

DEVELOPMENT OF CLADDING CONTRIBUTION FUNCTIONS FOR SEISMIC LOSS ESTIMATION

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ABSTRACT

One method to rapidly estimate seismic losses during the structural design phase is to use contribution functions. These are relationships between expected losses (e.g. damage repair costs, downtime, and injury) for a wide range of building components (e.g. cladding, partitions, and ceilings) and the building's response. This study aims to develop contribution functions for common types of cladding used in different types of buildings considering damage repair costs. In the first part of this study, a building survey was performed to identify types and quantity of cladding used in residential, commercial and industrial buildings in Christchurch, New Zealand; where it was found that the most common cladding types are glazing, masonry veneer, monolithic cladding and precast panels. The data collected during the survey was also used to develop cladding distribution (i.e. density) functions. The second step involved identifying fragility functions from relevant literature which are applicable to the cladding detailing used in New Zealand. The third step involved surveying consultants, suppliers and builders on typical repair/replacement cost. Finally, Monte Carlo simulations were performed to combine the cladding density function with the fragility functions and the repair cost for each type of cladding to derive contribution functions for various types of cladding and building usage. An example (case study) is provided to demonstrate its usage.

INTRODUCTION

The building envelope is the skin of the building which consists of external walls, doors, windows, roof, and lowest floor of the building. Cladding systems are non-structural building components which describe the external wall including the support mechanism back to the structure. Claddings serve the basic purposes of providing thermal insulation and weather resistance in addition to providing architectural features [1]. Furthermore, aspects such as lighting and ventilation are directly affected by the claddings used, which have a large influence on user comfort [2]. Due to these reasons, any damage to the cladding system would affect the building's integrity which may disrupt building usage until repairs are completed. Moreover, damage to cladding systems may also pose life-safety risk outside the building.

In recent seismic events around New Zealand, such as the 2010-2011 Canterbury earthquake sequence, it has been observed that cladding can incur significant damage during seismic shaking [1,3]. This is because cladding systems often incorporate stiff and brittle materials such as glass, concrete and stone [4] which incurs damage under small distortions. Due to this, it is important to consider the performance of cladding when evaluating the socioeconomic impacts of a building's response during seismic shaking.

Cladding systems are just one of the many building components which may get damaged during strong shaking events despite the structural system itself performing well. This has raised awareness of the need to minimise socioeconomic impacts in future events to increase resilience. One way to achieve this is to explicitly consider seismic losses during the building design phase. One of the most widely used seismic loss estimation methodologies is the Pacific Earthquake Engineering Research (PEER) centre's Performance Based Earthquake Engineering

(PBEE) framework [5]. This framework comprises of four key analysis steps; (i) calculating the frequency of a seismic shaking intensity being exceeded, (ii) performing structural analyses to predict the building's response under a given shaking intensity, (iii) estimate component damage based on the building's response, and (iv) predict the losses resulting from the estimated damage. Step (iii) requires the use of fragility functions, which are probabilistic distributions describing the probability of exceeding certain damage levels based on the building's response; while step (iv) requires loss distributions, which are cumulative distribution of losses for a given damage level. Examples of fragility and loss functions are shown in Figures 1a and 1b, respectively.

The difficulties of applying this framework in engineering practice are (i) information regarding the quantity and type of every single building component are often not known by the engineer at the design stage, (ii) fragility and loss functions can be difficult to source, and (iii) a good understanding of probabilistic computation is needed. One method to avoid these issues is to provide engineers with typical loss distributions which can be related directly to building response for different building usages. Such an approach has been previously proposed by Dhakal [6] and refined by Dhakal and Saha [7], where the component losses were provided as a ratio of each storey's value which inherently includes information on the type and quantity of the components, and their fragility/loss functions. These ratios represent the contribution of component losses to the storey-level losses, and as such can be simply added together to estimate the losses incurred on a single storey level. However, the terminology used to describe these new functions is similar to loss functions, which can create some confusion in distinguishing between the two. As such, the term "contribution functions" is introduced in this paper to describe these new distributions, and is described in more detail in later

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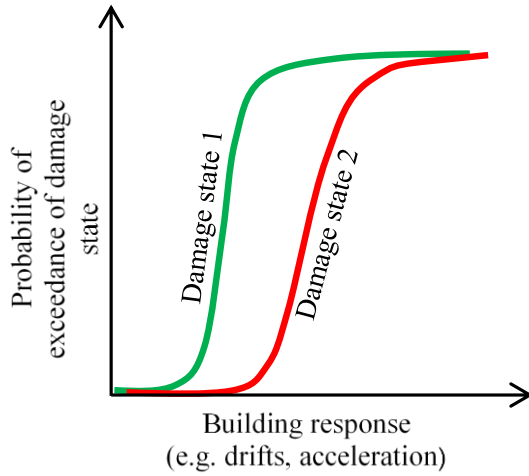
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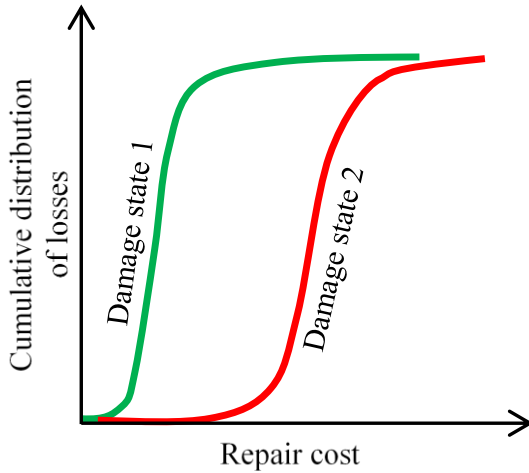
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sections. It should be noted that there are also other options available to simplify seismic loss estimation approaches [8], but these are not elaborated in further detail here.



(a)



(b)

Figure 1: Functions required in rigorous component-based seismic loss estimation; (a) fragility functions, and (b) loss distributions.

For this simplified approach to be widely adopted in practice, contribution functions need to be developed for a wide range of different building components. Contribution functions for ceilings and partitions have been developed and proposed by Dhakal et al. [9]. Due to the importance of cladding systems as previously described, there is also a need to develop contribution functions for these systems. The aim of this study is to address this need, and it involves identifying (i) the most

common types of claddings used in various building usage types, (ii) the typical quantity/density of claddings used in these building types, (iii) relevant fragility functions for each cladding type, and (iv) repair cost estimates for each damage type. These datasets are later combined to develop contribution functions, and an example demonstrating the application of the contribution functions is provided.

CLADDING TYPES

There are multiple types of cladding systems. It is quite difficult to distinguish them from one another, as there are different materials that can be used for cladding. Commonly used cladding materials are brick, glass, metal, concrete, timber, stone, vinyl, and composite materials that can include aluminium, wood, blends of cement and recycled polystyrene, wheat/rice straw fibres. The cladding systems can also be installed using different methods, which are adapted to different kinds of materials used in the construction of the cladding system.

Glazing

Stick curtain (continuous) and curtain wall (discrete) cladding systems are the most common types of glazing used in New Zealand. They are made of aluminium framing and glass panels connected back to the building structure. Heat soaked glass is used in these types of glazing to reduce the spontaneous breakage and the subsequent glass fallout; thereby reducing the associated replacement, maintenance and disruption costs and the risk of the building being classified as unsafe. Unitised curtain walls are composed of large glass units and are glazed within a factory and then sent to the construction site. Once on site, the units are hoisted onto anchors connected to the building. Unitised curtain walls have the advantages of faster construction, lower installation costs and better quality control, however, they can be more expensive than other systems [4].

The stick curtain, or stick system, is a metal 'stick' frame consisting of continuous perpendicular transoms and mullions surrounding pieces of glass or thin opaque panels. The vast majority of low to mid-rise curtain walls are installed in this way. Long pieces of aluminium (hence the name stick) are inserted between floors vertically and horizontally between vertical members to support and transfer the load of the glass back to the structure. Stick curtains are a popular option in multi-storey buildings and are often used when a client wishes for a predominantly glass building envelope. Framing members may be fabricated in a shop environment, but installation and glazing is typically performed on site. Due to the continuity of the stick curtain members, the transoms and mullions are detailed such that all movement must be accommodated between the glass and the frame. A gap is provided between the glazing and the frame to allow relative movement as specified in the NZ standard NZS4223.1 [10]. In contrast, curtain walls typically use a combination of this technique, as well as seismic joints within the transoms and seismic head joints with the structure [11]. Examples of glazing with typical connection details are shown in Figures 2 and 3, respectively.



Figure 2: Typical example of glazing cladding systems [1]; (a) curtain wall, and (b) stick curtain.

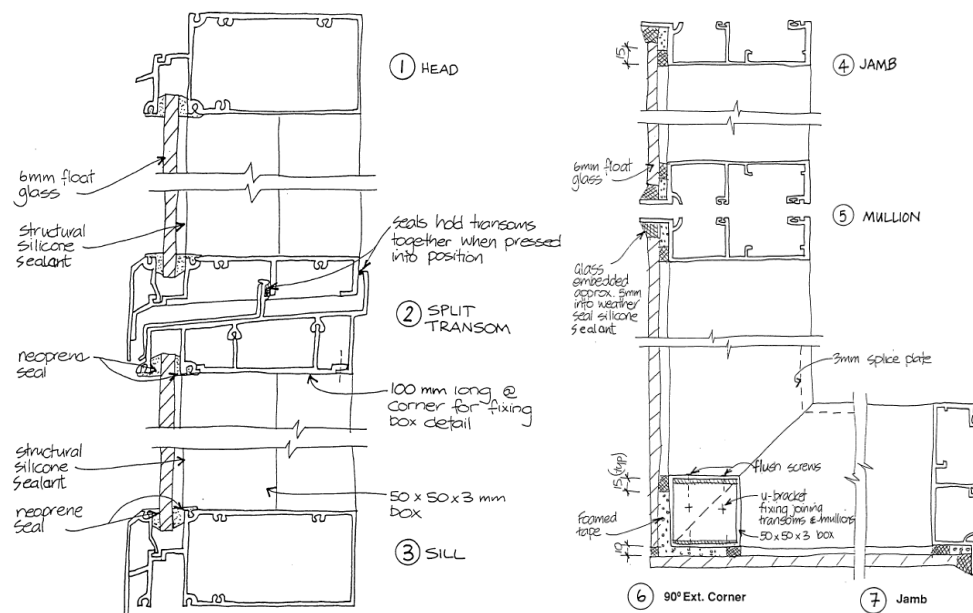


Figure 3: Typical glazing connection detail [12].

Masonry Veneer

Timber frame houses are the most common construction in New Zealand, which are most typically cladded with weatherboard followed by brick veneer. Typically, they are built with a thin air cavity between the external veneer and the inner sheathing, which functions as a drainage plane to allow any water that has penetrated the veneer to drain to the bottom of the cavity, where it encounters flashing and is directed to the outside through weep holes, rather than entering the building. Masonry veneers are only suitable for low-rise construction since they support their own weight at the ground level [1]. They have low out-of-plane strength; hence they require horizontal ties to the structure to provide out-of-plane restraint against wind and earthquake loads. Brick ties are used for this purpose, which may take the form of corrugated metal straps nailed or screwed to the structural framing, or as wire extensions to horizontal joint reinforcement in a solid masonry veneer or cavity wall. Masonry veneer cladding systems with typical connection details are shown in Figures 4 and 5.



Figure 4: Typical example of masonry veneer cladding system.

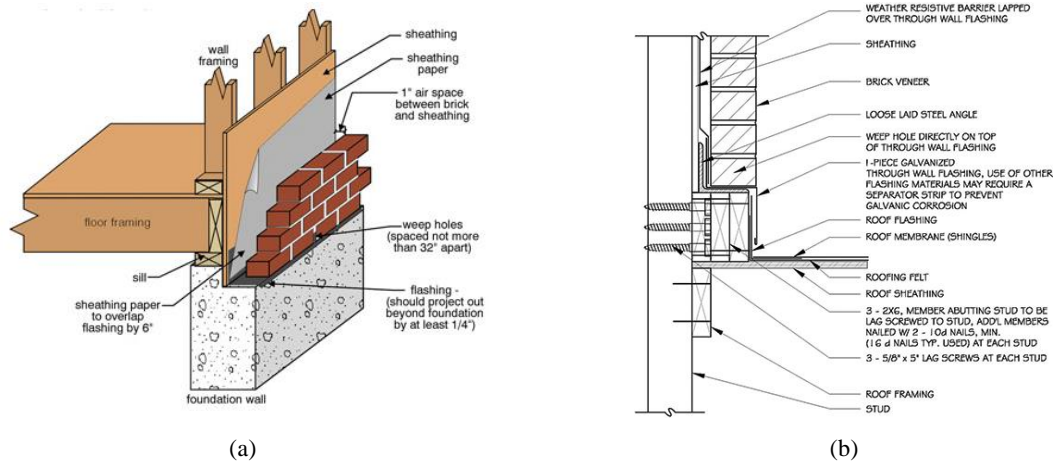


Figure 5: Masonry veneer cladding system; (a) connection [13], and (b) tie screw [14].

Monolithic Cladding

The monolithic cladding system typically consists of a sand-cement plaster applied over metal lath reinforcing on a rigid or non-rigid backing material [1]. The total system has either two or three coats, and it is finished with a layer of acrylic coating to make the cladding watertight. Uncoated plaster edges are very absorbent, and will also wick water from adjacent surfaces. The watertight performance is totally reliant upon the exterior coating system creating a face seal that is impervious to moisture. Monolithic cladding is brittle and cannot accommodate movement well; thereby making it vulnerable to cracking. Movement control joints are incorporated into the cladding to address this. Any faults in the cladding such as cracks in the plaster require immediate repair to ensure the system remains watertight. Monolithic cladding systems and a typical connection detail are shown in Figure 6.

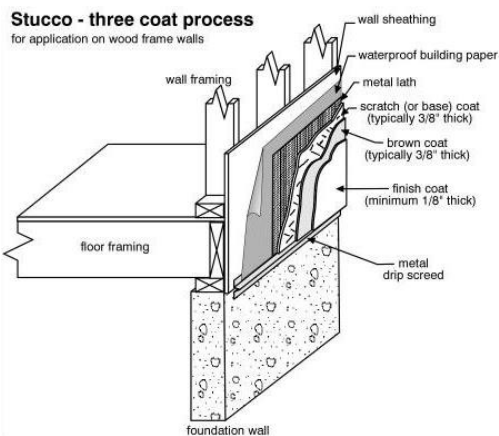


Figure 6: Monolithic cladding system with typical connection detail [15].

Precast Panels

Precast concrete panels have been the most popular cladding material in new non-residential buildings in New Zealand over the past decade [4]. The cladding system for a building may use different shapes and sizes of panels to create different architectural details. They are designed to resist wind forces and seismic forces generated from the panel self-weight [1]. Structural movement is accommodated in precast cladding systems through the connections of the panel to the structure and joints between panels [16]. Precast panel cladding systems and a typical connection detail are shown in Figure 7. Note that the tube spacer is not typically used in NZ buildings, but the fragility functions for the precast cladding system used in this study is sourced from Baird's PhD Thesis [1] on NZ cladding systems where he proposed a variation to the connection by placing a tubular spacer between the washers and by tightening the two washers against the tube.

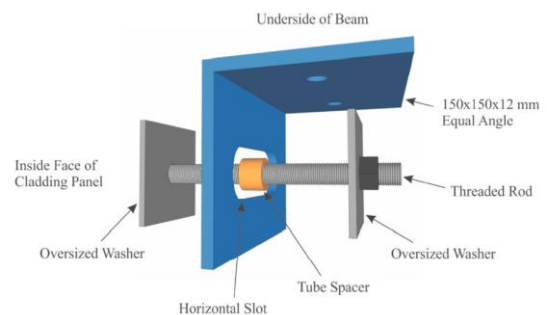
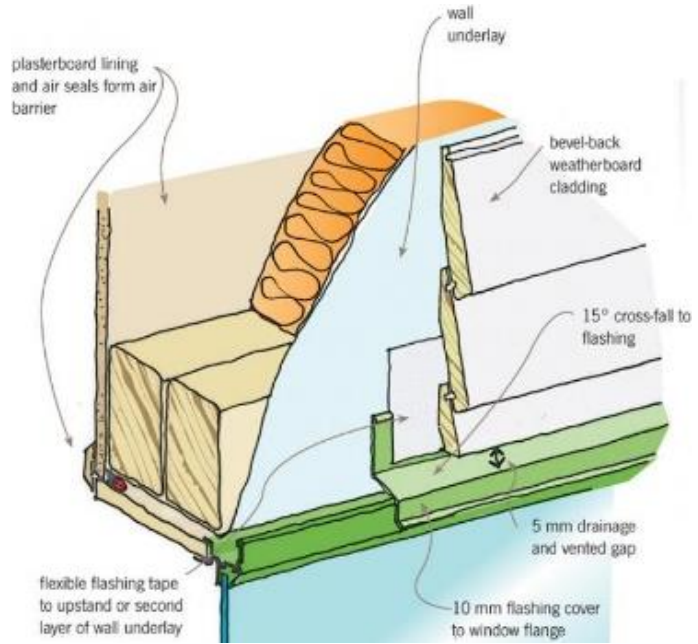


Figure 7: Precast cladding system with typical connection detail [1].



(a)

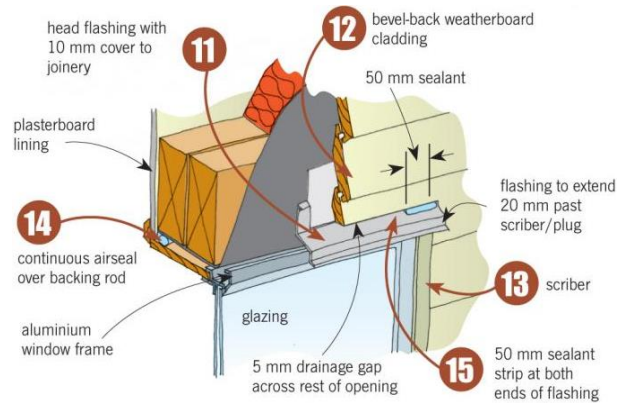


(b)

Figure 8: Lightweight cladding system; (a) residential, and (b) typical connection detail [17].



(a)



(b)

Figure 9: Lightweight cladding system; (a) commercial [18], and (b) typical connection detail.

Lightweight Panels

From an economic point of view, lightweight panel cladding systems are popular cladding choice for low-rise commercial, residential and industrial structures [1]. Lightweight panels can be simple metal sheets, plywood, insulated panels (or sandwich panels), Autoclaved Aerated Concrete (AAC), and compressed cement panels. Lightweight panel cladding systems and typical connection details for residential and commercial buildings are shown in Figures 8 and 9, respectively.

COMPONENT CONTRIBUTION FUNCTIONS

Definition and Use of Contribution Functions

The term “contribution functions” is proposed in this paper to describe relationships that link building response directly to the contribution of the component repair costs to the total storey-level repair costs. These functions already combine quantity distributions, fragility functions, and loss functions together,

and are normalized by the storey replacement cost. Therefore, these can be simply combined together to estimate the storey-level repair cost. Examples of contribution functions can be seen on the right-side of Figure 10.

Contribution functions are separated into four groups; (i) structural (e.g. beams and columns), (ii) non-structural drift-sensitive (e.g. partitions and cladding), (iii) non-structural acceleration-sensitive components located on the floor (e.g. furniture), and (iv) non-structural acceleration-sensitive components located overhead (e.g. ceiling and services). The first two groups are related to the peak interstorey drift at the storey of interest (IDS,i), the third is related to the peak total floor acceleration of the floor below (AFT,i), and the fourth is related to the peak total floor acceleration of the floor above ($AFT,i+1$). These building responses are shown on the left-side of Figure 10.

The storey loss as a fraction of storey value, l_s , can be calculated as shown in Equation 1:

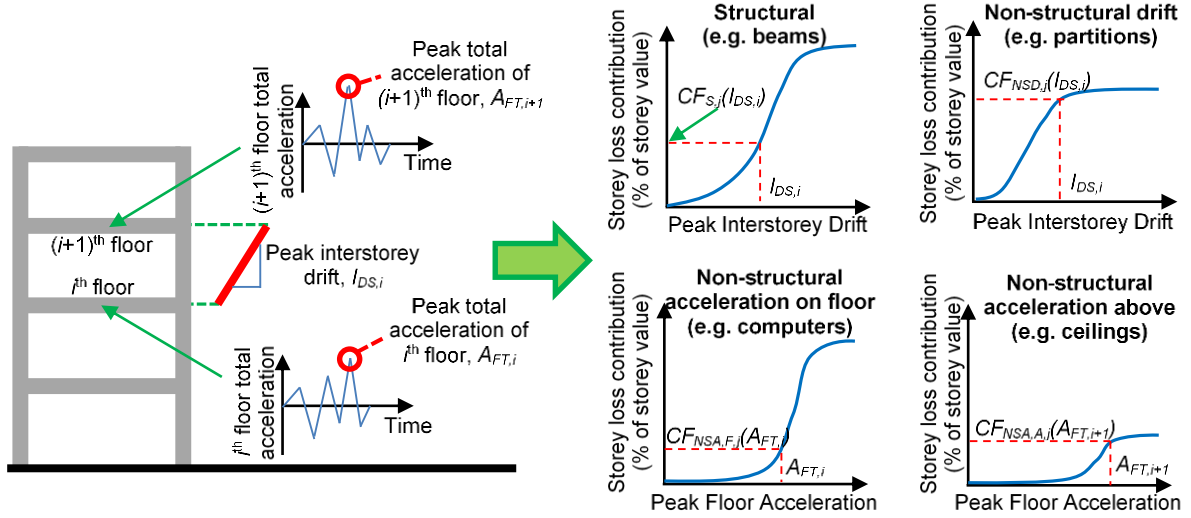


Figure 10: Application of contribution functions for rapid loss estimation.

$$l_s = \sum_{j=1}^{N_{NSA,F}} CF_{NSA,F,j}(A_{FT,i}) + \sum_{j=1}^{N_{NSA,A}} CF_{NSA,A,j}(A_{FT,i+1}) + \sum_{j=1}^{N_S} CF_{S,j}(I_{DS,i}) + \sum_{j=1}^{N_{NSD}} CF_{NSD,j}(I_{DS,i}) \quad (1)$$

where, CF are the contribution functions, N is the number of component types, and subscripts S , NSD , NSA,F , and NSA,A are used for structural components, non-structural drift-sensitive components, non-structural acceleration-sensitive components on floor, and non-structural acceleration-sensitive components above, respectively.

The total building loss, L_{Total} , expressed as a fraction of total building value can be calculated following Equation 2:

$$L_{Total} = \sum_{S=1}^{N_{storey}} (l_s \cdot a_s) / \sum_{S=1}^{N_{storey}} a_s \quad (2)$$

where, a_s is the floor area of the S^{th} storey level, and N_{storey} is the total number of storey.

Overview of Studies Related to Development of Contribution Functions

One of the earlier concepts of performing seismic loss estimation at a storey level was proposed by Aslani and Miranda [19]. Here, the expected loss due to a component at floor level for a given value of Engineering Demand Parameter (EDP) ($E[L_{C|EDP}]$) is calculated deterministically following Equation 3:

$$E[L_{C|EDP}] = A_C \times \sum_{i=1}^{n_{DS}} P(D_i|EDP) \times E[l_{C|D_i}] \quad (3)$$

where, A_C is the total area/number of the component on the storey of interest; $E[l_{C|D_i}]$ is the expected repair cost per unit area of the component for the damage state D_i ; n_{DS} is the number of discrete damage states considered in the component fragility; and $P(D_i|EDP)$ is the probability of damage being in the i^{th} damage state for a given EDP value (say edp). Here, $l_{C|D_i}$ are generated using the assigned probability distributions based

on the collected data, whereas $P(D_i|EDP)$ can be computed from the fragility functions following Equation 4:

$$P(D_i|EDP = edp) = \Phi\left(\ln\left(\frac{edp}{x_{m,i}}\right)/\beta_i\right) - \Phi\left(\ln\left(\frac{edp}{x_{m,i+1}}\right)/\beta_{i+1}\right) \quad \text{for } i \neq n_{DS} \quad (4a)$$

$$P(D_i|EDP = edp) = \Phi\left(\ln\left(\frac{edp}{x_{m,i}}\right)/\beta_i\right) \quad \text{for } i = n_{DS} \quad (4b)$$

where, $x_{m,i}$ and β_i are the logarithmic mean and dispersion of the component's capacity to resist i^{th} damage state, respectively; and $\Phi()$ is the standard normal cumulative distribution function.

Dhakal et al. [9] extended this methodology to account for (i) uncertainty in the repair cost values rather than using an expected value approach, and (ii) variation in quantity distribution. They have previously proposed a framework to develop contribution functions for interior drywall partitions and suspended ceilings. In this approach, a Monte Carlo simulation is performed to consider the variation in both component density and $l_{cr|D_i}$. The total component repair cost for a single Monte Carlo simulation trial can be obtained following Equation 5:

$$L_{C|EDP} = P(D_1|EDP) \times l_{cr|D_1} + P(D_2|EDP) \times l_{cr|D_2} + \dots \dots \dots + P(D_n|EDP) \times l_{cr|D_n} \quad (5)$$

where, $l_{cr|D_i}$ is the random variable of unit cost of repairing or replacing a component damaged to the i^{th} damage state. The total unit cost of component repair/replacement is then multiplied by the component density factor to convert the per unit component repair cost to repair cost per unit floor area. An example of this for dry wall partitions [9] is shown in Equation 6:

$$\bar{L}_{P|IDR} = L_{P|IDR} \times R_P \times H_P \quad (6)$$

where, $\bar{L}_{P|IDR}$ is the expected loss due to partition damage per square metre of floor area at a given drift level; $L_{P|IDR}$ is the loss per unit partition area; R_P is the random realisation of the partition density function (length per unit floor area); and H_P is the average partition wall height. Depending on the component, the density function can be expressed in terms of area, length or weight.

Inherent variations in critical parameters such as building regularity, geometry/layout, orientations, ground condition and actual earthquake input are considered in the structural analysis. Uncertainties in these parameters are hence not propagated in the development of the loss contribution functions where the result of structural analysis (*edp*) is taken as input.

A summary of the overall framework for developing contribution functions is shown in Figure 11. During a single trial of calculation a random inter-storey drift ratio is generated first and the probability of each damage state is calculated next by using Equation 4 above. Then, the repair or replacement costs corresponding to the different damage states are obtained from the idealized distribution curves of the costs. In order to consider all probable variations, several trials of simulations are run by using Equation 5 for each drift ratio. Afterwards, the randomly selected quantity distribution is combined as per Equation 6.

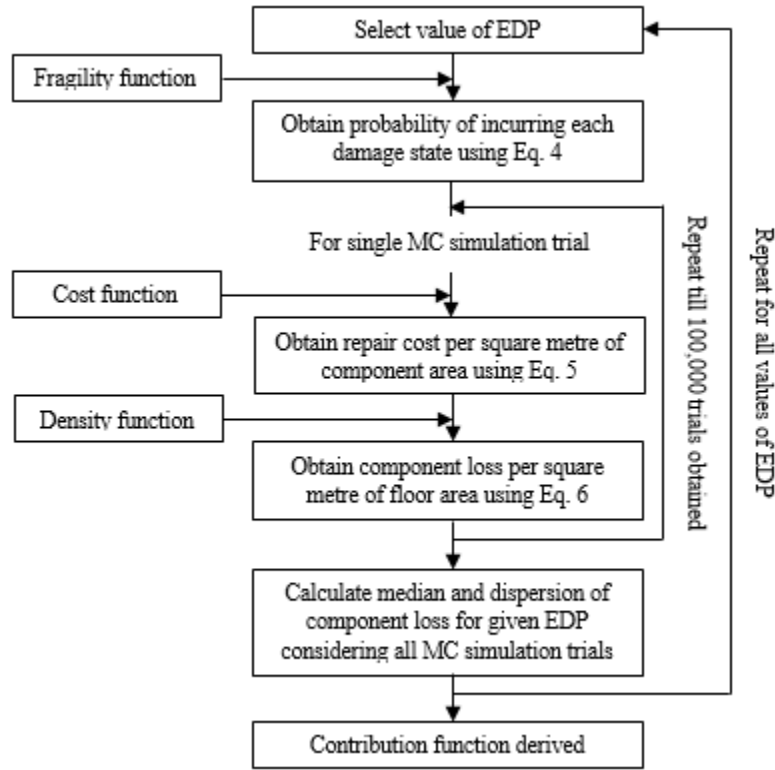


Figure 11: Overall framework for developing contribution functions.

METHODOLOGY

To develop the cladding contribution function as described in the previous section, the following steps were carried out:

- Field surveys of buildings were done to obtain information on typical cladding types, quantity, and building dimensions.
- Survey data were processed to identify the most common types of cladding and develop probabilistic distribution of cladding length to floor area ratio (R_{CL}) in residential, commercial and industrial buildings.
- Suitable fragility functions for each types of cladding were identified and selected from literature.
- Repair/replacement cost for each cladding type under different damage states were obtained from interviews with consultants, suppliers and builders or from literature.
- Monte Carlo simulations were performed with inputs from previous steps to develop contribution functions.

In the first step, a building survey is performed in Christchurch, New Zealand for residential, commercial and industrial buildings. The survey data was then used to identify the most common types of claddings used and cladding length to floor area ratio.

The next step is to source the fragility functions for different types of claddings by reviewing literature corresponding to the identified and classified cladding types. The details of the selected fragility functions are described later in the paper.

The next step is to obtain the repair/replacement costs for different types of claddings corresponding to each cladding type and associated damage states. The collection of repair costs for different cladding systems is described in detail in later sections. The repair cost per unit area of the cladding panel, $L_{CL|Di}$ are generated using the assigned probability distributions based on damage states identified from fragility functions.

In the last step, Monte Carlo simulation is used to generate the contribution functions for different types of cladding by coding a script in MATLAB. The input of random variables for the simulation include the probability of being in a damage state at a given engineering demand parameter (inter-storey drift ratio), repair costs, and the cladding length per floor area as shown in Figure 11.

The expected seismic loss per square metre of the cladding panel, $L_{CL|IDR}$, considering the probability and consequence of different damage states (i.e. $DS_1, DS_2, DS_3 \dots DS_n$), can be written as,

$$L_{CL|IDR} = P(D_1|IDR) \times l_{CLr|D_1} + P(D_2|IDR) \times l_{CLr|D_2} + \dots + P(D_n|IDR) \times l_{CLr|D_n} \quad (7)$$

where, $P(D_i|IDR)$ is the probability of the i^{th} damage state at a particular Inter-storey Drift Ratio (IDR), and $l_{CLr|D_i}$ is the random realisation of unit cost of repairing or replacing a cladding panel corresponding to the i^{th} damage state. Cladding loss in terms of percentage of complete replacement cost, $L_{CL_rep|IDR}$ can be calculated as,

$$L_{CL_rep|IDR} = \frac{L_{CL|IDR}}{L_{CL|D_n}} \times 100 \quad (8)$$

So far, seismic loss has been calculated per square metre of the cladding panel. To determine the contribution of the cladding damage in total seismic loss of a building, the distribution of the cladding length has to be combined with the cladding loss as,

$$\bar{L}_{CL|IDR} = L_{CL|IDR} \times R_{CL} \times H_{CL} \quad (9)$$

where, $\bar{L}_{CL|IDR}$ is the expected loss due to cladding damage per square metre of floor area at a given drift level. In this study, the height of the cladding panel, H_{CL} is considered constant as 2.7 m for residential buildings and 3.5 m for commercial and industrial buildings.

BUILDING SURVEY RESULTS

Common Cladding Systems

To identify the common types of cladding used in varying building usage, together with their distribution, an intensive survey was performed in and around Christchurch city for residential, commercial, and industrial buildings. Building usage, dimensions, cladding type and cladding length (after deducting the area taken by windows and doors) were recorded from the building survey. The dimension of the buildings was determined by using Google Earth images, by field estimation, or by examining architectural and structural drawings. The survey data was analysed to identify the most common types of

claddings used and the cladding length to floor area ratio. Cladding types were recorded for a large number of random samples of residential buildings from different locations in Christchurch, which are representative of both older and newer construction. To ascertain the adequacy of the collected data size, a sensitivity analysis was performed by adding a number of new random data entries. When the proportions of different cladding types did not noticeably change, despite additional random data entries, it was decided that the increased sample size is representative of the entire residential building stock in Christchurch. Similar sensitivity analyses were repeated for commercial and industrial buildings as well. The cladding distribution data collected from the field survey is presented in Appendix A.

From the field survey, residential buildings were observed to have a single type of cladding throughout the perimeter of the building whereas commercial and industrial buildings were observed to have a mixed use of different types of cladding in a single building. The proportions of different cladding types in residential, commercial, and industrial buildings deduced from the survey data are presented in Figure 12. Here, total length of an individual cladding system (e.g. masonry veneer) is presented as the percentage of the cumulative total lengths of different cladding systems of all buildings of a particular use (e.g. residential). Analysis of 100 data shows that masonry veneer, monolithic cladding, and lightweight panels are the most common types of cladding systems used in residential buildings as shown in Figure 12a. Figure 12b, generated from 63 random data, shows that glazing, lightweight panels, and precast panels are the three most common types of cladding systems used in commercial buildings. Similarly, lightweight panels, monolithic cladding, and precast panels are the three most common types of cladding systems used in industrial buildings as per the survey results of 35 sample data presented in Figure 12c.

Discussions with contractors indicated that lightweight panels often do not incur significant damage during earthquakes due to their increased flexibility and decreased weight. Based on this and the findings from the survey, the rest of this paper will focus on glazing, masonry veneer, monolithic, and precast panels cladding systems.

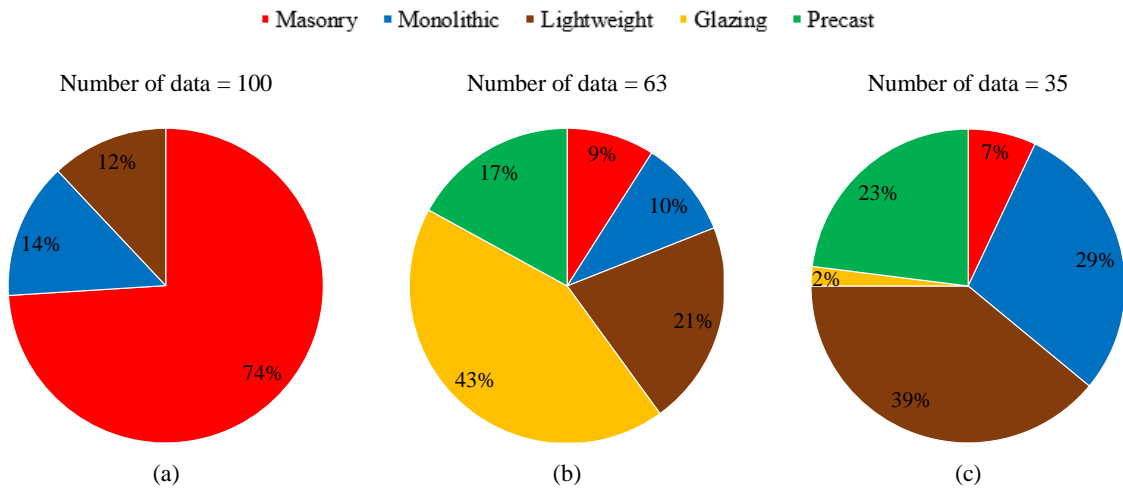


Figure 12: Common cladding systems; (a) residential, (b) commercial, and (c) industrial.

Cladding Density Functions: Distribution of Cladding Systems in Different Building Types

After identifying the common types of cladding, the same survey data were analysed to get the distribution of cladding

length- to-floor area ratio for residential, commercial, and industrial buildings as shown in Figure 13. These distributions of cladding length consider all types of claddings present in an individual building category. For all three types of buildings, an empirical distribution based on the actual data and a lognormal

distribution fit were plotted. A goodness-of-fit test [20], performed on the fitted distributions to the collected data, shows better fitting with lognormal distribution compared to normal distribution. From the cladding distribution, it is found that residential buildings have greater proportion of mean cladding length in comparison to commercial and industrial buildings. This may be because industrial buildings have relatively large openings to allow access for trucks and heavy equipment.

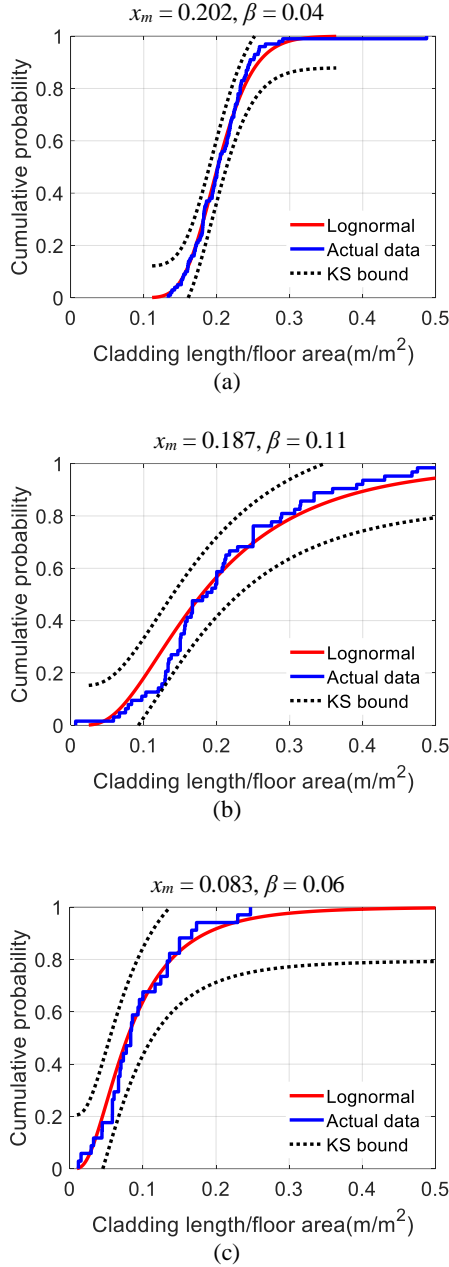


Figure 13: Cladding density functions for different building usage; (a) residential, (b) commercial, and (c) industrial.

FRAGILITY FUNCTIONS FOR CLADDING SYSTEMS

Claddings are unique non-structural components in the sense that their seismic performance depends on both drift and acceleration. The in-plane performance of a cladding depends on the average drift within the connections between the cladding and the structural system: whereas the out-of-plane performance of a cladding depends on the acceleration of the panel, which induces inertial force on the connections. Hence, for a given cladding type, the seismic performance of a cladding system, and its fragility functions, depend on the type and configuration of the connection between the cladding and the

structural system. However, development of new fragility functions for different configurations of the connections between the claddings and the structural systems is out of scope of this study. Therefore, fragility functions are sourced from literature for cladding types with connection details similar to NZ construction. For connection details significantly different from the tested claddings based on which the fragility functions are generated herein, the contribution functions developed in this study are not readily applicable and will need to be adjusted.

Glazing

The fragility function for glazing is taken from O'Brien et al. [21] which is based on the experimental works carried out on six specimens of 6*5 feet glass panel used in mid-rise curtain wall system. The connection details used in this glazing type is similar to the New Zealand mid-rise curtain wall system. Hence, herein the adopted fragility function is applicable to New Zealand. The pictures of typical damages for glazing are presented in Figure 14.

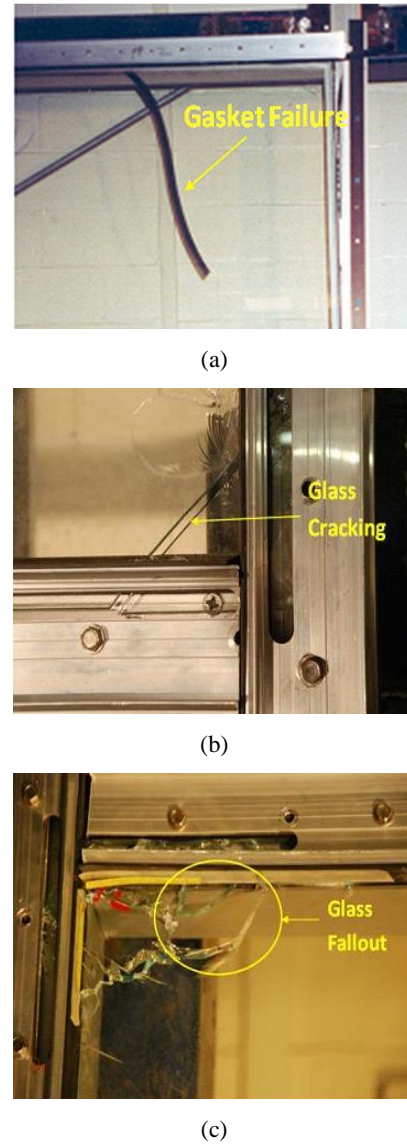


Figure 14: Observed glazing damages [21]; (a) gasket failure, (b) glass cracking, and (c) glass fallout.

Gasket failure and glass cracking are less severe damage states that govern the serviceability of the building but these damage states do not pose an immediate life safety hazard. However, the final damage state; i.e. glass fallout, is a failure mode which

can result in a life-safety hazard. The fragility curve parameters along with the description of these three damage states are presented in Table 1. Fragility curves generated from these parameters are also shown in Figure 15.

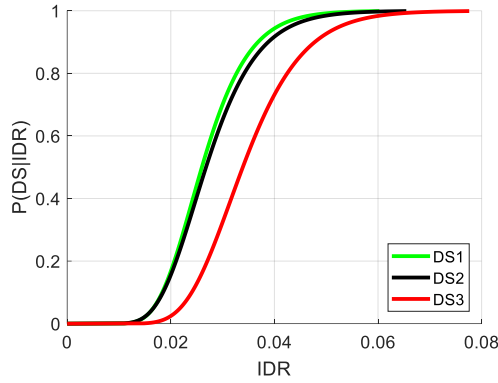


Figure 15: Glazing fragility function.

Table 1: Fragility curve parameters for glazing [21].

Damage Level	Description	x_m	β
DS1	Gasket failure	0.0260	0.272
DS2	Glass cracking	0.0268	0.289
DS3	Glass fallout	0.0339	0.268

Masonry Veneer

The fragility function for masonry veneer cladding is taken from Petry and Beyer [22] which is based on the experimental works carried out in unreinforced clay brick masonry walls. Here, masonry veneer walls are damaged since their connections to the supporting structure are stiff enough to transfer the drift of the structural system to the walls. Brick ties need to be screwed into the timber frame in modern construction, herein the adopted fragility function is applicable to New Zealand. Damage states defined for masonry veneer cladding based on experimental observations are presented in Figure 16.

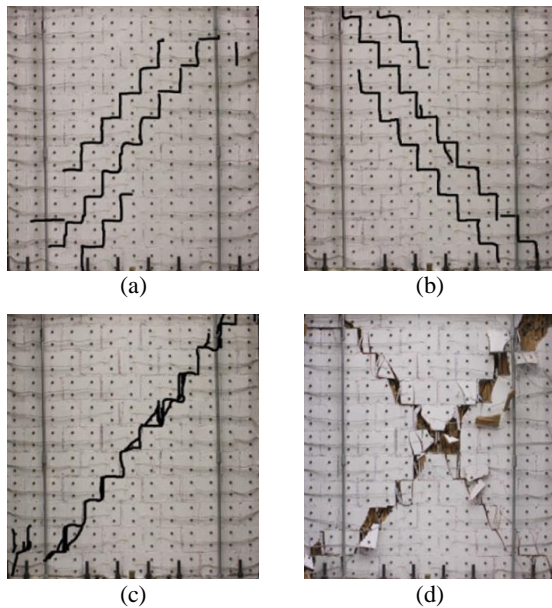


Figure 16: Observed damages to masonry veneer [22]; (a) stair step crack, (b) crack propagates through brick, (c) concentration in diagonal crack, and (d) shearing-off of corners.

Table 2: Fragility curve parameters for masonry veneer cladding [22].

Damage Level	Description	x_m	β
DS1	Stair step crack visible	0.0015	0.4
DS2	Crack propagates through brick	0.0035	0.4
DS3	Concentration in diagonal crack	0.0055	0.4
DS4	Shearing-off of corners	0.006	0.4

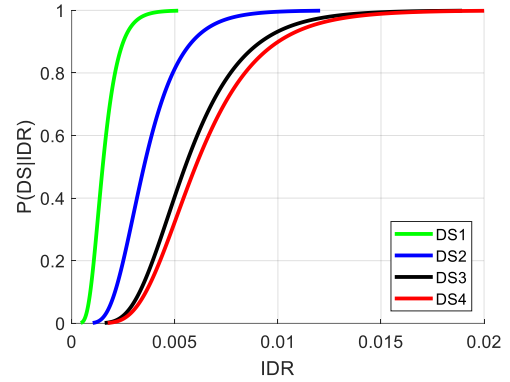


Figure 17: Masonry fragility function.

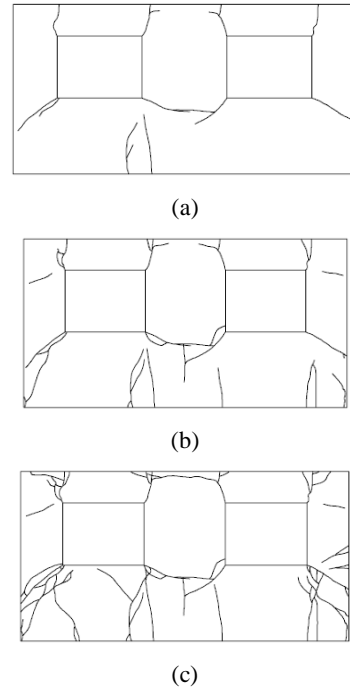


Figure 18: Observed damages to monolithic cladding systems [23]; (a) hairline cracks, (b) extension of cracks, and (c) branching of cracks.

The fragility curve parameters along with description of damage states are presented in Table 2, and the fragility curves generated from these parameters are shown in Figure 17.

Monolithic Cladding

The fragility function for monolithic cladding is taken from Arnold et al. [23] which is based on the experimental works carried out on stucco and gypsum sheathed walls. Stucco, EIFS, and Harditex are three different monolithic cladding systems used in New Zealand construction. Herein, the adopted fragility

function is applicable to stucco that is common in older construction. Pictures of observed damages for monolithic cladding are presented in Figure 18.

The fragility curve parameters, along with description of damage states, are presented in Table 3, and the fragility curves generated from these parameters are shown in Figure 19.

Table 3: Fragility curve parameters for monolithic cladding [23].

Damage Level	Description	x_m	β
DS1	Hairline cracks	0.002	0.4
DS2	Extension of cracks	0.004	0.4
DS3	Branching of cracks	0.007	0.4

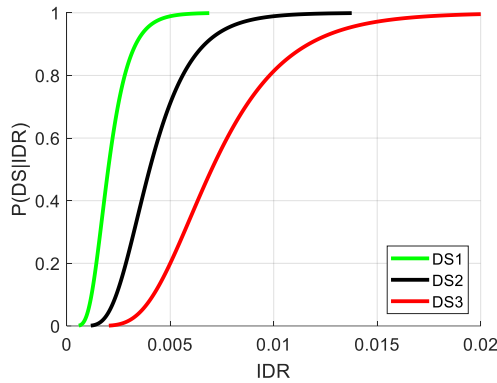


Figure 19: Monolithic fragility function.

Precast Concrete Cladding

The fragility function for precast concrete cladding is taken from Baird [1] which is based on the experimental works carried out in precast cladding panels. Common connection types to the precast concrete cladding panel are bearing, tie-back, slotted, fixed and dissipative. Herein adopted fragility function is only applicable to slotted connection. Pictures of observed damages for precast concrete cladding are presented in Figure 20.

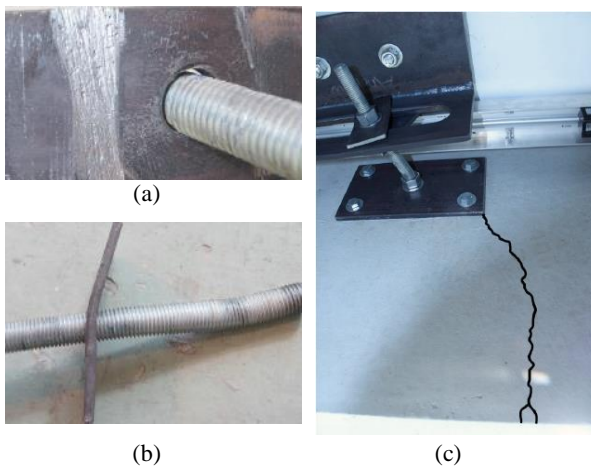


Figure 20: Observed damage to precast [1]; (a) galling of washer, (b) bending of washer and bolt, and (c) crack in cladding panel.

Precast panels are likely to be damaged in seismic events if their connections to the supporting structure are stiff enough to transfer the drift of the structural system to the panels, but Baird [1] found that for the typical precast panel connection details used in NZ the connections are likely to incur greater damage.

Here, fragility functions are developed based on experimental testing of slotted connections in which the ultimate failure performance level (DS4) was not tested. The extent of damage to slotted connections depends on the maximum lateral displacement of the connection. Since the connection at the bottom of the precast panel is fixed, the shear deformation of the precast panel is governed by the lateral displacement of the top connection. To obtain the lateral drift ratio, the lateral displacement of the top connection is divided by the distance between the top and bottom floor slab and ceiling; thereby making the precast cladding panel drift equal to the inter-storey drift. The fragility curve parameters with description of damage states are presented in Table 4, and the corresponding fragility curves are shown in Figure 21.

Table 4: Fragility curve parameters for precast concrete cladding [1].

Damage Level	Description	x_m	β
DS1	Galling of washer	0.008	0.2
DS2	Bending of washer and bolt	0.009	0.2
DS3	Crack in cladding panel	0.0117	0.2

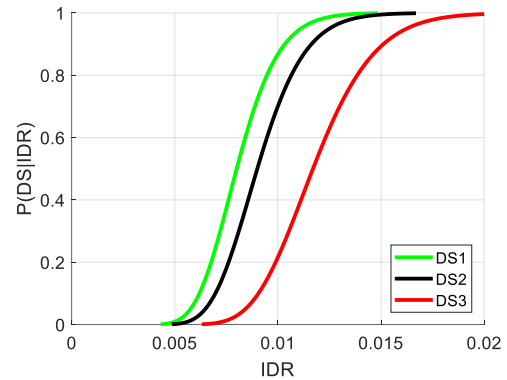


Figure 21: Precast fragility function.

REPAIR COST OF CLADDING SYSTEMS

In order to obtain the repair or replacement costs for different types of cladding damaged due to different damage states mentioned in the previous section, a number of questionnaires were sent by email to consultants, suppliers and builders with experience in designing/manufacturing/building different types of claddings. As there can be different sizes, materials and connection methods for a given category of cladding system resulting in different costs, it would be difficult for the respondents to provide a single value of repair or replacement cost. Hence, ranges of cost (rather than single values) were asked in the questions.

The questionnaires were sent to 57 companies, but most companies were unwilling to provide information about the cost of repair of the cladding. Hence, an alternate method was adopted to obtain the repair and replacement costs by communicating (face-to-face) with local builders at random construction sites, and this method was found to be more effective than sending questionnaires by email. Finally, three datasets were collected for masonry veneer cladding and four data sets were obtained for monolithic cladding, which were assumed sufficient for this study. Only one response was obtained for glazing, however, this was received from the largest commercial glazing supplier in New Zealand and is therefore deemed to be representative of most glazing repairs and new installations in commercial buildings. The

repair/replacement costs for precast concrete were obtained from the data reported by Baird [1] with a 12.68% construction cost inflation adjustment [24]. The cladding damage repair and replacement cost data collected from the survey and face-to-face communication with builders is presented in Appendix B.

In this study, the cost data range provided by each respondent is assumed to fit a normal distribution. For each data (i.e. a range of cost), the lower bound was assumed to represent the 10th percentile and the upper bound as the 90th percentile. All entries were given equal weightings before combining and calculating the mean and the standard deviation of the combined data. Thus derived repair/replacement costs for all types of cladding systems for different damage states are presented in Table 5.

Table 5: Repair/replacement costs for different damage states of four types of cladding.

Cladding Types	Damage State	Average Repair Cost (NZ\$/m ²)	Standard Deviation (NZ\$/m ²)
Glazing	DS1	73	5.47
	DS2	565	58.59
	DS3	565	58.59
Masonry	DS1	283.3	39.1
	DS2	375	29.3
	DS3	483.3	52.08
	DS4	608.3	97.66
Monolithic	DS1	97.5	12.7
	DS2	775	136.7
	DS3	1250	273.4
Precast	DS1	43.4	16.29
	DS2	63.8	24.91
	DS3	208.3	81.34

CONTRIBUTION FUNCTIONS FOR CLADDING SYSTEMS

The data input in terms of cladding distribution (i.e. density), fragility and repair/replacement cost are combined and uncertainties within each of these functions are carried forward through 100,000 Monte Carlo simulations at each individual value of *EDP* to develop the contribution functions for different types of cladding.

Loss in Terms of Percentage of Replacement Cost

Expected loss in terms of percentage of replacement cost for all four types of claddings are calculated using Equation 8. These are presented in Table 6 and Figure 22, which prove that masonry veneer and monolithic cladding start incurring losses at much smaller drifts compared to the other two types, especially glazing.

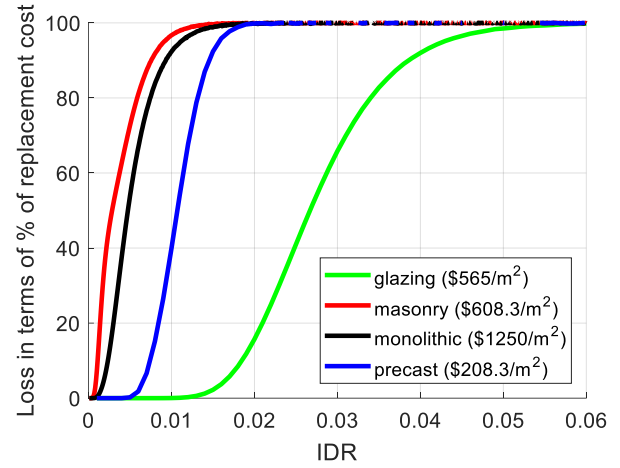


Figure 22: Comparison of percentage loss incurred by the four cladding types at different IDR.

Table 6: Percentage loss of the four cladding types at different IDR.

IDR	Percentage Loss			
	Glazing	Masonry	Monolithic	Precast
0.002	0.0	36.9	6.2	0.0
0.004	0.0	62.8	37.6	0.0
0.006	0.0	81.0	66.8	1.8
0.008	0.0	91.7	83.7	15.1
0.010	0.0	96.7	92.4	39.9
0.012	0.3	98.7	96.4	67.7
0.014	1.2	99.4	98.4	87.1
0.016	3.7	99.8	99.2	95.8
0.018	8.5	99.9	99.7	98.9
0.020	15.7	100	99.9	99.9
0.030	65.8	100	100	100
0.040	92.1	100	100	100
0.050	98.5	100	100	100
0.060	99.7	100	100	100

Table 7 shows the loss likely to be incurred by the four cladding types at serviceability limit state (SLS) and ultimate limit state (ULS) earthquakes. Here, SLS is represented by IDR=0.5%, which is typical of yielding drift for RC frames, and the ULS is represented by IDR=2.5% which is the maximum IDR allowed for ULS in the NZ seismic design standard [25]. As is obvious from the table, glazing and precast concrete claddings incur no loss in a SLS earthquake whereas masonry veneer and monolithic cladding incur 73% and 54% loss, respectively. In contrast, if we consider a ULS earthquake, glazing system incurs only 41% loss in comparison to 100% loss for the remaining three cladding systems. While precast panels and glazing appear to remain intact (i.e. not requiring any repair) in small-medium earthquakes, precast panels appear vulnerable to severe damage and collapse (i.e. 100% loss) during large earthquakes. In addition to losing its complete asset value, this could also potentially endanger the lives of people nearby as heavy panel blocks falling from a height can easily cause fatal injuries. Hence, the comparison between the losses for different cladding types suggests that only the glazing system appears to provide a resilient performance across different ground shaking intensities.

Table 7: Percentage loss of the four cladding types estimated at different design limit state actions.

IDR(%)	Glazing	Masonry	Monolithic	Precast
0.5	0	73	54	0
2.5	41	100	100	100

Expected Cladding Loss (NZ\$/m² of Floor Area)

The expected loss in NZ dollar per square meter of floor area for different cladding systems are calculated using Equation 9. Figure 23 plots the expected loss for glazing, masonry veneer, monolithic cladding, and precast panel cladding systems at different values of interstorey drift; the loss values for different interstorey drifts are also presented in Table 8.

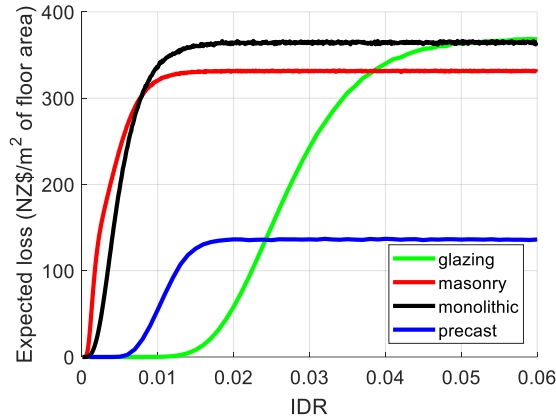


Figure 23: Comparison between expected cladding losses of the four cladding types at different IDR.

As can be inferred from Table 8, the full replacement costs of the four cladding types are 368.2, 331.9, 365, and 136.2 NZ\$/m² of floor area, respectively. In line with what was found in the previous section, masonry veneer and monolithic cladding incur losses much earlier compared to the other two types, especially glazing. The lower loss of precast panel cladding is understandable as its cost is only about a third of the cost of glazing and masonry veneer and only 16% of monolithic cladding. Note that the maximum loss of monolithic cladding per m² floor area is comparable to glazing and masonry veneer despite the cost of monolithic cladding being about double that of the others. This is mainly because monolithic cladding is common in industrial buildings for which the amount of cladding per unit floor area is less than half of that in commercial and residential buildings which dominate the use of glazing and masonry veneer.

The method proposed herein greatly simplifies the method of loss estimation and it is intentionally made to be simple for easy and quick application in every day design. Like the equivalent static force method, this simplified loss assessment approach is also meant to be applied in loss based design of simple regular structures, and not appropriate for very complex/unusual cases, for which a detail loss estimation procedure based on the PEER methodology needs to be followed. Nevertheless, despite the proposed method being simplified, the uncertainties in different aspects of loss estimation are accounted for without any compromise. The reliability of the final outcome (i.e. contribution functions) depends on the ability of the input data to represent the inevitable uncertainty associated with the considered variables without any bias. The concept presented in this paper has been applied previously to generate contribution functions of other structural and non-structural components, and to show how they can be used in conducting rapid loss estimation of example buildings. The contribution functions developed for all components have been applied in

randomly selected case study buildings, and the actual contribution of the components was found to be well within the range of the variability of the contribution functions. In this study too, the collected density and cost data cover a reasonable range of buildings (without any conscious bias) and should apply to most cases as indicated by the case study and verification presented in the paper.

Table 8: Expected loss of the four cladding types at different IDR.

IDR	Expected Loss (NZ\$/m ²)			
	Glazing	Masonry	Monolithic	Precast
0.002	0.0	122.4	22.6	0.0
0.004	0.0	207.9	137.3	0.0
0.006	0.0	268.6	244.2	2.5
0.008	0.0	304.1	306.4	20.6
0.010	0.0	320.4	336.7	54.3
0.012	1.0	327.5	351.7	92
0.014	4.5	329.3	358.3	118.7
0.016	13.7	330.9	361.5	130.2
0.018	31.4	331.6	363.6	134.9
0.020	58.1	331.9	365.0	136.2
0.030	243.2			
0.040	339.7			
0.050	363.6			
0.060	368.2			

CASE STUDY

Ideally, contribution functions for different components should be verified by comparing them against actual component damage repair cost data in earthquakes. Nevertheless, despite having access to a comprehensive repair database from EQC (Earthquake Commission) from the 2010-11 Canterbury earthquake sequence, it was not possible to extract the loss contributed by different components as the database included only the total repair cost for each house/building. Hence, an alternate approach is chosen here to verify the contribution function against the component loss calculated based on the actual quantity distribution for a case study building. This approach has an inherent limitation as the fragility and repair cost functions used in both calculations are the same; but these functions do not need further verification as the fragility functions are taken from experimental results and the repair costs are derived from data collected from builders/suppliers currently active in the industry.

To confirm the accuracy and usability of the contribution functions developed for cladding types, a case study is performed on a 10 storey RC frame building built in 1987 in Christchurch. The building was used for commercial purpose and the cladding type used was glazing. For all stories, the floor area, cladding length and inter-storey drift ratio were calculated, which are shown in Table 9. The estimated inter-storey drift ratios vary between 1.62% and 0.4% [9]. Using the calculated inter-storey drift and the floor area measured from the building plans, the approximate cladding loss in a given floor can be readily determined using the loss function shown in Figure 23. Once this is repeated for all floors, the total loss from cladding for the whole building can then be obtained by adding the floor level losses. Thus the likely cladding loss at a design level (i.e. 500 year return period) seismic event as predicted using the proposed loss function comes out to be about NZ\$ 35,600.

Table 9: Comparison between the predicted and the actual loss assessment for the case study.

Floor	Area (m ²)	IDR (%)	Length (m)	Actual (NZ\$)	Loss Function Prediction (NZ\$)	% Difference
10	531	0.40	104.95	4.29E-06	4.055E-06	-5.93
9	531	0.67	104.95	0.326	0.308	5.94
8	531	0.92	104.95	15.71	14.84	5.89
7	531	1.13	104.95	206.75	195.23	5.91
6	531	1.32	104.95	1256.55	1186.59	5.90
5	531	1.47	104.95	4622.41	4365.85	-5.88
4	751	1.41	133.81	3229.23	3384.25	-4.58
3	751	1.52	133.81	5864.33	6171.53	4.98
2	759	1.59	126.38	9316.08	10397.55	-10.4
1	719	1.62	114.80	8424.89	9848.48	-14.5
			Total	32936.26	35564.62	-7.39

The next step to be completed is to calculate the expected loss using the actual cladding lengths. In order to do this, the actual length measured from the building plans are used along with the calculated inter-storey drifts, cladding fragility functions and the mean repair costs for different damage states. This is repeated for all floors throughout the building to obtain the total loss. The comparison between the actual calculation and the loss function estimation is shown in Table 9. As can be seen in the Table, the difference between the contribution function estimation and the detail calculation is 7.39%.

Next, the actual repair cost information reported by Housing NZ [26] for some buildings after Canterbury earthquakes is used for qualitative verification of the developed contribution functions for some cladding types. Table 10 shows the cladding repair cost for different buildings damaged in Canterbury earthquakes [26]. Due to lack of complete structural details individual findings cannot be validated against the proposed contribution functions. Instead, damage states are identified based on the damage description and compared to the IDR

obtained from Figure 23 using the reported values of repair cost per square meter of floor area. This comparison is shown only for the four houses with brick veneer and one with monolithic cladding, as Summerhill stone cladding and lightweight panel type cladding are not included in this study. Nevertheless, IDR values for Summerhill stone are shown in brackets using the brick veneer contribution functions to understand the error they induce when applied to other types of masonry veneers.

As can be seen from the Table, thus derived IDR values fall around or above the median drift capacities for the reported damage states (see the fragility functions in previous Sections) for the monolithic cladding and the 4 brick veneer houses (except arguably the third brick veneer house, for which the damage and repair cost were trivial and consequently the predicted IDR is at a lower end of the DS1 fragility curve). Hence, the proposed contribution functions can be argued to be readily applicable in quick estimation of cladding losses of buildings with acceptable accuracy.

Table 10: Earthquake repair cost for different cladding types damaged in Canterbury earthquakes [26].

Floor	Area (m ²)	Damage Description	Repair Cost (NZ\$)	Cost per Floor Area (NZ\$/m ²)	Damage State	IDR (%)
Brick veneer: DS1($\mu_{IDR}=0.15\%$, $\beta=0.4$), DS2($\mu_{IDR}=0.35\%$, $\beta=0.4$), DS3($\mu_{IDR}=0.55\%$, $\beta=0.4$) and DS4($\mu_{IDR}=0.6\%$, $\beta=0.4$)						
100		Vertical and step cracking	21353	213.5	DS2	0.42
98		Minor hairline staggered cracking	6571	67.1	DS1	0.14
110		Minor hairline staggered cracking	525	4.8	DS1	0.07
120		Vertical and step cracking	20007	166.7	DS2	0.29
Stone veneer						
100		Minor staggered cracking	1488	14.9	DS1	(0.09)
80		Vertical and step cracking	24675	308.4	DS2	(0.84)
110		Staggered crack lines	24279	220.7	DS2	(0.44)
92		Major veneer and ties damage	20698	225	DS4	(0.45)
100		Vertical and step cracking	20599	206	DS2	(0.4)
239		Minor staggered cracking	6550	27.4	DS1	(0.1)
Monolithic cladding: DS1($\mu_{IDR}=0.2\%$, $\beta=0.4$), DS2($\mu_{IDR}=0.4\%$, $\beta=0.4$) and DS3($\mu_{IDR}=0.7\%$, $\beta=0.4$)						
90		Minor damage	5582	62	DS1	0.28
Lightweight panels						
110		Moderate damage, step cracking	37787	343.5	DS2	-

CONCLUSIONS

Combining cladding distribution/density functions developed using an extensive building survey data and cladding cost functions derived using range of repair/replacement costs received from consultants, suppliers and builders together with fragility functions availed from literature, contribution functions of four main types of cladding were developed in this study. These contribution functions can be readily used in simplified building loss estimation and in loss based design methodologies like Loss Optimisation Seismic Design (LOSD).

From the field survey performed in Christchurch, common types of claddings used are identified as: masonry veneer in residential buildings, glazing and precast concrete panel in commercial buildings, and lightweight and monolithic claddings in industrial buildings. The mean cladding length to floor area ratio obtained from the survey data is found to be 0.202 (with dispersion; i.e. $\beta = 0.04$), 0.187 ($\beta = 0.11$) and 0.083 ($\beta = 0.06$) m/m² for residential, commercial and industrial buildings, respectively. The full replacement cost for glazing, masonry veneer, monolithic and precast concrete cladding systems obtained from supplier/builder survey is 565 ($\beta = 58.59$), 608.3 ($\beta = 97.66$), 1250 ($\beta = 273.4$) and 208.3 ($\beta = 81.34$) NZD/m² respectively, which shows that precast concrete panel stands out as a cheap cladding option and monolithic cladding as expensive enough to potentially affect the overall construction cost of the building.

It was found that glazing, masonry veneer, monolithic and precast concrete cladding systems incur 50% loss at inter-storey drift levels equal to 0.027, 0.003, 0.005 and 0.011, respectively. Hence it can be concluded that among the four cladding types (and the specific anchor/connection details) considered herein, masonry veneer is the most vulnerable cladding system whereas glazing is the most resilient one. Expected cladding loss for masonry veneer, monolithic and precast concrete cladding systems are maximum at 0.2% drift which are found to be 331.9 ($\beta = 90.59$), 365.0 ($\beta = 259.42$) and 136.2 ($\beta = 98.74$) NZD per square metre of floor area, respectively. Whereas, expected glazing loss is maximum at 0.6% drift which is found to be 368.2 ($\beta = 215.7$) NZD per square metre of floor area. Application of the developed contribution functions to a case study scenario and some real post-earthquake damage repair cost data showed that the simplified loss estimation approach is reasonably accurate. Note that the contribution functions developed in this study is valid only for the connection details for which the fragility functions used herein were derived. Separate contribution functions may need to be developed for different cladding types or the same cladding type with different connection details.

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APPENDIX A. CLADDING LENGTH DISTRIBUTION

Tables A1, A2, and A3 provide a summary of the cladding length distribution used in this study for residential, commercial and industrial buildings, respectively. For residential building's length distribution (each row in the table), building ID, number of storey, floor area, and length of monolithic, masonry and

lightweight cladding in the building are presented in columns 1 to 6, respectively. For commercial and industrial building's length distribution (each row in the table), building ID, number of storey, floor area, and the lengths of glazing, monolithic, masonry, lightweight and precast cladding in the building are presented in columns 1 to 8, respectively. All dimensions are measured in metres.

Table A1: Cladding length distribution for residential buildings.

Bldg. ID	Storey	Area (m ²)	Monolithic (m)				Masonry (m)				Lightweight (m)			
			F	B	LS	RS	F	B	LS	RS	F	B	LS	RS
1	1	118	13	13	9.1	9.1								
2	1	131	8.4	8.4	15.6	15.6								
3	1	124					7.5	7.5	16.5	16.5				
4	1	93									11.6	11.6	8	8
5	1	189									14	14	13.5	13.5
6	3	363	11.6	11.6	31.25	31.25								
7	2	254	12.2	12.2	10.4	10.4								
8	2	361					19.2	19.2	9.4	9.4				
9	2	297					14	14	10.6	10.6				
10	1	235					13.8	13.8	17	17				
11	1	296					12.3	12.25	24.2	24.2				
12	1	152					11.2	11.2	15.3	15.3				
13	1	262					11.5	11.5	22.8	22.8				
14	1	308					14	14	22	22				
15	1	240					11.9	11.9	20.2	20.2				
16	1	220					11	11	20	20				
17	1	260	13	13	20	20								
18	1	224					10.6	10.6	21.1	21.1				
19	1	235					13.5	13.5	17.4	17.44				
20	1	151					9.1	9.1	16.6	16.6				
21	1	203	13	13	15.6	15.6								
22	1	234	13	13	18	18								
23	1	169					11	11	15.4	15.4				
24	1	212					10.6	10.6	20	20				
25	1	247					13	13	19	19				
26	1	209					11	11	19	19				
27	1	231	11	11	21	21								
28	1	242	12	12	20.2	20.2								
29	1	209					11	11	19	19				
30	1	171					11.5	11.5	14.9	14.9				
31	1	261					14.5	14.5	18	18				
32	1	204					12	12	17	17				
33	1	264					12	12	22	22				
34	1	216					10	10	21.6	21.6				
35	1	315	15	15	21	21								
36	1	233					13.7	13.7	17	17				
37	1	234					13	13	18	18				
38	1	322					13.4	13.4	24	24				
39	1	266					19	19	14	14				
40	1	300	25	25	12	12								
41	1	95									11.5	11.45	8.33	8.33
42	1	148									17	17	8.7	8.7
43	1	220					22	22	10	10				
44	1	159									9.72	9.72	16.4	16.4
45	1	160									10	10	16	16
46	1	150									10	10	15	15

F - Front, B - Back, LS - Left Side, RS - Right Side

Table A1: Cladding length distribution for residential buildings (Continued).

Bldg. ID	Storey	Area (m ²)	Monolithic (m)				Masonry (m)				Lightweight (m)			
			F	B	LS	RS	F	B	LS	RS	F	B	LS	RS
47	1	361	10	10	15	15	9.5	9.5	38	38	10	10	14.5	14.5
48	1	126					9	9	14	14				
49	1	145												
50	1	150					11.2	11.2	14.3	14.3				
51	1	160					12.1	12.14	15	15				
52	1	182					11.3	11.3	16.5	16.5				
53	1	186												
54	1	173					12	12	16	16				
55	1	192					9.6	9.6	18	18				
56	1	173												
57	1	169	11	11	15.4	15.4	13	13	14.2	14.2	14.6	14.6	9.6	9.6
58	1	185	10.24	10.24	16.6	16.6	9	9	15.3	15.32				
59	1	138					11.5	11.45	16.7	16.7				
60	1	191												
61	1	140					9.3	9.3	16.3	16.3				
62	1	152												
63	1	156					10.8	10.8	15.6	15.6				
64	1	176					12.3	12.3	12.6	12.6				
65	1	168					12	12	12.6	12.55				
66	1	155					13	13	9	9				
67	1	151					8.9	8.9	15.5	15.5				
68	1	117									13.6	13.6	9.5	9.5
69	1	138												
70	1	129					18	18	24	24				
71	1	294					18	18	24	24				
72	1	432					18	18	22	22				
73	1	270					16.3	16.3	26	26				
74	1	356					16.6	16.62	25.5	25.5				
75	1	424	15.5	15.5	21.8	21.8	11.8	11.8	19.8	19.8				
76	1	338	10.24	10.24	16.6	16.6	16	16	20	20				
77	1	234					16.3	16.3	25	25				
78	1	320					16.9	16.9	21.4	21.4				
79	1	344					14.4	14.4	16	16				
80	1	306					16.9	16.9	24	24				
81	1	230					15.2	15.23	19.4	19.36				
82	1	406					16.7	16.7	21.5	21.5				
83	1	295					15	15	23	23				
84	1	359					12	12	30	30				
85	1	345					13.2	13.2	24	24				
86	1	360					16.5	16.5	23.3	23.3				
87	1	279					17.7	17.7	26	26				
88	1	384					13.4	13.4	27	27				
89	1	324					11	11	15	15				
90	1	362					10	10	17	17				
91	1	165					10	10	16	16				
92	1	170					12	12	16	16				
93	1	160					11.5	11.5	14	14				
94	1	160					9.4	9.4	15.8	15.8				
95	1	162					9.6	9.6	16.1	16.11				
96	1	149					12	12	14.8	14.8				
97	1	155					8.33	8.33	14.8	14.8				
98	1	178												
99	1	123					9.8	9.8	15	15				
100	1	147												

F - Front, B - Back, LS - Left Side, RS - Right Side

Table A2: Cladding length distribution for commercial buildings.

Bldg. ID	Storey	Area (m ²)	Glazing (m)			Monolithic (m)			Masonry (m)			Lightweight (m)			Precast (m)		
			F	B	S	F	B	S	F	B	S	F	B	S	F	B	S
1	2	800	20	20	40												
2	4	2275			32										50	50	35
3	3	6000	27									33	60	72	100	100	60
4	3	2000	60	30		90	150	150									
5	5	1650	40	40	25												
6	1	600	10		20	10		10									
7	2	900		14											30	12	30
8	1	750	8	8	7	12	12	18									
9	1	1250	50	50	28												
10	2	1250	20	20	16							80	80	40			
11	2	400							10	10							
12	1	500	2									5	10	20	25	25	25
13	1	1080	33		20				36	13		5	0	0	0	0	0
14	1	400	2	22	24							20	20	30			
15	1	400	5	22	24							12					
16	1	800	28	0	35				24	5							
17	1	800	24	0	0					40							
18	1	150	8			0	10	14									
19	1	400	20									20	20				
20	1	400	20		20	3	22	1				20	20		20	10	
21	1	484	20			3		1							20	10	
22	1	300	10	10	15												
23	1	300	10	10	15												
24	1	240	16	2			16	30									
25	1	240	16	2			16	30				10	10				
26	1	900	15									15	15	40	15	60	
27	1	600										15		20	15	40	
28	1	900	20	20								10	10	30			
29	1	300															
30	1	100													10	10	10
31	1	675										15	15	45			10
32	1	675	12	12	40							15	15	30			
33	1	450													15	15	30
34	1	6000										20	20				
35	1	700	20	20	35												
36	1	736	15	15	30				5	5	5				10	10	8
37	1	184	8	8							25						
38	6	2340	270	270	330												
39	1	360	18						18	20							
40	1	360													7	18	20
41	1	450							15	15	32						
42	1	360	8						2	18					8	10	
43	1	690										25	25	30			
44	1	400	10												10	40	
45	1	400										10	10	40			
46	1	600							18	18	40						
47	1	510	10											28	3	8	0
48	1	600	30	0	20		30										
49	1	600	30		20		30										
50	1	300	20	0	5				10	5							
51	1	300	20		5				10	5							
52	20	600															20
53	7	2888		76		33		30									

F - Front, B - Back, S - Side

Table A2: Cladding length distribution for commercial buildings (Continued).

Bldg. ID	Storey	Area (m ²)	Glazing (m)			Monolithic (m)			Masonry (m)			Lightweight (m)			Precast (m)		
			F	B	S	F	B	S	F	B	S	F	B	S	F	B	S
54	1	400	15	15					20	20	20						
55	3	3600	90	90	20				30	30	10						
56	2	2400										120	120	80			
57	2	175										35	5				
58	11	525	18	18	7										18	18	7
59	11	589	15	15	8										15	15	8
60	15	600	200	200	100							100	100	50	200	200	10
61	4	1600	40	40	10				40	40	80						
62	1	625	5	5	3	20	20	15									
63	1	600	10	10	20	30	30	15									

F - Front, B - Back, S - Side

Table A3: Cladding length distribution for industrial buildings.

Bldg. ID	Storey	Area (m ²)	Glazing (m)			Monolithic (m)			Masonry (m)			Lightweight (m)			Precast (m)		
			F	B	S	F	B	S	F	B	S	F	B	S	F	B	S
1	1	8100				90	90	90									
2	1	3750	20			50	50							75	40	40	
3	1	1500			3	20	20	10									
4	1	2250										50	60	32			
5	1	19500			3		5								150	150	130
6	1	4590										54	54	85			
7	1	1125			5							54	54	80			
8	1	28000				56	200		75								
9	1	48000				250	250	120									
10	1	600													10	10	40
11	1	1350				50	20	20									100
12	1	4000				100	100	40									
13	1	4800							80		60		80				
14	1	2250				25	25	30							40	40	0
15	1	2400										60	60	40			
16	1	2400										60	60	40			
17	1	1125										45	45	25			
18	1	10800						25				180	180	60			
19	1	784	20						3	28	28						
20	1	2250										5				45	50
21	1	2250	25													50	45
22	1	1200				50	50	10									
23	1	2100				70	70	30									
24	1	900	20			10	30	30									
25	1	800	10			10	20	40									
26	1	600													30	30	5
27	1	300															
28	1	600				15	15	30									
29	1	750				50	50	15									
30	1	1200				20	20	60									
31	1	2000	5			10			30			20					
32	1	4740													78	78	60
33	1	1500	10	10	10							20	20	10			
34	1	1400				10	70	20									
35	1	1600	10	20		10	10	30									

F - Front, B - Back, S - Side

APPENDIX B. CLADDING SYSTEM REPAIR COST

Repair cost data obtained from the supplier and builder survey for glazing, masonry, monolithic and precast cladding systems are shown in Table B1. Cladding types, damage state, type of

damage, repair work required, number of responses, lower and upper bounds of the repair cost are presented in columns 1 to 7, respectively.

Table B1: Repair cost for cladding systems.

Cladding Types	Damage State	Damage Types	Repair Work Required	Response	Lower Bound of Repair Cost (\$/m ² of Surface Area)	Upper Bound of Repair Cost (\$/m ² of Surface Area)
Glazing	DS1	Gasket failure	Rubber in new gasket	1	66	80
	DS2	Glass cracking	Glaze new glass with new gasket	1	490	640
	DS3	Glass fallout	Glaze new glass with new gasket	1	490	640
Masonry	DS1	Stair step crack visible	Repair damage mortar and repoint	1	250	400
				2	250	300
				3	200	300
	DS2	Crack propagate through brick	Replace new bricks	1	300	400
				2	350	400
				3	350	450
	DS3	Concentration in diagonal crack	Replace new panel	1	450	550
				2	400	600
				3	400	500
	DS4	Shearing-off of corners	Recladding	1	550	750
2				500	700	
3				400	750	
Monolithic	DS1	Hairline cracks	Stucco crack routing and filling	1	60	110
				2	90	110
				3	50	90
	DS2	Extension of cracks	Cover wallboard cracks	4	130	130
				1	500	700
				2	600	1100
	DS3	Branching of cracks	Replace new cladding	3	800	1300
				4	600	800
				1	900	2000
	Precast	DS1	Galling of washer	Inspect connections	2	600
3					200	1000
4					200	1200
DS2		Bending of washer and bolt	Repair/replace connections	1	22.5	84.2
DS3		Crack in the cladding panel	Install new cladding	1	31.9	127.6
					104.2	416.7