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Transect Survey as a Post-Disaster Global Rapid Damage Assessment Tool

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Following a damaging earthquake the immediate emergency response is focussed on individual collapsed buildings or other 'hotspots' rather than the overall state of damage. This lack of attention to the global damage condition of the affected region can lead to the reporting of misinformation and generate confusion, causing difficulties when attempting to determine the level of post-disaster resources required. A pre-planned building damage survey based on the transect method is recommended as a simple tool to generate an estimate of the overall level of building damage in a city or region. A methodology for such a transect survey is suggested, and an example of a similar survey conducted in Christchurch, New Zealand, following the 22 February 2011 earthquake is presented. The transect was found to give suitably accurate estimates of building damage at a time when information was keenly sought by government authorities and the general public.

INTRODUCTION

In the scientific community a transect is a sampling method widely used to assess the abundance of animals or plants, or to estimate the density of a population of a species in an area (Marques 2004). Transects take a number of forms, including a *line transect*, *strip transect* and *point transect*. In a *line transect* an observer travels a pre-determined path along which the count of the phenomena of study is recorded, as is the distance from the line to each sighted phenomena. In a *strip transect* only the phenomena occurring between two parallel line segments are counted. It is suggested that an analogy of a *strip transect* could be used to estimate the global level of damage of a city region following a large damaging earthquake or other disaster.

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On 22 February 2011 the city of Christchurch, New Zealand, was struck by a M_W6.2 earthquake. Despite being an aftershock of the larger M_W7.1 Darfield earthquake on 4 September 2010, the damage to Christchurch was considerably more severe in February with many buildings extensively damaged or collapsed, and a total of 185 lives lost. The immediate emergency response resulted in the entire Central Business District (CBD) being closed to the public for safety reasons and Urban Search and Rescue (USAR) teams searching all buildings, vehicles and piles of rubble for victims, with engineering assessments initially being limited to an 'as-needed' response. As a means of producing a quick estimate of the overall level of building damage in the CBD, the authors undertook a transect survey of the city on 24 February 2011 following a predetermined route, with the results immediately communicated to Civil Defence and Christchurch City Council representatives, and also communicated more generally to the media (Moon et al. 2012). It is acknowledged that similar forms of the transect survey method have been deployed previously, such as reported by Bray et al. (2000) following the Kocaeli earthquake.

PROPOSED TRANSECT METHODOLOGY

As part of emergency management planning, a transect survey can be pre-planned and prepared for use in estimating the overall level of building damage immediately following a large damaging earthquake or other disaster. A pre-selected route could be designed such that rapid damage assessments of all buildings directly along the route (on both sides of the street) could be used as a sample to estimate the overall level of building damage to a predefined level of confidence. For a geographical region having varying building types and varying soil conditions across the region, the procedure could be deployed multiple times through smaller sub-regions having approximately homogenous building stock and ground conditions in order to provide accurate regional surveying. A flowchart of the steps required to design such a survey is shown in **Figure 1** and these steps are expanded beyond.

Step 1 – Define the boundary of the area of interest

Firstly, the boundaries of the area to be assessed need to be defined. These boundaries may be associated with the extent of damage or be related to city/regional governance zones such as the CBD, a local council/county, or a suburb.

Step 2 – Collect data on the buildings

Secondly, building data should be known beforehand and be readily accessible in the event of a disaster. As a minimum requirement the construction type of each surveyed building must be known. From this inventory, the number of each type of building class (eg construction type, geometry) in the area should be collated. Ideally, additional details such as age and presence of any structural alterations/improvements (eg, seismic retrofits) should also be collected. It should be noted that while this paper deals with an earthquake, once Step 2 is completed the rest of the procedure can be used to assess other disasters that have a wide-spread effect on communities, such as wind events, flooding or fires.

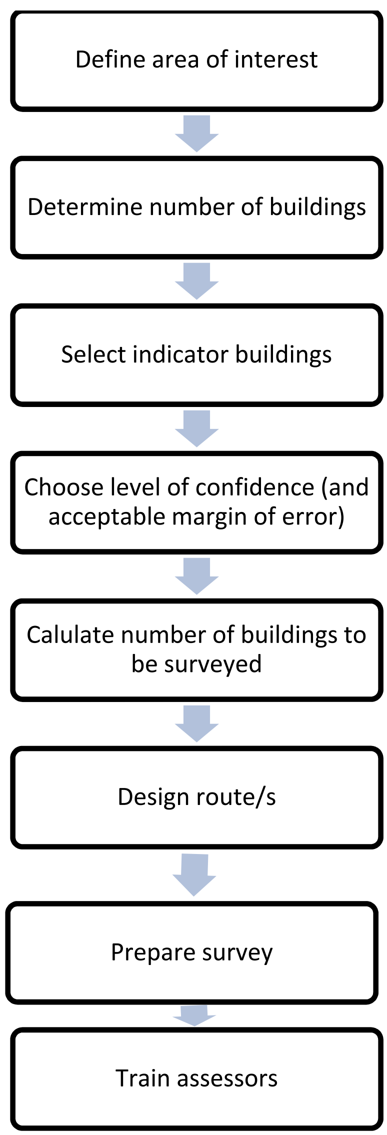


Figure 1. Flow chart of transect design

Step 3 – Select indicator buildings

Once the building classes have been defined, it is possible to select several 'indicator' buildings. These indicator buildings are representative of a particular building type and geometry and were first used by Christchurch City Council structural damage assessment teams (Marshall et al. 2013). In the event of a large damaging earthquake or similar disaster, the indicator buildings can be monitored and checked after all major aftershocks, and when additional damage is observed all buildings of that class can be rechecked. This procedure eliminates the need for all buildings to be reinspected after every large aftershock. The Applied Technology Council is similarly encouraging the use of instrumented data to supplement rapid post-earthquake damage assessment of buildings (ATC 2012).

Step 4 – Choose acceptable level of statistical confidence

Once the area to be surveyed has been defined and the numbers of each type of building determined, the desired level of confidence and acceptable margin of error for a post-earthquake survey should be selected. A confidence level of 95% with a margin of error of 5% is used here for illustration. Statistical parameters should be selected for each municipality based upon their preferred sample size, number of transects required, and variability of building stock.

Step 5 – Calculate minimum number of each building type to be surveyed

The number of buildings in each building class required to be surveyed in a post-disaster transect can be calculated from the adopted statistical parameters and the total numbers of each building class present within the survey region. If *N* is the total number of buildings of a particular class in the area, then the minimum number of buildings to be surveyed, *n*, can be calculated by Equation 1:

$$n \geq \frac{\alpha^2 N}{\left(\beta^2 (N-1) + \alpha^2\right)}, \tag{1}$$

where α is the confidence level factor and β is the acceptable margin of error (eg β is 0.05 for a maximum margin of error of 5%). For a confidence level of 95%, α is 0.98, while for confidence levels of 99% and 90%, α is 1.29 and 0.82 respectively (Mathworld 2013; Elzinga et al. 2001).

Step 6 – Design transect route or routes

The transect route(s) must be selected such that there are at least the required number of each building class present along the route. Ideally the route(s) should include some flexibility in case some streets are inaccessible post-disaster. Depending on the size of the survey area and the heterogeneity of the building stock within the survey area, two or more individual routes with multiple survey teams may be necessary in order to account for the number of buildings to be surveyed and the spatial variability of ground motions over a region due to attenuation and site effects.

Step 7 – Prepare survey

Once the transect route has been selected, survey sheets can be prepared in advance for emergencies. As a minimum, the survey sheets should include construction type, unique building identifiers linked with other information on the city/other databases, and ideally a sketch or photograph (to avoid confusion where building numbers are not easily visible). GPS coordinates should also be used in the event that building numbers are removed or destroyed. The survey sheets should be kept updated to account for new construction, renovations and demolitions.

Step 8 – Train assessors

Following a disaster, small teams of at least three assessors can be used to conduct the transect: one assessor describing the visible damage and the likely behavioural cause; one recorder checking addresses, coordinates, and building types and documenting damage levels; and a second recorder documenting all building damage via a photographic log. GPS embedded photographs are most useful. The assessments may consist of classifying each building as either 'green', 'yellow' or 'red', similar to the manner in which placards are assigned to buildings during rapid assessments where buildings are normally inspected from the outside only, as described in ATC-20-1 (ATC 2005). In this survey, buildings with no or minor structural damage (0 – 10%) were classified as having 'light' damage, those with major structural damage (10 – 30%) but not in imminent danger of collapse were classified as having 'medium' damage, and those on the verge of collapse, or deemed unsafe for entry, were classified as having 'heavy' damage (> 30% damage). The surveys may be conducted in hard copy and entered electronically after the transect, or undertaken using mobile devices such as tablets or phones.

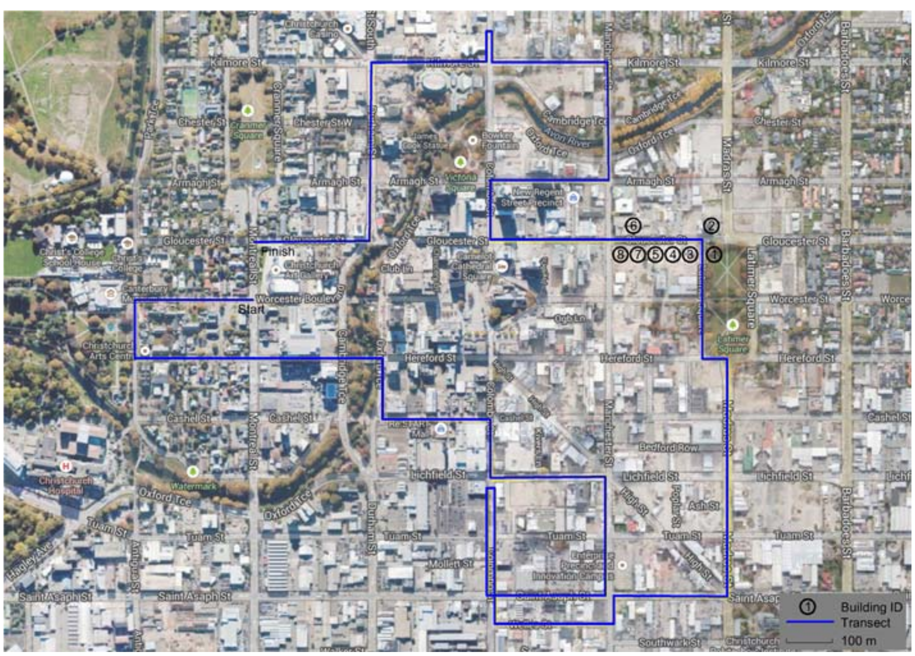
THE CHRISTCHURCH TRANSECT

For the first few days following the 22 February 2011 Christchurch earthquake, engineering resources were primarily directed at assessing the damage to residences and local services in the Christchurch suburbs and to repairing essential lifelines. Engineering activities in the CBD were principally focussed on Urban Search and Rescue and all so-called 'critical buildings', where large heavily damaged buildings posed a threat of collapse and restricted the opening of main arterial travel routes. On 24 February 2011 Biggs, Ingham and Moon sought to establish the overall damage condition of buildings in the CBD due to the 22 February 2011 earthquake, and especially the condition of those buildings of unreinforced masonry (URM) construction. Biggs' experience as a forensic engineer, including working at Ground Zero on 9/11 (Biggs 2007), Ingham's experience in rapid damage assessment of buildings in Christchurch following the September 2010 earthquake (Ingham & Griffith 2011a) and in prior post-earthquake building assessment in Indonesia (Griffith et al. 2010) and Moon's knowledge of local Christchurch buildings resulted in the team having the necessary skills to undertake a meaningful survey.

An analogy of a *strip transect* was chosen as the survey method to be used in the Christchurch CBD on 24 February 2011 to estimate the global scale of building damage following the 22 February 2011 earthquake. Almost no prior planning was done for this transect. Therefore, a route was selected based on the authors' existing knowledge of the city. While there was insufficient time to pre-plan the transect to capture a particular confidence level, the expectation was that the route would provide a reasonable level of confidence when examined in detail post-investigation. The route chosen is shown in **Figure 2**. Buildings directly along the route (on both sides of the street) were assessed for damage using the broad light, medium and heavy damage classifications as described earlier with the address, building type and damage level recorded, and each building was photographed.

The transect route was chosen to encompass a large proportion of URM buildings with which the authors were familiar from their previous reconnaissance work following the September 2010 earthquake. Fortuitously, Moon had followed a similar route two days prior to the earthquake and had a photographic record from which the new damage could be identified. Although the route was chosen to include as many URM buildings as possible, all types of buildings encountered along the transect were assessed. The route was also designed to include one of the two multi-storey concrete buildings that fully collapsed in the 22 February 2011 earthquake. Therefore, although the building types recorded during this transect did not exactly reflect the overall distribution of building types within the city, the transect route did contain a sample of all city building types. Because of the significant number of aftershocks that were being experienced at the time when the transect was undertaken, and because of the significant danger associated with potential falling hazards, the authors sought to minimize the risk to themselves at all times. Therefore, buildings were assessed solely from outside and usually only those building faces visible from the street were observed.

(a) View of Christchurch CBD with respect to 22 Feb 2011 epicentre



(b) Location of buildings shown in Figure 4

Figure 2. Route of the 24 February 2011 transect

The transect process consisted of two assessors describing the visible damage and the likely behavioural cause. As one assessor was describing the damage for a building, the recorder was documenting that building's address, building type and damage level and that building's damage via a photographic log. Meanwhile the second assessor had advanced to the next building to begin inspection and await arrival of the recorder. The assessments consisted of classifying building damage as either 'light', 'medium' or 'heavy', with no placards installed on the buildings. During the transect, buildings were assessed based solely on their own apparent structural condition rather than by accounting for any dangers posed by adjacent buildings. The Christchurch transect involved surveying 294 buildings in just over 6 hours.

Figure 3 shows photographs of the Provincial Chambers building in Christchurch shortly before and after the 22 February 2011 earthquake, which illustrates the extent to which the February earthquake exacerbated the prior earthquake damage to URM buildings. It is interesting to note that many of the buildings in Christchurch were relatively undamaged prior to the 22 February 2011 earthquake and that the significantly stronger ground shaking induced extensive further damage in both stone and clay brick masonry construction (Moon et al. 2014).

a) 20 February 2011 b) 24 February 2011

Figure 3. Provincial Chambers building in the Christchurch CBD before and after 22 February 2011

OBSERVATIONS ALONG THE CHRISTCHURCH TRANSECT ROUTE

Buildings of many different construction types were observed along the transect route, including steel (ST), reinforced concrete (RC), reinforced concrete with masonry infill, reinforced concrete masonry (RCM), precast concrete (PC), timber (T) and URM. Observed damage was typical of damage modes seen following other earthquakes, and is described in detail elsewhere (Clifton et al. 2011; Dizhur et al. 2011; Kam et al. 2011). Damage observed along a small section of the transect route, identified in **Figure 2(c)**, is examined in more detail below.

Figure 4 shows the damage to all the buildings along a short section of the transect route. The locations of buildings 1 – 8 (**Figure 4** (a-h)) are shown in **Figure 2** (b). As can be seen, the range of damage levels varied greatly. Building 1 showed no damage to the timber structure and partial collapse of an external extension to a URM firewall, and so was assigned 'light' status. Buildings 2 and 6 also showed no visible damage and were also classified 'light'. Buildings 3 and 7 showed some external cracking, but appeared to not be in imminent danger of collapse, so were classified 'medium'. Building 4 exhibited severe cracking and was classified 'heavy'. Buildings 5 and 8 both suffered extensive damage including loss of external walls and were also classified 'heavy'. This range in damage levels in small areas was typical of that observed in the Christchurch CBD during the transect.

TRANSECT SURVEY RESULTS

The transect was conducted approximately 48 hours after the earthquake. While many buildings remained in their immediate post-earthquake damage state, others were affected by search and rescue operations which included partial demolition of some buildings and clearing of rubble in the search for survivors.

The results of the Christchurch transect observations are shown in **Figure 5**. The graph shows the number of surveyed buildings for each building type, and the breakdown of each building type into the different damage classification colours.

a) Timber – Classification: Light

b) RC with masonry infill – Classification: Light

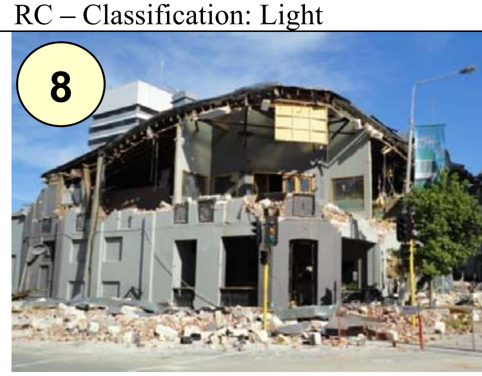
c) RCM – Classification: Medium

d) RC – Classification: Heavy

e) URM – Classification: Heavy

f) RC – Classification: Light

g) URM – Classification: Medium



h) URM – Classification: Heavy

Figure 4. Damage examples along transect

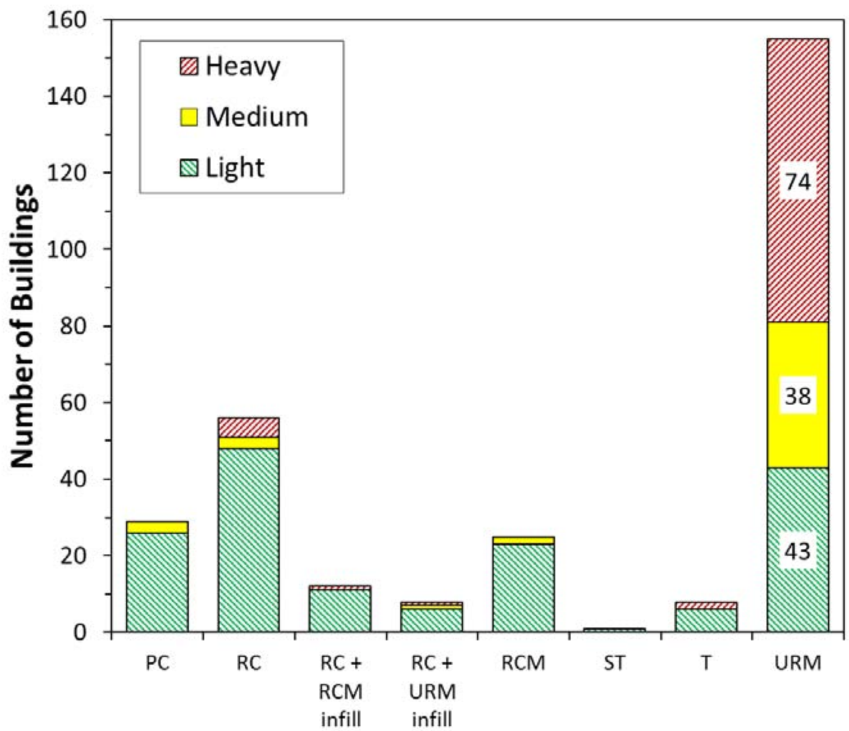


Figure 5. Distribution of damage states for each building type from transect survey

The data presented in **Figure 5** clearly shows that the majority of the buildings were constructed of URM and that they performed the worst during the earthquake. Almost half of all URM buildings were classified as red, compared to less than 10% for all other building types. This extent of damage is to be expected as URM buildings are known to behave poorly when subjected to large lateral loads, and the URM buildings tended to be older and therefore have a lower seismic capacity than newer reinforced concrete or steel buildings.

From the transect data, it was estimated that approximately one-third of all buildings in the CBD would need to be demolished. This estimate was based on the assumption that all of the red tagged buildings and 50% of all the yellow tagged buildings would be uneconomical to repair or would need to be demolished urgently for safety reasons, and that the transect was a good representation of the distribution of and damage to all building types throughout the CBD.

WHAT WAS DONE WITH THE CHRISTCHURCH TRANSECT DATA?

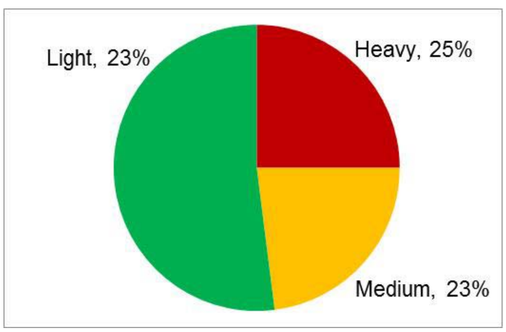
All buildings along the route that were observed to have a potentially catastrophic failure mechanism were immediately reported to emergency management officials. The transect data was processed during the evening of 24 February 2011, and immediately published on the NZSEE Clearing House (Blog 2011). The data was provided to the Civil Defence Emergency Management team and to Christchurch City Council the following morning, along with all photographs from the transect, and results from the transect were communicated directly to the media through interviews. Within a few weeks a summary of the earthquake damage observed in the course of the transect survey had been published in 'The Structural Engineer' (Ingham et al. 2011). For personnel from Christchurch City Council who were responsible for historic buildings, the provided data was in many cases their first opportunity to assess the extent of damage to the built heritage in the Christchurch CBD.

The initial media coverage of the Christchurch CBD focussed on the catastrophic building collapses and locations where fatalities had occurred. The transect data provided the first quantitative evidence that as many as one third of all CBD buildings were likely to be demolished. This estimate formed a simple message useful in conveying the scale of the disaster to the general public, and this message was quickly communicated around the world (TVNZ 2011; Guardian 2011; BBC 2011; Asia One 2011) and adopted as a main message by politicians (New Zealand Herald 2011).

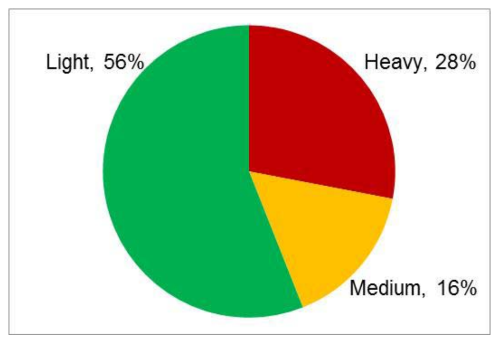
The data gathered through the transect was also useful to local authorities, including emergency management officials. In addition to the immediate reports of newly identified critically damaged buildings, the transect data provided examples of typical damage observed in different building types. On Friday 25 February, emergency management decided that some 'indicator' buildings were to be selected and requested the authors to identify a suite of candidate buildings based upon their transect observations. An example building typical of each construction type was chosen. Subsequently, each 'indicator' building was monitored and reinspected after each major aftershock. In the event that an 'indicator' building displayed significant additional damage during an aftershock, or showed signs of movement, all buildings of that construction type were then reinspected. Results from the transect allowed those in charge to be more confident that their selection of indicator buildings were representative of particular construction types. Building 4 in **Figure 4**(d) was among those selected as an 'indicator' building.

In addition to its immediate use, the data collected as part of the transect has formed a solid basis for ongoing research on the performance of buildings in the CBD during the 22 February 2011 earthquake. The early timing of the transect in relation to the earthquake meant that observations were made before significant demolition and clean-up work was conducted.

At the time when the transect was performed, the focus by authorities was on search and rescue. Engineering assessments in the CBD were limited to an 'as-needed for emergency assessment' basis and most other engineering resources were assigned to assessing suburban residences. Rapid building assessments in the CBD had not begun, and therefore these results were the first overall study of the damage levels of buildings within the CBD. **Figure 6** shows the overall distribution of damage classifications assigned during the transect (**Figure 6**(a)) and those assigned by the Civil Defence volunteers in the following month (**Figure 6**(b)). The Civil Defence data, published by the Christchurch City Council (2011), covers over 4,000 buildings within the CBD, and shows an overall damage distribution that is strikingly similar to that obtained from the transect which only surveyed 294 buildings, despite there being almost daily aftershocks in the weeks between the transect and the overall study.



a) Data from authors' CBD transect survey (294 buildings) – 24 February 2011



b) CBD data from Civil Defence (4000+ building surveyed) – 24 March 2011

Figure 6. Building damage data for Christchurch CBD, February and March 2011

The transect provided a useful method for surveying building damage in the CBD. Given the size of the city it was not practical to assess all buildings in such a short time, so a sample was needed. The familiarity of the authors with buildings along the route allowed them to better distinguish the new damage from existing, giving a clearer picture of the damage specifically attributable to the 22 February 2011 earthquake. Although the number of URM buildings along the chosen route far exceeded that of other buildings, this distribution was not solely due to the choice of route. Many URM buildings existed in the central, historic heart of Christchurch, and were often small in footprint size when compared to more modern steel and concrete buildings. Therefore, it was not surprising that there were a larger number of smaller, older, URM buildings in the study than large, modern, multi-storey buildings.

A transect, following a set route and surveying all buildings along that route, was chosen as the sampling method due to it being a rapid, efficient and relatively safe way to conduct a building damage survey and provide a reliable estimate of the global damage to the CBD. Due to the inherent dangers of unstable buildings and continuing aftershocks it was considered impractical to sample all city blocks, so instead a familiar route was chosen, and all buildings along the route surveyed, ensuring that the maximum number of buildings in the CBD were surveyed for the time and distance covered by the team. Given the homogeneity of building types and age of construction and uniformity in the ground motion due to the relatively small dimension of the CBD, any alternative path may have been expected to yield similar results.

STATISTICAL OVERVIEW OF THE CHRISTCHURCH TRANSECT DATA

The number of each type of building sampled during the transect, and the percentage of the sample that each building type represents, is shown in **Table 1**. This data was prepared months after the transect was performed, to assess the statistical confidence level actually obtained by the transect with only previous experience in the CBD and "engineering judgement" as the pre-planning. Of particular note is that the percentage of timber buildings in the transect survey is significantly less than representative of the total in the CBD. This is due to a concentration of small timber buildings in the north east of the 'four avenues'. Given a sample from the downtown 'commercial core', the transect would be more representative of timber buildings than these figures suggest.

Table 1. Buildings Surveyed in Transect and CBD Building Population Estimate

CBD Building Type	Number of Buildings in Transect	% of Total (Transect)	Estimate of Buildings in CBD (Subsection)	% of Total (CBD)
Precast Concrete	29	10	176	6
Reinforced concrete	56	19	448	17
RC + RCM infill	12	4	209	8
RC + URM infill	8	3		
RCM	25	8	342	13
Steel	1	0.3	138	5
Timber	8	3	1028	38
Unreinforced masonry	155	52	370	14

TOTAL	294	100	2711	100

Accurate data on the true distribution of building types in the Christchurch CBD is difficult to obtain. While the Civil Defence published data on building damage for over 4,000 buildings (**Figure 6**), the construction types of these building was not revealed. However, building types for 2,711 buildings can be inferred from Christchurch City data reported by Ingham & Griffith (2011b; 2011c) for URM buildings and by Kam et al. (2011) for all other building types. While this building count likely represents about only 60% of buildings in the CBD, it is the best data currently available, and hence is the data used in this analysis.

STATISTICAL ANALYSIS

The Christchurch transect was not pre-planned other than through "engineering judgement" by the authors, and therefore was not specifically designed to generate results of any predetermined statistical accuracy. However, following the transect the level of confidence that could be assumed from the data was calculated. In a population *N* with sample size *n*, for a 68% confidence interval, the margin of error (MOE) can be approximated by Equation 2 (Mathworld 2013; Elzinga et al. 2001).

$$MOE = \frac{0.50}{\sqrt{n}}, \tag{2}$$

For small populations such as in this case, or large samples, a finite population correction (FPC) factor can be used to modify the margin of error. This correction is given by Equation 3.

$$FPC = \sqrt{\frac{(N-n)}{(N-1)}}, \tag{3}$$

The margins of error for a 68% confidence level for the transect results are shown in **Table 2**. The number of buildings of each construction type required to be sampled to ensure a margin of error of 5% are presented in **Table 3**. These data are calculated using Equation 1, with α = 0.50 and β = 0.05.

Table 2. Margin of Error for 68% Confidence Interval for Transect Sample

CBD Building Type	Population	Transect Sample	Adjusted margin of error
Precast concrete	176	29	9%
RC	448	56	6%

RC + masonry infill	209	20	11%
RCM	342	25	10%
Steel	138	1	50%
Timber	1028	8	18%
URM	370	155	3%
TOTAL	2711	294	3%

Table 3. Sample Size Required for 68% Confidence Level and 5% Margin of Error

CBD Building Type	Population	Sample size required (transect value in brackets)
Precast concrete	176	64 (29)
RC	448	82 (56)
RC + masonry infill	209	68 (20)
RCM	342	78 (25)
Steel	138	59 (1)
Timber	1028	92 (8)
URM	370	79 (155)
TOTAL	2711	522 (294)

From these tables, it can be inferred that for most building types the unplanned route was still able to achieve a 68% level of confidence with a margin of error of about 10% or less.

OTHER SOURCES OF ERROR

Assuming that all assessors have equal experience, the largest source of error in these results is due to the difficultly associated with determining the type of construction and level of damage of a building from a rapid external inspection only. These difficulties result in statistical sampling bias, which will always exist when access to the entire building is not possible. Therefore, future studies are needed to correlate the accuracy between rapid and detailed assessments for different building types. Until such studies are completed it should be assumed that the true margin of error is greater than anticipated.

CONCLUDING NOTES AND RECOMMENDATIONS

The methodology for a transect-style survey is given. The Christchurch transect represented the first global assessment of building damage in the Christchurch CBD following the earthquake. The transect provided valuable data by briefly assessing all buildings along a pre-determined route, enabling a quick estimate of overall building damage levels. From the data it was estimated that approximately one-third of all buildings in the CBD would need to be demolished[1]. This technically sound message was quickly communicated by the media around the world, and was useful in enabling political leaders to quickly understand the magnitude of the disaster.

The surveying that was conducted as part of the Christchurch transect was limited to external inspections of buildings, and often of just the façade. This procedure can be compared to the rapid building safety assessments described in ATC-20, and while not suitable for a detailed assessment it provided a useful estimate of the overall damage levels at a time when most resources were still focused on search and rescue. The transect results were similar to those published by Christchurch City Council on 24 March 2011 following their rapid damage assessment of the whole CBD, indicating that the "engineering judgement" transect technique provided a satisfactorily accurate estimate of the overall building damage to the Christchurch CBD.

It is recommended that future transects be pre-planned as outlined for similar applications in other cities. Ideally, transect routes should be pre-planned following the suggested methodology and devised such that they cover a sufficient area to account for site variability and attenuation and number of building types (including structural system, number of stories, occupancy type) for the desired levels of statistical accuracy. Following an earthquake or other disaster, a survey of these pre-planned routes would allow a quick estimate of global damage levels, and enable emergency management teams to quickly assess the overall severity with a selected statistical confidence level and margin of error.

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[1] Reports on the actual number of buildings demolished, or partially demolished, in the Christchurch CBD by June 2013 varied from 879 (CERA, 2013) to 1350 (Blog, 2012). Using the previous estimate of about 4000 buildings in the CBD this equates to between 18% and 30% of buildings. However, the fate of many more buildings remains undecided, and the initial prediction of one-third of city buildings requiring demolition is likely to be an underestimate.

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