The development of a formal framework for discussing earthquake resilience of the built environment

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ABSTRACT: Resilience is a generic word which is currently used in a wide range of contexts, the common basis being that it refers to the ability to recover from a sudden shock or series of shocks. To have specific meaning the context needs to be specified. The context consists of three components – resilience ‘of what’ ‘to what’ in ‘what form’. In respect of the built environment the most common context in which the term is used is in respect of the resilience ‘of communities’ to the impact ‘of major events’ in terms of their ‘functionality’. But it is not restricted to this. For each element of the built environment and each type of event the factors that contribute to resilience will be different. In the case of resilience to earthquakes the primary context is the total affected community and its ability to recover from such an event. Each element of the built environment will contribute to this resilience, and it is this contributory resilience that each makes to the overall community resilience, not just the resilience of individual elements in isolation, that is important. The purpose of this paper is to provide a framework for ensuring clarity of meaning in discussing earthquake resilience of the built environment.

1 INTRODUCTION

Resilience has become a buzz word in a range of fields including human psychology, the natural environment, and disaster risk management. Inserting the word in Google produces over 40 million results, most of them relating to these fields. Its meaning and the context in which it is used, however, varies widely, depending on the background of the writer and particular application. The word is derived from the Latin word ‘resilio’ which meant rebound and in most cases its use retains this concept either literally or figuratively. The Oxford Dictionary (OUP 2014) separates these two meanings as ‘the ability of a substance or object to spring back into shape’ and ‘the capacity to recover quickly from difficulties’. While the first meaning is relatively precise, the second meaning is open to a wide range of interpretations in regard to what is meant by ‘recover’, ‘quickly’ and ‘difficulties’. In the environmental field its meaning has also been extended to the capability of a system to adapt to changing conditions, particularly in connection with climate change studies (UNISDR 2005). For a word used so widely across a number of disciplines, both academically and in the wider community including government policy making, this lack of clarity can limit its usefulness unless the context in which it is being applied is carefully defined. This requires identification of what is being described, what is the type of impact and its magnitude for which it is being described, and in what way it is being described.

This need for clarification has been recognised for some time. Significant contributions have been made in publications by Bruneau et al. (2003), Mantena (2006), Brand and Jax (2007), Cimellaro et al. (2010), Wright et al. (2012) and MacAskill and Guthrie (2014), each of which contain extensive lists of references to other work. Most of these have been made in the context of either disaster risk management or environmental sustainability, and often as an introduction to a framework for undertaking assessment of resilience. Each approach appears to have limitations when considering resilience in its widest sense, including its use by government and the general community, and in respect of the built environment, which is the underlying focus of this paper. The framework presented in this paper most resembles that of MacAskill and Guthrie (2014) but extends it to embrace the whole spectrum of the use of the term without becoming too academic for non-specialists in the subject.

2 OUTLINE OF PROPOSED GENERAL FRAMEWORK

A general framework within which application of the term resilience can be specifically defined will comprise three parts, one defining the **object**, including its **scale**, one specifying the **impact type and magnitude** for which it is being applied, and one defining which **form of resiliency** is being described.

2.1 The object

Objects to which the property of resiliency is ascribed vary widely. In the proposed framework they will generally be entities grouped into the following **categories**:

- Physical objects like constructed assets;
- People;
- Organisations like businesses and governments;
- Systems for delivering services usually involving a networked combination of physical infrastructure, people and control systems;
- Ecological systems; and
- Overall communities which would generally be comprised of objects in all of the above categories.

Within each of these categories there will be a hierarchy of **sub-categories** specifying individual types of objects within each category. For example the ‘constructed assets’ can be sub divided into buildings and other constructed assets, buildings can be sub-divided into houses, commercial buildings, schools, hospitals, etc.

The object of the term resilience can be any these categories and sub-categories as an individual entity or as a group of entities, and the grouping can be of similar entities, such as people of a similar age group or buildings of a similar type, or different entities such as the whole community which embraces all types of entities. When grouped the size of the group may vary from a small group within a local community, to an entire urban community, to a whole nation, or to international groupings of nations. Consequently in specifying the object of the resilience it is also necessary to specify its **scale**.

For each of these objects the characteristics describing the property of resilience will vary according to the category, sub-category and scale.

2.2 The impact

As with the object to which the term resilience is applied, so can the nature of the impact be divided into several categories including:

- Physical events such as earthquakes, tropical cyclones, floods, drought, explosions, vehicle impact;
- Financial and economic impacts such as the financial crises from individual level to business level to national and international level;
- Health related impacts such a as injuries, disease and dementia at the individual level to epidemics and pandemics at regional, national and international level; and
- War, riots and terrorism.

Each of these will have a hierarchy of sub-categories to describe particular **types** of event and for each of these further sub-categories to describe particular hazards generated by each type of event. For example earthquakes are a sub-category of physical events, while ground shaking is one of the hazards generated by earthquakes. The different categories and sub-categories may be considered in isolation, or in conjunction with each other where they occur together, or where one type can lead to another type – e.g. ground shaking from an earthquake resulting in destruction of a house can give rise to a health impact on the occupants and/or a financial impact on the owners. In this case the earthquake shaking might be described as a primary event, while the health and financial impacts as secondary impacts.

For each of these types of impact the level of resilience will vary according to the **magnitude** of the impact which will often include a geographic scale and/or time scale which consequently also needs to be specified.

2.3 Form of resiliency

Resiliency defined in terms of an elastic type rebound to an original state, implying as it does no impairment or damage, is described as **mechanical resiliency**. Although normally thought of in the structural sense this term can be applied to any category of object. For instance in the case of an individual person it can be described as the capacity of an individual to withstand a physical impact without significant injury, or in the case of a system to withstand a shock to the system without breakdown of the system. A characteristic of mechanical resiliency is that that it is purely a property of the object to which it is applied independent of external factors other than the type and magnitude of the impact for which it is being attributed.

Resiliency described in terms of time of recovery to an original state requires an understanding of what is meant by ‘original state’. It normally does not mean the original physical state associated with mechanical resiliency. All objects of resiliency have functions associated with them. When used in this form resiliency generally refers to the time taken to recover functionality of one type or another of the object to which the property of resiliency is being ascribed. Consequently this form of resiliency is described as **functional resiliency**. In the case of an individual person subjected to a physical attack it would be measured by the time taken to recover from injuries. In the case of a system it would be a measure of the time taken to recover its original functionality.

Complex systems are collections of individual objects, implying that the resilience of the system is dependent on the **contributory resilience** of objects both inside and outside the system. A good example may be seen in the recent outbreak of Ebola in West Africa. The ability of nations to recover from the epidemic depends not only on individual actions but the number of people infected, the performance of the medical system, the ability to access global resources, etc. This dependency on the performance of other entities not only complicates descriptions of functional resilience of specific objects but also means that entities possess another resilience property which is the contribution they make to the resilience of another object.

As the scale increases so does the importance of contributory resilience relative to the functional resilience of entities in isolation, but the difference between these is not always recognised. This is particularly relevant to assessments of the resilience of communities to major disasters.

3 RESILIENCE AND THE BUILT ENVIRONMENT

3.1 The object

In the context of the proposed framework the built environment is mostly comprised of entities in the physical objects category. In general the built environment can be subdivided into at least three major sub-categories, each of which can generally be further sub-divided forming a hierarchy of constructed assets to which the term resilience may be applied singly or grouped together.

Three of the major sub-categories are:

- Buildings;
- Constructed assets of industrial facilities;
- Constructed infrastructure assets which usually form a significant part of most lifeline systems.

Each of these can be further subdivided. For instance buildings may be subdivided into single family homes, apartment blocks, and commercial and government office blocks, each of which can be further sub-divided in terms of age, form of construction and size. The constructed assets of industrial facilities may include factories, refinery structures, holding tanks, and conveyor systems. Constructed assets of infrastructure assets include road, railways, bridges, water and sewage treatment works, port facilities, electricity and communication transmission structures, pipelines, and airport structures.

3.2 The impact

The most common types of impact on the built environment that are considered in relation to resilience are those arising from physical events, although blast from war and terrorism has also become important in recent years. These, along with their significant associated hazards, are:

- Earthquakes – ground shaking, liquefaction, landslides, tsunamis;
- Tropical cyclones – wind, rain, riverine and flash floods, storm surge, landslides;
- Severe storms including tornadoes – wind, rain, hail, flash floods, lightning;
- Other major rainfall events – riverine and flash floods, landslides
- Fire – building fires, bush fires
- Blizzards – snow, freezing conditions
- Industrial explosions – fire, blast.

Each of these can vary greatly in magnitude, including the geographical area affected by them. Individual large magnitude earthquakes and tropical cyclones can impact large geographical areas, severe storms are much smaller in geographical extent, while building fires are generally limited to a single building. The time horizon is also important, as some impacts occur over weeks or months, e.g. earthquake aftershocks, floods, or supply chain disruptions. These different characteristics can have a big influence on the resilience of objects of the built environment.

3.3 Form of resiliency

3.3.1 *Mechanical resilience*

High mechanical resilience of constructed assets implies elastic or near elastic behaviour of structural components. Consequently for structural impacts which do not exceed their design working loads the mechanical resilience of engineered objects of the built environment would be expected to be very high, while for impacts above this level the mechanical resilience would be expected to decrease as the ultimate design loads are approached. At ultimate design loads it is normally understood that that the risk of failure will be less than 5 per cent. Above these loads the risk of failure will depend on the coefficient of variation of strength which in turn will depend on the properties of the construction materials, and the structural systems used including the level of redundancy. These are factors associated with robustness which are often not included in building regulations but can have a significant effect on resilience at these impact levels. Unfortunately one of the consequences of design driven by economic rationalism is a tendency to produce structures that just satisfy code criteria without concern for what happens if code levels are exceeded. Non-engineered construction will generally have a much lower level of impact loads below which the resilience is high, and above which the mechanical resilience will generally be assumed to be low unless observed performance suggests otherwise.

Mechanical resilience is important because at impact levels for which it is high then the functional resilience will generally be high and the contributory resilience to the resilience of other objects will be at its maximum. It therefore sets an upper bound to the impact levels for which high levels of resilience of the built environment and its maximum potential contribution to other categories of objects can usually be guaranteed.

3.3.2 *Functional resilience*

Although many engineers tend to equate resilience of the built environment with the mechanical resilience, for the owners and users of the most constructed assets it is the functional resilience that is important. This will of course depend on the function of the constructed asset which varies greatly. The primary function of residential buildings is to provide a safe and comfortable home for the occupants; the primary function of an office building is to provide a facility for businesses and other organisations to accommodate office staff and technical equipment like computer systems; the primary function of a water treatment plant is to provide clean water for drinking and other purposes, and so on. The functional resilience of these facilities will be a description of how quickly these facilities will recover their original functionality following a specified impact.

If the loss of mechanical resilience is relatively small there may be no loss of functional resilience since many constructed assets can suffer some damage without impairing their functionality, or can be quickly repaired to restore functionality. This has proved particularly important in respect of modern structures in earthquakes with the in-built ductility allowing the structures to deform beyond their elastic limits while retaining their integrity, enabling them to retain their functionality in general up to their ultimate design load. For impacts beyond the ultimate design load, functional resiliency will usually be a function of the mechanical resilience if this remains high, and if not of the rapidity with which the constructed asset can be repaired or reconstructed if it is seriously damaged. For example a Fijian bure may be more resilient at this level of impact than a more substantial western building even if both have a very low mechanical resiliency, since normally it can be quickly rebuilt.

Being usually dependent on the rapidity of repair and reconstruction, the functional resilience of the built environment is very dependent on the resilience of the construction industry, supply of construction materials, the major lifeline infrastructure, and provision of funds when subject to the same overall impact event. In an event impacting on a single structure or with a limited geographical extent, the resilience of all these may be high, but in an event like a major earthquake with high maximum intensities of the associated hazards and a large geographic extent the resilience of these may be severely impaired, resulting in low functional resilience of structures suffering significant damage. Constructed assets not affected by damage to them can become non-functional due to the lack of resilience of essential services being supplied by the lifeline infrastructure – e.g. disruption of water and energy services resulting in low functional resilience irrespective of their mechanical resilience.

Structures can be designed to enhance their functional resilience for impacts above the ultimate design loads and it is also possible to incorporate alternatives to reduce their dependency on other services to improve their functional resilience to impacts of large magnitude and extent, but this is normally beyond the design brief for them and often only considered for structures critical to the supply of essential services.

Consequently the assessment of functional resilience of constructed assets involves much more than mechanical resilience, which itself is only a useful guide to it at levels of impact less than those implied by the their ultimate design loads - and in large scale events this may not even be a good guide.

3.3.3 *Contributory resilience*

In large magnitude events the contribution made by constructed assets to the resilience of other objects of resilience, whether in their own category or in other categories, is often just as important as their own resilience. Both the mechanical resilience and functional resilience of the constructed asset or group of assets may contribute to this, but other characteristics of them can also be important, and using either of these as a measure of contributory resilience can be misleading.

A function of most buildings is to provide a safe usable environment for the occupants. If this functionality is destroyed by an earthquake then functional resilience will be measured by the time taken to restore this functionality. If lives are lost that is an issue of occupant resiliency. Buildings designed to avoid total collapse in a given level of event, even though suffering damage severe enough for them to be declared unsafe for occupation after the event, have a high contributory resilience to occupant resiliency at this level of event even though their mechanical resilience is very low and their functional resilience may be low. Since this is the stated primary objective of many building codes it means that it is contributory resilience to occupant resilience that is seen as primarily important not the mechanical or functional resilience of the buildings themselves.

However in the context of community disaster resilience, contributory resilience of buildings is also important in other ways. Poor building performance can affect not only the resilience of the individual occupants, but the resilience of the owners, the businesses occupying the building, and networked lifeline systems which may be operating from the building. Also important are the resilience of the emergency relief organisations and building and insurance industries on which many owners depend for relief, repair and reconstruction if damage occurs.

Assessing the level of the contributory resilience of constructed assets, whether singly or in groups, to the resilience of other objects of resilience when impacted by large scale events requires knowledge of all the dependencies of the other objects and the relative importance of the contribution to the total mix. It is a complex issue and thus it is not surprising that it is subject of most current research on the resilience of the built environment. It forms a subset of the larger field of disaster resilience in general which embraces all categories of objects that can contribute to it, and which is being driven by the increasing desire of governments at all levels as well as international organisation like the United Nations, the World Bank, and the OECD to reduce disaster risk by increasing the resilience of communities to these large scale events, despite the success that has been achieved in reducing deaths and injuries through current levels of mechanical resilience. Consequently even if not explicitly stated most discussion about the resilience of the built environment is primarily about the contributory resilience of the elements of the built environment to community disaster resilience, not their own resilience per se.

4 THE CANTERBURY EARTHQUAKES – A CASE STUDY

Brunsdon et al. (2014) described the resiliency demonstrated in the Canterbury earthquakes using the generic definition of resilience and concluded that the overall resilience which was demonstrated was good, although there were some lessons to be learned from the experience. Following is a description using the framework which enables a much more detailed picture to emerge of a mixture of good and poor resiliency being demonstrated and the sources contributing to this.

4.1 Mechanical resilience

In the first earthquake at the intensity of ground motions produced in the urban area of Christchurch most of the constructed assets designed in accordance with modern design codes performed well in terms of mechanical resilience. This was to be expected as the ground motions would have been less than ultimate design values in most cases. Examples of low resilience were largely limited to old masonry buildings which were known to be suspect in this respect.

The second earthquake produced ground motions in the eastern and central areas of Christchurch which were considerably greater than the ultimate design values in many cases, resulting in many modern constructed assets demonstrating poor mechanical resistance to the extent that a large number of buildings and other constructed facilities required repairs or reconstruction.

4.2 Functional resilience

In the first earthquake only a small number of buildings suffered damage serious enough to render them unusable, although a much larger number of buildings suffered some damage. Although the largest event to have impacted on a New Zealand community in modern times, it did not overwhelm the community to the extent that pressures on emergency relief, the engineering profession, and the building and insurance industries significantly affected the rate of recovery. As a consequence the demonstrated functional resilience of most modern elements of the built environment to the level of impact experienced was probably considered reasonably high apart from some modern houses seriously affected by liquefaction, a type of impact not given very much consideration in their design. As it was close to a design event considerable satisfaction was expressed within the engineering profession and the community with this outcome.

In the second earthquake many modern buildings were severely damaged and declared unusable, and many constructed elements of the infrastructure such as roads, bridges and pipelines failed which severely affected the delivery of essential services in many areas. The extent of the damage was such that the emergency response and recovery phases were severely affected by the severe pressure placed on engineering profession, government policy makers, and the building and insurance industries. The result has been extensive delays in the restoration of many elements of the built environment demonstrating low functional resilience of these to the event.

4.3 **Contributory resilience**

Following the first earthquake the recovery of the community of Christchurch as a whole and of the various organisations like the building industry and the insurance industry was regarded as relatively good. Full recovery of the original state had not been achieved by the time of the second earthquake but it was considered to be well under control and to have demonstrated a level of resiliency to a major earthquake event of which the community and New Zealanders generally could be proud. It was considered that the contributory resilience of the built environment had been a significant factor in this.

However this level of resiliency was not achieved at the higher impact level of the second earthquake, which was compounded by it occurring before full recovery from the previous event had been achieved. In terms of occupant life safety the built environment demonstrated a high level contributory resilience with almost all the deaths being attributed to the failure of two buildings which were not typical of modern construction standards due to age and design and construction errors. But the overall community is still far from recovered despite the significant passage of time since the event with some sectors demonstrating more resilience than others. The performance of the built environment has contributed to the long recovery time with the large number of buildings which proved to be not only lacking in mechanical resilience but also in functional resilience being a major underlying factor. This has had a big impact on economy of the central business district, the building industry and on the insurance industry. The contributory resilience from the built environment to the resilience of these can only be described as low at the level of impact experienced. Other factors have contributed to this situation as well but the poor mechanical and functional resilience of a significant portion of the built environment is the underlying cause.

Some sections of the community have shown good resilience. The New Zealand economy proved to be very resilient and in fact appeared to benefit from the large inflow of reinsurance funds and increased construction activity which resulted from the earthquakes as a consequence of the poor mechanical resilience of much of the built environment. Businesses in Christchurch appear to have demonstrated a relatively high level of resiliency to the event by relocating within a relatively short period of time to relatively unaffected areas to the west of Christchurch. The international reinsurance industry proved quite resilient to the impact on it helped by the surplus of funds it has experienced in recent years. Apart from small local companies with a high concentration of policies in the Canterbury region, the private insurance industry also proved to be quite resilient contributing significantly to the resilience of the commercial building sector.

The demonstrated resilience of the housing sector of the Christchurch community was relatively low. This was not because of low mechanical resilience as serious structural damage to housing was not a major cause of loss of functionality. Both the mechanical resilience and functional resilience of the great majority of houses in the Christchurch area proved to be better than expected. It was problems arising from the liquefaction resulting in the loss of functionality of a minority of houses which underlay the low resilience of the sector. For example, damage to underground pipes left structurally intact homes without water and sewer services. Long delays in determining future land use policy in the areas affected, disputes arising from the dual nature of the insurance of houses with the risk being shared between the private sector and the government scheme, compounded by the lack of resilience of the latter to the magnitude of the claims arising from the event, and a shortage of alternative accommodation for displaced occupants, all contributed to the overall resilience of the housing sector. It was a situation in which the contributory resilience of the built environment was more important than its own resilience in isolation. Much of the lack of resilience experienced in the performance of some sectors of the lifelines sector could be attributed to similar low levels of contributory resilience from elements of the built environment on which they were dependent.

5 CONCLUDING REMARKS

Resilience is a widely used term in the community as well as in respect of the built environment. As a word it can have many different meanings when applied to specific situations. If the specific meaning is not specified it can result in a great deal of fuzziness and misinformation. A framework for specifying the meaning in particular applications has been proposed based on the need to specify what is the **object** to which the property of resilience is being ascribed, what is the **impact** including the magnitude of it for which the resilience is being ascribed, and what **form** of resilience is being described, **mechanical**, **functional** or **contributory**. The most widespread use of the term in respect of the built environment is in regard to community resilience to events giving rise to disasters. In this context contributory resilience is the most important form of resilience of the built environment, and it can be misleading to use either mechanical resilience or functional resilience alone as a substitute for it. The framework provides a rational means of analysing the contributions from the built environment to community resilience when impacted by events like major earthquakes.

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