Integrated Design for Achieving Building Seismic Resilience

A. Liu
BRANZ, New Zealand

SUMMARY:

Large scale catastrophic earthquakes are the greatest challenges in achieving resilience of built environments. Resilience of building structures is the fundamental element in achieving resilient built environments.

This study had examined current building regulations and seismic design standard in New Zealand and the examination showed that improvements are needed in following areas. (1). The current building regulation and seismic standard addresses buildings in isolation and the integrated nature of building structures in a built environment needs to be considered so that buildings, which are essential in built environments, are resilient in massive destructive earthquakes; (2). Specified objectives in New Zealand building code (NZBC) need clarification so that performance requirements in seismic design standard can be justified to be compliant with NZBC; (3). The integrated nature of building elements in a complete building should be considered in all aspects of building design for earthquakes as well as in certifying building products.

Keywords: Integrated Design, Resilience, Seismic Design, Buildings

1. INTRODUCTION

Resilience of built environment is often defined as how quickly built environments can regain essentially the same function, structure, identity etc after a disaster. Achievement of resilient built environments or a resilient nation has to be the paramount objective which all of our activities endeavour to achieve.

A built environment consists of many individual components: the people (the users) residing in it, the essential post-disaster facilities (hospitals, so on), utilities (power supply, water, gas so on), building structures (residential buildings, commercial buildings, industrial buildings etc), infrastructures (roads, airports so on) so on. All these components are interconnected to each other, and hence resilience of a built environment refers to the integrated resilience of all components in a built environment, which is beyond resilience of any one single component.

A built environment could be exposed to various hazards including man-made hazards or natural hazards. In comparison with man-made hazards, such as fire events, blasting so on, the natural hazard related events are characterised by their massive destructive powers. Therefore the greatest challenge in achieving resilience of built environments is natural disasters, such as, earthquakes, flooding and so on. Among many natural hazards, earthquakes are probably the biggest threats to the built environments because earthquakes have no warnings and can cause the massive destruction in a very short time period (as short as a few seconds).

There has been increased research developments worldwide in recent years on resilience of our built environments (Edwards 2009)(NIBS 2010). Regarding research on resilience of built environments, there have been many research activities on emergency responses and recovery after disasters occur and lots of researches were directed to identify the roles each party is playing in an emergency operation, such as, central government, local government, private organisations, defences so on.

Building stock, which is one of many components in a built environment, is the most important part of a built environment because (1) building structures are central to people's lives, work, recreation so on and the continuous function of building structures after a destructive large scale seismic event is a major challenge to the recovery of a built environment or even a country; (2) catastrophic building collapse is the greatest threat in causing casualties, injuries and economical loss especially when the affected population is large, necessitating the need for great resources of emergency response; (3) collapses and damages of building structures are the main cause for in-direct seismic loss after a major earthquake. In a built environment, resilience of the building structures is related to the first of four elements in the proposed emergency planning in New Zealand, reduction, readiness, response and recovery. Hence the achievement of resilient building structures is the fundamental issue in achieving a resilient built environment, similar to a healthy state of a person in coping with potential infection hazards. There have been activities on making resilience building stock, however the effort has been mainly focused on existing buildings and assuming that the current building regulation and building seismic design standards are adequate to meet our future needs in achieving resilient built environment. For example, there are many activities on seismic upgrading of the existing building stocks according to the current design standards. In carrying out seismic strengthening of existing buildings, the focus is on assessing and strengthening each isolated building without adequate allowance for its effect on the surrounding environment (such as the falling hazards to pedestrians) or the interconnections between the subject building and the surrounding built environment (such as a partial collapse of a tall building could cause significant delay to the return of the adjacent buildings).

Are the current building regulations and design standards adequate to guarantee the resilience of the new building structures to meet the future needs of our fast changing society? Will the building structures designed to current codes be resilient for future earthquake hazards? Or will the buildings designed to current codes become earthquake prone buildings in the near future?

The paper presented here is to clarify whether or not there is a need for improving the current building regulations and practice in terms of achieving resilient built environments. The current New Zealand building regulations and seismic design standard for buildings were examined first against the objective of resilient built environments. Then the current engineering practice was examined to find out whether or not the current practice is adequate to achieve resilient built environments.

2. CURRENT NEW ZEALAND BUILDING REGULATIONS VERSUS RESILIENCE OF BUILDING STRUCTURES IN A BUILT ENVIRONMENT TO EARTHQUAKES

Current NZ building regulation environment is a performance-based code and it has a multi-level code format for building designs. At higher levels, New Zealand building code (NZBC) sets out overall building design objectives. At lower level, there are compliance methods which are used by building design engineers to establish the compliance with the building code.

Regarding structural design of buildings, NZBC has Clause B1- Structure and the objectives specified are as follows:

(1) safeguard people from injury caused by structural failure,
(2) safeguard people from loss of amenity caused by structural behaviour, and
(3) protect other property from physical damage caused by structural failure

Functional requirement specified by NZBC Clause B1 is that buildings, building elements and sitework shall withstand the combination of loads that they are likely to experience during construction or alteration and throughout their lives.

Performance requirement specified by NZBC Clause B1 is

(1). Buildings, building elements and sitework shall have a low probability of rupture, becoming unstable, losing equilibrium, or collapsing during construction or alteration and throughout their lives.

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

(3). Accounts shall be taken of all physical conditions likely to affect the stability of buildings, building elements and sitework, including gravity loads, earthquake actions, so on.

(4). Due allowance shall be made for

(a). The consequence of failure,
(b). The intended use of the building,
(c). Effects of uncertainties resulting from construction activities, or the sequence in which construction activities occur,
(d). variation in the properties of materials and the characteristics of the site, and
(e). Accuracy limitations inherent in the methods used to predict the stability of buildings.

(5). The demolition of buildings shall be carried out in a way that avoids the likelyhood of premature collapse.

(6). Sitework, where necessary, shall be carried out to:
(a). Provide stability for construction on the site, and
(b) Avoid the likelihood of damage to other property.

(7). Any sitework and associated supports shall take account of the effects of
(a). Changes in ground water level,
(b) Water, weather and vegetation, and
(c) Ground loss and slumping.

It is clear that NZBC does not clearly distinguish the destructive scale of an event or the scale of the established built environment in specifying building structural designs. While many actions specific to a building will only affect the subject building, such as, gravity load, live load, even fire so on, natural disasters, such as earthquakes, are different. Earthquakes can occur in less-established built areas or in well-established built environments and an earthquake of a certain magnitude could cause significantly different disaster consequences, depending on the scale of the affected built environments. In detail, if an earthquake occurs in a rural area, the damage consequence is negligible. In contrast, if the same earthquake, which is of the same destructive power, occurs in a well-established built environment, the casualties and the damage cost could be much higher because much more people are affected and much more hazards are expected due to high building density and more tall buildings. Even for a particular building, there are more threats from the adjacent building structures. Furthermore there is a much greater need for rescue and recovery efforts after a disaster. Hence scale of the built environment needs to be considered in seismic design of building structures.

In summary, the examination of current New Zealand building code clause B1- structures revealed the following inadequacies:

(1). Concept of the built environment is not in the equation of designing buildings for earthquakes according to the current NZBC and therefore the current building regulation framework is inadequate to guarantee achievement of a resilient built environment in a major earthquake disaster.

(2). The code specified objectives should distinguish the large scale destructive events from an isolated event in designing buildings. Current building regulation does not require for considering the establishment scale of the built environment, to which the subject building belongs, in specifying building designs.

(3). The code specified objectives consider the subject building in isolation and improvement is needed to allow for the integrated nature of buildings in a built environment.

3. COMPLIANCE METHODS FOR DESIGNING BUILDINGS FOR EARTHQUAKES TO ACHIEVE RESILIENT BUILT ENVIRONMENT TO EARTHQUAKES

Regarding building seismic design, the compliance method in New Zealand is commonly the use of seismic loading code AS/NZS1170.5 (SNZ 2004) and relevant material codes. AS/NZS1170.5 adopts a two limit state design procedure and the two limit states are ultimate limit state and serviceability limit state. AS/NZS1170.5 specifies design performance requirements for the two limit states and these performance requirements are deemed to be compliant with NZBC. AS/NZS1170.5 also specifies the methods for determining the seismic design actions for the two limit states and specifies the verification methods used for seismic analysis, which are deemed to satisfy the established performance requirements.

Design performance requirements for earthquake actions, which are specified in NZS1170.5 are as follows:

(a) at Ultimate Limit State
- (1) Avoidance of collapse of the structural system; and
- (2) Avoidance of collapse or loss of support to parts; and
- (3) Avoidance of damage to non-structural system necessary for emergency building evacuation that renders them inoperative.

(b) at Serviceability Limit State
- (1) To avoid damage to the structure and non-structural components that would prevent structure from being used as originally intended without repair after SLS1 EQ; and
- (2) To avoid damage to either a structure deemed as a critical post-earthquake designation or all the elements required maintaining those operations after SLS2 earthquake.

When the performance requirements as described above in AS/NZS1170.5 are compared with the specified objectives by NZBC, it is not very clear whether or not the performance requirements can achieve the code intended objectives. For instance, it is unclear whether or not the performance requirements in AS/NZS1170.5 have achieved the code specified requirement “safeguard people from loss of amenity caused by structural behaviour”.

In determining the seismic design actions for buildings, AS/NZS1170.5 specifies three verification methods and they are equivalent static method, modal response spectrum method and numerical integration time history analysis, varying from simple to very sophisticated. For all these three methods, considerations in determining seismic design actions of a building are limited to the building’s own properties.

For instance, the factors allowed for in calculating design seismic actions of a particular building when using equivalent static method are the dynamic property of the subject building, which is the fundamental period, deformation capability of the subject building termed as displacement ductility, seismic weight of the building, subsoil category, the seismic zone, Z factor, depicting the geological location but irrespective of the established scale of the built environment. In detail, the horizontal seismic shear, V, acting at the base of the structure in the direction under consideration, when determined using equivalent static method, is calculated from:

$$V = C_d (T_1) W_t \tag{1}$$

Where C_d (T_1) is the horizontal design action coefficient, which is a function of the building's own period T_1, displacement ductility, soil class, seismic zone, importance level associated with the intended use of the subject building, and W_t is the total seismic weight of the subject building.

AS/NZS1170.5 also specifies the procedures for structural analysis and the relevant material codes specify the modelling techniques. However the compliance documents have very little considerations in analyzing building's seismic response by either including the structure below the ground level into the structural modelling or allowing for ground – foundation- upper structure interactions. NZBC considers buildings and building elements to be of similar importance level in specifying the objectives. Seismic actions are due to ground shaking so the entire building structure including foundation elements and superstructure will response to the ground movements. Clearly the foundation elements, which are an integral part of the complete building, need to be considered in analyzing building's performance in earthquakes. Often the structural engineers need only to analyze the upper structure assuming that the foundation will be able to resolve the generated actions to the ground and the knowledge overlap between structural engineers and geotechnical engineers is not adequate, consequently the foundation levels are the areas being ignored.

In summary, examination of compliance methods for designing buildings for earthquakes against the resilience of built environments reveals the following findings:

(1). As expected, concept of the built environment is not considered in many aspects of designing buildings for earthquakes according to the current compliance methods. Therefore building structural design according to current compliance method will not guarantee achievement of resilient built environments.

(2). There is an unclear gap between the performance requirements in compliance documents and the code intended objectives. It is suggested that the objectives specified in NZBC be better clarified so that the compliance document, which is NZS1170.5, can better quantify the establishment with the code specified objectives.

(3). Consideration of the integrated nature of building elements in a building is inadequate in the current compliance documents. Especially of concern is that the foundation elements should be adequately modeled in analyzing structural performance of buildings in earthquakes and there is a need for bridging the gap between geotechnical engineering and structural engineering.

4. CURRENT PRACTICE IN CERTIFYING BUILDING PRODUCTS VERSUS RESILIENCE OF BUILDING STRUCTURES IN A BUILT ENVIRONMENT TO EARTHQUAKES

Current compliance documents often specify alternative solutions. In certifying the alternative products or systems, it is common practice that new building material/new proprietor building systems are tested on isolated components. In addition, many building components are often tested for gravity only because they are assumed to play no part in building's response to earthquake events. Simulation of the boundary conditions and the definition of the loading regime often have assumed that the building components are mainly used for that purpose. As far as the certification test shows pass, the tested components can replace the systems in the original specification freely.

As a result, any actions beyond the assumed envelope could potentially cause failure and also the reserved capacity due to presence of the previously assumed non- structural elements in the original specification no longer exists and resilience of the entire building reduces, further deteriorating the achievement of structural integrity in earthquakes.

One example is the proposed alternative ground concrete floor slabs, which uses various fibres to replace reinforcing in the original RC slabs cited in compliance documents, such as, NZS3604 "Timber Framed Buildings" (SNZ 2011). The assumed function for concrete slab is to transfer the gravity load to the ground, so the certifying tests only test the adequacy for transferring the gravity load. A ground floor slab is part of the building structure and it is an essential part in achieving structural integrity in a major earthquake. Tests on ground floor slabs for gravity load will not be able to prove the adequacy of ground floor slab for maintaining integrity in earthquakes.

5. FINDINGS FROM EARTHQUAKE DAMAGE OBSERVATIONS

There have been many reported earthquakes around the world, which frequently reveal that the integrated nature of built environments has to be taken into account in dealing with natural hazards, such as earthquakes. As urbanization progresses, the extent of integration will increase and the affected population and building volumes could be significantly larger. Integrated nature of a built environment has to be taken into account at all levels in order to achieve resilient built environments and resilient nations.

Recent Canterbury earthquake series in New Zealand demonstrate the effects of integrated nature of building structures in built environments in many ways.

5.1. Need for Considering Built Environment Scale in Seismic Design of Building Structures

Canterbury earthquakes in 2010 and 2011 illustrate that a seismic disaster of same magnitude would result in much more severe damage and casualties to a well-established urban built environment than a less-developed built environment, due to the nature of large - scale destructive power of earthquakes, and therefore it is important to allow for the integrated nature of building structures in a built environment in conducting building seismic design. The September 2010 Canterbury event had a magnitude of 7.1 and was near the rural town of Darfield (Allen etc 2010), at a depth of 10 km. The aftershock in February 2011 had a magnitude of 6.3 and was centred 10 km south-east of the CBD near the port suburb of Lyttelton, at a depth of 5 km (Bradley 2012). The damage from February 2011 event was much more costly in comparison with the Sept 2010 event partially because of the difference in the urbanization of the affected areas. The affected area in Feb 2011 event, which was Christchurch city, was an important hub for Canterbury area and is the second largest city in New Zealand. Canterbury population is about 13% of total population in New Zealand, and economical activities in Canterbury were proportionally about 13% of total national GDP. Being an important built environment in nationwide scale meant that the consequence was very severe as reported in news media throughout the world. The rescue and recovery task was enormous in comparison with the size of the country, so the entire country was declared as an emergency state for a couple of weeks. Economic impacts were huge and the direct damage cost is estimated roughly to be about NZD30b, which is about 17% total GDP, and the entire country's economy was affected by this event. In-direct cost is usually higher than direct cost, so this series of earthquakes has become the costliest natural disaster in the world in terms of the economic size of the country. This clearly demonstrates the effect of scale of a built environment especially when the design actions have massive destructive power.

5.2. Allowance for Integrated Nature between Building Structures in Built Environment in Earthquakes

In Feb 2011 earthquake in Christchurch, many observations led to a conclusion that seismic design of one single building has to allow for the integrated nature of the subject building with the surrounding built environment.

Code specified objective of building structural design by NZBC is life safety. In Feb 2011 Canterbury earthquake, majority of deaths or injuries were caused by falling elements (mainly URM elements) onto people outside the buildings (Sutton 2012), apart from the deaths in CTV building and this clearly showed that, even the partial collapse of structural components or non structural components of the subject building won't impose hazards to people inside the building and won't impose hazards to the adjacent buildings, it is still a hazard to people in the built environment and seismic design of individual building has to consider the integrated nature of built environment. After the major event in Feb 2011, many buildings especially in CBD have remained to be closed for long time (some buildings remained closed one year after the event) not because these buildings were all badly damaged but because there were potential hazards associated with unstable parts of the adjacent buildings. This demonstrates that the integrated nature of building structures in a built environment needs to be taken into account.

5.3. Integrated Nature of Building Elements within A building in Earthquakes

Observed earthquake damages to building structures in Canterbury earthquake series also revealed inadequate consideration of the integrated nature of building elements within a complete building.

Residential timber framed houses are taken as examples. Residential houses in New Zealand are mainly light timber framed buildings and they were observed to have performed well if no land damage was involved. However the observed extensive damage to the modern residential buildings with concrete slabs has surprised many. In New Zealand, the concrete slab on ground for timber framed residential houses, which has become very popular from 1980s, is usually 100mm thick and does not need to contain any mesh or any reinforcement. In Canterbury earthquake series, huge cracks in the concrete slabs were observed where the ground movement (land damage) occurred due to liquefaction or where the lateral land spreading occurred. This was attributed to the inadequate design for structural integrity and robustness at the ground slab level and inadequate consideration of the interactions between upper structure and ground. The ground slab is indeed part of the building structure but not much engineering considerations have been given to designing the foundation slab. The integrity of the buildings might have been maintained at the roof ceiling level, but the big cracks in the ground slab level caused significant distortion of the entire building because no diaphragm action could be developed at ground level; subsequently many houses in this damage category became uneconomical to repair. The earthquake damage to the residential houses is huge for a town of about 10% total NZ population and the recovery and reconstruction have been slow.

Figure 1 shows the observed damage for a modern residential house with concrete ground slab during Feb 2011 Earthquake. The inadequate design for the structural integrity at ground level has caused the extensive damage of the house.

Should the ground slab foundation structure have been properly constructed, the houses probably have performed as base-isolated structures and the damage levels could be significantly less. A base-isolated structure always requires robust diaphragm action above the isolated plane.

Figure 1. Loss of Integrity at Ground level due to Big Cracks in Concrete Slab

6. CONCLUSIONS AND RECOMMENDATIONS

Resilience of built environments and resilient nation is the paramount objective of our daily activities and the greatest challenge is resilience of built environments in earthquakes. Resilience of building structural stock in a built environment is the fundamental element for achieving resilient built environment. Examination of current building regulations and building design standard for earthquakes in New Zealand in terms of achieving resilient built environments and resilient nations reveals the followings:

1. Integrated nature of building structures in a built environment is not considered in seismic design of building structures. Earthquakes have massive scale of destructive power and seismic design for building should not treat individual building in isolation as in current NZBC and AS/NZS1170.5.

2. Integrated nature of building structures with the surrounding built and establishment scale of the built environment, such as, population and economical importance, available emergency response capacity so on need to be taken into account in determining proper seismic design levels for building structures.

3. Integrated nature of building elements within a building need to be considered. This necessitates the need for communication between different disciplines, such as, geotechnical engineers and structural engineers so on.

4. Certification of building products, even non-structural components, should allow for the potential impact on the global behaviour of an entire building in various conditions, especially when dealing with natural hazards.

5. Code specified objectives of building structural design for earthquakes need to be better quantified in order that the compliance method can be justified. Proactive attitudes need to be taken in order to achieve resilient building structures to meet ever increasing needs.

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