Performance of Concrete Buildings in the 2016 Kumamoto Earthquake – Can NZ learn from others?

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ABSTRACT: The recent earthquakes in New Zealand have highlighted the vulnerability to damage and risk to life safety of some of the existing building stock across the country. Christchurch is gradually recovering 5 years on. Many buildings in the CBD have been demolished and are now being rebuilt. Other buildings are being extensively repaired. Many building owners, tenants and others with an interest in their buildings have expressed surprise and concern on the level of damage sustained in the recent earthquakes based on their observation and experiences. The impact on business continuity and society generally has been identified as significant.

This paper contrasts the recent NZ experience with our observations of building performance and community response and resilience in the April 2016 Kumamoto earthquake sequence in Japan. Similar to the 22 February 2011 Christchurch earthquake and various aftershocks, these shallow earthquakes in Kumamoto occurred in an urban area and again similar to Christchurch these earthquakes exceeded the design code for the area.

This paper provides insights on the seismic demands of the Kumamoto earthquakes. It then focusses on the observed performance of concrete buildings in Kumamoto along with observations on the post-earthquake response of the Japanese community following this earthquake sequence. It compares our observations from the Kumamoto earthquake with the New Zealand experience and explores whether there are possible learnings for New Zealand to consider.

1 INTRODUCTION

Between 14 April and 16 April, 2016, a series of earthquakes struck Kumamoto Prefecture on Kyushu Island, Japan (Figure 1). The 16 April Kumamoto event resulted in a reported 50 fatalities and almost 3000 injuries, with most deaths occurring due to collapse of residential houses concentrated in Mashiki Town to the east of Kumamoto (Japan Times, 2016). Death toll and injuries would likely have been considerably higher if the 14 April event had not already occurred since many people had evacuated their houses before the 16 April main-shock.

A NZSEE reconnaissance team made up of structural engineering researchers and practitioners (the authors), in collaboration with a Japanese team funded by Japan Science and Technology Agency, visited the Kumamoto Prefecture between 29 June and 3 July 2016. The objective was to learn from

this earthquake sequence. A particular focus was the performance of concrete buildings along with aspects of the post-earthquake response which may be relevant for consideration in New Zealand. This paper provides an overview of our observations from visiting Kumamoto and summarises some of our findings. This topic is explored further including comparisons of seismic design and building assessments between Japan and New Zealand in a paper the authors have prepared titled "Performance of Concrete Buildings in the 2016 Kumamoto Earthquake and Seismic Design in Japan" to be published shortly in the NZSEE bulletin. The bulletin paper also includes back ground information including building damage reports for each of the buildings visited.

2 SEISMICITY

The largest foreshock of the Kumamoto sequence occurred at 21:26 JST on 14 April, with a magnitude of Mj6.5, in the Northern regions of the Hinagu Fault. This event was followed by further seismic activity, including the magnitude Mj7.3 main-shock at 01:25 JST on 16 April due to right lateral strike-slip movement of the Futagawa Fault. The main-shock was approximately 15 km South-East of Kumamoto City at a depth of 12 km (Epstein et al, 2016). In Mashiki near the Hinagu and Futagawa faults, both major events resulted in the maximum possible intensity of 7 on the Japan Meteorological Agency Intensity (JMAI) scale.

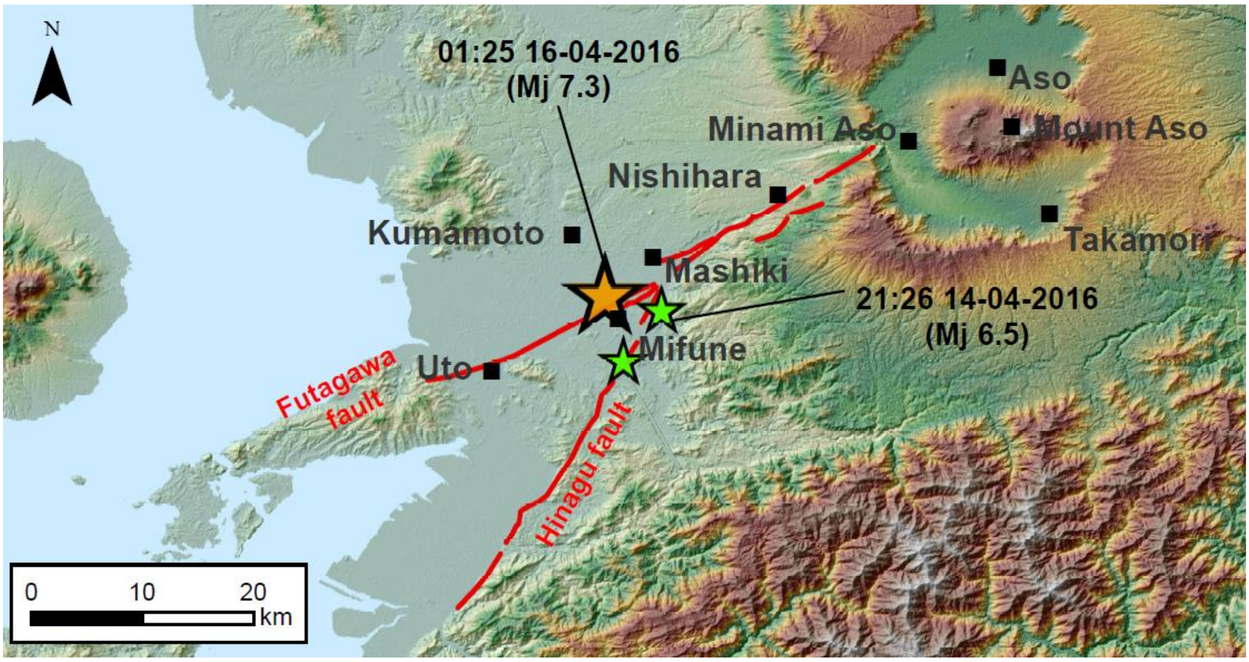

Figure 1. Epicentre and Fault map of Kumamoto Prefecture. Earthquake magnitudes shown represent Japan Meteorological Agency (JMA) Local earthquake scale – Adapted from Chiaro et al (2017).

Similar to the Canterbury Earthquake Sequence, the majority of the significant damage occurred in the second strong seismic event; but unlike Christchurch these events occurred so close together there was insufficient time to fully assess damage from 14 April event before 16 April event occurred just 28 hours later.

Figure 2 provides a comparison of response spectra for the 14 and 16 April 2016 Kumamoto and 22 February 2011 Christchurch events. Above 0.7 sec, the three events resulted in very similar levels of shaking, but at short periods the maximum response for the Kumamoto event was approximately twice as large as the maximum response from the Christchurch earthquake. A comparison of the Christchurch and Kumamoto design spectra for soft ground is also shown. Kumamoto is a coastal region with a variety of ground conditions ranging from 'Hard' (defined as type 1 in the Japanese building code) to 'Soft' (defined as type 3). The peak of the response spectrum for all three ground conditions is 0.9g. The spectrum for soft ground has been presented here to be consistent with the site

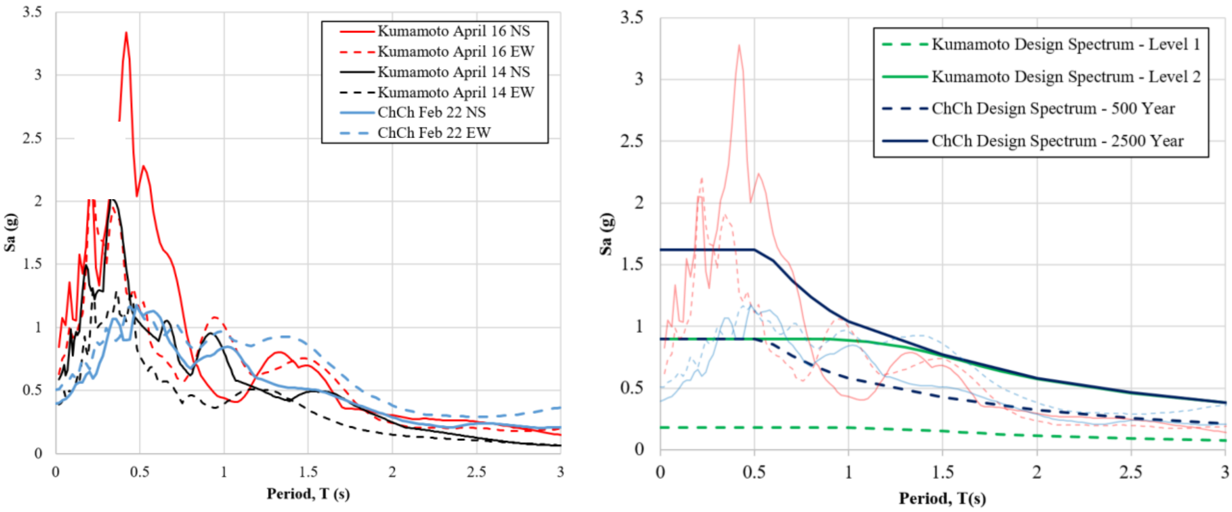

Figure 2. Kumamoto vs. Christchurch Response Spectra (left). Kumamoto vs. Christchurch Design Spectra (right). Response of April 16 Kumamoto and Feb 22 Christchurch event included. Level 1 represents the 'Damage Limit State' (similar to NZ SLS1) and Level 2 represents the 'Safety Limit State' (similar to NZ ULS) Kumamoto response spectra obtained from data recorded at K-net station KMM006. Christchurch response spectra represents average response of data from CanNet stations CCCC and CHHC as well as NSMN stations CBGS and REHS.

Japan Seismic Hazard Information Station (J-SHIS) publishes JMAI values for different return periods throughout Japan. Table 1 provides a comparison of JMAI values recorded in the 16 April event and probabilistic JMAI values for 475, 1000, and 2500 year return periods published on the J-SHIS website (J-SHIS, 2016). The comparison indicates that several stations close to the fault recoded ground motions at or above 2500 year motions. Kumamoto City experienced ground shaking representative of 500 to 1000 year motions.

Table 1. Summary of recorded and probabilistic JMAI values for stations near Kumamoto JMAI exceedance probabilities were obtained from www.j-shis.bosai.go.jp (J-SHIS, 2016)

Location	Station ID	Station Distance from Epicentre (km)	JMAI Probability of Exceedance in Station Area			Kumamoto April 16th Event JMAI Magnitude
			2% in 50 Yrs. (1/2500)	5% in 50 Yrs. (1/1000)	10% in 50 Yrs. (1/500)	
Toyono	KMMH14	13.2	6 -/6 +	6 -	5 +/6 -	6 +
Mashiki	KMMH16	7.3	6 +/7	6 +	6 -	7
Yabe	KMM009	22.3	6 -	5 +/6 -	5 +	6 -
Uto	KMM008	12.1	7	6 +	6 +	6 +
Tomochi (Misato)	KMM011	18	6 -/6 +	5 +/6 -	5 +/6 -	6 -
Kumamoto	KMM006	4.7	7	6 +/7	6 +	6 +
Yatsushiro	KMM012	31.1	7	6 +/7	6 +	6 -
Kikuchi	KMMH03	28	6 -/6 +	6 -	6 -	6 -/6 +

3 EARTHQUAKE IMPACT

The overall impression gained when the reconnaissance team visited Kumamoto 2 months after the earthquake was of a fully functioning city with the majority of the population able to carry on their daily lives with minimal disruption. Multi-storey concrete and steel buildings generally performed very well, most enabling immediate occupancy after the earthquakes. No closed off "red zones" were observed.

Inspection placards following post-earthquake rapid inspections were evident on many buildings.

These were based on a traffic light system of red, yellow and green placards generally similar in style to those used in New Zealand and the USA to denote whether an inspected building was deemed unsafe, limited entry or inspected.

Figure 3. Post earthquake inspection placards Kumamoto City

Unlike the New Zealand system however, the building tags are advisory only, and although they were generally observed by the public, this is not strictly enforced. Fencing around damaged buildings was relatively limited in nature compared with those erected in New Zealand reflecting the advisory nature of such notices. This approach allowed owners and tenants to enter and occupy yellow and red placarded buildings post-earthquake if they wanted. The reconnaissance team observed people retrieving belongings from damaged buildings during our visit and even some people occupying yellow tagged buildings.

Following the rapid assessment a more detailed damage assessment was carried out by Japanese engineers using the Japanese Damage Evaluation Guideline (JDEG). This approach calculates the residual capacity of the building following an earthquake and designates a rating. These range from slight damage with a residual capacity $R \geq 95\%$ to severe damage with $R < 60\%$ or collapse with $R = 0\%$. R is calculated by using observational information as to the extent of damage to individual building structural elements, for example columns, shearwalls and beams on each floor and in each direction and combines this with strength and ductility indices and seismic capacity reduction factors for different building types. The seismic capacity reduction factors have been developed based on extensive testing of the different types of Japanese concrete buildings and expert knowledge of the Japanese structural building code requirements. Buildings scoring less than R=95% are targeted for repair and seismic strengthening.

A consequence of this relatively rapid assessment approach, (and the relatively large structural engineering workforce in Japan compared with New Zealand) is that assessment of many buildings following the Kumamoto earthquake had been completed by the time the reconnaissance team visited. Repairs were observed to be already underway in some buildings.

Building placards can be removed or changed following the rapid assessment, if the identified issues or risks are addressed or if a more detailed assessment changes the rating. Private building owners are responsible for ensuring that repairs or reconstruction takes place while public buildings are systematically addressed by the regional government. A varying level of funding is made available by the national government for both private and public buildings for repairs and reconstruction, depending on yearly budgets and damage sustained following the earthquake.

Considerable focus was observed in maintaining community services in place following the earthquakes in Kumamoto. Government and school facilities were kept on site through the use of temporary offices and classrooms located adjacent to the damaged structures on carparks, playing fields and the like.

4 MODERN CONCRETE BUILDING PERFORMANCE

Reinforced concrete construction has been widely used throughout Kumamoto City in government and school facilities as well as public and private apartment buildings. The most common structural system observed in residential reinforced concrete structures was moment frames with open ground floor, desirable by Japanese developers for maximizing the area usable for parking. Other common structural systems in residential buildings included combinations of moment frames in the long direction and shear walls in the transverse direction. Government and school facilities were commonly moment frames combined with shear walls. Base isolation was used in 24 buildings in the Kumamoto prefecture.

Figure 4. Examples of multi-storey buildings with no damage.

Multi-storey concrete and steel buildings generally performed very well, most enabling immediate occupancy after the earthquakes. Damaged multi-storey buildings were generally constructed prior to 1981, when the Japanese Building code was updated following the 1978 Miyagi Earthquake.

Based on observations of structures throughout the Kumamoto Prefecture it was evident that multi-story buildings were generally much stiffer and stronger than their New Zealand counterparts, with very few examples of modern buildings exhibiting damage consistent with high, or even moderate, ductility demands during the earthquake. Examples of such buildings are shown in Figure 4. Buildings with open ground floors for parking are very common, most with negligible damage despite the appearance of a soft story.

These anecdotal observations are supported by the limited red and yellow placards applied to modern buildings in Kumamoto Prefecture. A summary of the buildings assessed in the Mashiki Town area showed that, of the assessed reinforced concrete structures, 71% were constructed post 1981 of which 89% were assessed as undamaged with the remaining 11% being deemed as only moderately damaged.

A common observation in modern multistory reinforced concrete residential buildings was shear failure in “non-structural walls”. These non-structural wall components were made of reinforced concrete and were commonly tied into the structural system with what Japanese designers referred to as “half connections”. This connection is shown in Figure 5, where only half of the thickness of the wall has reinforcement extending into the lateral force resisting system. These walls are not considered to contribute to the lateral strength of the building during design, but are accounted for when determining the stiffness of the structure. This practice appears to be a contributing factor to the lower ductility behavior of the observed reinforced concrete structures.

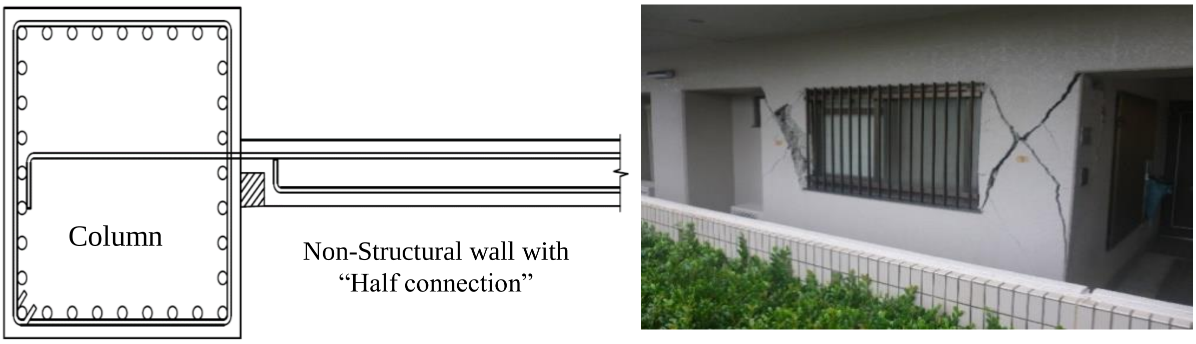

Figure 5. Typical Non-structural wall connection and example of damage to “non-structural” wall.

5 PRE – 1981 CONCRETE BUILDING PERFORMANCE

The Japanese Building Standard Law (BSL, 2016), the building code, was significantly revised in 1981 following damage in the 1978 Miyagi Earthquake. Many pre-1981 buildings do not comply with the current seismic standards. Damage observed from the Kumamoto earthquake tended to be concentrated in the pre-1981 buildings. A summary of the buildings assessed in the Mashiki Town area showed that, of the 52 assessed reinforced concrete structures, 15 were constructed pre 1981 of which 5 were assessed as undamaged, 8 suffered moderate damage and 2 had collapsed.

Figure 6. Examples of damage to pre-1980s concrete buildings

Figure 6 provides three examples of pre-1980s concrete buildings with severe damage to columns and beam-column joints. Damage observed in such buildings often tended to be concentrated in the open ground floor, (used for parking) while “non-structural walls” provided additional stiffness on upper stories.

6 PERFORMANCE OF BASE ISOLATED BUILDINGS

Three base isolated multi-storey reinforced concrete residential buildings located close to Kumamoto city centre were inspected. All three structures had been constructed post 2000 and all had some level of residual displacement and two showed some damage, but all had been green placarded and were fully occupied.

In one building the plane of isolation was generally located on the first floor but with the external stairs extending to ground level supported on a slider. It appears the base of the stair did not slide as intended resulting in significant cracking and damage to the stair concrete walls and associated elements between ground and first floor. Approximately 300mm of residual displacement was observed in this and the adjacent base isolated building. No internal access was gained to either building to inspect any possible damage to the isolators.

Access was gained to the basement area of the third building where the isolators and dampers were located. Observations of the damage indicate that while the main building structure including the laminated elastomeric bearing isolators performed well, due to some unconventional design choices, the structure supporting the damping system, a combination of steel and lead dampers, sustained heavy damage. The stub columns connecting the dampers to the structure above were observed to be significantly damaged along with the ground floor slab in these areas as they were not well connected to the main structural system. Figure 7 provides some examples of the damage observed.

Figure 7. Damage to external stair to one base isolated building, Damage to stub columns at steel and lead dampers to another base isolated building.

7 NONSTRUCTURAL ELEMENT PERFORMANCE

Limited damage was observed to non-structural elements, in part due to clean up since the earthquakes but also due to design features used to minimize damage and maintain functionality. These included using passive fire protection measures, including extensive use of steel fire doors, rather than active sprinkler systems to provide fire protection, thus avoiding potential damage due to failure of charged sprinkler pipe connections in the event of an earthquake.

A number of buildings were observed which had been designed with no suspended ceiling system thus avoiding damage by the simple expedient of eliminating the element. It was also noted by Japanese researchers, that several facilities in Japan have opted to remove suspended ceiling tiles following the extensive damage to such systems in the 2011 Tohoku Earthquake to avoid potential damage.

Many examples were observed of building major mechanical plant, including chillers, being located externally at ground level adjacent to the building. This approach reduced the potential for shaking damage to these plant elements compared to their being located on the roof as is typical in New Zealand in the event of an earthquake.

Careful consideration of flexible connections, appropriate fixings, supports and bracing of piping was observed across a wide range of buildings indicating that there is a focus on avoiding damage to non-structural elements. This contrasts to the approach historically taken in New Zealand where there has typically been little focus on these elements.

8 CONCLUDING OBSERVATIONS

April 2016 Kumamoto earthquakes share similarities with the 2010-11 Canterbury Earthquake Sequence; both comprised of multiple damaging events, including a shallow event of similar shaking intensity in close proximity to a major urban centre. These similarities provide a unique opportunity for comparison of building performance in the two countries and possible lessons for structural design.

When considering low damage design in New Zealand we often tend to think of technology type

solutions including, for example, active and passive dampers, complex analysis and sophisticated innovative designs. Often these solutions come with an increased capital cost compared with other more conventional building designs. Clearly these approaches have their place but are there other options to provide resilient buildings for the New Zealand community?

The observations from the 2016 Kumamoto earthquake highlighted a difference in the resilience of New Zealand and Japanese buildings and the subsequent impact on the community and city as a whole. The overarching impression in Kumamoto was of a functioning city with the majority of the population being able to carry on with their daily lives with minimal disruption, and no sight of closed off areas or “Red Zones” two months after the earthquake. In contrast, an exclusion zone was maintained in Christchurch CBD for over 2 years following the February 2011 earthquake.

Modern code designed structures in Kumamoto sustained limited damage and exhibited good performance on the whole. The inspected buildings pointed to a design philosophy emphasising stiffer and stronger buildings than those commonly seen in New Zealand and few examples of high ductility demands were noted.

Cast-in-place concrete was observed to be the predominant construction material for large residential complexes, commercial and institutional buildings. Use of precast floor systems, structural tilt slab wall panels systems and precast stairs, with or without sliders, was not observed. The similarities in design solutions between many modern code designed Japanese buildings was noticeable with regular frame and wall layouts, continuous columns and no transfer girders or other complexities. Presumably these are limited by the Japanese code requirements.

The Japanese BSL provides for two different tiers of design. Lower rise buildings less than 31m high, i.e. most typical buildings, are designed using a relatively simple code which uses an allowable stress design approach along with checks on stiffness distribution up the building, torsional susceptibility checks and an interstorey elastic range drift check without consideration of ductility to check onset of damage. There appears to be limits or prohibitions on use of transfer girders, discontinuous columns and other complexities. Higher rise buildings are required to be designed to a more complex code with significantly more design requirements including a level 2 safety limit design case. This approach allows for efficiency in design effort and costs for lower rise buildings. On the other hand, the BSL does not focus on the identification of ductile mechanisms and capacity design to the same extent as New Zealand Standards.

Consistency in design approach where the vast majority of buildings use similar cast-in-place concrete construction and similar building systems as observed in Kumamoto allows contractors to become very familiar with the construction requirements improving quality of construction and reducing costs due to efficiency gains, leading to improved building outcomes.

Non-structural elements were observed to have performed well in the Kumamoto earthquake. The stiffer buildings designed in Japan reduce drift induced demands on non-structural elements improving building resiliency. This approach along with practices such as passive fire protection and avoidance of suspended ceilings reduced internal damage allowing buildings to remain functional after the earthquake.

Overall, the observations of the performance and community response in Kumamoto highlighted similar goals to New Zealand where life safety was concerned; however, in terms of resilience and return to function, the observations were quite contrasting to what was experienced in New Zealand following both the Christchurch and Kaikoura Earthquakes. This contrast suggests that the New Zealand structural engineering profession should carefully consider if the widely accepted design philosophy relying on high ductility response of modern structures could be replaced by a focus on strength and stiffness leading to lower ductility demands and faster recovery after earthquakes.

The authors encourage the continued exchange and comparison of design philosophies and field experiences between the earthquake engineering professions of Japan and New Zealand.

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