FACADE DAMAGE ASSESSMENT OF MULTI-STOREY BUILDINGS IN THE 2011 CHRISTCHURCH EARTHQUAKE

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SUMMARY

The magnitude 6.3 earthquake that struck Christchurch on the 22nd February 2011 caused widespread damage to the multi-storey buildings within Christchurch's central business district (CBD). Damage to the facades of these buildings was a clear contributor to the overall building damage. This paper presents the damage assessment of the facade systems from a survey of 217 multi-storey buildings in the Christchurch CBD. The survey covers only buildings greater than three stories in height, excluding the majority of unreinforced masonry facades, of which damage has been well documented. Since a building can have more than one type of facade system, a total of 371 facade systems are surveyed. Observation of facade damage is discussed and is presented in terms of its performance level. Trends in facade performance are examined in relation the structural parameters such as construction age and height.

INTRODUCTION

The earthquake that struck New Zealand's second largest city on the afternoon of the 22nd February 2011 took the lives of 182 people; the second largest toll from a natural disaster in New Zealand [1]. The epicentre was located approximately 10 km from the city at a shallow depth of 5 km. The close proximity of the earthquake resulted in severe ground shaking throughout Christchurch. The maximum felt intensity was MM IX and the maximum recorded peak ground acceleration (PGA) was 2.2g. The recorded PGA within the Christchurch Central Business District (CBD) ranged from 0.6g and 0.8g [2]. The horizontal spectral acceleration demand for the Christchurch Hospital site is shown in Figure 1 for the September 4 and February 22 events compared with NZS 1170.5 elastic design spectra for Christchurch.

The earthquake caused widespread failure to older Unreinforced Masonry (URM) structures as well as the failure of two Reinforced Concrete (RC) buildings. Many buildings within the Christchurch CBD withstood the effects of the earthquake from a structural perspective but are considered unusable because of damage to facades, ceilings, partitions and contents. Current seismic design provisions typically require that non-structural components be secured so as to not present a falling hazard; however, these components can still be severely damaged such that they cannot function [3].

Not only can damage to the facade cause a building to be unusable, but there is also the risk of injury or death from things such as falling panels, masonry or glass, as shown in Figure 2. It is also clear that facade systems are particularly vulnerable to earthquakes since new and continuing damage to facade systems has been observed throughout Christchurch in recent aftershock events.

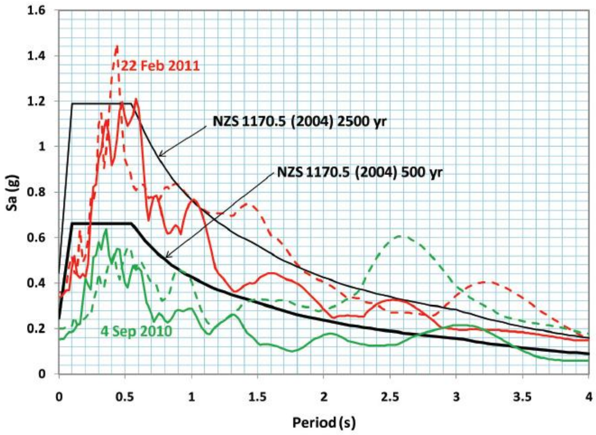

Figure 1: Horizontal spectral acceleration for Christchurch Hospital (8 km epicentral distance) from September 4 and February 22 events compared with NZS 1170.5 elastic design spectra for Christchurch [4].

This paper presents the damage assessment overview of the facade systems of 217 buildings in the Christchurch CBD. The buildings surveyed are only those greater than three stories in height in order to exclude the majority of unreinforced masonry facades as well as to restrict the survey population. For buildings with multiple facade systems, multiple assessments are conducted of the same building. In total 371 facade systems are surveyed. The survey is based on what is visible from outside the building, making it equivalent to a Level 1, or rapid safety assessment [5]. Therefore, it was not possible to assess things such as the status of the connections or whether windows were jammed. The consequence of this is that the results of the survey will be conservative, as less obvious forms of damage certainly exist. Only with a more detailed survey could the true extent of damage be determined.

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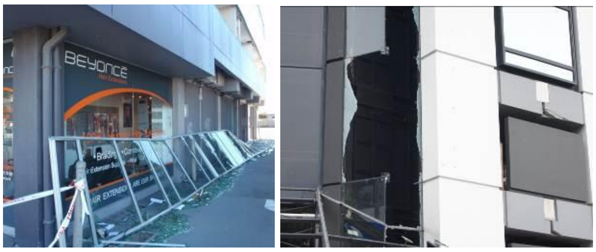

Figure 2: Examples of heavy damage to facade systems caused by the February 22 earthquake.

NEW ZEALAND FACADE TECHNOLOGY

Facade systems can be classified by two main types; claddings and infills. The simplest way to differentiate between the two types is that infills are constructed within the frame of the structure, while claddings are attached externally to the primary structure [6].

Cladding

Claddings often incorporate stiff, brittle materials such as glass, concrete and stone. The weight of a cladding can be described as being light, medium or heavy. Light cladding is defined as not having a mass exceeding 30 kg/m^2. Medium cladding is defined as having a mass exceeding 30 kg/m^2, but not exceeding 80 kg/m^2. Heavy claddings can be defined as having a mass exceeding 80 kg/m^2 [7].

Precast concrete panels, a heavy cladding, have been the most popular cladding material used in new non-residential buildings in New Zealand over the past decade [8]. Two examples of buildings in Christchurch that feature precast concrete panels are show in Figure 3. Autoclaved Lightweight Concrete (ALC, also called Autoclaved Aerated Concrete) panels features on several buildings within the Christchurch CBD and are also among the most widely used material for claddings in Japan [9].

Cladding connections can have numerous configurations; however they are typically located on either the beams or columns respectively. The generic connection method for heavy cladding consists of a bearing and tie-back connection. The fixed bearing connections support the claddings gravity loads, while the ductile tie-back connections allow relative movement between the cladding and the structure. Tie-back connections must also be capable of accommodating the out-of-plane forces on the panel, including wind.

Figure 3: Examples of heavy cladding present on Christchurch buildings.

Light-medium weight claddings, like those shown in Figure 4, are generally fixed to the structure with connections that do not allow movement, hence inter-storey movement must be able to be accommodated within the system. Stick systems are a popular lightweight option in modern multi-storey buildings. The stick system consists of extruded aluminium frames holdings panes of glass. A rubber seal is used to allow the glass within the frame to move while keeping the building weather tight.

Figure 4: Examples of light-medium weight cladding present on Christchurch buildings.

One of the more recent variations of the stick system is the double skin facade system. The double skin consists of two layers of facade material (typically glass) which creates a sealed cavity to improve the thermal performance of the building. Double skin facade systems are being employed increasingly in high profile buildings, being touted as an exemplary 'green' building strategy.

Infill

Infills have traditionally been made of heavy rigid materials, such as clay bricks or concrete masonry blocks. However, more lightweight infill panel options such as light steel/timber framed infill walls (drywalls) are available.

It is typical for an infill panel to be combined with a glazing infill system. Glazing infill consists of an aluminium frame attached directly to the infill panel or structure. The frame has rubber gaskets to hold the panes of glass in place and keep the system watertight whilst allowing some in-plane movement. This type of system is simple to construct and is particularly prevalent in low to mid-rise office structures. Often the glazing will form the majority of the overall infill. It can sometimes be difficult to distinguish between domestic and commercial glazing infill systems. A domestic system can simplistically look very similar to a system which has been rigorously designed for a particular building.

Figure 5: Examples of infill on Christchurch buildings.

Design Standards

New Zealand design standards specify serviceability limit state (SLS) criteria for earthquakes in the form of deflection limits. These deflection limits are related to earthquake actions with an annual probability of exceedance of 1/25 [10]. There is also an ultimate limit state (ULS) requirement that the facade continues to be supported and does not interfere with evacuation in a design level earthquake. Facade damage should be expected in an ULS event according to current design standards. This is because the SLS limits define deflections beyond which repairs can be expected. However, the damage should not be life-threating.

BUILDING AND FACADE SURVEY

The building survey was conducted within the four avenues (Bealey, Deans, Moorhouse and Fitzgerald) that encompass the Christchurch CBD. A total of 217 buildings were surveyed, as shown in Figure 6.

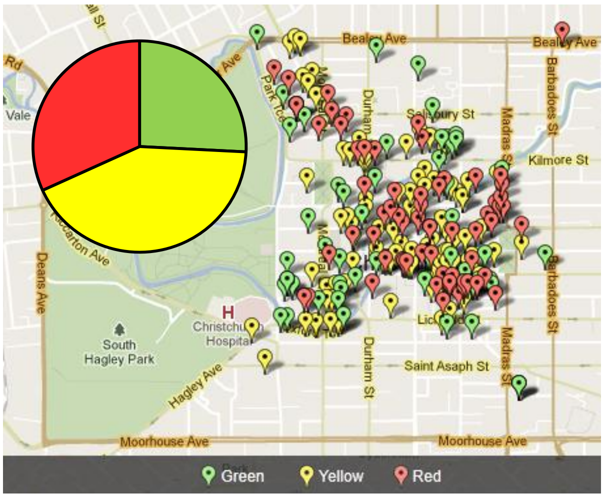

Figure 6: Locations of buildings surveyed and their placard composition.

After the February 22nd earthquake, all buildings were inspected and given either a green, yellow or red placard to represent the safety of the building. A green placard indicated that a building had been assessed and no apparent structural or other safety hazards were found. A yellow placard indicated that a building had restricted access and a red placard indicated a building must not be entered because it was deemed unsafe [5]. 74% of the buildings in the survey received either a yellow or red placard.

Shown in Figure 7 is the building construction information. The majority of buildings surveyed are low to mid-rise in height and were of reinforced concrete construction. 65% of the buildings primary occupancy use is office use, followed by 18% apartments and 9% hotels. The building age was estimated at the time of survey or found from city records following further investigations. The majority of buildings are less than 50 years old following a large boom in construction after the 1960s.

A total of 371 facade systems were surveyed on the 271 buildings. A maximum of two facade systems were surveyed per building and a facade system was only surveyed if it occupied at least 10% of the building's surface area.

The survey classified the facade systems by eleven individual typologies based on those used in the Post-earthquake Building Performance Assessment Form [11]. The age of the facade in relation to the building was recorded. 97% of facade systems appeared to be the same age of the building, with the remaining systems having been retrofitted.

It should be remembered that the survey is based on what is visible from outside the building and less obvious forms of damage certainly exist.

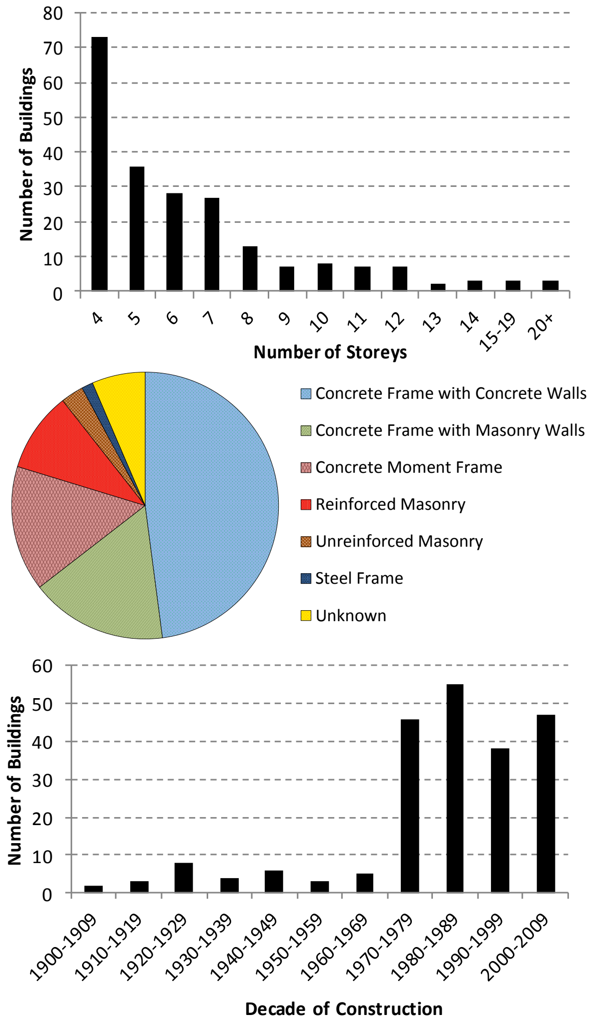

Figure 7: Building construction information (from top): building height, construction type and construction age.

FACADE DAMAGE

The presentation of facade damage is grouped according to the facade classifications introduced earlier.

Heavy Cladding

The majority of heavy claddings surveyed were precast concrete panels. Precast panels can be either storey-height panels that provide multiple architectural functions or panels that are purely aesthetic. The function of spandrel panels, like those in Figure 8 for example, is typically only to hide reinforced concrete members from view. There were approximately an equal proportion of storey-height panels and aesthetic panels surveyed.

Figure 8: Structure with disconnected spandrel panels.

Storey-height heavy panels commonly have openings for windows. The window system inside the panels could have been classified as a glass infill, however, for this survey they have been included as part of the panel system. This was decided since the surrounding panels have such high in-plane stiffness, movement allowance is not required for these window systems.

The majority of heavy claddings exhibited little to no damage. Where damage was present, it likely consisted of cracking or corner crushing. Corner crushing was most likely due to pounding with adjacent panels, as seen in Figure 9 (left). Within the CBD only one case of panel disconnection was observed. It was the result of several spandrel panels shearing off their bolted connections and falling to the sidewalk below, as shown in Figure 8. Fortunately no one was killed by these falling panels; however there was the risk of multiple fatalities as the heavy panels fell on approximately five tonnes of concrete fell to the sidewalk.

The panels were attached to the structure by an angle which was fixed to the panel by a cast-in anchor. Horizontal slots were present in all metal angles to allow sliding of the bolt, however, upon inspection, many of these bolts had sheared off close to the bolt head.

The slotted connections should theoretically have prevented large in-plane forces being carried in the panels. This is because slotted connections allow relative movement between the structure and the panels. However, it was observed that the bolt heads had not been able to move along the slots because their washers had been welded to the metal angle. This would have resulted in significant forces being transferred through the panels under in-plane deformation of the structure, likely leading to the shear failure.

Minor damage was also observed in the form of panels having residual displacements and/or rotations. The ejection or rupture of sealing joints due to movement between panels was also common, as shown in Figure 9 (right).

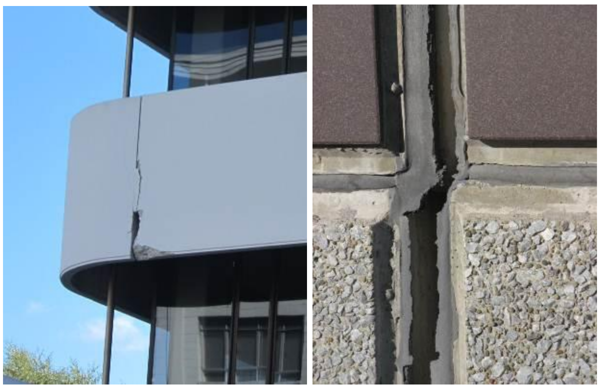

***Figure 9:** Corner crushing of spandrel panels (left), torn polysulphide seal (right).*

Complete disconnections of large concrete panels were also observed in the magnitude 6.3 aftershock on June 13th 2011. The remaining connection is shown in Figure 10 (left). However these panels were attached to a two-storey building and outside of the four avenues so are not included in the survey.

Frame elongation caused significant damage to the connections and panels in a multi-storey reinforced concrete perimeter frame building within the Christchurch CBD. Shown in Figure 10 (right) is a close up of the connection between the panel and the beam.

***Figure 10:** Connection of coffered precast panels that failed in June 13 aftershocks (left), precast panel and connection damage due to beam elongation (right).*

Light-Medium Weight Cladding

Light-medium weight cladding includes a broad range of facade systems. Each typology of light-medium weight cladding can also include a large range of systems. For example, the curtain wall typology includes numerous arrangements of extruded aluminium members infilled with glass or lightweight panels. Often light-medium weight cladding incorporates a large amount of glazing. They can therefore appear to look a lot more lightweight than they in fact are, with some systems (such as the double skin) containing a substantial amount of weight.

Lightweight claddings of all ages showed various levels of damage. Cracked or broken glass is usually the most obvious indicator of damage to light-medium weight cladding systems. Older systems normally provide less movement allowance for the glass and consequently were more likely to exhibit glazing damage, like that shown in Figure 11. Several buildings with older, non-seismic glazing frames were re-glazed between September and February, only to be damaged again in the February earthquake.

***Figure 11:** Damage to light-medium weight cladding.*

Newer systems exhibited proportionately less likely moderate to severe damage. However, issues do still exist with current design and construction techniques since several lightweight cladding systems less than 20 years old were heavily damaged.

For light-medium weight claddings, the difference between reaching SLS and ULS can be only a small step. This was evident by systems showing either negligible damage or significant damage with broken and fallen glass. Once the glass in the cladding is broken, SLS is surpassed and there is also a falling hazard. Managing the risk of falling glass is a difficult issue to deal with. Although most damage cases observed involved standard glass, one evident approach to try and reduce the risk of falling glass was the use of laminated and toughened glass. Using these types of glass had both positive and negative consequences.

The use of laminated glass aims to prevent the glass being able to break up and fall as sharp pieces. This was successful in most damaged laminated glass observed; however, some cases were also observed where the entire laminated pane fell from frame, presenting a significant falling hazard.

Toughened (tempered) glass is stronger than normal glass and when it is damaged it breaks into thousands of small glass fragments that present a much smaller falling hazard. Damage to toughened glass was typically observed as an empty frame and a pile of glass fragments on the footpath. Although the use of toughened glass involves accepting that the glass is going to fall if it is broken, it was clear the hazard of the falling fragments was lower than that of glass shards or entire panes.

Damage to the frame of light-medium weight claddings was difficult to distinguish from street level, so it is likely this type of damage was overlooked. However there were observed cases of frames being bent and warped, as well as one case where the glass has punctured through the frame itself. Failure of the frame was rare, with only one curtain wall system having a large-scale failure. This involved multiple sections of a curtain wall system completely detaching from the building, as shown in Figure 12. The entire aluminium frame and glazing along one side of the building at the second floor fell to the ground. Closer inspection showed that the aluminium frame was screwed into a wooden sub-frame and the failure was a result of the screws both shearing off and tearing out of the wood.

Figure 12: ***Disconnection of a light-medium weight cladding.***

A lot of heavy damage was observed in spider glazing, as can be seen in Figure 13. Spider glazing is a reasonably modern system so it would be expected that it should have performed better than other systems, however this was not the case. It appeared that damage originated around the 'spider' that holds each glass pane, likely a result of the 'spider' creating stress concentrations in these regions due to the restraint of the connection to the structure.

One of the recently installed spider glazing systems was designed to allow ULS seismic inter-storey displacement of +/-50 mm. The actual measured inter-storey displacement during the February 22 earthquake was 220 mm, over four times the structure's design level displacement. The amount of movement a spider glazing system can accommodate is not large (50 mm is near the limit of a spider aesthetic system) and this was apparent by the amount of damage observed.

Figure 13: Examples of damage to spider glazing systems.

Infill

Infill systems include masonry and glazing infill systems that are located within the frame of the structure. Infill facades performed very poorly in comparison with other facade systems, as can be seen in Figure 14.

Older glazing infill systems were particularly susceptible to damage. These systems typically consist of highly modulated glazing frames that do not contain any in-plane movement allowance apart from the small gaps which surrounds each glass pane. These gaps are typically only a few millimetres and consequently only allow a minimal amount of in-plane drift before the glass begins to carry force. Once this occurs, the stiff, brittle glass is at high risk of cracking and dislodging from the frame.

Figure 14:   Examples of damage to infill systems.

Typically modern glazing infill performed well and didn't have any breakage. However, since the survey was visual only, it is possible further damage exists to the facade systems which is not clearly visible. For example, many residential homes exhibited warping of their glazing frames without any cracks forming in the glass. This warping made opening windows and doors impossible in some cases. Therefore it is possible that some glazing infill cases were also distorted.

The vulnerability of masonry infill was clearly showcased by the damage sustained by the eight storey St Elmo Courts building (-43.532, 172.631), pictured in Figure 16. The collapse hazard of this building resulted in surrounding buildings and streets being completely off limits for numerous weeks. This building has now been demolished. Other unreinforced masonry infill cases also showed significant damage.

Reinforced masonry infill did not typically show much damage other than small cracks, however, it was evident the infill had an effect on the seismic performance of the primary structure [12], as can be seen in Figure 15, where the infill had a short column effect causing shear cracking in the column.

Figure 15: Short column effect due to infill.

FACADE PERFORMANCE LEVELS

The facade performance levels (or damage states) suggested by FEMA are the following: Operational, Immediate Occupancy, Life Safety and Hazards Reduced [3]. One of the problems with using these performance levels as a means to assess damage is that they are intended for use in design. In particular, the hazards reduced level is aimed at preventing serious injury caused by large or heavy items falling. However, not all surveyed facades met this design criterion. In order to avoid the confusion, the hazard reduced performance level is herein re-named the 'High Hazard' performance level to accurately include any cases where there was a high risk of serious injury or fatality from facade damage. Figure 16 presents photographs and a graphic illustration of the different facade performance levels sustained during the Christchurch earthquake.

The basic requirements for setting facade performance objective levels are relatively simple. For example, the basic performance objective would be that a facade remains undamaged following frequent earthquakes and that it does not fail in large (very rare) earthquakes. However, this objective level means that the facade may be damaged to some degree in occasional earthquakes. Definitions of the performance levels that were used in the survey are described below and are based around those suggested by FEMA 356 [3].

It is important to distinguish that the level of structural and non-structural damage can be different and hence the structural and non-structural performance levels are not necessarily the same. It is generally expected that the damage level of the non-structural components will be worse than the damage level of the structure. Shown in Figure 17 is the performance based design matrix that combines both structural and non-structural performance levels. A target building performance level consists of a selection of a structural performance level and a non-structural performance level [3]. The four highlighted squares represent the four target building performance levels suggested by FEMA 356 [3].

Operational Performance Level

The facade is able to support its pre-earthquake functions, although minor clean-up and repair may be required.

Immediate Occupancy Performance Level

Damage to the facade is present but building access and life safety systems remain available and operable. Minor window breakage could occur. Presuming that the building is structurally safe, occupants could safely remain in the building, although normal use may be impaired and some clean-up required. The risk of life-threatening injury due to facade damage is very low.

Figure 16: Facade performance levels.

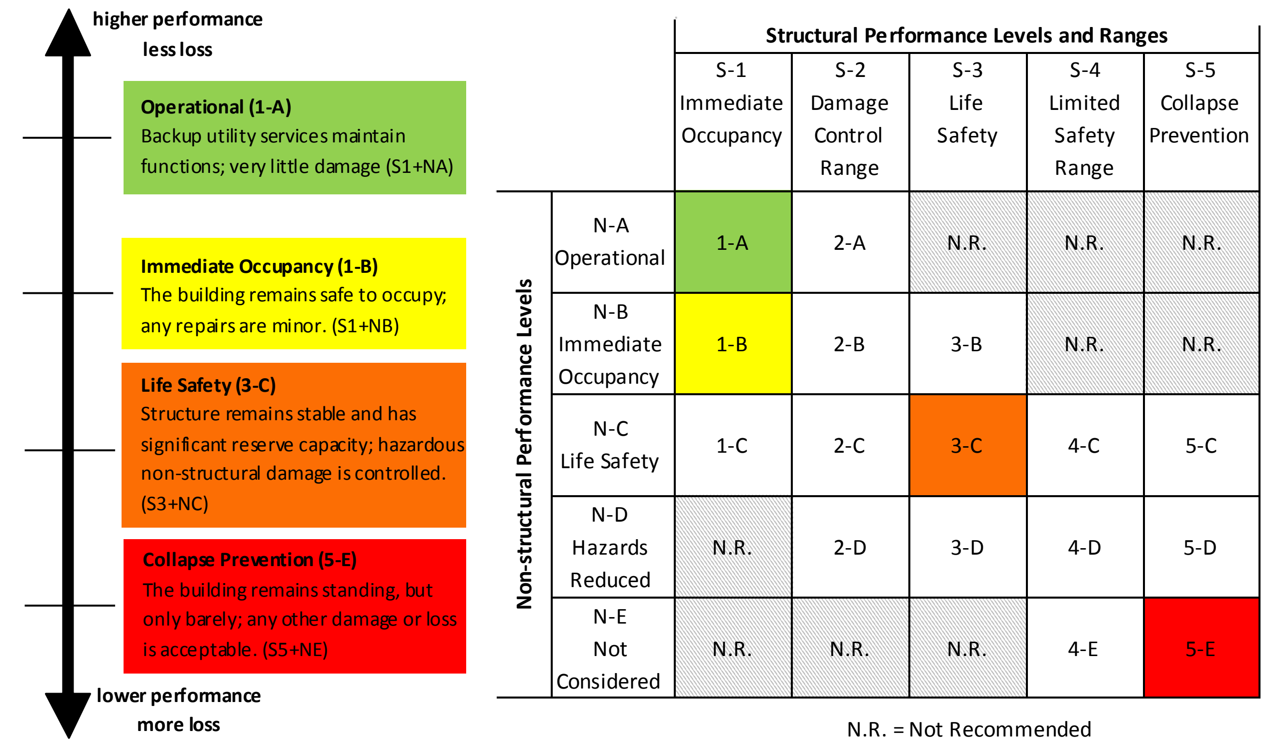

Figure 17: Post-earthquake structural and non-structural building performance levels [13].

Life Safety Performance Level

Damage to the facade is present but the damage is non-life threatening. Potentially significant and costly damage has occurred to the facade but the majority of the system has not become dislodged and fallen, threatening life safety either inside or outside the building. Egress routes within the building are not extensively blocked, but may be impaired by lightweight debris. While injuries may occur during the earthquake from the failure of facade components, overall, the risk of life-threatening injury is very low. Restoration of the facade may take extensive effort.

High Hazard Performance Level

Damage to the facade is present creating multiple falling hazards. Extensive damage has occurred to the facade with the potential to seriously threaten life safety outside the building. Widespread window breakage is likely and disconnection of components of the facade system from the structure is possible. Restoration of the facade is likely only possible with a complete replacement of the system.

FACADE PERFORMANCE

This section aims to identify trends in the performance of facade systems in relation to the structural information gathered for each building.

The facade systems are grouped according to the groups previously identified. The cladding typologies surveyed are listed below and the frequency that they were identified is shown in Figure 18.

Heavy cladding

- Concrete panels
- Stone panels

Light-medium weight cladding

- Curtain wall
- Lightweight panels
- Stick curtain
- Stucco
- Spider glazing
- Brick Veneer
- Double Skin

Infill

- Glazing infill
- Masonry infill

Firstly, the composition of performance levels for each facade system is presented in Figure 19. The performance level of each facade system was determined according to the criteria discussed in the section titled ‘Facade Performance Levels’. Overall, 64% of facade systems surveyed were deemed operational, 14% deemed Immediate Occupancy, 12% deemed Life Safety and 10% deemed High Hazard. This means that the performance of 37 facade systems was outside an acceptable level for even a very rare earthquake event as it posed a significant risk to life safety.

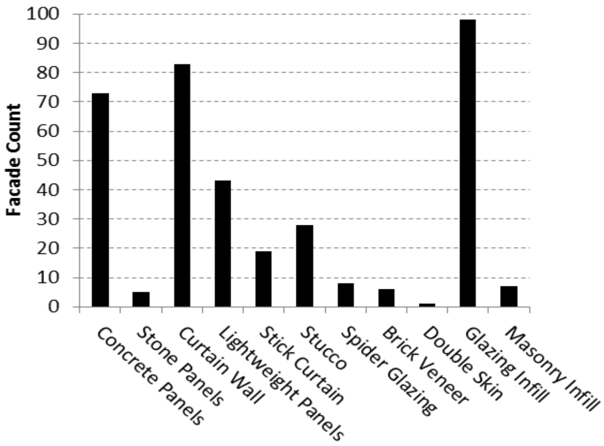

Figure 18: Facade typology composition.

It could be concluded that heavy claddings performed better than most facade systems; with 94% of heavy claddings deemed either operational or immediate occupancy. However, it is possible a more thorough assessment of the connections from inside the buildings may lower this percentage. More importantly the possible consequence of heavy claddings falling is severe which means further attention towards their treatment is necessary.

The composition of performance levels for light-medium weight claddings varied greatly. Overall, 82% of lightweight claddings were deemed either operational or immediate occupancy, exhibiting either no damage or very minor damage such as ejected window seals or cracked glass.

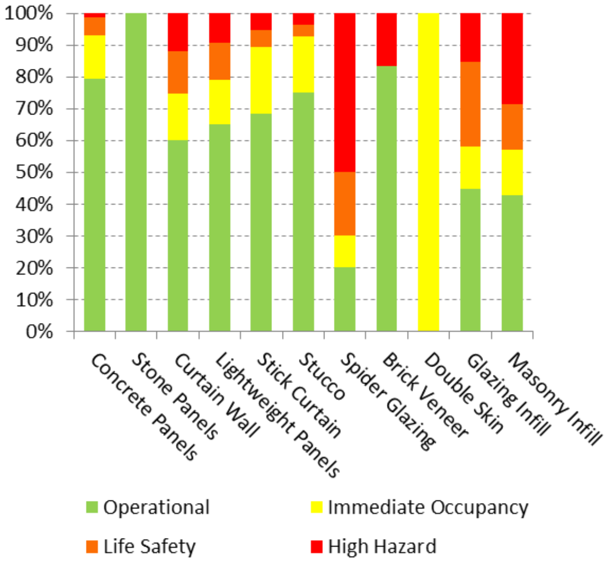

Figure 19: Facade performance by facade typologies.

A large number of high hazard cases were also observed. This was usually due to a significant portion of the glazing falling from the system. The glass damage was recorded for all lightweight cladding that contained glass. Nearly half of all glazed lightweight claddings had glazing damage and 39% presented a falling hazard. Only 60% of infill systems were deemed either operational or immediate occupancy. 17% were deemed high hazard, the highest of the facade groups.

Shown in Figure 20 is the facade performance grouped by building's predominant structural typology. The typologies are listed from left to right in terms of the frequency that they were identified. As expected, facade systems attached to unreinforced masonry performed by far the worst, likely a consequence of the poor structural performance. The remaining structural typologies showed fairly consistent facade performance. It would not be expected that structural typology would have a large influence on facade performance. However, one possible point of difference is between the facade performance of 'concrete frame with concrete walls' and 'concrete moment frame'. It can be seen that more damage was observed in concrete moment frames; this may possibly be due to concrete moment frames being more flexible structures than concrete frames with dominant shear walls.

Shown in Figure 21 is the facade performance grouped by building construction age. The building age was estimated at the time of survey or found from city records following further investigations. The majority of buildings are less than 50 years old following a large boom in construction after the 1960s.

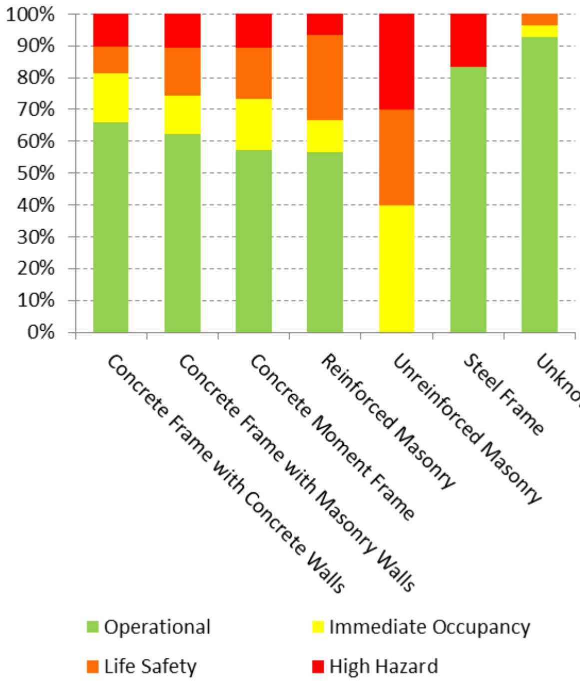

Figure 20: Facade performance by construction type.

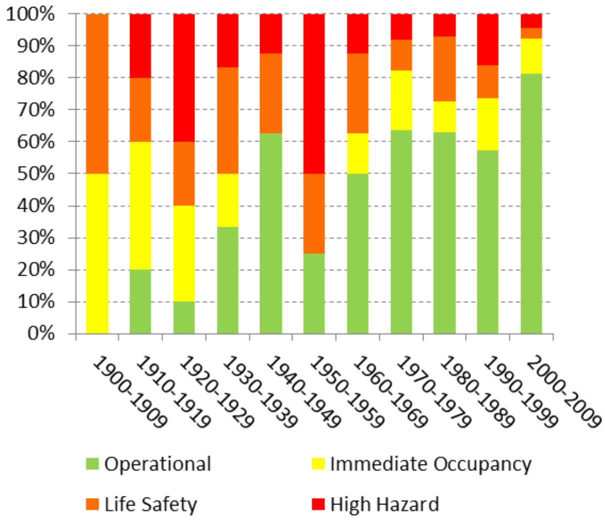

Figure 21: Facade performance by building age.

There is an evident trend that the newer the building, the better the facade performance. Buildings built in the 1950s exhibited the highest number of 'high hazard' cases. It is encouraging to see that facade systems built from 2000 onwards were clearly the best performing.

Finally, shown in Figure 22 is the facade performance grouped by the buildings height (number of storeys). A building's natural period is correlated to its height, so it is possible trends relating facade damage to the earthquake spectra could be observed, however it does not appear there is any such trend. The low amount of data present for taller buildings is likely the reason for the apparent higher level of damage in buildings 14 storeys and taller.

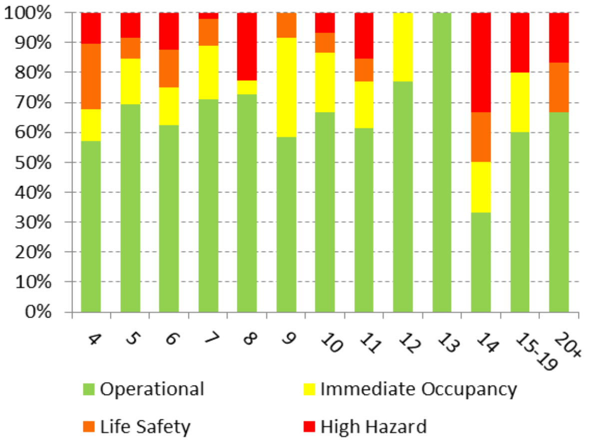

Figure 22: ***Facade performance by number of building storeys.***

DISCUSSION

It is evident from what has been presented that many facade systems are not meeting their design criterion since they still pose a reasonable risk to life safety. In order for this to improve, assigning responsibility of ensuring a building's facade is seismically proficient is needed. This coupled with mandated regulations for suppliers and installers will help to ensure suitable design and construction is achieved. Currently there are no standards written specifically for the design and/or installation of facade systems. As a consequently of this, there is no way for quality control to be enforced since there is no regulation that needs to be adhered to.

There is a general lack of accountability and responsibility by engineers and architects as to who has the design responsibility. Consequently, in a cost-driven market, cost constraints can end up negatively affecting decision making around facade design.

There is also limited technical understanding within the consultancy industry of façade systems - what works and why. The product features that are required to generate performance and compliance with codes are not well understood. On this basis, decisions revert to easiest selection method (low cost) due to difficulty in comparing different systems. Education and better communication between all parties is necessary to improve the current situation.

A long-term research programme is currently taking place at the University of Canterbury aimed at improving the earthquake performance of facade systems, developing integrated design procedures and investigating cost-effective, damage-free facade solutions. Solutions to improve the building performance (structural plus non-structural) include improving the disconnection of the facade from the structure, using the facade for controlled stiffening or damping and integrating the facade with the structure.

CONCLUSION

Earthquake damage to facade systems undoubtedly poses a large threat to life. The economic implication from facade damage is also significant due to business downtime and repair costs. Many buildings within the Christchurch CBD remain unoccupied due to non-structural damage despite the building retaining its structural integrity. In addition to the damage sustained in September 2010 and February 2011, continued facade damage has occurred in the subsequent aftershocks.

A survey of 217 buildings and their 371 respective facade systems showcased all types of damage to all the different typologies of facade systems. The survey has shown that in order to have facade systems that do not incur significant damage in design level earthquakes, major improvements are still required.

In order to reduce damage to facade systems in the future, both technical and political issues need to be addressed. Improvements are required to better understand the behaviour of many facade systems and whether the methods used to isolate them are satisfactory. Design guidelines are required for both designers and installers of facade systems. Communicating common errors that should be avoided is also important.

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