New factors for the seismic vulnerability assessment of reinforced concrete buildings

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Abstract: Strong earthquakes recorded worldwide have indicated less known failure modes of reinforced concrete structures, produced by new factors which should be accounted in future seismic evaluation methods of buildings. These new factors for the vulnerability assessment of buildings have been highlighted by recent seismic recordings. Equipment placed on various construction elements provided new information on the characteristics of the seismic waves, the distribution of seismic waves in the building and the mode in which buildings interact with other neighbouring buildings, the variation of the seismic acceleration's vertical components, and the influence of the foundation ground on the failure mechanisms. In this article, there are presented these new factors and the unknown brittle failure modes developed by reinforced concrete buildings subjected to seismic action between 2009 and 2011. These presented factors should be introduced in the near future in the seismic vulnerability assessment of buildings as well as in the seismic design codes.

Keywords: assessment; failure mechanism; reinforced concrete structures; earthquake; seismic wave; recordings; seismic vulnerability.

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1 Introduction

Anti-seismic design for buildings is presently conducted by applying horizontal forces on the bearing structure. These forces were determined based on seismic recordings at the level of the ground and take into consideration a reduced number of characteristic parameters of the respective seismic zone. The development of modern tectonic recording techniques by GPS and other devices have led to a better understanding of the manner in which these forces are transmitted and act upon buildings, new results which enable an exact understanding of failure modes. These recordings allowed the identification of new factors which led to brittle failures of reinforced concrete structures designed according to present norms. Regarding these failure modes, after the earthquakes from 2009–2011, Wallace and Moehle (2012) stated: "... however many of the failures are not yet understood and many suggest that there are deficiencies in current US design provisions". A correct modern anti-seismic design must be based on a full understanding of these new factors determined by the characteristics of the seismic sources and the real mode of transmission of forces into buildings with several inertial masses. A close description of the damages of reinforced concrete structures after the earthquakes from 2011 from Turkey was performed by Tapan et al. (2013).

Methods for the seismic risk assessment of steel, masonry and reinforced concrete structures have been studied by a team of researchers from University Federico II from Napoli, coordinated by Prof. F.M. Mazzolani, presented by Faggiano et al. (2011), Formisano (2012), Formisano et al. (2011, 2015a, 2015b) and Indirli et al. (2013). Methods for determining brittle failure modes were also studied by Pardalopoulos et al. (2013).

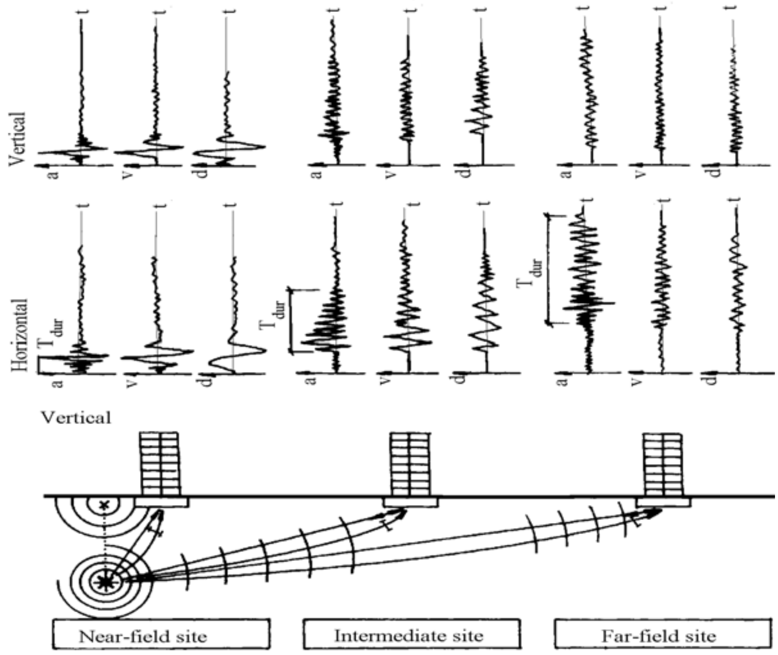
2 New factors for the seismic vulnerability assessment of reinforced concrete buildings

An identification of new factors which resulted in brittle failure modes of buildings in seismic zones has been made according to Gioncu and Mazzolani (2011) and FEMA 383 (2003) by:

2.1 Improvement of earthquake monitoring

These factors were determined with the help of a monitor system composed by regional networks of seismic recordings, with the use of satellite-based observation (GPS monitoring stations). These recordings provided new data for anti-seismic design, indicating clear differences between recorded accelerations, velocities or displacements. A development of these recordings must be performed in order for them to provide information on the characteristics of the seismic waves, as in Figure 1, on small distances (near-field) and large distances (far-field) from the seismic fault.

Figure 1 Types of accelerations, velocities and displacements recorded at various distances from the epicentre

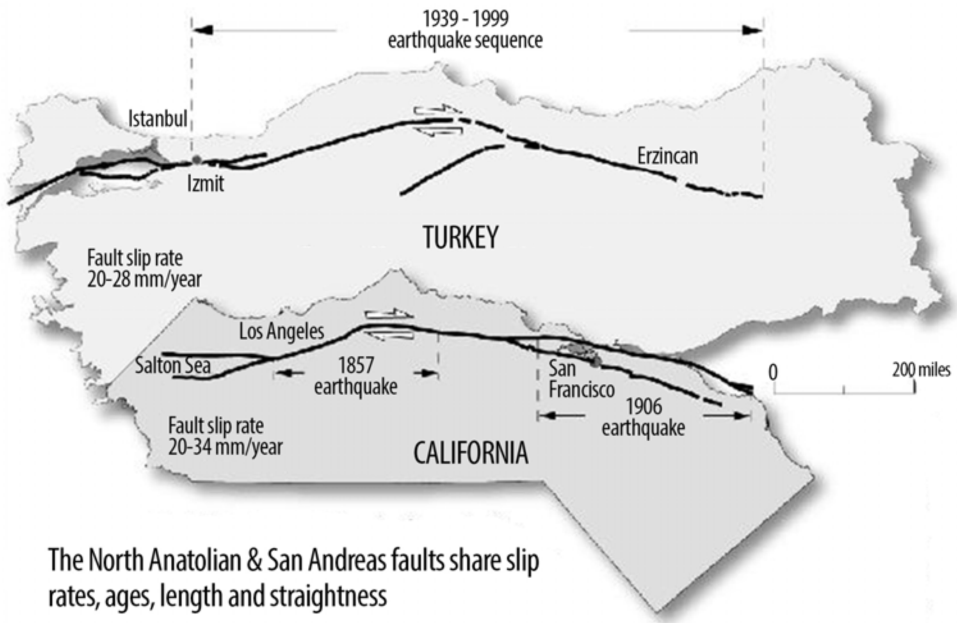


Source: Gioncu and Mazzolani (2011)

2.2 Improvement of the understanding of earthquake occurrence

Studies have shown the fact that 90% of the earthquakes occur along tectonic plates and 10% of them are recorded far from these faults. It must be understood the way in which these earthquakes occur in function of the boundary types of the tectonic plates, due to the fact that at the same distance of the seismic fault, similar buildings can fail differently as a result of the totally different characteristics of the seismic waves. As an example, the characteristics of the earthquakes produced by the North Anatoliana fault, Kocaeli earthquake – 1999, are similar with those produced by the St. Andreas fault, Northridge earthquake – 1994, being an inter-plate strike-slip fault type, as it can be seen in Figure 2.

Figure 2 Comparison of two transform faults after Gioncu and Mazzoloani (2011)



2.3 Improvement of the fundamental knowledge of earthquake effects

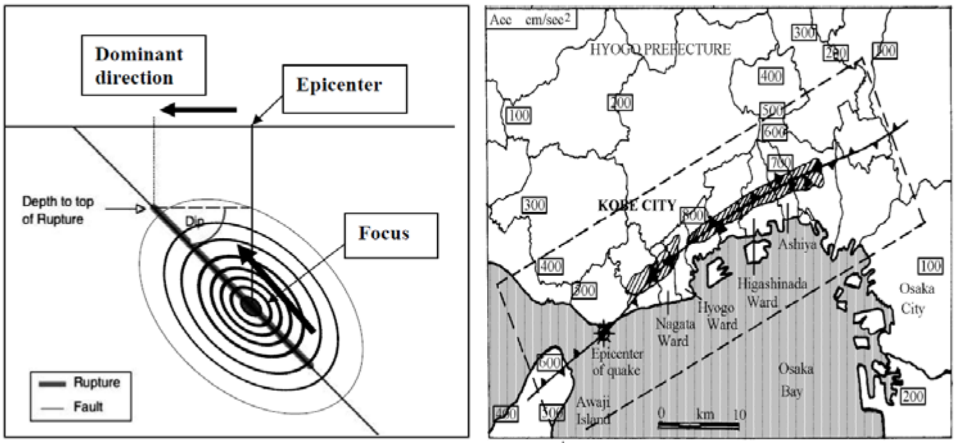
Recent studies have shown that by introducing new factors in seismic engineering related to modelling the effects of the earthquakes, properties of the seismic sources and the mode of transmission of the seismic waves from the source to the building, the recorded material damages and human loss can be significantly reduced. These factors will affect the seismic zones and the duration of the seismic action, as well as the parameters related to the rupture mode of the tectonic plates. The most important factors which influence the failure of reinforced concrete structures are:

2.3.1 Surface fault rupture

The factors which influence the characteristics of the seismic waves are: the type of fault depth, rupture surface, amount of fault slip, age of faulting, length of fault rupture. As a result of the rupture, the forces are transmitted in all directions, but mainly they are propagated along the direction of the rupture plan, forming predominant transmission directions (Gioncu and Mazzolani, 2011). A good example is the Kobe earthquake where the direction of rupture was underneath the most urbanised part of the city and produced important damages), as it can be seen in Figure 3. Mortezaei and Ronagh (2013) states:

"Ground motion in the near-field of a rupture fault can contain a large energy, or "directivity" pulse very different from far-fault earthquake and cyclic loading. Structures designed to withstand the latter will respond with higher deflection but remain ductile and absorb lower earthquake forces generally".

Figure 3 (a) Fault rupture progress (b) Effect of the forward directivity during the 1995 Kobe earthquake



(a) (b)

Source: Gioncu and Mazzolani (2011)

2.3.2 Pulse type

Reinforced concrete buildings can develop plastic hinges in function of the number of loading cycles. A low number of cycles cannot develop plastic hinges, although the buildings have been designed with the necessary ductility, they record a brittle failure.

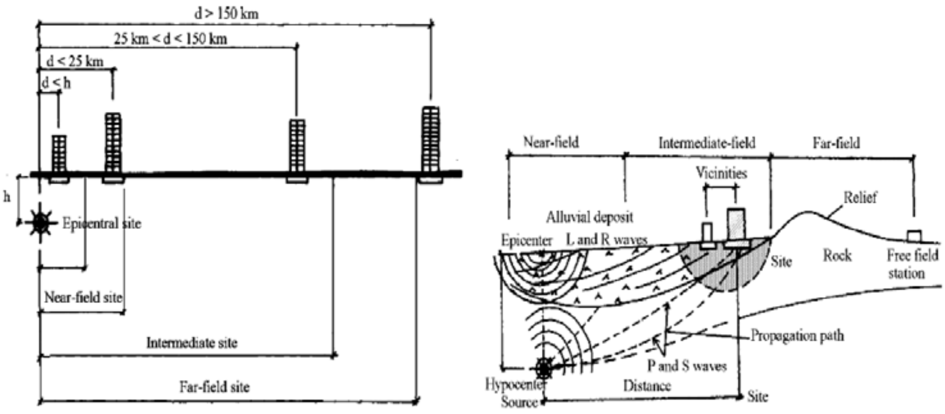
2.3.3 Type of seismic waves and the distance to the epicentre

In function of the distance and type of the seismic waves, reinforced concrete buildings develop different failure mechanisms. These failures can be generated by body waves (P and S) and surface waves (L and R), as seen in Figure 4. "Surface waves carry the greatest amount of energy from shallow shock and are usually the primary cause of destruction which results from earthquakes affecting densely populated areas" (Gioncu and Mazzolani, 2011).

2.3.4 Earthquake duration

The duration of ground motions in near-source are shorter than the duration recorded in far-source fields. This allows for a longer recording of the seismic ground motion which can result in forming of plastic hinges and dissipation of a larger quantity of the seismic energy in buildings placed further from the source and the impossibility of developing of plastic hinges in structures placed closer to the seismic source. In Figure 4, it is shown the mode in which the seismic waves act on buildings in function of the distance to the seismic source.

Figure 4 (a) Body (P and S) and surface (L and R) seismic waves (b) Site classifications in function of the distance from the epicentre



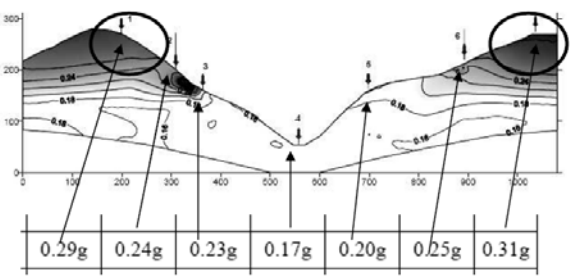
(a) (b)

Source: Gioncu and Mazzolani (2011)

2.3.5 Topographic surface irregularities

The seismic motion is amplified and damages are concentrated near cliff and ridge crests due to the wave interferences causing very complex patterns of frequency-dependent amplifications, as shown in Figure 5 (Klimis and Anastasiadis, 2002).

Figure 5 Spectral accelerations at characteristic points of the valley in a near source site

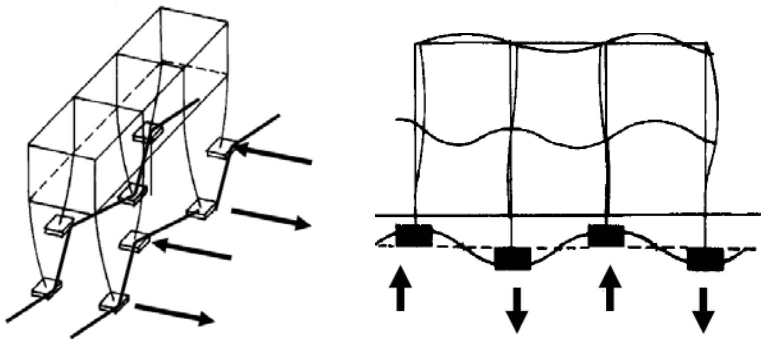


Source: Gioncu and Mazzolani (2011)

2.3.6 Spatial variation of ground motions

Due to the distance to the seismic source and the nature of the foundation ground, seismic waves generate different motions for different parts of a building. At buildings placed close to the epicentre, near-field, and those built on weak soil, the effects of these asynchronous movements of different parts of the same building generate brittle failure methods, as a result of the appearance of new efforts in the bearing elements which have not been designed with the necessary ductility due to provisions which neglected this effect (Gioncu and Mazzolani, 2011; Gyorgy et al., 2006), as it can be seen in Figure 6.

Figure 6 Wave effects: torsional excitation of columns by passage of love waves and rocking excitation by passage of Rayleigh waves



Source: Gioncu and Mazzolani (2011)

2.4 Improvement of the seismic design of structures

Elaboration of new anti-seismic design philosophies for structures placed in zones with moderate and strong seismic movement, as well as the development of materials, technologies and new structural systems can be can be performed by introducing new provisions in the design codes which will highlight the effects of the following factors:

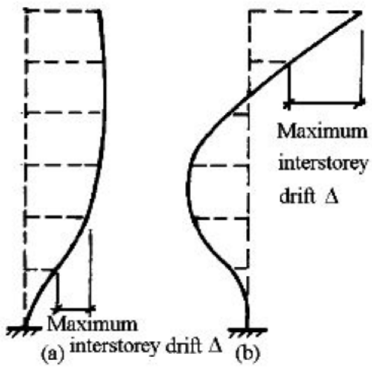
2.4.1 Buildings weight and city-soil effect

Buildings placed on stiff soil reduce the peak acceleration in the soil, while weak soil increases these values. However, buildings in densely populated areas, subjected to seismic motion transmit in the foundation ground a part of the seismic energy, thus modifying the free-field ground motions and interact with each other on neighbouring structures. The importance of the soil-structure interaction on the failure modes of buildings is presented by Gioncu and Mazzolani (2010) "…due to the vibration introduced in the soil, each building produces a perturbation of the ground motion, being a secondary seismic source". It is recommended the introduction of an urban field amplification factor in the design codes which takes into account the effects of interaction between buildings.

2.4.2 Stiffness and interstory-drift

Recent recordings of the relative storey displacements measured on buildings point out the development of different failure mechanisms of buildings in function of the type of earthquake. In buildings situated far from the seismic source, the first mode of vibration is predominant and interstory drifts are maximum at the inferior part of the buildings, while for buildings close to the seismic source, the second and third modes of vibration are predominant with maximum values of the interstory drift at the superior part. In the first case, the plastic hinges form at the inferior part of the buildings, while buildings close to the seismic source tend to have plastic hinges at the superior part, as shown in Figure 7.

Figure 7 Interstory drifts, (a) influence of first vibration mode (b) influence of superior vibration modes



Source: Gioncu and Mazzolani (2011)

2.4.3 Vertical components amplification

For near-field buildings, the P waves introduce larger values of the vertical components of the accelerations than the horizontal components, producing brittle failures of reinforced concrete buildings. Regarding this effect Kam and Pampanin state: "The effects of the high vertical acceleration of the 22 February 2011 earthquake could have also amplified the compression force demand on RC walls with already non-negligible axial load". These buildings develop brittle failure modes especially at the superior levels of the buildings (Mosoarca, 2013). The recordings made by Lemnitzer et al. (2012) indicate the fact that between the ground floor and the level of the last storey slab, the acceleration is multiplied with a factor between 2.5 to 4.

2.4.4 Peak ground velocity

Gioncu and Mazzolani (2011) state: "velocity records are most significant for characterizing the ground motions in the near-source areas. It is a damage potential indicator due to high influence on the material properties (strain-rates)". These modifications of the concrete and reinforcement properties are significantly different from the quasi-static (Asprone et al., 2012). Recordings from several buildings during earthquakes have shown speeds up to 1,000 m/sec. between the damages and these speeds, Todorovska and Rahmani (2011) state there is a connection: "Our analysis provides specific quantitative knowledge about the changes of wave velocities associated with damage, and about their variability due to factors other than damage". Due to the large speed of loading and the reduced number of cycles, the compression capacity of concrete and the tensile capacity of the reinforcement increase very much so that the walls cannot develop plastic hinges on a large area and localised cracks in the concrete are recorded, leading to brittle failure modes (Mosoarca, 2013). This strain-rate effect can be the main cause for a less known failure mode, recorded by the shear walls after the

Christchurch earthquake: "The lack of a distributed cracking pattern in the plastic hinge zone of the RC walls is also an unexpected observation that requires further research", according to Kam and Pampanin (2011). The effects of the strain-rate on the failure mode of shear walls are hard to clarify and require further studies due to the fact that the large speed of loading is difficult to simulate in laboratories. Regarding these failure modes generated by the strain-rate, Carillo et al. (2011) says: "…when the seismic behaviour of an element or system is studied using the quasi-static method imprecise interpretations of results can be generated, when the governing failure mode is strongly affected by the strain rates…"

3 New provisions of increasing the performance level of buildings in seismic zones

In the last years, researchers have started elaborating provisions for avoiding brittle failures of buildings. Among the most important new recommendations we enumerate:

1. Elaborating provisions for the vertical conformity of buildings from rigidity, resistance and ductility point of view, in function of the distance to the seismic source (Gioncu and Mazzolani, 2011).
2. Proposal for length of plastic hinges in function of the type of earthquake (Mortezaei and Ronagh, 2013).
3. Modification of the design spectrum from ultimate limit state calculation with factors which take into account the ductility of the structure and the performance of the structure after other earthquakes (Wilkinson et al., 2013).
4. To avoid brittle failures under bending and axial forces, limitations to axial forces have been proposed (Bonelli et al., 2012).
5. To limit instability failures, limits on wall slenderness must be applied to the potential plastic zone (Wallace and Moehle, 2012).
6. Adaptation in the design process of material laws for the reduction of the unfavourable effects of the strain-rate effect.
7. Implementation in the design codes of the correct directions of action of the seismic forces at the level of each storey in function of the positioning of the building relative to the seismic source. A close attention must be given for the dimensioning of the concrete sections and reinforcements from the superior part of the buildings in order to reduce the unfavourable effects generated by the large values of the vertical components of the acceleration and velocity (Mosoarca and Anastasiadis, 2013).

4 Conclusions

A careful analysis of the failure mechanisms developed by buildings in seismic zones as well as new research and information in the seismology field, together with recent recordings on building elements during earthquakes have indicated the existence of new factors which can lead to brittle failures of RC structures and which should be introduced in the seismic vulnerability assessment methods of buildings. For this, it is necessary that the results of the academic research to be transferred to structural design engineers by the implementation of design codes containing clear provisions for the reduction of the effect of these new factors.

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This paper is dedicated to Professor V. Gioncu who passed away on March 2013. His contributions in the field of earthquake engineering were recognised from the international engineering community by numerous publications and honours. We have lost our beloved mentor, and we truly miss his thoughts and suggestions, his passion and enthusiasm for both life and engineering problems. We will always grateful for all that we learned from him. Also special thanks to the, H.I.STRUCT and ASA Design Office for the financial aid provided for developing this research.

References

Asprone, D., Frascadore, R., Di Ludovico, M., Prota, A. and Manfredi, G. (2012) 'Influence of strain rate on the seismic response of RC structures', *Engineering Structures*, Vol. 35, pp.29–36.

Bonelli, P., Restrepo, J.I., Boroschek, R. and Carvallo, J. (2012) 'The 2010 great Chile earthquake-changes to design codes', *Proceedings of the International Symposium on Engineering Lessons Learned from the 2011 Great East Japan Earthquake*, 1–4 March, pp.1778–1787, Tokyo, Japan.

Carrillo, J. and Alcocer, S. (2011) 'Degradation properties of reinforced concrete walls with opening', *Dyna, Year 78*, No. 170, pp.106–115.

Faggiano, B., Formisano, A., De Gregorio, D., De Lucia, T. and Mazzolani, F.M. (2011) 'A quick level methodology for the volcanic vulnerability assessment of buildings', *Applied Mechanics and Materials*, Vol. 82, pp.639–644.

FEMA 383 (2003) *Expanding and Using Knowledge to Reduce Earthquake: Losses*: *NEHRP Program, Strategic Plan 2001–2005*.

Formisano, A. (2012) 'Seismic damage assessment of school buildings after 2012 Emilia Romagna earthquake', *Ingegneria Sismica*, Vol. 29, Nos. 2–3, pp.72–86.

Formisano, A., Florio, G., Landolfo, R. and Mazzolani, F.M. (2015a) 'Numerical calibration of an easy method for seismic behavior assessment on large scale of masonry building aggregates', *Advances in Engineering Software*, Vol. 80, pp.116–138.

Formisano, A., Landolfo, R. and Mazzolani, F.M. (2015b) 'Robustness assessment approaches for steel framed structures under catastrophic events', *Computers and Structures*, Vol. 147, pp.216–228.

Gioncu, V. and Mazzolani, F.M. (2010) 'Problems of seismic behaviour of buildings situated in urban habitats', *Proceedings of the Final COST Actions C26, Urban Habitat Constructions under Catastrophic Events*, 16–18 September, pp.87–92, Naples, Italy.

Gioncu, V. and Mazzolani, F.M. (2011) *Earthquake Engineering for Structural Design*, Spon Press-Taylor and Francis, ED.

Gyorgy, J., Gioncu, V. and Mosoarca, M. (2006) 'Behaviour of steel MRFs subjected to near-field ground motions', *Proceedings STESSA 2006*, Yokohama, 14–17 August, pp.129–136.

Indirli, M., Kouris, L.A.S., Formisano, A., Borg, R.P. and Mazzolani, F.M. (2013) 'Seismic damage assessment of unreinforced masonry structures after the Abruzzo 2009 earthquake: the case study of the historical centers of L'Aquila and Castelvecchio Subequo', *International Journal of Architectural Heritage*, Vol. 7, No. 5, pp.536–578.

Kam, W.Y. and Pampanin, S. (2011) 'The seismic performance of RC buildings in the 22 February 2011 Christchurch earthquake', *Structural Concrete*, Vol. 12, No. 4, pp.223–233.

Klimis, N.S. and Anastasiadis, A.J. (2002) 'Comparative evolution on topography effect via code recommendations and 2-D numerical analysis', *Proceedings of 12-th European Conference on Earthquake Engineering*, 9–13 September 2002, paper No.745, London.

Lemnitzer, A., Skolnik, D.A., de la Lerra, J.C. and Wallace, J.W. (2012) 'Seismic monitoring of reinforced concrete building following the Mw 8.8 Feb. 27th, 2010 offshore Maule Earthquake in Chile', *15 WCEE*, Lisboa, Portugal.

Mortezaei, A. and Ronagh, H.R. (2013) 'Plastic hinge length of reinforced columns subjected to both far-fault and near-fault ground motions having forward directivity', *Structural Design Tall Buildings*, Vol. 22, pp.903–926.

Mosoarca, M. (2013) 'Seismic behaviour of reinforced concrete shear walls with regular and staggered openings after the strong earthquakes between 2009 and 2011', *Engineering Failure Analysis* [online] http://dx.doi.org/10.1016/j.engfailanal.2013.05.014 (accessed 11 April 2016).

Mosoarca, M. and Anastasiadis, A. (2013) 'New factors influencing the failure mechanisms of reinforced concrete buildings located in seismic areas', *International Van Earthquake Symposium*, Paper ID: 110, p.88, Van, Turkey.

Pardalopoulos, S.J., Thermou, G.E. and Pantazopoulou, S.J. (2013) 'Screening criteria to identify brittle R.C. structural failures in earthquakes', *Bulletin of Earthquake Engineering*, Vol. 11, No. 2, pp.607–636.

Tapan, M., Comert, M., Demir, C., Sayan, Y., Orakal, K. and Ilki, A. (2013) 'Failures of structures during the October 23, 2011 Tabanlı (Van) and November 9, 2011 Edremit (Van) earthquakes in Turkey', *Engineering Failure Analysis* [online] http://dx.doi.org/10.1016/jengfailanal.2013.02.013 (accessed 11 April 2016).

Todorovska, M.I. and Rahmani, M. (2012) 'Recent advances in wave travel time based methodology for structural health monitoring and early earthquake damage detection in buildings', *15 WCEE*, paper No. 5514, Lisboa, Portugal.

Wallace, J. and Moehle, J. (2012) 'Behavior and design of structural walls-lessons from recent laboratory tests and earthquakes', *Proceedings of the International Symposium on Engineering Lessons Learned from the 2011 Great East Japan Earthquake*, 1–4 March, Tokyo, Japan.

Wilkinson, S., Grant, D., Williams, E., Paganoni, S., Frazer, S., Boon, D., Mason, A. and Free, M. (2013) 'Observation and implication of damage from the Mw6.3 Christchurch, New Zealand earthquake 22 February 2011', *Bulletin of Earthquake Engineering*, Vol. 11, No. 1, pp.107–140.