risk of loss of life if a fire occurs within the building.

The case study in this report, based on the New Zealand Acceptable Solutions, has demonstrated that the increased risk is at a level where it would be acceptable to most authorities only if risk reduction was impracticable or grossly disproportionate to the improvement gained.

10.2 Design philosophy

The philosophy of performance- based design is to enable each building to be individually designed to achieve a safe and economic solution to meet the specified performance objectives. Logically this requires the performance of the building to be assessed for all realistic design scenarios to enable the overall performance to be measured against the stated objectives of the code. Even though the code objectives may not be specifically quantified, it is appropriate that less likely events should be included in the assessment, to enable a comparison of performance level with other more common events. Post- earthquake fire is a low probability event but with high potential consequences, and it is appropriate that it be included in the risk analysis.

If prescriptive solutions are to be included as a means of compliance, the integrity of the philosophy requires that they have a sound technical basis consistent with the performance requirements of the code. This is particularly relevant where the document is used as a performance measure for alternative solutions.

10.3 Principal performance concerns.

Consideration of past earthquakes and ongoing research in several countries has identified three major factors contributing to the high level of risk in post-earthquake fire. These are

- A high probability of failure of many fire safety systems, due to often inadequate design requirements, design implementation and detailing, and inspection and testing regimes. (Note that in this context fire safety systems include all methods used to warn people of an emergency, provide safe evacuation, and restrict the spread of fire, and includes both active and passive protection.)
- A high level of dependence on vulnerable external services (electricity and water supply).
- The non-availability of external intervention by Fire Service personnel to assist evacuation and control fire spread.

10.4 Performance code trends

Most countries with performance- based codes are moving toward developing a probabilistic risk analysis model for design. This enables the earthquake vulnerability of systems to be specifically assessed for each individual situation.

Where a prescriptive design option is to be included, some provision needs to be made to include the implications of earthquake damage. Options being considered in some countries for a partial prescriptive design solution include;

- Designing the post-earthquake building for a reduced heat release fire, with the design fire size increased as the system reliability decreased.
- Designing the building for a normal design fire but assuming that one or more of the principal fire safety systems is inoperative.

10.5 The New Zealand Building Code provisions

The New Zealand Building Code provisions for fire do not provide any quantified performance objectives, so the prescriptive Acceptable Solutions have become the principal criteria for assessment of alternative designs. Unfortunately no technical basis is given for many of the provisions, so the specific area of concern initiating a requirement is not always apparent. There are also a number of apparent inconsistencies, and technical justification has not been made available for a number of recent amendments. The document therefore lacks the technical foundation and the transparency to enable it to be used confidently and effectively as a measure of performance.

The Acceptable Solution for fire has no specific mention of post-earthquake fire. Design of fire safety system for earthquake loads is included in other section of the building code, and the Acceptable Solution appears to assume that the design to these provisions will ensure adequate safety.

However recent research in New Zealand and consideration of overseas research and earthquake observation indicates that current design recommendations of the approved documents are inadequate.
Of particular concern in the New Zealand context are;

- The lack of any methodology to allow for the vulnerability of public utilities, especially electric power and water.
- The lack of adequate and consistent design standards and coordination procedures to ensure that system design and installation is consistent with the overall building performance
- The lack of provisions in the Approved Documents to limit damage to passive fire protection due to building deflections in an earthquake.
- The low reliability of mechanical smoke control, particularly in sophisticated, multi-element systems.

In relation to the vulnerability of water supply, it is of concern that a single mains water supply with electric pumps to boost to operating pressure appears to be acceptable to satisfy the Acceptable Solution. For seismically active areas this represents a significant reduction on the requirements of the Sprinkler Code NZS 4541:1996 (SNZ, 1996), which requires independent dual supplies.

10.6 Case study

The case study in this report considered a 20 storey concrete framed office building designed to the Acceptable Solutions. The risk assessment found that there was a significant risk of loss of life in both moderate and design earthquake events. The principal contributors were the vulnerability of the public water supply to the sprinkler system, and the loss of integrity of the stair enclosures permitting smoke spread into the stairs.

10.7 Other concerns.

Post Earthquake Occupations of buildings

There is a significant risk of loss of life in any building re-occupied before the fire safety systems have been checked for performance after the earthquake. Unseen damage to fire separations may allow fire and smoke spread, and any failure of detection or suppression systems will reduce available escape times.

Retrofitting of old buildings.

The case study in this report has assumed a modern building with currently acceptable earthquake performance. In the retrofitting of older buildings, there is likely to be an increased risk due to higher potential damage to systems and building elements. This may result in less reliable safety systems and more obstruction and delays to persons evacuating the building.

In addition, the New Zealand Building Code requires the retrofitted systems to achieve compliance to a level as nearly as is reasonably practicable to that required for a new building. The level of reasonableness assumes a degree of cost/benefit consideration, but in most cases the decision will be subjective. The end result in most cases will be a reduced level of performance to that expected for a new building.

Fire Resistance Ratings.

The F ratings in the Acceptable Solution are based on ensuring that fire separations maintain an appropriate level of protection for sufficient time for occupants to escape. However the requirements are based on fire resistance determined in standard fire tests, which may overestimate the survival time of the separation in a realistic fire. In addition any damage or dislocation to building fittings and ceilings may obstruct means of escape and increase the required time for safe evacuation.

Defend in Place options.

Defend in place options are accepted as an appropriate means of protecting occupants in specific types of buildings, especially tall residential buildings and buildings where people's mobility is impaired or restricted. It is evident that the fire separation in these cases must be designed to resist a design earthquake without loss of integrity and to resist the fire exposure due complete burnout of the fire compartment without suppression systems or outside intervention. Also a high reliability is required of any air handling systems that are could allow fire or smoke spread.

If adequate means of escape is not available in these situations, it is critical that building occupants are fully trained and aware of the importance of the necessary procedures in a fire emergency. Voice communication systems should not be relied after an earthquake.

11. Recommendations.

11.1 General

It is anticipated that there will be development towards full probabilistic design methodologies for the New Zealand Building Code in the future. This will allow post-earthquake reliability of fire safety systems to be specifically considered in the analysis, However it is likely that that there will continue to be a prescriptive design option in the New Zealand Building Code and the following recommendations include for this assumption.

The recommendations are based on the information contained in this report. They are intended to reduce the risk in post-earthquake fire, and to improve the technical status of the Acceptable Solution for fire. They include;

- Amending the Building Code Approved Documents to identify post-earthquake fire as a design scenario in seismic areas, and to require consideration of post-earthquake system reliability.
- Improving the post-earthquake reliability of active and passive fire safety systems.
- Improving and validating the technical basis of the Acceptable Solution for fire.
- Incorporating inspection of fire safety systems as part of the post-earthquake safety assessment of damaged buildings.

11.2 Building Code requirements.

Assessment of fire designs against the performance requirements of the Building Code will continue to be subjective and open to individual interpretation until performance requirements are quantified. Without quantified performance objectives it is also be extremely difficult to carry out cost/benefit analyses to justify amendments to the code and/ or Approved Documents. The following recommendations are intended to address this issue.

It is recommended that;

- Quantified performance requirements be developed for the Building Code fire safety clauses.
- The Building Code be amended to specify an appropriate earthquake design level for fire safety systems. It accordance with Building Act provisions, a cost/benefit analysis would be desirable to determination of an appropriate earthquake level.

11.3 Approved Documents.

It is recommended that;

- Priority be given to completion of current amendments to New Zealand Standards NZS4203, NZS4219 and NZS4541, to ensuring that the amended documents are compatible, and that their provisions will achieve a performance appropriate for life safety systems.
- The New Zealand Building Code Acceptable Solutions be amended to provide an appropriate level of redundancy in fire design to allow for vulnerability of building fire safety systems and public utilities. A cost/benefit analysis is recommended to determine appropriate redundancy factors.
- Sprinkler protected buildings be required to have two independent water supplies, to compensate for the known earthquake vulnerability of the utility systems. Mandatory on-site water storage and emergency power supply could be considered as an economic option.
- The current F rating requirements in the Acceptable Solutions be reviewed to incorporate consideration of real fire performance and seismic vulnerability of sprinkler systems, as well as potential delays in post-earthquake evacuation due to building damage.
- All future amendments to the Acceptable Solutions include a quantified technical and/or cost benefit justification. This would increase practitioner confidence in the document. It would also clarify the performance issues addressed by the amendments and allow for better-informed and more appropriate application of the individual requirements.

11.4 Implementation issues.

It is recommended that;

- Post-earthquake reconnaissance teams for building safety should include fire safety professionals. The inspection should include examination and testing as appropriate of all fire safety systems, both active and passive, and consideration of potential ignition sources due to damaged systems, services and equipment.
- Territorial authorities should ensure that mechanical systems required for life safety are adequately designed and detailed by appropriately qualified professionals using the earthquake response parameters specific to the individual building and system location. This will require detailed input from the structural design consultant.
- Territorial authorities should ensure that the inspection, testing and reporting procedures, especially for sophisticated fire safety systems, are regularly reviewed and audited.

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Appendix A : Modified Mercalli earthquake intensity scale

Intensity	Construction Category					
	Pre-code			Post-code "Brittle' Era	Capacity Design Era	Special Low Damage
	I D	II C	III B	IV A	V	VI
MM12			*Most destroyed*	*Many* Destroyed	Heavily damaged, some with partial collapse	Moderately damaged
MM11		*Most destroyed*	*Many* destroyed	Heavily damaged, some collapsing	Damaged, some with partial collapse	Minor damage, a few moderate damages
MM10	*Most destroyed*	*Many* destroyed	Heavily damaged, some collapse	Damaged, some with partial collapse	Moderately damaged, a few partial collapses	A few instances of damage
MM9	*Many* destroyed	Heavily damaged, some collapse	Damaged, some with partial collapse	Damaged in some cases, some flexible frames seriously	Damaged in some cases, some flexible frames moderately	
MM8	Heavily damaged, some collapse	Damaged, some with partial collapse	Damaged in some cases	A few instances of damage		
MM7	Cracked, some minor masonry falls	A few damaged				
MM6	slight damage may occur					

Construction Types:

Buildings Type I (Masonry D in the NZ 1965MM scale)

Buildings with low standard of workmanship, poor mortar, or constructed of weak materials like mud brick or rammed earth. Soft storey structures (e.g. shops) made of masonry, weak reinforced concrete, or composite materials (e.g. some walls timber, some brick) not well tied together. Masonry buildings otherwise conforming to Buildings Types I - III, but also having heavy unreinforced masonry towers. (Buildings constructed entirely of timber must be of extremely low quality to be Type I).

Buildings Type II (Mason,y C in the lIZ 1966MM scale)

Buildings of ordinary workmanship, with mortar of average quality. No extreme weakness, such as inadequate bonding of the corners, but neither designed nor reinforced to resist lateral forces. Such buildings not having heavy unreinforced masonry towers.

Buildings Type III (Masonry B in the NZ 1966MM scale)

Reinforced masonry or concrete buildings of good workmanship and with sound mortar, but not formally designed to resist earthquake forces.

Structures Type IV (Masonry A in the lIZ *1966MM scale)*

Buildings and bridges designed and built to resist earthquakes to normal use standards, i.e. no special collapse or damage limiting measures taken (mid-1930's to c.1970 for concrete and to c. 1980 for other materials).

Structures Type V

Buildings and bridges, designed and built to normal use standards, i.e. no special damage limiting measures taken, other than code requirements, dating from since c. 1970 for concrete and c. 1980 for other materials.

Structures Type VI

Structures, dating from c. 1980, with well-defined foundation behaviour, which have been specially designed for minimal damage, e.g. seismically isolated emergency facilities, some structures with dangerous or high contents, or new generation low damage structures.

Appendix B : New Zealand Building Code : fire clauses

C FIRE SAFETY

C1 OUTBREAK OF FIRE

Provisions	Limits on application
OBJECTIVE	
C1.1 The objective of this provision is to safeguard people from injury or illness caused by *fire*.	
FUNCTIONAL REQUIREMENT	
C1.2 In *buildings* fixed appliances using the controlled combustion of solid, liquid or gaseous fuel, shall be installed in a way which reduces the likelihood of *fire*.	
PERFORMANCE	
C1.3.1 Fixed appliances and services shall be installed so as to avoid the accumulation of gases within the installation and in *building* spaces, where heat or ignition could cause uncontrolled combustion or explosion.	
C1.3.2 Fixed appliances shall be installed in a manner that does not raise the temperature of any *building element* by heat transfer or concentration to a level that would adversely affect its physical or mechanical properties or function.	

C2 MEANS OF ESCAPE

Provisions

OBJECTIVE

C2.1 The objective of this provision is to:

(a) Safeguard people from injury or illness from a *fire* while escaping to a *safe place*, and

(b) Facilitate *fire* rescue operations.

FUNCTIONAL REQUIREMENT

C2.2 *Buildings* shall be provided with *escape routes* which:

(a) Give people *adequate* time to reach a *safe place* without being overcome by the effects of *fire*, and

(b) Give fire service personnel *adequate* time to undertake rescue operations.

PERFORMANCE

C2.3.1 The number of *open paths* available to each person escaping to an *exitway* or *final exit* shall be appropriate to:

(a) The *travel distance*,

(b) The number of occupants,

(c) The *fire hazard*, and

(d) The *fire safety systems* installed in the *firecell*.

C2.3.2 The number of *exitways* or *final exits* available to each person shall be appropriate to:

(a) *The open path travel distance*,

(b) The *building height*,

(c) The number of occupants,

Limits on application

Provisions

(d) The *fire hazard*, and

(e) The *fire safety systems* installed in the *building*.

C2.3.3 *Escape routes* shall be:

(a) Of *adequate* size for the number of occupants,

(b) Free of obstruction in the direction of escape,

(c) Of length appropriate to the mobility of the people using them,

(d) Resistant to the spread of *fire* as required by Clause C3 "Spread of Fire",

(e) Easy to find as required by Clause F8 "Signs",

(f) Provided with *adequate* illumination as required by Clause F6 "Lighting for Emergency", and

(g) Easy and safe to use as required by Clause D1.3.3 "Access Routes".

Limits on applications

C3 SPREAD OF FIRE

Provisions

OBJECTIVE

C3.1 The objective of this provision is to:

a) Safeguard people from injury or illness when evacuating a *building* during *fire*.

b) Provide protection to fire service personnel during firefighting operations.

c) Protect adjacent *household units* and *other property* from the effects of *fire*.

d) Safeguard the environment from adverse effects of *fire*.

FUNCTIONAL REQUIREMENT

C3.2 *Buildings* shall be provided with safeguards against *fire* spread so that:

a) Occupants have time to escape to a *safe place* without being overcome by the effects of *fire*,

b) Firefighters may undertake rescue operations and protect property,

c) Adjacent *household units* and *other property* are protected from damage, and

d) Significant quantities of *hazardous substances* are not released to the environment during *fire*.

PERFORMANCE

C3.3.1 Interior surface finishes on walls, floors, ceilings and suspended *building elements*, shall resist the spread of *fire* and limit the generation of toxic gases, smoke and heat, to a degree appropriate to:

a) The *travel distance*,

Limits on application

Requirement C3.2 (d) applies only to *buildings* where significant quantities of *hazardous substances* are stored or processed.

Provisions

b) The number of occupants,

c) The *fire hazard,* and

d) The active *fire safety systems* installed in the *building.*

C3.3.2 *Fire separations* shall be provided within *buildings* to avoid the spread of *fire* and smoke to:

a) Other *firecells,*

b) Spaces intended for sleeping, and

c) *Household units* within the same *building* or *adjacent buildings.*

C3.3.3 *Fire separations* shall:

a) Where openings occur, be provided with *fire resisting closures* to maintain the *integrity* of the *fire separations* for an *adequate* time, and

b) Where penetrations occur, maintain the *fire resistance rating* of the *fire separation.*

C3.3.4 *Concealed spaces* and cavities within *buildings* shall be sealed and subdivided where necessary to inhibit the unseen spread of *fire* and smoke.

C3.3.5 *External walls* and roofs shall have resistance to the spread of *fire*, appropriate to the *fire load* within the *building* and to the proximity of other *household units* and *other property.*

C3.3.6 Automatic fire suppression systems shall be installed where people would otherwise be:

a) Unlikely to reach a *safe place* in *adequate* time because of the number of storeys in the *building,*

b) Required to remain within the *building* without proceeding directly to a *final exit*, or where the *evacuation time* is excessive,

c) Unlikely to reach a *safe place* due to confinement under institutional care because of mental or physical disability, illness or legal detention, and the *evacuation time* is excessive, or

Limits on applications

Performance C3.3.2 shall not apply to *Detached Dwellings*, or within *household units* of *Multi-unit Dwellings.*

Performance C3.3.4 shall not apply to *Detached Dwellings.*

Provisions

d) At high risk due to the *fire load* and *fire hazard* within the *building*.

C3.3.7 Air conditioning and mechanical ventilation systems shall be constructed to avoid circulation of smoke and *fire* between *firecells*.

C3.3.8 Where an automatic smoke control system is installed, it shall be constructed to:

a) Avoid the spread of *fire* and smoke between *firecells*, and

b) Protect *escape routes* from smoke until the occupants have reached a *safe place*.

C3.3.9 The *fire safety systems* installed shall facilitate the specific needs of fire service personnel to:

a) Carry out rescue operations, and

b) Control the spread of *fire*.

C3.3.10 Environmental protection systems shall ensure a low probability of *hazardous substances* being released to:

a) Soils, vegetation or natural waters,

b) The atmosphere, and

c) *Sewers* or public *drains*.

Limits on applications

Performance C3.3.10 applies only to *buildings* where significant quantities of *hazardous substances* are stored or processed.

C4 STRUCTURAL STABILITY

Provisions	Limits on application

OBJECTIVE

C4.1 The objective of this provision is to:

(a) Safeguard people from injury due to loss of structural stability during *fire*, and

(b) Protect *household units* and *other property* from damage due to structural instability caused by *fire*.

FUNCTIONAL REQUIREMENT

C4.2 *Buildings* shall be constructed to maintain structural stability during *fire* to:

(a) Allow people *adequate* time to evacuate safely,

(b) Allow fire service personnel *adequate* time to undertake rescue and firefighting operations, and

(c) Avoid collapse and consequential damage to adjacent *household units* or *other property*.

PERFORMANCE

C4.3.1 Structural elements of *buildings* shall have *fire* resistance appropriate to the function of the elements, the *fire load*, the *fire intensity*, the *fire hazard*, the height of the *buildings* and the *fire* control facilities external to and within them.

C4.3.2 Structural elements shall have a *fire* resistance of no less than that of any element to which they provide support within the same *firecell*.

C4.3.3 Collapse of elements having lesser *fire* resistance shall not cause the consequential collapse of elements required to have a higher *fire* resistance.

Appendix C: New Zealand Building Code : structure

B STABILITY

B1 STRUCTURE

Provisions	Limits on application

OBJECTIVE

B1.1 The objective of this provision is to:

(a) Safeguard people from injury caused by structural failure,

(b) Safeguard people from loss of *amenity* caused by structural behaviour, and

(c) Protect *other property* from physical damage caused by structural failure.

FUNCTIONAL REQUIREMENT

B1.2 *Buildings, building elements* and *sitework* shall withstand the combination of loads that they are likely to experience during *construction* or *alteration* and throughout their lives.

PERFORMANCE

B1.3.1 *Buildings, building elements* and *sitework* shall have a low probability of rupturing, becoming unstable, losing equilibrium, or collapsing during *construction* or *alteration* and throughout their lives.

B1.3.2 *Buildings, building elements* and *sitework* shall have a low probability of causing loss of *amenity* through undue deformation, vibratory response, degradation, or other physical characteristics throughout their lives, or during *construction* or *alteration* when the *building* is in use.

B1.3.3 Account shall be taken of all physical conditions likely to affect the stability of *buildings, building elements* and *sitework*, including:

(a) Self-weight,

(b) Imposed gravity loads arising from use,

Provisions	Limits on application
(c) Temperature,	
(d) Earth pressure,	
(e) Water and other liquids,	
(f) Earthquake,	
(g) Snow,	
(h) Wind,	
(i) *Fire,*	
(j) Impact,	
(k) Explosion,	
(l) Reversing or fluctuating effects,	
(m) Differential movement,	
(n) Vegetation,	
(o) Adverse effects due to insufficient separation from other *buildings,*	
(p) Influence of equipment, services, non-structural elements and contents,	
(q) Time dependent effects including creep and shrinkage, and	
(r) Removal of support.	
B1.3.4 Due allowance shall be made for:	
(a) The consequences of failure,	
(b) The intended use of the *building,*	
(c) Effects of uncertainties resulting from *construction* activities, or the sequence in which *construction* activities occur,	
(d) Variation in the properties of materials and the characteristics of the site, and	
(e) Accuracy limitations inherent in the methods used to predict the stability of *buildings.*	

Provisions

B1.3.5 The demolition of *buildings* shall be carried out in a way that avoids the likelihood of premature collapse.

B1.3.6 *Sitework*, where necessary, shall be carried out to:

(a) Provide stability for *construction* on the site, and

(b) Avoid the likelihood of damage to *other property*.

B1.3.7 Any *sitework* and associated supports shall take account of the effects of:

(a) Changes in ground water level,

(b) Water, weather and vegetation, and

(c) Ground loss and slumping.

Limits on applications

Appendix D : New Zealand Building Code: Acceptable Solutions C/AS1 : fire safety precautions

Table 4.1: Fire Safety precautions
Key to table references

Part 2	Paragraph	2.4.2
Part 3	Paragraphs	3.1.5, 3.13.1 and 3.19.2
Part 4	Paragraphs	4.3, 4.3.1, 4.3.3, 4.4.1, 4.5.2, 4.5.3, 4.5.4, 4.5.7, 4.5.9, 4.5.10, 4.5.13, 4.5.14, 4.5.15, 4.5.19
Part 5	Paragraphs	5.5.1, 5.6.5, 5.6.7, 5.9.4(c)
Part 6	Paragraphs	6.2.1, 6.4.1, 6.7.1, 6.8.1, 6.8.5, 6.8.6, 6.10.1, 6.11.1, 6.15.1, 6.19.9, 6.21.1, 6.23.1 (d), 6.23.2, 6.23.3
Part 8	Paragraphs	8.2.1, 8.2.2, 8.2.3
Appendix A	Paragraphs	A1.1.1 and A1.1.2

Fire safety precautions

Type	Description
1	No Type 1 currently specified.
2	Manual fire alarm system.
3	Automatic fire alarm system with heat detectors and manual call points.
4	Automatic fire alarm system with smoke detectors and manual call points.
5	Automatic fire alarm system with modified smoke/heat detection and manual call points.
6	Automatic fire sprinkler system with manual call points.
7	Automatic fire sprinkler system with smoke detectors and manual call points.
8	Voice communication system.
9	Smoke control in air handling system.
10	Natural smoke venting.
11	Mechanical smoke extract.
12	No Type 12 currently specified.
13	Pressurisation of safe paths.
14	Fire hose reels.
15	Fire Service lift control.
16	Emergency lighting in exitways.
17	Emergency electrical power supply.
18	Fire hydrant system.
19	Refuge areas.
20	Fire systems centre.

Special applications

a Not required where:

i) the *escape routes* serve an *occupant load* of no more than 50 in *purpose groups* CS, CM, WL, WM, WH and WF, or

ii) the *escape routes* are for *purpose group* SA and serve no more than 10 beds, (or 20 beds for trampers huts, see Paragraph 6.20.6), or

iii) exit doors from *purpose group* SA and SR *firecells* open directly onto a *safe place* or an external safepath (see Paragraph 3.14).

b Where only a single *escape route* is available, no less than a Type 4 alarm is required. See Paragraph 3.15.3 for situations where sprinklers are required.

c Required where Fire Service hose run distance, from the Fire Service vehicular access (see Paragraph 8.1.1) to any point on any floor, is greater than 75 m.

d Emergency lighting extended to *open paths* throughout the *firecell.*

e Type 5 is permitted as an alternative alarm system within *firecells* containing sleeping accommodation. (See Appendix A for description of Type 5.)

f A direct connection to the Fire Service is not required provided a telephone is installed and freely available at all times to enable “111” calls to be made.

Note:
The numbered references are more fully explained in Appendix A.

Table **4.1/1: Fire safety precautions for active purpose group firecells**

Occupant load 100 maximum

Purpose Group	**Escape height**							
	0m (or single floor)	<4 m (or 2 floors)	4 m to <10 m (or 3 floors)	10 m to <25 m	25 m to <34 m	34 m to <46 m	46 m to <58 m	Over 58 m
CS	F0	F30	F30	F45	F30	F30	F30	F60
	2af 18c	2af 18c	3b 9 16 18c	4 9 16 18	6 9 13 15 16 18	7 9 13 15 16 18	7 9 13 15 16 18	7 9 13 15 16 17 18 19
CM (Note 5)	F0	F30	F30	F45	F30	F30	F30	F60
	2af 18c	2af 18c	3b 9 16 18c	3b 9 15 16 18	6 9 13 15 16 18	7 9 13 15 16 18 20	7 9 13 15 16 18 20	7 9 13 15 16 17 18 19 20
WL WM WH (Note 5)	F0	F30	F30	F45	F30	F30	F30	F60
	2af 18c	2af 18c	3b 16 18c	3b 15 16 18	6 15 16 18	6 9 15 16 18	7 9 13 15 16 18	7 9 13 15 16 18 19
WF	F0	F30	F30	F30	F30	F30	F30	F60
			18c	16 18	16 18	13 15 16 18	13 15 16 18	13 15 16 18 19 20
Column	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**

Notes:

1. **Use of Table**: Refer to Paragraph 4.4 for instructions on using this table to determine the *fire safety precautions* in *firecells.*
2. **Adjoining firecells having a FO rating**: Paragraph 6.2.1 requires adjoining *firecells to* be separated by *fire separations* with *FRR* no less than 15/1 5/1 5.
3. **Intermediate Floors**: Where a *firecell* contains *intermediate floors* a 15/15/15 *FRR* shall apply to the *intermediate floors* and supporting elements, and smoke control systems Type 9 and either Type 10 or Type 11, are required (see Paragraphs 4.5.16 to 4.5.18, 6.14.3 and 6.21.5 to 6.22.14).
4. **Car Parking**: Refer to Paragraphs 6.10.3 to 6.10.6 for car parking provisions within *buildings.*
5. **Sprinklers**: Refer to Paragraph 5.6.l2forsprinkler requirements in *FHC4 firecells where the escape* height is two floors or higher.

Table 4.1/2: Fire safety precautions for active purpose group firecells — Occupant load 101 to 500

Purpose Group	Escape height: 0m (or single floor)	<4 m (or 2 floors)	4 m to <10 m (or 3 floors)	10 m to <25 m	25 m to <34 m	34 m to <46 m	46 m to <58 m	Over 58 m
CL (Notes 6,7)	F0	F30	F30	F45	F30	F30	F30	F60
	3f 16 18c	3f 16 18c	3b 9 16 18c	4 9 16 18	6 9 13 15 16 18	7 9 13 15 16 18	7 9 13 15 16 18	7 9 13 15 16 17 18 19 20
CM (Note 5)	F0	F30	F30	F45	F30	F30	F30	F60
	3f 16 18c	3f 16 18c	3b 9 16 18c	3b 9 15 16 18	6 9 13 15 16 18	7 9 13 15 16 18 20	7 9 13 15 16 18 20	7 9 13 15 16 17 18 19 20
WL WM WH (Note 5)	F0	F30	F30	F45	F30	F30	F30	F60
	3f 16 18c	3f 16 18c	3b 16 18c	3b 15 16 18	6 15 16 18	6 9 15 16 18	7 9 13 15 16 18	7 9 13 15 16 18 19 20
WF	F0	F30	F30	F30	F30	F30	F30	F60
	3f 16 18c	6 16 18c	6 16 18c	16 15 16 18	16 15 16 18	6 9 13 15 16 18	7 9 13 15 16 18	7 9 13 15 16 18 19 20
Column	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**

Notes:

1. **Use of Table**: Refer to Paragraph 4.4 for instructions on using this table to determine the *fire safety precautions* in *firecells.*
2. **Adjoining firecells having a FO rating**: Paragraph 6.2.1 requires adjoining *firecells to* be separated by *fire separations* with *FRR* no less than 15/1 5/1 5.
3. **Intermediate Floors**: Where a *firecell* contains *intermediate floors* a 15/15/15 *FRR* shall apply to the *intermediate floors* and supporting elements, and smoke control systems Type 9 and either Type 10 or Type 11, are required (see Paragraphs 4.5.16 to 4.5.18, 6.14.3 and 6.21.5 to 6.22.14).
4. **Car Parking**: Refer to Paragraphs 6.10.3 to 6.10.6 for car parking provisions within *buildings.*
5. **Sprinklers**: Refer to Paragraph 5.6.l2forsprinkler requirements in *FHC4 firecells where the escape* height is two floors or higher.
6. **CL cinemas and theatres:** Type 16d is required for all *escape heights*.
7. **CL**: For *firecells*, which are not cinemas or theatres, with *escape height* less than 4.0 m and *occupant load* not greater than 250, Type 2af is a permitted alternative to Type 3f.

Table **4.1/3: Fire safety precautions for active purpose group firecells**

Occupant load 501 to 1000

Purpose Group	Escape height							
	0m (or single floor)	<4 m (or 2 floors)	4 m to <10 m (or 3 floors)	10 m to <25 m	25 m to <34 m	34 m to <46 m	46 m to <58 m	Over 58 m
CL (Notes 6)	F0	F30	F30	F30	F30	F30	F30	F60
	4 16 18c	4 16 18c	4 9 16 18c	7 9 16 18	7 9 13 15 16 18	7 9 13 15 16 18	7 9 13 15 16 18	7 9 13 15 16 17 18 19 20
CM (Note 5)	F0	F30	F30	F30	F30	F30	F30	F60
	4 16 18c	4 16 18c	4 9 16 18c	7 9 15 16 18	7 9 13 15 16 18	7 9 13 15 16 18 20	7 9 13 15 16 18 20	7 9 13 15 16 17 18 19 20
WL WM WH (Note 5)	F0	F30	F30	F30	F30	F30	F30	F60
	4 16 18c	4 16 18c	4 16 18c	7 15 16 18	7 15 16 18	7 9 15 16 18	7 9 13 15 16 18	7 9 13 15 16 18 19 20
WF	F0	F30	F30	F30	F30	F30	F30	F60
	4 16 18c	6 16 18c	6 16 18c	7 15 16 18	7 15 16 18	7 9 13 15 16 18	7 9 13 15 16 18	7 9 13 15 16 18 19 20
Column	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**

Notes:

1. **Use of Table**: Refer to Paragraph 4.4 for instructions on using this table to determine the *fire safety precautions* in *firecells.*
2. **Adjoining firecells having a FO rating**: Paragraph 6.2.1 requires adjoining *firecells to* be separated by *fire separations* with *FRR* no less than 15/1 5/1 5.
3. **Intermediate Floors**: Where a *firecell* contains *intermediate floors* a 15/15/15 *FRR* shall apply to the *intermediate floors* and supporting elements, and smoke control systems Type 9 and either Type 10 or Type 11, are required (see Paragraphs 4.5.16 to 4.5.18, 6.14.3 and 6.21.5 to 6.22.14).
4. **Car Parking**: Refer to Paragraphs 6.10.3 to 6.10.6 for car parking provisions within *buildings.*
5. **Sprinklers**: Refer to Paragraph 5.6.l2forsprinkler requirements in *FHC4 firecells where the escape* height is two floors or higher.
6. **CL cinemas and theatres:** Type 16d is required for all *escape heights*.

Table **4.1/4: Fire safety precautions for active purpose group firecells** — Occupant load over 1000

Purpose Group	Escape height							
	0m (or single floor)	<4 m (or 2 floors)	4 m to <10 m (or 3 floors)	10 m to <25 m	25 m to <34 m	34 m to <46 m	46 m to <58 m	Over 58 m
CL	F0	F30	F30	F30	F30	F30	F30	F60
	7 16d 18c	7 16d 18c	7 9 16d 18c	7 9 16d 18	7 9 13 15 16d 18	7 9 13 15 16d 18	7 9 13 15 16d 18	7 9 13 15 16d 17 18 19 20
CM (Note 5)	F0	F30	F30	F30	F30	F30	F30	F60
	7 16d 18c	7 16d 18c	7 9 16d 18c	7 9 15 16d 18	7 9 13 15 16d 18	7 9 13 15 16d 18 20	7 9 13 15 16d 18 20	7 9 13 15 16d 17 18 19 20
WL WM WH (Note 5)	F0	F30	F30	F30	F30	F30	F30	F60
	7 16 18c	7 16 18c	7 16 18c	7 15 16 18	7 15 16 18	7 9 15 16 18	7 9 13 15 16 18	7 9 13 15 16 18 19 20
WF	F0	F30	F30	F30	F30	F30	F30	F60
	7 16 18c	7 16 18c	7 16 18c	7 15 16 18	7 15 16 18	7 9 13 15 16 18	7 9 13 15 16 18	7 9 13 15 16 18 19 20
Column	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**

Notes:

1. **Use of Table**: Refer to Paragraph 4.4 for instructions on using this table to determine the *fire safety precautions* in *firecells.*
2. **Adjoining firecells having a FO rating**: Paragraph 6.2.1 requires adjoining *firecells to* be separated by *fire separations* with *FRR* no less than 15/1 5/1 5.
3. **Intermediate Floors**: Where a *firecell* contains *intermediate floors* a 15/15/15 *FRR* shall apply to the *intermediate floors* and supporting elements, and smoke control systems Type 9 and either Type 10 or Type 11, are required (see Paragraphs 4.5.16 to 4.5.18, 6.14.3 and 6.21.5 to 6.22.14).
4. **Car Parking**: Refer to Paragraphs 6.10.3 to 6.10.6 for car parking provisions within *buildings.*
5. **Sprinklers**: Refer to Paragraph 5.6.l2forsprinkler requirements in *FHC4 firecells where the escape* height is two floors or higher.

Acceptible Solution C/AS1 PART4: REQUIREMENTS FOR FIRECELLS

Table 4.1/5: Fire safety precautions for active purpose group firecells — Occupant load 40 maximum

Purpose Group	Escape height: 0m (or single floor)	<4 m (or 2 floors)	4 m to <10 m (or 3 floors)	10 m to <25 m	25 m to <34 m	34 m to <46 m	46 m to <58 m	Over 58 m
SC SD (note 6)	F0	F30	F30	F30	F30	F30	F30	F60
	7 16d 18c	7 16d 18c	7 16d 18c	7 9 15 16d 18	7 8 9 13 15 16d 18 20	7 8 9 13 15 16d 18 20	7 8 9 13 15 16d 18 20	7 8 9 13 15 16d 17 18 19 20
SA (Note 5)	F0	F30	F30	F30	F30	F30	F30	F60
	4aef 16a 18c	4aef 16a 18c	4e 14 16a 18c	4e 14 15 16 18	7e 8 9 15 16 18	7e 8 9 13 15 16 18 20	7e 8 9 13 15 16 18 20	7e 8 9 13 15 16 17 18 20
SR (Note 7)	F0	F30	F30	F30	F30	F30	F30	F60
		2a	2f 16a	4e 14 16 18	7e 15 16 18	7e 15 16 18	7e 15 16 18 20	7e 13 15 16 18 20
Column	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**

Notes:

1. **Use of Table**: Refer to Paragraph 4.4 for instructions on using this table to determine the *fire safety precautions* in *firecells.*
2. **Adjoining firecells having a FO rating**: Paragraph 6.2.1 requires adjoining *firecells to* be separated by *fire separations* with *FRR* no less than 15/1 5/1 5.
3. **Intermediate Floors**: Where a *firecell* contains *intermediate floors* a 15/15/15 *FRR* shall apply to the *intermediate floors* and supporting elements, and smoke control systems Type 9 and either Type 10 or Type 11, are required (see Paragraphs 4.5.16 to 4.5.18, 6.14.3 and 6.21.5 to 6.22.14).
4. **Car Parking**: Refer to Paragraphs 6.10.3 to 6.10.6 for car parking provisions within *buildings.*
5. **Sprinklered firecells**: *Purpose group* SA may have an occupant load up to 160 beds in *firecells* with a type 7 alarm (see Paragraph 6.7.2)
6. **Occupant load in SC and SD firecells:** The *occupant load* in a group sleeping area *firecell* is limited to 12 to 20 beds and in a *suite* to 6 beds (See Paragraphs 6.6.3 to 6.6.5). For *firecells* (such as an operating theatre) required to remain occupied during a *fire*, see Paragraphs 5.6.8 and 5.6.9.
7. **SR household units**: See Paragraph 6.8.6 which describes where *household units* containing upper floors may be treated as single floor *firecells*.

Appendix E : Case Study Building BRANZFIRE input.

Gross Floor Area		934 sq.m
Storey height		3.42 m
Effective ceiling height		3.27 m

Main Compartment

Net equiv. area	29.4 x 29.4 =	864 sq.m
External wall, glazed area	120 x 2.0 =	240 sq.m
leakage	3.2 x.120 x 2 x 0.00021 *=	0.080 = 2 x .04sq.m
Floor, fire dampers 2% (assumed) openings		
	4.2 sq.m x 0.02 =	0.084
leakage	864 sq.m x 0.000052 *=	<u>0.045</u>
		0.13 sq.m

Stairs

Plan dimension	9.8 m x 1.15.m	
Wall, leakage	2(9.8 + 1.15) x 3.42 x 0.00011* =	0.0082
Door		<u>0.0157*</u>
		0.0239 = 2 x 0.012 sq.m
(See below for effective wall leakage to outside)		
Open door		2 x 1 sq.m
Roof, 0.25 sq.m opening with fire dampers (say) 2%=		0.01 sq.m
Floor, open shaft below (say)		0.05 sq.m

<u>Lifts.</u>

Total effective plan dimension	12.6 m x 2.3 m	
Wall, leakage	2(12.6 + 2.3) x 3.42 x 0.00084 =	0.086
Doors (5 off)	5 x 0.0157* =	<u>0.079</u>
		0.165 = 2 x 0.083 sq.m
(See below for effective wall leakage to outside)		
Roof, 0.6 sq.m to machine room, (say) 50% eff.=		0.30 sq,m
Floor, open shaft (say)		0.33 sq.m

Shaft leakage to outside

Between modelled floors, leakage from lifts and stairs is modelled to the outside. However the actual amount of leakage will be controlled by the leakage areas from the intermediate floors to the outside. Typically, this area is 0.080 sq.m as above. As each stair has only 0.024 sq.m leakage area compared with 0.165 for the lifts, leakage from the stair is assumed to be negligible, and leakage from the lift taken as a full height slot of (3.42 x) 0.02m.

<u>Wall damage to shafts.</u>
For the <u>moderate damage</u> it is assumed that cracking occurs at the joints in the lining materials, resulting in openings of a nominal 2 mm width.
For each stair, there are some 75 linear metre of joint, plus a door. This gives a total of 0.16 sq.m , of which 0.12 sq.m is into the main floor area. This is equivalent to a continuous slot of (3.42 x) 0.04 m. at each floor.
Similarly for the lifts, 102 linear metres of joint gives an effective slot of (3.42 x) 0.06m.at each floor.
Note that, at intermediate floors, the leakage modelled to the outside is limited as noted above.

For major damage, it is assumed that the lining materials show significant separation from the framing. Leakage areas assumed are 0.3 m wide equivalent slots to the stairs, and 0.6 m to the lift shaft. This damage is initiated by inter-storey deflections, which will reduce towards the top of the building. Leakage to intermediate floors is therefore taken as for the moderate damage case above, which is more conservative for tenability in the modelled rooms and shafts.

It is likely that a significant amount of external glazing is broken in the earthquake. The proportion of glazing broken is taken as 2/3 of the total for 2 parallel walls, giving 40 metres length.

* Reference for typical leakage areas is Klote and Milke (1992).

```
Monday,January 13,2003,05:31 PM
Input Filename : C:\Program Files\BRANZFIRE2002—5\data\CS1.mod

BRANZFIRE Multi-Compartment Fire Model (Ver 2002.7)

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commercial purposes.

Case Study, Fire Level 3 - No sprinklers, Door to stair 1 open, walls damaged.

==========================================================================
Description of Rooms
==========================================================================

Room 1 : level 3 fire floor
         Room Length (m) =                                  29.40
         Room Width (m) =                                   29.40
         Maximum Room Height  (m) =                         3.27
         Minimum Room Height  (m) =                         3.27
         Floor Elevation (m)  =                             7.020
         Room 1 has a flat ceiling.

         Wall Surface is glass (plate)
         Wall Density (kg/m3) =                             2700.0
         Wall Conductivity (W/m.K) =                        0.760
         Wall Emissivity =                                  0.90
         Wall Thickness (mm) =                              5.0

         Ceiling Surface is concrete
         Ceiling Density (kg/m3) =                          2300.0
         Ceiling Conductivity (W/m.K) =                     1.200
         Ceiling Emissivity =                               0.50
         Ceiling Thickness (mm) =                           150.0

         Floor Surface is Carpet 4 flooring material
         Floor Density (kg/m3) =                            204.0
         Floor Conductivity (W/m.K) =                       0.170
         Floor Emissivity =                                 0.90
         Floor Thickness = (mm)                             20.0

         Floor Substrate is concrete
         Floor Substrate Density (kg/m3) =                  2300.0
         Floor Substrate Conductivity (W/m.K) =             1.200
         Floor Substrate Thickness (mm) =                   150.0

Room 2 : stair no 1
         Room is modelled as  a single zone.
         Room Length (m) =                                  9.80
         Room Width (m) =                                   1.15
         Maximum Room Height  (m) =                         64.98
         Minimum Room Height  (m) =                         64.98
         Floor Elevation (m)  =                             7.020
         Room 2 has a flat ceiling.

         Wall Surface is plasterboard, gypsum paper-faced
         Wall Density (kg/m3) =                             760.0
         Wall Conductivity (W/m.K) =                        0.160
         Wall Einissivity =                                 0.88
         Wall Thickness (iran) =                            16.0

         Ceiling Surface is concrete
         Ceiling Density (kg/m3) =                          2300.0
         Ceiling Conductivity (W/m.K) =                     1.200
         Ceiling Emissivity =                               0.50
         Ceiling Thickness (mm) =                           150.0

         Floor Surface is concrete
         Floor Density (kg/m3) =                            2300.0
         Floor Conductivity (W/m.K) =                       1.200
         Floor Emissivity =                                 0.50
         Floor Thickness = (mm)                             100.0

Room 3 : stair no 2
```

```
        Room is modelled as a single zone.
        Room Length (m) =                                      9.80
        Room Width (m) =                                       1.15
        Maximum Room Height  (m) =                             64.98
        Minimum Room Height  (m) =                             64.98
        Floor Elevation (m)  =                                 7.020
        Room 3 has a flat ceiling.

        Wall Surface is plasterboard, gypsum paper–faced
        Wall Density (kg/m3) =                                 760.0
        Wall Conductivity (W/m.K) =                            0.160
        Wall Emissivity =                                      0.88
        Wall Thickness (mm) =                                  16.0

        Ceiling Surface is concrete
        Ceiling Density (kg/m3) =                              2300.0
        Ceiling Conductivity (W/m.K) =                         1.200
        Ceiling Emissivity =                                   0.50
        Ceiling Thickness (mm) =                               150.0

        Floor Surface is concrete
        Floor Density (kg/m3) =                                2300.0
        Floor Conductivity (W/m.K) =                           1.200
        Floor Emissivity =                                     0.50
        Floor Thickness = (mm)                                 100.0

Room  4  : lift shaft
        Room is modelled as a single zone.
        Room Length (m) =                                      12.60
        Room Width (m) =                                       2.30
        Maximum Room Height  (m) =                             64.98
        Minimum Room Height  (m) =                             64.98
        Floor Elevation (m)  =                                 7.020
        Room 4 has a flat ceiling.

        Wall Surface is plasterboard, gypsum paper-faced
        Wall Density (kg/m3) =                                 760.0
        Wall Conductivity (W/m.K) =                            0.160
        Wall Emissivity =                                      0.88
        Wall Thickness (mm) =                                  16.0

        Ceiling Surface is concrete
        Ceiling Density (kg/m3) =                              2300.0
        Ceiling Conductivity (W/m.K) =                         1.200
        Ceiling Emissivity =                                   0.50
        Ceiling Thickness (mm) =                               150.0

        Floor Surface is concrete
        Floor Density (kg/m3) =                                2300.0
        Floor Conductivity (W/m.K) =                           1.200
        Floor Emissivity =                                     0.50
        Floor Thickness = (mm)                                 100.0

Room  5  : level 4
        Room Length (m) =                                      29.40
        Room Width (m) =                                       29.40
        Maximum Room Height  (m) =                             3.27
        Minimum Room Height  (m) =                             3.27
        Floor Elevation (m)  =                                 10.440
        Room 5 has a flat ceiling.

        Wall Surface is glass (plate)
        Wall Density (kg/m3) =                                 2700.0
        Wall Conductivity (W/m.K) =                            0.760
        Wall Emissivity =                                      0.90
        Wall Thickness (mm) =                                  5.0

        Ceiling Surface is concrete
        Ceiling Density (kg/m3) =                              2300.0
        Ceiling Conductivity (W/m.K) =                         1.200
        Ceiling Emissivity =                                   0.50
        Ceiling Thickness (mm) =                               150.0
```

```
        Floor Density (kg/m3) =                                     204.0
        Floor Conductivity (W/m.K) =                                0.170
        Floor Emissivity =                                          0.90
        Floor Thickness = (mm)                                      20.0

        Floor Substrate is concrete
        Floor Substrate Density (kg/m3) =                           2300.0
        Floor Substrate Conductivity (W/m.K) =                      1.200
        Floor Substrate Thickness (mm) =                            150.0

Room 6 : level 20
        Room Length (m) =                                           29.40
        Room Width (m) =                                            29.40
        Maximum Room Height  (m) =                                  3.27
        Minimum Room Height  (m) =                                  3.27
        Floor Elevation (m)  =                                      65.160
        Room 6 has a flat ceiling.

        Wall Surface is glass (plate)
        Wall Density (kg/m3) =                                      2700.0
        Wall Conductivity (W/m.K) =                                 0.760
        Wall Emissivity =                                           0.50
        Wall Thickness (mm) =                                       5.0

        Ceiling Surface is concrete
        Ceiling Density (kg/m3) =                                   2300.0
        Ceiling Conductivity (W/m.K) =                              1.200
  Ceiling Emissivity =                                              0.50
  Ceiling Thickness (mm) =                                          150.0

        Floor Surface is Carpet 4 flooring material
        Floor Density (kg/m3) =                                     760.0
        Floor Conductivity (W/m.K) =                                0.160
        Floor Emissivity =                                          0.88
        Floor Thickness = (mm)                                      20.0

        Floor Substrate is concrete
        Floor Substrate Density (kg/m3) =                           2300.0
        Floor Substrate Conductivity (W/rn.K) =                     1.200
        Floor Substrate Thickness (mm) =                            150.0

==========================================================================
Description of Wall Vents
==========================================================================
From room  1  to 2 .Vent No 1
                  Vent Width (m) =                                  1.000
                  Vent Height (m) =                                 2.000
                  Vent Sill Height (m) =                            0.000
                  Vent Soffit Height (m) =                          2.000
                  Opening Time (sec) =                              0
                  Closing Time (sec) =                              0

From room  1  to 2 .Vent No 2
                  Vent Width (m) =                                  0.040
                  Vent Height (m) =                                 3.270
                  Vent Sill Height (m) =                            0.000
                  Vent Soffit Height (m) =                          3.270
                  Opening Time (sec) =                              0
                  Closing Time (sec) =                              0

From room  1  to 3 .Vent No 1
                  Vent Width (m) =                                  0.040
                  Vent Height (m) =                                 3.270
                  Vent Sill Height (m) =                            0.000
                  Vent Soffit Height (m) =                          3.270
                  Opening Time (sec) =                              0
                  Closing Time (sec) =                              0

From room  1  to 4 .Vent No 1
                  Vent Width (m) =                                  0.060
                  Vent Height (m) =                                 3.270
                  Vent Sill Height (m) =                            0.000
```

```
                    Vent Soffit Height(m)=                        3.270
                    Opening Time (sec) =                          0
                    Closing Time (sec) =                          0

From room   1  to outside, Vent No 1
                    Vent Width(m)=                                10.000
                    Vent Height(m)=                               2.000
                    Vent Sill Height(m)=                          0.000
                    Vent Sof fit Height(m)=                       2.000
                    Opening Time (sec)=                           700
                    Closing Time (sec) =                          0

From room   1  to outside, Vent No 2
                    Vent Width (m) =                              10.000
                    Vent Height (m) =                             2.000
                    Vent Sill Height (m)=                         0.000
                    Vent Soffit Height (m) =                      2.000
                    Opening Time (sec) =                          800
                    Closing Time (sec) =                          0

From room   1  to outside, Vent No 3
                    Vent Width (m) =                              10.000
                    Vent Height (m) =                             2.000
                    Vent Sill Height (m) =                        0.000
                    Vent Sof fit Height (m)=                      2.000
                    Opening Time (sec) =                          900
                    Closing Time (sec) =                          0

From room   1  to outside, Vent No 4
                    Vent Width (m)==                              20.000
                    Vent Height (m) =                             2.000
                    Vent Sill Height (m) =                        0.000
                    Vent Soffit Height (m) =                      2.000
                    Opening Time (sec) =                          1000
                    Closing Time (sec) =                          0

From room   1  to outside, Vent No 5
                    Vent Width (m) =                              20.000
                    Vent Height (m)=                              2.000
                    Vent Sill Height (m)=                         0.000
                    Vent Soffit Height (m)=                       2.000
                    Opening Time (sec) =                          1100
                    Closing Time (sec) =                          0

From room   1  to outside, Vent No 6
                    Vent Width (m)=                               20.000
                    Vent Height (m)=                              2.000
                    Vent Sill Height(m)=                          0.000
                    Vent Soffit Height(m)=                        2.000
                    Opening Time (sec)=                           1200
                    Closing Time (sec)                            0

From room   1  to outside, Vent No 7
                    Vent Width (m)=                               20.000
                    Vent Height (m)=                              2.000
                    Vent Sill Height (m)=                         0.000
                    Vent Sof fit Height(m)=                       2.000
                    Opening Time (sec) =                          1300
                    Closing Time (sec) =                          0

From room   2  to   5, Vent No 1
                    Vent Width (m) =                              0.040
                    Vent Height (m)=                              3.270
                    Vent Sill Height(m)=                          3.420
                    Vent Soffit Height(m)=                        6.690
                    Opening Time (sec)  =                         0
                    Closing Time (sec)  =                         0

From room   2  to   6, Vent No 1
                    Vent Width (m)=                               0.040
                    Vent Height (m)=                              3.270
                    Vent Sill Height (m)=                         58.140
                    Vent Soffit Height (m)=                       61.410
```

```
                   opening Time (sec) =                     0
                   Closing Time (sec) =                     0

From room 3 to 5,  Vent No 1
                   Vent Width (m) =                         0.040
                   Vent Height (m) =                        3.270
                   Vent Sill Height (m) =                   3.420
                   Vent Soffit Height (m) =                 6.690
                   Opening Time (sec)=                      0
                   Closing Time (sec)=                      0

From room 3 to 6,  Vent No 1
                   Vent Width (m) =                         0.040
                   Vent Height (m) =                        3.270
                   Vent Sill Height(m) =                    58.140
                   Vent Soffit Height(m) =                  61.410
                   Opening Time (sec)=                      0
                   Closing Time (sec)=                      0

From room 4 to 5,  Vent No 1
                   Vent Width (m) =                         0.060
                   Vent Height (m) =                        3.270
                   Vent Sill Height (m) =                   3.420
                   Vent Soffit Height(m) =                  6.690
                   Opening Time (sec)=                      0
                   Closing Time (sec)=                      0

From room 4 to 6,  Vent No 1
                   Vent Width (m) =                         0.060
                   Vent Height (m) =                        3.270
                   Vent Sill Height(m) =                    58.140
                   Vent Soffit Height(m) =                  61.410
                   Opening Time (sec)=                      0
                   Closing Time (sec)=                      0

From room 4 to outside, Vent No 1
                   Vent Width (m) =                         0.020
                   Vent Height (m) =                        51.300
                   Vent Sill Height (m) =                   6.840
                   Vent Soffit Height (m) =                 58.140
                   Opening Time (sec) =                     0
                   Closing Time (sec) =                     0

From room 5 to outside, Vent No 1
                   Vent Width (m) =                         0.040
                   Vent Height (m) =                        2.000
                   Vent Sill Height (m) =                   0.000
                   Vent Soffit Height (m) =                 2.000
                   Opening Time (sec) =                     0
                   Closing Time (sec) =                     0

From room 6 to outside, Vent No 1
                   Vent Width (m) =                         0.040
                   Vent Height (m) =                        2.000
                   Vent Sill Height (m) =                   0.000
                   Vent Soffit Height (m) =                 2.000
                   Opening Time (sec) =                     0
                   Closing Time (sec) =                     0

================================================================================
Description of Ceiling/Floor Vents
================================================================================
Upper room 1 to lower outside, Vent No 1
                   Vent Area (m2) =                               0.13
                   Opening Time (sec) =                           0
                   Closing Time (sec) =                           0
                   Open method =                                  Manual

Upper room 2 to lower outside, Vent No 1
                   Vent Area (m2) =                               0.05
                   Opening Time (sec) =                           0
                   Closing Time (sec) =                           0
                   Open method =                                  Manual
```

```
Upper room 3 to lower outside, Vent No 1
                   Vent Area (m2) =                          0.05
                   Opening Time (sec) =                      0
                   Closing Time (sec) =                      0
                   Open method =                             Manual

Upper room 4 to lower outside, Vent No 1
                   Vent Area (m2) =                          0.33
                   Opening Time (sec) =                      0
                   Closing Time (sec) =                      0
                   Open method =                             Manual

Upper room 5 to lower room 1 , Vent No 1
                   Vent Area (m2) =                          0.13
                   Opening Time (sec) =                      0
                   Closing Time (sec) =                      0
                   Open method =                             Manual

Upper room 6 to lower outside, Vent No 1
                   Vent Area (m2) =                          0.13
                   Opening Time (sec) =                      0
                   Closing Time (sec) =                      0
                   Open method =                             Manual

Upper outside to lower room 2 , Vent No 1
                   Vent Area (m2) =                          0.01
                   Opening Time (sec) =                      0
                   Closing Time (sec) =                      0
                   Open method =                             Manual

Upper outside to lower room 3 , Vent No 1
                   Vent Area (m2) =                          0.01
                   Opening Time (sec) =                      0
                   Closing Time (sec) =                      0
                   Open method =                             Manual

Upper outside to lower room 4 , Vent No 1
                   Vent Area (m2) =                          0.30
                   Opening Time (sec) =                      0
                   Closing Time (sec) =                      0
                   Open method =                             Manual

Upper outside to lower room 5 , Vent No 1
                   Vent Area (m2) =                          0.13
                   Opening Time (sec) =                      0
                   Closing Time (sec) =                      0
                   Open method =                             Manual

Upper outside to lower room 6 , Vent No 1
                   Vent Area (m2) =                          0.13
                   Opening Time (sec) =                      0
                   Closing Time (sec) =                      0
                   Open method =                             Manual

=========================================================================
Ambient Conditions
=========================================================================
Interior Temp (C) =                                           20.0
Exterior Temp (C) =                                          20.0
Relative Humidity (%) =                                      65

========================================================================
Tenability Parameters
========================================================================
Monitoring Height for Visibility and FED (m) =               2.00
Occupant Activity Level =                                    Light
Visibility calculations assume:                              reflective signs
FED Start Time (sec)                                         0
FED End Time (sec)                                           1800

========================================================================
Sprinkler / Detector Parameters
```

```
=========================================================================
No thermal detector or sprinkler installed.

=========================================================================
Mechanical Ventilation (to/from outside)
=========================================================================
Mechanical Ventilation not installed in Room 1
Mechanical Ventilation not installed in Room 2
Mechanical Ventilation not installed in Room 3
Mechanical Ventilation not installed in Room 4
Mechanical Ventilation not installed in Room 5
Mechanical Ventilation not installed in Room 6

==========================================================================
Description of the Fire
==========================================================================
Radiant Loss Fraction =                                        0.35
Underventilated Soot Yield Factor =                            1.00
Smoke Emission Coefficent (l/m) =                              0.80
Characteristic Mass Loss per Unit Area (kgls.m2) =             0.011
Air Entrainment in Plume uses McCaffrey (recommended)

Burning Object No 1
work station composite
               Located in Room                                 1
               Energy Yield (kJ/g)=                            12.4
               C02 Yield (kg/kg fuel) =                        1.270
               Soot Yield (kg/kg fuel) =                       0.015
               H20 Yield (kg/kg fuel) =                        0.442
               Fire Height (m) =                               0.500
               Fire Location (m)                               Centre

                Time (sec)               Heat Release (kW)
                0                        0
                40                       30
                80                       122
                120                      274
                160                      486
                200                      760
                240                      1095
                280                      1490
                320                      1946
                400                      3040
                480                      4380
                560                      5960
                680                      8786
                800                      12160
                920                      16080
                1040                     20550
                1200                     27360
                1400                     37240
                1600                     48640
                1800                     61560
                2000                     76000

========================================================================
Postflashover Inputs
========================================================================
Postflashover model is ON.
         FLED (MJ/m2) =                                        800
         Fuel Density (kg/m3) =                                500
         Average heat of Combustion (MJ/kg) =                  16.0
         Wood Crib Stick Thickness (m) =                       0.050
========================================================================
```

Appendix F : Required Safe Egress Time : Calculation.

Data

Net floor area		800 m
Design Occupant Density		0.1 person/sq.m
Max. Open Path length to stair entry		30 m for 2 stairs available
		40 m for 2 stairs available
Door width		1.0 m
Stair Width		1.12 m
Stair Geometry		
Tread / riser		275 / 180 mm
Storey height		3.42 m
Effective landing travel length		3.6 m
<u>Open Path Travel</u>		
Travel speed (Smax)		73 m/min.
Max. travel time	tu = 30 / 73 =	0.4 m for 2 stairs available
or, allowing some investigation time (say)		0.7 m for 1 stair
<u>Capacity of doors</u>		
Effective width	We = 1.0 – 0.1 =	0.9 m
Max. Specific Flow	Fs = 1.3 x 60 =	78 person/min/m
Max. Calculated Flow	Fc = 0.9 x 78 =	70.2 person/min.
Min. time to evacuate floor	(no queuing) 80 / 70.2 =	1.14 min.
<u>Capacity of Stair.</u>		
Effective Width	We = 1.12 – 2 x 0.165 =	0.79 m
Specific Flow	(for 275 x 180 tread)	60.6 person/min/m
Calculated Flow	Fc = 60.6 x 0.79 =	47.9 person/min.
Resultant flow at exit door	Fcd = 47.9 / 0.9 =	53.2 < 70.2
Stair capacity controls		
Stair Flow Density	D = Dmax =	1.86 person/min
Speed on stair	S = 64 (1 - .266 x 1.86) =	32.3 m/min
Effective length of stair	Ls = 1.85 x 3.42 + 3.6 =	9.93 m / flight
Travel time on stair	ts = 9.93 / 32.3 =	0.31 min/ flight.
<u>Evacuation Time</u>		
Assume all floors start to enter stair/s at the same time.		
Stair/s will be full after	=	0.31 mins
Number of persons in stair	= 0.31 x 47.9 =	15 persons/floor/stair
Time to evacuate 1 floor	= 80 / 47.9 =	1.67 mins for 1 stair
(no queuing)	x 0.5 =	0.84 mins for 2 stairs

Assume 3 minute pre-movement time

Assume 0.5 minute travel from base of stair/s to final exit

Time to evacuate building	= (19 x 1.67) + 3.7 +0 .5 =	35.9 mins for 1 stair
	= (19 x 0.84) + 3.4 + 0.5 =	19.9 mins for 2 stairs.

Reference : Nelson and MacLennan (1995)

Appendix G : scenario evacuation model.

Refer Spreadsheet printout on following pages.
The tenability times for a fire on each floor and each damage scenario are assessed from the BRANZFIRE printout. These are then combined on the spreadsheets below to determine an average number of occupants at risk for each scenario.

The nomenclature and calculations used for the spreadsheet is as follows.

T1 = tenability time for stair No. 1. (This is the stair with open door where appropriate)

T2 = tenability time for stair No. 2
.
T3 = number of persons who can evacuate past any point on the stair in time T1, assuming 2 stairs are available
= (T1 – 3.4) x 95.8

T4 = number of persons who can evacuate past any floor in time T2, assuming 2 stairs are available only until the smoke layer in the fire floor reaches door head height
= ((T2 – 3.7) + (5.5 – 3.4)) x 47.9, where (5.5 – 3.4) x 47.9 is number of persons that can pass the fire floor in 1 stair before the smoke layer lowers.

P = number of persons at risk for each scenario for a fire of any floor
= number of persons on and above the fire floor before the fire less the number who can evacuate past the fire floor before the stairs become untenable
= (21 – N) x 80 – T3 (or - T4 as appropriate.), where N = number of fire floor.

SUM(P) = the sum of the positive values of P for each scenario

AVG = SUM(P) / 19 = average for SUM(P) over all floors for each scenario.

Occupants at risk : calculation

Refer Spreadsheet in Appendix H.

For the selected earthquake events, the product of the individual feature probabilities of each scenario (from Table 9.2) is obtained to give an overall probability for the scenario for that earthquake. The overall probability for the scenario (is then multiplied by the average number of occupants at risk (AVG as above), and the results summed to give the total for the particular earthquake event. to obtain total number at risk. The results are presented in Figure 9.3.

Tenability time	1	2	Scenario Number 3	4	5	6	7	8	9	10	11	12
T1	10.9	14.0		8.4	8.4	7.3	10.9	14.0	14.4	8.4	8.4	7.3
T2	11.0	33.6		8.4	10.0	22.2	11.0	33.6	40.0	8.4	10	22.2
T3	718.5	1015.5		479.0	479.0	373.6	718.5	1015.5	1053.8	479.0	479.0	373.6
T4	449.7	1532.2			401.8	986.2	449.7	1532.2	1838.8		401.8	986.2
Floor N		P = Number of persons at risk										
20	-638.5	-1452		-399	-399	-906	-638	-1452	-1759	-399	-399	-906
19	-558.5	-1372		-319	-319	-826	-558	-1372	-1679	-319	-319	-826
18	-478.5	-1292		-239	-239	-746	-478	-1292	-1599	-239	-239	-746
17	-398.5	-1212		-159	-159	-666	-398	-1212	-1519	-159	-159	-666
16	-318.5	-1132		-79	-79	-586	-318	-1132	-1439	-79	-79	-586
15	-238.5	-1052		1	1	-506	-238	-1052	-1359	1	1	-506
14	-158.5	-972		81	81	-426	-158	-972	-1279	81	81	-426
13	-78.5	-892		161	161	-346	-78	-892	-1199	161	161	-346
12	2	-812		241	241	-266	2	-812	-1119	241	241	-266
11	82	-732		321	321	-186	82	-732	-1039	321	321	-186
10	162	-652		401	401	-106	162	-652	-959	401	401	-106
9	242	-572		481	481	-26	242	-572	-879	481	481	-26
8	322	-492		561	561	54	322	-492	-799	561	561	54
7	402	-412		641	641	134	402	-412	-719	641	641	134
6	482	-332		721	721	214	482	-332	-639	721	721	214
5	562	-252		801	801	294	562	-252	-559	801	801	294
4	642	-172		881	881	374	642	-172	-479	881	881	374
3	722	-92		961	961	454	722	-92	-399	961	961	454
2	802	-12		1041	1041	534	802	-12	-319	1041	1041	534
SUM(P)	4417	0	0	7294	7294	2058	4420	0	0	7294	7294	2058
AVG	232	0	0	384	384	108	233	0	0	384	384	108

Scenario evacuation model printout.

Scenario Number

13	14	15	16	17	18	19	20	21	22	23	24
11.0	33.6		8.5	10.0	24.3	11.0	33.6	40	8.5	10.0	24.3
11.0	33.6		8.5	10.0	24.3	11.0	33.6	40.0	8.5	10.0	24.3
728.1	2893.2		488.6	632.3	2002.2	728.1	2893.2	3506.3	488.6	632.3	2002.2

P = Number of persons at risk

-648	-2813.2		-409	-552	-1922	-648	-2813	-3426	-409	-552	-1922
-568	-2733.2		-329	-472	-1842	-568	-2733	-3346	-329	-472	-1842
-488	-2653.2		-249	-392	-1762	-488	-2653	-3266	-249	-392	-1762
-408	-2573.2		-169	-312	-1682	-408	-2573	-3186	-169	-312	-1682
-328	-2493.2		-89	-232	-1602	-328	-2493	-3106	-89	-232	-1602
-248	-2413.2		-9	-152	-1522	-248	-2413	-3026	-9	-152	-1522
-168	-2333.2		71	-72	-1442	-168	-2333	-2946	71	-72	-1442
-88	-2253.2		151	8	-1362	-88	-2253	-2866	151	8	-1362
-8	-2173.2		231	88	-1282	-8	-2173	-2786	231	88	-1282
72	-2093.2		311	168	-1202	72	-2093	-2706	311	168	-1202
152	-2013.2		391	248	-1122	152	-2013	-2626	391	248	-1122
232	-1933.2		471	328	-1042	232	-1933	-2546	471	328	-1042
312	-1853.2		551	408	-962	312	-1853	-2466	551	408	-962
392	-1773.2		631	488	-882	392	-1773	-2386	631	488	-882
472	-1693.2		711	568	-802	472	-1693	-2306	711	568	-802
552	-1613.2		791	648	-722	552	-1613	-2226	791	648	-722
632	-1533.2		871	728	-642	632	-1533	-2146	871	728	-642
712	-1453.2		951	808	-562	712	-1453	-2066	951	808	-562
792	-1373.2		1031	888	-482	792	-1373	-1986	1031	888	-482
4320	0	0	7163	5304	0	4320	0	0	7163	5304	0
227	0	0	377	279	0	227	0	0	377	279	0

Scenario Evacuation model printout (page 2)

Appendix H : Case study building : occupants at risk (typical printout).

Case 2: Moderate Earthquake

Scenario	Feature Probability					No. at
	Door	Press.	Sprinkler	Barrier		Risk
1	0.05	0.3	0.1	0.1	0.0002	0.03
2	0.95	0.7	0.9	0.7	0.0011	0.00
3		0.3	0.1	0.2	0.0003	0.00
4		0.7	0.9	0.1	0.0014	0.52
5			0.1	0.7	0.0095	3.63
6			0.9	0.2	0.0027	0.29
7			0.1	0.1	0.0004	0.08
8			0.9	0.7	0.0025	0.00
9				0.2	0.0007	0.00
10				0.1	0.0032	1.21
11				0.7	0.0221	8.47
12				0.2	0.0063	0.68
13				0.1	0.0029	0.65
14			.	0.7	0.0200	0.00
15				0.2	0.0057	0.00
16				0.1	0.0257	9.67
17				0.7	0.1796	50.09
18				0.2	0.0513	0.00
19				0.1	0.0067	1.51
20				0.7	0.0466	0.00
21				0.2	0.0133	0.00
22				0.1	0.0599	22.56
23				0.7	0.4190	116.89
24				0.2	0.1197	0.00
SUM	1	2	4	8	1	216.28

Refer to Appendix G for basis of calculation.