The Seismic Failure of Glass and Glazing in Domestic Construction

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Abstract

A large percentage of the damage done to buildings in an earthquake is to non-structural items. Until recently, building regulations in many countries aimed to preserve the structural integrity of buildings, and accepted damage to non-structure. Now, with rising replacement costs more emphasis is being placed on providing regulations for the seismic resistance of non-structure.

In past earthquake events glazing has been the most expensive single item of replacement in buildings. Currently in New Zealand building regulations domestic glazing has only very limited protection against deflection failure. This study assesses the expected replacements cost of glass and glazing in Wellington City, and costs of installing seismic allowance windows in domestic construction. It also looks at the added risk of worsened fire spread after an earthquake due to glass breakage.

The outcome of this research is a recommendation that protection of glazing from seismic movement needs to be included in the New Zealand building regulations for domestic buildings.

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1. Introduction

Introduction

A large percentage of the damage done to buildings in an earthquake is to non-structural items. Until recently, building regulations in many countries aimed to preserve the structural integrity of buildings, and accepted damage to non-structure. Now, with rising replacement costs and awareness of how non-structure affects building performance, more emphasis is being placed on providing regulations for the seismic resistance of non-structure.

Architectural items such as partitions, doors, windows, cladding and finishes need proper seismic detailing, as well as incorporating the standard detailing for creep, shrinkage, fire and temperature effects. This report investigates one of the non-structural items in a building, glass. Few countries include sections for this in their building regulations. The New Zealand Building Code recognises the problem for buildings that require specific engineering, however it fails to protect domestic buildings from glass breakage.

Glass Breakage

Glass often breaks in earthquakes, due to impact or stresses induced on the glass by movement in the frame. Glass breakage in earthquakes can cause several problems, the three most important of which are causing death and injury, cost of replacement, and increasing the risk of fire spread.

Death and Injury

Falling glass from seismic breakage may cause harm to persons underneath. There is a higher risk associated with glazing from high-rise curtain wall systems falling into the street below than with domestic glazing systems. There are two reasons for this, the area of glazing is often less in domestic construction, and there tends to be less people in the immediate proximity to glazing in houses. In addition, large, unprotected openings in exterior walls of commercial buildings can make the space unsafe and unusable until the glazing is replaced. As death and injury is not perceived to be a serious threat in domestic construction it will not be investigated further in this study.

Cost

In the 1971 San Fernando earthquake glass was the largest single cost for replacement [9]. It was this event that initiated research into earthquake protection of non-structure. The cost of replacement can be a very high percentage of total damage cost, especially in moderate earthquakes where there is no, or little, structural damage caused to buildings. In a moderate earthquake[1], glass breakage is likely to be around 5 –50% of the replacement value, and will involve the cracking of large windows and any that do not allow for any movement [1]. In a severe earthquake, shattering of windows will almost certainly occur, with glass thrown into and out of the building. Small windows and those that allow for movement may be undamaged, depending on the nature of the ground motion [1].

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1. A moderate earthquake is considered one of intensity MM VII – VIII. A severe earthquake has intensity MM IX or higher. A table of the Modified Mercalli Scale follows in the appendix.

Fire

It has been seen in past earthquake events that fire breaking out after the shaking can cause considerable damage [2]. The spread of post earthquake fire is dependent on many things, such as construction materials and separation of buildings. It was reported after the Great Hanshin Earthquake in Japan that fire spread between buildings of fire protected wood was due to fire spread through the buildings' openings not through their walls [10]. The New Zealand Building Code recognises the problem of fire spread between buildings through windows but does not currently take into account the potential greater fire spread due to windows being broken by an earthquake.

Problem Statement

Glass breakage due to earthquake may pose an unacceptable level of risk to domestic property. This may mean that New Zealand building regulations do not adequately protect glass in domestic buildings.

The Cause

Glass breaks due to lack of allowance for movement of the glass panel within the frame, and for the frame within the structure. There has been information available since the 1970's on how to detail window frames to allow for some movement, but it was up to the building owner or designer to use these techniques. They were not specified in the regulations. Now, in the current regulations some buildings are protected but not residential buildings. There are several alternatives in how to detail different glazing systems for seismic movement, and these will be covered in Chapter 2.

The Aim and Structure of this Study

This study will look at the New Zealand building regulations to asses whether there is adequate safeguard for the seismic performance of windows, and if not what possible changes could be made to ensure adequate behaviour of glazing systems to reduce the risks mentioned previously.

To achieve this, the New Zealand Building Code (hereafter referred to as NZBC), and the relevant standards will be studied. Techniques and details for improving the seismic performance of windows will be evaluated for cost and effectiveness in reducing the risks previously mentioned. This will be covered in Chapter 2.0 and will provide a basis for analysis of the problem and potential solution. Chapter 3 includes a basic prediction of replacement costs of glass breakage and installation cost of seismic allowance windows. Fire following earthquake will also be investigated. This allows economic evaluation of suggested solutions.

Conclusion to Chapter 1

The evidence that glass breakage due to earthquake movement has led to the inclusion of clauses in standards for engineered buildings. The problem has been identified as serious enough to warrant addition into building regulations. This report will investigate the NZBC, to identify whether it provides adequate regulations for the protection of glass for non-engineered buildings, or if it should include more specific clauses for this type of building.

2. Background

Introduction

This chapter gives a brief introduction to the properties of glass and its use in buildings. It then examines current techniques of protecting glass from seismic movements. As such, it attempts to set a basis for this report on how the effects of glass breakage can be mitigated. It also compares the benefits and disadvantages of different systems. The New Zealand Building Code and the relevant New Zealand standards are reviewed for the content on protection of windows, which will be used in the analysis.

Glass Breakage

The flat glass used in most buildings is soda-lime glass, whose properties of a non-porous surface and weathering resistance make it suited for exterior use in buildings. The main ingredient is sand (SiO_2), and many other ingredients can be added to change the properties for a particular purpose.

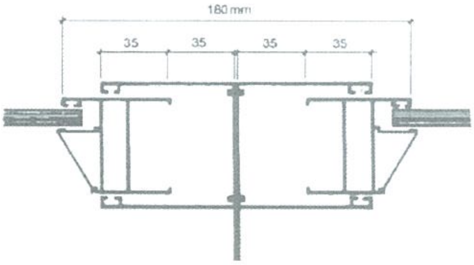
Glass breaks in seismic movement of buildings when the frame exerts pressure on the edge of the glass. When the glass is restrained, or a corner impacts the frame, or flexing is too great, fracture of the glass will occur. The Building Research Association of New Zealand defines glass failure as the inability of the glazing to prevent penetration [3]. Glass has a minimal tolerance of movement. Although its compressive strength is high, (880- 930 Nmm^{-2}) [12], it has very low tensile strength. Toughened, or tempered, glass has a higher tensile bending strength than normal glass, 50 Nmm^{-2} compared to 30 Nmm^{-2}. Upon breaking the glass disintegrates into tiny pieces. Heat-treated glass has a higher tensile strength than normal glass (around 40 Nmm^{-2}), but it still shatters like float glass when it fails [12]. The most common failure mode of glass is brittle failure.

Since the 1920's, when an industrial process was developed for the manufacture of glass, more and more glass has been used in buildings. Used for its transparent qualities to allow natural light and views, the trend in construction has been to reduce the supporting structure to increase this transparency.

Methods of Protection

When a building deflects in an earthquake, pressure is exerted onto the glass by the frame. It is very rare for a building to be so rigid that it does not deflect at all [14]. Some protection can be achieved by allowing the glass to move within the frame, with the use of soft putties, and until a few years ago this was the conventional approach. However, this is often not enough in earthquake, or high wind prone areas. To allow for more movement the window frame must be able to move separately from the building. In most multi-storeyed buildings considerable horizontal movement is needed, up to ±20 mm is common, and up to ±35 mm can be required. This can create large mullions and frames as seen in Figure 1 [14]. Figure 1 shows a typical detail to allow 35 mm of movement. The overall width of the mullion is 180 mm minimum.

Figure 1. Typical detail to allow 35 mm of movement.[14]



Provision for seismic movement is only one requirement for seismic design. All window details must also keep out rain and wind, allow for thermal expansion, provide adequate acoustic seal, and, of course, be long lasting.

There are four main approaches to detailing windows for seismic movement, and different types could be used within the same building [14].

<u>Glass moves within Frame</u>

The glass is glazed directly into the frame, with gaps around the glass sufficient to allow movement. This is common approach in 'stick' system windows, where mullions run through more than one floor. This approach does not allow as much movement as the other techniques. Often this approach is used in conjunction with other details.

<u>Seismic Frame</u>

The glazing frame moves in a seismic frame, which moves as the building does. It is usually fixed at sill level.

Unitised System

Individual window units interlock to form a curtain wall. The joints between each unit allow for vertical and horizontal movements. This technique is very common in multi-storeyed buildings. Silicon is often used for fixing the glass into the system, but is not used in this case to allow movement.

Structural Silicone

This technique relies on the elasticity of silicon to 'cushion' the glass within the frame. Silicones that are commonly used in glazing have differing properties, and only some are appropriate for fastening glass or other materials to the framing system, as the primary means of restraining the glass. The silicone used for this is not recommended for weather sealing the joint. The application of silicone, especially for structural purposes such as windows, need to be carefully controlled. Factory glazing, such as the unitised system, is much preferred to on site glazing as it creates fewer construction defects.[14]

New Zealand Building Regulations

The Building Act 1991

"The Building Act 1991 establishes a national, uniform, building control system" [5]. This control system regulates the factors that ensure buildings perform in a way which:

- Protects people from injury and illness.
- Protects people, especially those with disabilities, from loss of amenity.
- Protects other property from damage.
- Facilitates efficient use of energy.

New Zealand Building Code

The NZBC is a performance-based schedule to meet the regulations authorised by the Building Act 1991. It contains the compulsory provisions for compliance with the Act. This means that it informs designers and builders what has to be done, not how to do it. Territorial authorities are responsible within their districts for the administration of the building control legislation. All new buildings built in New Zealand must comply with the NZBC. Approved documents listed in the NZBC contain acceptable solutions. The acceptable solutions give examples of construction that comply with the NZBC.

<u>NZS 4203: 1992 General Structural Design and Design Loadings for Buildings</u>

This standard sets out requirements for the general structural design for buildings, and the design loadings such as wind, earthquake and snow loadings. It is referenced in the NZBC in Approved Document B1/1: Structure –General. The standard has specific clauses for building parts. A part is defined as "an element which is not intended to participate in the overall resistance of the structure to lateral displacement under earthquake conditions in the direction being considered."

Although the standard does not specifically mention glass, it covers the protection of parts due to movement with this clause: "4.12.18 Connections between the parts and the building structure shall be designed to accommodate the inter-storey deflections determined in accordance with 4.7.4." Deflections are limited for differing heights of buildings. For buildings under 15 m height, deflections cannot be more than 0.02 times the storey height. For buildings over 30 m in height, deflections can be no more than 0.015 times the storey height.

This means that the problem of glass breakage due to seismic movements has been identified as a risk and covered by this standard. However, this standard only is applicable to buildings that require specific engineering.

<u>NZS 3604: 1999 Timber Framed Buildings</u>

This standard covers buildings that are domestic or residential, this includes multi-unit or group dwellings, communes, maraes, boarding houses etc. This standard has clauses on the weatherproofing of windows and glazing but only briefly mentions movement when referring to another standard: "11.6.12 Windows shall comply with the strength, deflection and water leakage requirements of sections 10 and 12 of NZS 4211."

<u>NZS 4211: 1985 Specifications for Performance of Windows</u>

This standard states the requirements for the performance of windows to be installed in exterior walls. Section 12 discusses water leakage. Section 10 covers overall strength and deflection, and states: "10.3 The maximum deflection due to bending of any structural member, including the outer window frame, measured relative to the end of the member at 1.0 times the design wind pressure shall not exceed 1/180 of the span of the member." This works out to 0.05 times the window length, which is more than NZS 4203 allows for deflection. This standard has no mention of allowing for movement around the frame or of the glass within the frame.

Conclusion to Chapter 2

The inclusion of protection for building parts, which includes windows, in NZS 4203 indicates that the problem has been recognised as serious enough to warrant specific attention. However, the standards for domestic building within New Zealand do not include any mention of protecting glass from seismic movements. NZS 4211 states a limitation for the amount of allowable deflection for windows but this is more than NZS 4203 allows for engineered buildings. This is very significant as it suggests that windows are not as well protected for domestic building than for engineered buildings. As the risk of glass failure in an earthquake has already been identified, this omission is seen to be of serious concern.

3. Cost

Introduction

In general new building techniques are not implemented into regular practise if they cost more than existing methods. For this reason it is important to evaluate the expected costs of protecting glazing to compare to the estimated loss caused by not doing so. From this, any recommendations can be shown to be worthwhile or not.

Comparison of Cost

At present windows cost approximately 15% of new domestic construction in New Zealand [16], with nearly all being aluminium framed. In the year up to June 2001, in New Zealand approximately 17,000 new residential buildings were built, excluding apartments and multi-unit buildings. House prices averaged out at $154,000 each [19].

Supply Costs

Table 1 is a comparison between costs of differing frame and glass types. Most common in new dwellings currently is aluminium frames with clear 6mm float glass, which is the cheapest window type.

It is important to note that labour costs are more for replacement of windows in existing buildings than for installation in new construction. Labour will also be more intensive (and hence expensive) for fire rated and seismic framed windows as they take longer to install.

Table 1: Supply cost of Glazing Types and Frames.

Frame Type	Glass Type	Supply Cost $/m^2
Timber	Clear float 6mm	340
	Wired 6mm	390
Aluminium	Clear float 6mm	190
Steel	Clear float 6mm	400
	Wired 6mm	550
Fire Rated[1]	Wired 6mm	600
	"Pyran" 6mm	900
Seismic (aluminium)	Clear float glass	310[2]

Table 1 shows that frames allowing for seismic movement are likely to be twice as expensive as standard aluminium frames. Aluminium frames perform worst in earthquakes, with the frame flexing and often creating intolerable stress in the glass. As the threat to life is not perceived as being significant from domestic glass breakage (as discussed in Chapter 1), in order to recommend that seismic frames be made compulsory it is necessary to demonstrate that it is economically viable and financially beneficial to do so.

The costs for different types of glazing for a $150,000 medium quality house are illustrated in Table 2. Three types of frame are compared, standard aluminium, standard timber, and seismic, for houses with three sizes of glazing. Fire rated

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[1] Fire resisting windows complying with NZS 4232, and have a FRR of -/30/-.

[2] This is based on a cost estimate from commercial windows.

windows are not compared for price as they are only used when it is specified as necessary in the Building Code, and as such cost is accepted or the design altered.

Table 2: Cost of Different Frames in a Typical New House.

Area of Glazing	Frame Type	Value $	% of $150,000
20 m^2	Aluminium	3800	2.53
	Timber	6800	4.53
	Seismic	6200	4.13
30 m^2	Aluminium	5700	3.80
	Timber	10200	6.80
	Seismic	9300	6.20
40 m^2	Aluminium	7600	5.07
	Timber	13600	9.07
	Seismic	12400	8.27

Table 2 demonstrates that using seismic frames instead of standard aluminium frames only increases the cost of a medium quality 150 m^2 house by 2 or 3%. This would mean, (assuming a 3% increase), for the year to June 2001, in New Zealand, it would have required an extra expenditure of roughly NZ$8.5M to install seismic movement windows in domestic construction.

It also shows that although installing seismic movement frames almost doubles the price of standard aluminium frames, there is little difference between seismic frames and timber framed windows. However, seismic frames presently have a higher labour cost than standard timber frames which could make them marginally more expensive overall.

Expected Earthquake Damage Costs

Damage costs can be estimated from the cost of replacement of damaged property. Wellington has a high risk of a large-scale earthquake. Total earthquake loss has been estimated at NZ$5 B. Illustrated in Table 3 is the range of expected replacement costs of glazing loss caused by earthquakes to domestic property within Wellington City. Three shaking intensities are calculated for, with an estimate of damage caused by each of the intensities. It is assumed:

- MMI VII would damage 10% of all domestic glass in Wellington
- MMI VIII would damage 20%
- MMI IX would damage 30%

For each damage estimate the costs are divided between the replacement of timber windows, aluminium windows or just glazing as a percentage of the total damaged stock. It is more likely that in most cases only the glass will break, and the frame will be repairable. This makes Total B in Table 3 the most likely scenario. There are approximately 60,000 residential properties within Wellington City, these are assumed to have either 20 m^2, 30 m^2, or 40 m^2 of glazing, being a representative range for this type of building. Earthquakes of intensities VII – IX are realistic for the Wellington region, with a maximum intensity of MMI X estimated for the Wellington fault. Replacement costs are based on the supply costs in Table 1.

Table 3: Replacement Costs for Glazing in Wellington City

Replacement Item	%	Replacement Costs $(million)								
		MMI VII (10%)			MMI VIII (20%)			MMI IX (30%)		
		20 m^2	30 m^2	40 m^2	20 m^2	30 m^2	40 m^2	20 m^2	30 m^2	40 m^2
Timber	33	13.46	20.20	26.93	26.93	40.39	53.86	40.39	60.59	80.78
Aluminium	33	7.52	11.29	15.05	15.05	15.04	30.10	22.57	33.86	45.14
Glazing	33	2.18	3.27	4.36	4.36	4.36	8.71	6.53	9.80	13.07
TOTAL A	**100**	**23.17**	**34.74**	**46.33**	**46.33**	**59.80**	**92.66**	**69.50**	**104.25**	**139.00**
Timber	25	10.2	15.3	20.4	20.4	30.6	40.8	30.6	45.9	61.2
Aluminium	25	5.7	8.55	11.4	11.4	17.1	22.8	17.1	25.65	34.2
Glazing	50	3.3	4.95	6.6	6.6	9.9	13.2	9.9	14.85	19.8
TOTAL B	**100**	**19.2**	**28.80**	**38.4**	**38.4**	**57.6**	**76.8**	**57.6**	**86.4**	**115.20**

Labour is more intensive for replacing windows and glazing than installing in a new construction. Table 3 shows that expected replacement costs for glazing and window frames range from $20M to $140M. This is a staggering cost when it is considered glazing is only a single element of buildings.

Conclusions to Chapter 3

Presently, windows that allow for seismic movement are designed for each individual building and this increases costs over standard windows. The costs in Tables 2 and 3 show that economically protecting domestic glass is a valid recommendation to make as the increase in costs for one year of protecting domestic glazing in new construction in New Zealand from seismic movement, is less than even half the lowest expected replacement cost for broken domestic glazing in Wellington.

4. Fire

Introduction

A secondary effect of a large earthquake is fire. Fire following earthquake can cause major damage to urban areas, and studies done on Wellington have estimated millions of dollars of damage that could be caused by post-earthquake fires [13][7]. The risk of severe fire increases with shaking intensity, due to more damage to buildings and fire fighting systems and an increased number of ignitions.

Fire spread becomes a problem as there is often little fire fighting water available due to disruption of underground water pipes. This necessitates the reliance on passive fire protection systems of the buildings to resist the spread of fire. Unfortunately most domestic buildings in New Zealand have little fire protection and are clad in combustible materials. Fire also spreads through building openings, such as windows, igniting combustible materials inside. If the glass is broken due to shaking this can occur quicker, and with less radiation emitted from the fire.

The current building code acceptable solutions do not allow any combustible surface within 1m of the building. However, older buildings, built to older regulations are often closer together. This makes the older suburbs of more at risk of major fire.

Evidence of Fire from Past Earthquake Events

Post–earthquake fire has been the cause of the two worst urban fires this century other than those caused by military action; Kanto, Japan 1923 and San Francisco 1906. The two most recent cases of significant post-earthquake fire were in America in 1994 and Japan in 1995. The worst event in New Zealand was the Napier earthquake of 1931.

<u>The Northridge Earthquake</u>

United States, 1994.

Magnitude: 6.8, Intensity: VIII

There were approximately 110 earthquake related fires, with 60% of these in residential dwellings [11]. Fire related damages to property and contents were estimated at over US $13 M. There was one death attributed to fire [15].

The worst fires occurred at a mobile home park. Observations of the fire indicate that the method of unit-to-unit fire spread was mainly through the windows. Once a unit became fully involved in fire, the thermal radiation was sufficient to cause the breakage of windows in an adjacent unit or to ignite combustibles within the unit directly through the windows [20].

It was also witnessed at this event that falling bricks and shattered glass would also have posed a severe life-safety threat for anyone on the streets [15].

The Great Hanshin Earthquake (Kobe)

Japan, 1995.

Magnitude: 7.2. Intensity: VIII-XI

The total financial loss from the earthquake was estimated to be in excess of US$100 B. Kobe City suffered extensive loss due to fires caused as a result of the shaking damage. There were many fires, and once started they spread rapidly and destroyed much of the city. The fires burned for 24 hours, consuming in excess 5000 buildings and displacing thousands of people [18]. Over 500 deaths were caused by fire. Many of these were people trapped alive, and then killed by fire [2].

Many of the buildings consumed by fire had non-combustible claddings, but fire spread to them because flames from adjacent buildings penetrated openings in external walls [6]. These openings include windows broken by the severe ground motion. Other buildings had wired glass in their windows. Although some of these were cracked due to the earthquake or the heat of the flames, the wire kept the glass in place and did not allow the flame to penetrate to the inside of the building [6]. These windows with small gauge wire are common in Japan. Wire glass exterior windows appeared to be effective in reducing the fire spread [6].

The Napier Earthquake

Hawke's Bay, New Zealand, 1931.

Magnitude: 7.75

No estimations of loss due to fire have been made for this earthquake. There were over 250 fatalities due to the earthquake and fires [2]. In Napier, three fires broke out in chemists' shops, and 1 spread to a fourth building. It was thought that the fire would be contained to these 4 buildings but due to high winds, the fire raged through the whole business district. Napier lost 86,000 m^2 of commercial property [2]. In other areas most fires burnt 1 or 2 buildings. The fire service had no water, and had to pull down and dynamite buildings to stop fire spread [8].

At the enquiry, the Fire Superintendent made a recommendation for wire glass windows and fireproof doors to be used in city business areas [2], so that in future fire spread would never be so rampant. This indicates fire spreading through windows was a major contributor to the high level of fire spread.

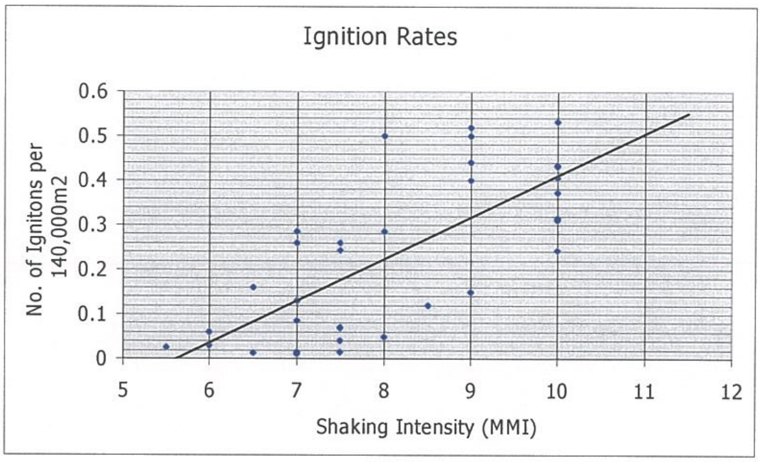
Fire Resistance of Glass

Normal glass will break and fall out by the time flashover occurs within a building [4]. However, the absence of glass in a neighbouring building (due to an earthquake) will increase the chance of fire spreading to this building. Normal glass in place can reduce the radiation passing through it by a factor of 0.3 - 0.4. Radiation is attenuated by fire rated and Georgian wired glass by a factor of 0.5 [4]. This means if the glass in a neighbouring building has broken and fallen out due to the earthquake there is a greater risk of fire spreading to it from the original fire building.

Expected Cost of Fire Damage

Ignition rates for post-earthquake fire can be estimated from shaking intensity from trends from past earthquake events. This relationship between ignitions rates per building and intensity is shown in Figure 1. The data for the graph is in Table 6, Appendix B.

Figure 2. Ignition Rates from Previous Earthquake Events.



Three rates of ignition have been calculated for each intensity; the average (from the trend line), and one standard deviation above and below. Estimating how many buildings each fire consumes is harder to achieve, as there is little historical data available. The rate of burning is the average number of burned structures per ignition. Three rates of burning have been found by using the estimated rate from a previous study of Wellington [13] (A), the observed rate in Kobe City, 1995 [10] (C), and the average of the two (B). Table 4 shows the number of domestic buildings burnt in Wellington when combining these three rates of ignition and burning.

Table 4: Number of Domestic Buildings Burnt in Wellington

		MMI VII			MMI VIII			MMI IX		
Rate of Ignition		0	0.06	0.22	0	0.16	0.32	0.1	0.26	0.42
Residential Ignitions		0	3.6	13.2	0	9.6	19.2	6	15.6	25.2
		Residential Buildings Burnt								
Rate of Burning A	8.8	0	31.68	116.16	0	84.48	168.96	52.8	137.28	221.76
B	20.05	0	72.18	264.66	0	192.48	384.96	120.3	312.78	505.26
C	31.3	0	112.68	413.16	0	300.48	600.96	187.8	488.28	788.76

The study of Wellington estimated approximately 230 houses would be consumed by fire after a large-scale earthquake assuming low wind speeds [13]. This falls within the mid-range of results in Table 4.

In Wellington it is assumed that due to damage to the underground water distribution system caused by a large earthquake there will be very little, or no fire fighting water[13]. Also, due to the high number of ignitions, and other emergencies requiring the Fire Services resources in the aftermath of an earthquake there can be assumed to be no active fire fighting. Owing to this, when there is an ignition within a building, it is likely to consume the entire building and its contents. Table 5 illustrates the estimated total cost of consumed buildings, using the estimated number of residential buildings burnt from Table 4.

Table 5: Cost of Consumed Building and Contents

House & Contents Price	Rate of Burning	MMI VII			MMI VIII			MMI IX		
		Cost of Consumed Buildings and Contents $ (millions)								
$250,000	A	-	7.92	29.04	-	21.12	42.24	13.2	34.32	55.44
	B	-	18.05	66.17	-	48.12	96.24	30.08	78.20	126.32
	C	-	28.17	103.29	-	75.12	150.24	46.95	122.07	197.17
$300,000	A	-	9.50	34.85	-	25.34	50.69	15.84	41.18	66.53
	B	-	21.65	79.40	-	57.74	115.49	36.09	93.83	151.58
	C	-	33.80	123.95	-	90.14	180.29	56.34	146.48	236.63
$350,000	A	-	11.09	40.66	-	29.57	59.14	18.48	48.05	77.61
	B	-	25.26	92.63	-	67.67	134.74	42.11	109.47	176.84
	C	-	39.44	144.61	-	105.17	210.34	65.73	170.90	276.01
$400,000	A	-	12.67	46.46	-	33.79	67.58	21.12	54.91	88.70
	B	-	28.87	105.86	-	76.99	153.98	48.12	125.11	202.10
	C	-	45.07	165.26	-	120.19	240.38	75.12	195.31	315.50

Table 5 shows a range of costs of fire from nothing, to hundreds of millions of dollars. This demonstrates the considerable range in possible damage costs. Costs will vary exceedingly depending on what areas, or suburbs the ignitions are located in. Probable locations of ignitions could be predicted, for example where suburbs have older gas reticulation, but with a high level of uncertainty.

The higher range of costs shown in Table 5 (Rate C) are the costs that could occur if fire spread is as rampant as it was in Kobe. It is unlikely this would occur however, as domestic regions are not as densely built up in Wellington as in Japan.

Conclusions to Chapter 4

This chapter has illustrated the risk of post-earthquake fire and the extreme costs associated with it. Severe fire spread can increase the risk of loss of life and injury, and increases the strain upon a city to recover from a serious disaster. More people are displaced, and more rebuilding is needed at a greater cost to insurers and property owners. Current research is attempting to quantify this risk more accurately [13].

Although installing windows that can sustain seismic movement will not stop fire spread, having windows in place can reduce building-to-building fire spread. It was seen in Kobe that fire often spread to surrounding buildings through opening in the exterior walls.

With the glazing intact on a neighbouring building, the fire has to burn hotter and longer to spread to it. The fire cannot spread as easily and hence as quickly, to combustible material within the receiving building. This gives the fire service a greater chance of extinguishing the fire in the original building, or at least controlling fire spread to neighbouring buildings, and increases the chance of successful evacuation from buildings at risk.

5. Discussion & Conclusions

Introduction

This chapter includes discussion and conclusions drawn from the results of the previous chapters. It comments on the NZBC, cost of replacement of existing glazing and the installation of seismic frames, standardising manufacture of seismic frames, and existing and new buildings. Following this discussion the conclusions and recommendations found from this study are identified.

There are inherent uncertainties when predicting future events. This study uses a simplistic evaluation of predicted damage using assumed damage ratios for three intensities of earthquake in Wellington City. This gives an appreciation for the extent of costs due to glass breakage in domestic buildings in earthquakes.

Current Building Regulations

The evidence of glass breakage due to ground motion has led to inclusion of specific clauses to protect buildings parts, including windows, in engineered buildings. This shows that the problem has been recognised as serious enough to warrant being included in New Zealand's building regulations for engineered buildings.

Although the risk to life is greater for glass breakage in high-rise, commercial buildings, which could have been the impetus behind the inclusion of these clauses, it also protects these buildings from high replacement costs of broken glazing and windows. This study shows, in Chapter 3, that there is also significant risk of financial loss due to glass breakage in residential buildings.

Within the current building regulations domestic buildings do not have the same level of protection. There is specific mention of allowable deflection in domestic windows, but this is more than is allowed in engineered buildings and it is included for wind design loads and not for seismic movement.

Cost of Installation

Installing windows that allow for seismic movement in new residential construction in New Zealand would only increase costs by 3%. This is a very small increase in capital costs over the lifetime of the building, (residential buildings have a design life of 50 years). Taking into account inflation, it would cost significantly less than replacing the windows at a later date. Also, due to the high expectancy of a large earthquake in New Zealand in the next 50 – 100 years, this increase in initial cost becomes more economically viable.

Chapter 4 illustrates the added risk of fire following earthquake. Current research has estimated that for Wellington, 1 - 5 % of the total earthquake loss will be due to fire following a large earthquake [13]. Although seismic framed windows cannot stop fire spread, having windows still in place after the shaking can reduce fire spread by radiation between buildings. This can decrease the amount of buildings damaged, provide the fire service more time to suppress the fires, and can allow more time for people to evacuate buildings at risk from fire.

Using Georgian wired glass would give more protection to residential buildings from fire but may be seen as an unacceptable solution due to aesthetic reasons. A clear fire rated glass, 'pyran', is available but costs five times as much as standard glass.

Standardising Manufacture of Seismic Frame Windows

Currently, windows that allow for seismic movement are designed for each individual building, taking into consideration the calculated deflection. This increases cost of time and labour for design and manufacture of these window frames. However, for the type of construction considered under NZS 3604, light timber framed residential buildings, a reasonable estimation of the expected deflection could easily be made and a proprietary window system designed that would allow for this deflection. If a standardised system were to be designed it would significantly reduce costs of purchasing and installing seismic allowance windows.

Existing Buildings

As the NZBC is only relevant to new buildings, including a clause for protection of glazing in domestic buildings would only protect new construction. Older buildings would not benefit from the inclusion. However, if a section was added to the NZBC to include compulsory upgrading of glazing and window frames when buildings were being upgraded or retrofitted, some older buildings would become protected from glass breakage. Existing residential buildings would still be at risk but this portion of the building stock would diminish over time as buildings were upgraded.

Another alternative is to provide incentives to buildings owners to install seismic frames in their existing buildings. This can be achieved by lower insurance premiums or even a supplemented cost of seismic framed windows by the government of territorial authority although this is very unlikely. It could be linked to other good building practise incentives, such as energy use, by including double glazing windows.

Conclusions from this Study

- There is currently only limited protection of domestic glazing from deflection failure within the New Zealand building regulations.

- Financial loss from glass breakage alone in Wellington City caused by earthquake was estimated to range from:

  - For an earthquake of intensity VI: NZ $20 – 46 M
  - For an earthquake of intensity VII: NZ $38 – 92 M
  - For an earthquake of intensity IX: NZ $ 76 – 139 M

(The total financial loss due to glass breakage is likely to be higher than this as entire buildings will be destroyed due to worsened spread of fire.)

- Installing windows that allow for seismic movement in all new domestic construction in New Zealand, for the year up to June 2000, would have only increased capital expenditure by 3%.

- Due to the high expectancy of earthquakes in New Zealand, economically, it is worthwhile to install frames that allow for seismic movement.

- Buildings owners are unlikely to choose a more expensive construction unless there are financial incentives or it is enforced within the legislation of the NZBC.

Recommendations from this Study

- The potential financial loss from glass breakage due to earthquake is serious enough to warrant inclusion in the New Zealand building regulations. Including a clause to protect domestic glazing from seismic movement, in a small way would protect property from fire spread after an earthquake. This fulfils the third aim of the Building Act to protect other property from damage.

- The cost for seismic frame windows in domestic housing could be reduced by manufacture of a standardised system that would allow for typical expected deflection of buildings built to NZS 3604: Light timber framed buildings.

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Appendix A

Modified Mercalli Intensity Scale:

MMI VI: Felt by all, many people frightened and run outdoors. Some heavy furniture moved. A few instances of fallen plaster or damaged chimneys. Damage slight.

MMI VII: Everyone runs outdoors. Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; some chimneys broken. Noticed by persons driving motor cars.

MMI VIII: Damage slight in specially designed structures; considerable in ordinary substantial buildings with partial collapse; great in poorly built structures. Panel walls thrown out of frame structures. Fall of chimneys, factory stacks, columns, monuments, and walls. Heavy furniture overturned. Sand and mud ejected in small amounts. Changes in well water. Disturbs persons driving motor cars.

MMI IX: Damage considerable even in specially designed structures; well designed frame structures thrown out of plumb; great in substantial buildings; with partial collapse. Buildings shifted off foundations. Ground cracked conspicuously. Underground pipes broken.

MMI X: Some well built bridges and wooden structures seriously damaged; most masonry and frame structures with foundations destroyed; ground badly cracked. Rails bent. Landslides considerable from river banks and steep slopes. Shifted sand and mud. Water splashed (slopped) over banks.

MMI X11: Few if any masonry structures remain standing. Bridges destroyed. Broad fissures in ground. Underground pipe lines completely out of service. Earth slumps and land slips in soft ground. Rails bent greatly.

MMI XII: Damage total. Waves seen on ground surfaces. Lines of sight and level distorted. Objects thrown upwards into the air.

Appendix B

Ignition Rates

Table 6: Ignition Rates for Previous Earthquake Events

Event	Area	Magnitude	No. of ignitions per 140,000m^2
San Francisco, 1906	San Francisco	9	0.5
	Berkley	7.5	0.26
	San Jose	9	0.15
	Santa Rosa	9	0.52
	Oakland	8	0.05
Santa Barbara, 1925	Santa Barbara	8.5	0.12
Long Beach, 1933	Long Beach	9	0.44
San Francisco, 1957	San Francisco	7	0.01
Anchorage, 1964	Anchorage	1	0.31
Santa Rosa, 1969	Santa Rosa	7.5	0.07
San Fernando, 1971	Los Angeles City	7	0.085
	Pasadena	6	0.06
	Los Angeles County	6	0.03
	Burbank	7	0.26
	San Fernando	9	0.4
	Glendale	6.5	0.16
Coalinga, 1983	Coalinga	8	0.5
Morgan Hill, 1984	San Jose	5.5	0.025
	Morgan Hill	7	0.285
Kobe, 1995	Nishi-ku	7.5	0.015
	Tarumi	7.5	0.069
	Suma	7.5	0.242
	Amagaski City	7.5	0.041
	Nagata	10	0.431
	Hyogo	10	0.434
	Chuo	10	0.531
	Nada	10	0.373
	Higashi-nada	10	0.315
	Ashiya City	10	0.406
	Nishinomiya City	10	0.242
	Kita	6.5	0.013
	Osaka	7	0.014
Scawthorn , Table 5		7	0.013
		8	0.285
		9	0.4

Standard deviation =1.7