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Earthquake Vulnerability and the State-of-the-Art of Hybrid Structural Reinforcement and Soil Improvement Methods for Non-Engineered Structures

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ABSTRACT

In the course of the last decades many efforts have been focused on the design of effective countermeasures to retrofit pre-existing engineered structures -including both buildings and civil constructions- to properly resist the effects of primary and secondary seismic failure-induced mechanisms. On the other hand, due to several reasons which will be here summarized, non-engineered buildings (e.g.: unreinforced masonry structures, shack housing in developing countries, adobe dwellings, etc.) have not been so widely studied. As these structures are far from simple, they pose many interesting issues regarding earthquake vulnerability and the challenging tasks of either retrofitting their design or performing soil and foundation improvements in frequently difficult psycho-environmental settings. In this presentation, some of the most outstanding features of non-engineered buildings will be detailed. Also, a summary of some of the most effective approaches of hybrid structural and soil improvements will be discussed with some guidelines for future studies

Introduction

Seasonal phenomena (i.e.: strong winds, extreme temperatures, heavy rains, floods, etc.), quotidian natural or man-made hazards (i.e.: humidity, animal or insect infestation, public safety, etc.) and local constraints (i.e.: topography, soft soil deposits, available construction materials, per capita income, etc.) have been shaping the architectural profile of traditional housing for centuries, even millennia, all around the globe. However, moderate to large seismic events are unpredictable in nature and their occurrence can be separated in time by many decades or even centuries. Thus, the practical lessons from these events find it harder to permeate through the architectural customs, especially in developing areas of the world. Only in places where earthquakes are frequent, the communities have learnt to incorporate to their vernacular houses some seismic resistant strategies (Sakhawarz, 1998). Sadly, in many developing or recently industrialized countries, there is an extensive lack of knowledge of the potential hazards the communities should be aware of (Attri et al., 2013), so the achieved understanding from past earthquakes has been either lost or quickly forgotten (Bilham, 2010). This fact does not leave much room for optimism in many seismic areas: for example, in the town of Cañas (Guanacaste region in Costa Rica), recent projections estimate that between a 32 percent and a 50 percent of the total building stock will be heavily affected when the next earthquake strikes (Climent et al., 2003). In figure 1, an illustrative example of non-engineered, earthquake-vulnerable house of this region is shown, regardless the experience of past seismic events: 1950, Ms 7.7, and 1973, Ms 6.5 (Climent et al., 2003):

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Figure 1. Bamboo-framed house under construction in Cañas (Guanacaste region), in Costa Rica, precariously adapted to a steep topography (Photos by V. López-Ausín)

As another example, we may mention the coastal city of Juchitán de Zaragoza, in the State of Oaxaca (Mexico). Although the region is influenced by the subduction boundary of the Cocos and North American plates and its seismic activity is considered to be among the strongest in the country, with frequent earthquakes (BC Consultores, 2012), in Juchitán de Zaragoza these events have more spaced in time. Although historically the city has been struck by some notable seismic events (as the recent 1999 Oaxaca earthquake, Mw 7.5 (Bravo et al., 2004) or the 2008 Unión Hidalgo earthquake, Mw 6.6 (Alvarez-Ramirez et al., 2012), which epicentre was just 50 km far from Juchitán de Zaragoza), many residents confessed little or no concern at all for earthquake hazards when questioned by the authors. As no casualties and seldom structural damage was reported, the seismic hazard is not among the priorities of the residents and, thus, almost none seismic resilient buildings can be found across the city, as the one shown in figure 2, supported by liquefactable sand deposits:

Figure 2. Left: Interior of a timber-roofed building with randomly mixed RC and timber columns and a single unreinforced masonry wall. Right: improvised wooden posts against poorly connected RC columns of the same building (Photos by S. Ortiz-Palacio)

Earthquakes, while brief in duration, can be extensively destructive, and a dramatic number of the developing countries in seismic regions of the Earth do not have the technical and human resources or the know-how to elude their effects and learn from the structural behaviour of their buildings, therefore breeding an ongoing lack of awareness of the problem and thus avoiding the implementation of countermeasures for the future. One recent example is the 2010 Haiti earthquake: in the aftermath of the 7.0 Mw seismic event, an estimated 222,570 to 316,000 people were killed (Guha-Sapir et al., 2011) with somewhere between 100,000 to 250,000 homes destroyed (Bilham, 2010; McWilliams and Griffin, 2013), as shown on table 1. But, while in other seismic-prone countries the striking of large earthquakes have led to the development of enhanced building codes, social improvement of awareness, government involvement in the reconstruction of the affected regions and the retrofitting of the others, etc., in Haiti –as well as many other developing countries, as Turkey, the Philippines, etc. (McWilliams and Griffin, 2013)- there is not a sense of improvement, as the reconstruction is slow and based on the old flawed traditional schemes.

Lessons from the Past: Earthquake Vulnerability in Figures

Residential dwellings have been estimated to represent more than 80 percent of the building structures around the globe (Chaudhary, 2014), most of which are not believed to be properly engineered (that is, designed by architects or engineers and constructed by skilful workers with adequate materials), which may be as low as one percent of the total according to Oliver (2007), who also estimates that more than a 90 percent of the buildings are estimated to be non-engineered. Narrowing our scope to developing countries, these figures are consistent with other studies, which describe that over a 90 percent of the population in developing countries lives, works or studies in non-engineered buildings, as indicated by Arya (2000). This fact is emphasised by recent catastrophic earthquakes, summarised in Table 1:

Table 1. Summary of the most destructive earthquakes (5,000 or more deaths) in the 21st century (Cluff, 2007; Holzer and Savage, 2013; Hussain et al., 2006; Kuwata et al., 2005; USGS, 2014).

Region	Year	Magnitude	Death toll[1]	Buildings[1]
Bhuj (India)	2001	7.6	20,085	1,112,000
Bam (Iran)	2003	6.6	31,000	32,900
Sumatra-Andaman (Southeast Asia)	2004	9.1	227,898[2]	80,000
Kashmir (Pakistan)	2005	7.6	86,000	780,000
Indonesia	2006	6.3	5,749	578,000
Wenchuan (China)	2008	7.9	86,287	26,360,000
Haiti	2010	7.0	222,570-316,000	285,677
Tohoku (Japan)	2011	9.0	22,626[2]	332,395

(1) Estimated (the buildings included are those either collapsed or significantly damaged)
(2) Most of the casualties took place in the aftermath, because of the effects of an earthquake-triggered tsunami

Over a 90 percent of the death toll due to earthquakes since 1900 have been caused by building collapses (Spence and So, 2009). These authors have also pointed out the importance of finding out the reasons behind the fatalities caused by seismic events in order to be able to predict the magnitude of casualties for after-earthquake response and to understand how each thinkable factor intervenes in the casualty rate. The projections for the future, in this sense, are shocking: Holzer and Savage (2013) estimate 3.21 million casualties for the 21st century, considering as inputs in their simulations the total death toll in the 20th century and the increase rate estimations in world population. Thus, it should be a primary goal to improve seismic resilience around the world (Dowrick, 2003; Scawthorn and Chen, 2014), developing a seismic retrofitting culture in all earthquake prone regions of the earth, as not only are developing countries in a predicament due to earthquake effects on non-engineered buildings. To a lesser extent, some vernacular dwellings and historical buildings as well as modern but inadequately engineered structures in developed countries are earthquake vulnerable (i.e.: traditional timber housing with stone roofs in Japan, stone masonry in Spain, RC multi-story buildings with low horizontal stiffness, etc.). It would be advisable to adopt a culture of continuous appraisal of the seismic events, promptly learning the past lessons in order to rationally incorporate them to the seismic codes and retrofitting methods, as many buildings have been revealed to be seismically weaker than previously thought, both in developed and developing countries. As Bilham (2010) states, *"in recent earthquakes, buildings have acted as weapons of mass destruction. It is time to formulate plans for a new United Nations mission — teams of inspectors to ensure that people do not construct buildings designed to kill their occupants."*

Non-Engineered Buildings in Developed Countries: The 2011 Lorca Earthquake in Spain

The 2011 Lorca earthquake, Mw 5.1, with a maximum intensity of VII (Frontera et al., 2012), caused 9 deaths and affected extensively many masonry and reinforced concrete buildings. A 12 percent of the total building stock affected by the event was identified as heavily damaged or to be demolished (Aretxabala and Sanz, 2011). Some historical masonry buildings with timber floors with non-diaphragm effect (Cabañas Rodríguez et al., 2011) suffered extensive damage, as the Clarisas' Convent and the Church of San (Aretxabala and Sanz, 2011) or the total collapse of the Santiago Chapel roof (Rueda et al., 2011). On the other hand, most of the damages in modern reinforced concrete buildings have been shown to be related to their typology: rigid heavy floors connected to RC columns, in which all the stability responsibility relies upon the degree of fixity at their connections, with no other stabilizing elements incorporated in the structure (Cabañas Rodríguez et al., 2011). This flaw led to the total collapse of a modern RC building during the earthquake. Additionally, a measured acceleration of 0.41g, far above the 0.12g basic acceleration prescribed for the region by the Spanish seismic code for buildings, NCSR-02, has raised a discussion about the need to have a thorough revision of the code, pointing out some of its defects. Some authors mention a crucial defect, as the code does not address the maximum allowable horizontal displacement of a building (Aretxabala and Sanz, 2011).

The Substitution of Vernacular Housing in Favour of Modern Designs

There is a controversy regarding the suitability of prioritizing traditional housing instead of modern building typologies (Jha and Duyne, 2010). Logic prepares us to think that modern techniques should be regarded as preferable but, as seen in the Lorca earthquake, changing from vernacular structures to concrete buildings can lead to failure in a seismic event if the materials or if the architectural or structural designs are of poor quality (Langenbach, 2006; McWilliams and Griffin, 2013). Also, non-rational substitution policies add to the invaluable anthropological loss of a vernacular building and all the knowledge and links with the society that once created them, fed during generations into its design (Klaufus, 2000; Oliver, 2007). Some authors even consider the house *"as an extension of the person"* (Carsten and Hugh-Jones, 1995), a central theme of social relations (Dayaratne and Kellett, 2008).

Understanding Non-Engineered Buildings Behaviour

To fathom how can we enhance the performance of non-engineered buildings during earthquakes, a wide array of constraints unfolds for engineers and architects to consider in the development of new enhancement techniques (Arya, 2000; Arya et al., 2014; Dowrick, 2003; Kusumastuti et al., 2008; McCormick et al., 2008; Sherpa, 2010): seismic response and failure mechanisms and post-yield performance; architectural design flaws; availability of materials; age of the building; skills of the professional and non-professional workers;

regional and local geotechnical properties; psycho-environmental evidences, degree of social and technical development. Due to the diversity of vernacular typologies in the world, no generalisation of retrofitting methods can be established as each dwelling has its own personality and individual needs.

Taxonomical Review

All the above analysis should be applied to individual housing typologies, so some classification system should be adopted in order to extract from any building the relevant information regarding seismic resilience. For that matter, many taxonomical efforts have traditionally divided non-engineering buildings in groups depending on the materials used for their construction (Arya, 2000; Arya et al., 2014; Okazaki et al., 2012; Papanikolaou and Taucer, 2004): earthen structures (hand-made, adobe blocks, rammed earth, etc.), masonry buildings (in stone, fire-brick or other materials), timber houses, poorly built RC structures, etc. Meanwhile, other recent initiatives are trying to give a far more precise approach to the matter of classification of vernacular construction, as the GEM (Global Earth Model) initiative, found in Brzev et al. (2013), creating a condensed index describing all the information regarding the architectural and mechanical characteristics of any given building, which would universalise and adopt resilient techniques from far apart regions.

Retrofitting: Traditional Approaches

As Green (2007) states, most of the investigations regarding the retrofitting and reinforcement of earthquake vulnerable structures have been more dedicated to large buildings than to small non-engineered houses. What is more, among those researches, seldom attempts at developing seismic isolation systems or ground improvement methods have been made when compared to the available literature on structural retrofitting of poorly constructed houses. Also, although some guides propose extensive instruction for foundation repairing and retrofitting (BRANZ, 2014), there are few studies of geotechnical seismic isolation and ground improvement techniques for non-engineered housing, when compared to the available works on structural retrofitting. However, recent works are increasingly showing the potential effectiveness of implementing low-cost geotechnical-themed measures along with structural, more conventional methods. Some of them are detailed next.

Hybrid Structural-Geotechnical Measures: Recent Efforts on Introducing Geotechnical Design into the Retrofitting and New Construction of Buildings

Whenever possible, ground improvement techniques or seismic isolation of buildings should be concomitant with structural retrofitting of buildings. The structural approach has been increasingly being studied during the last decades, citing as a non-comprehensive list of recent efforts: Arya et al. (2014); (Bariola et al., 1989; Blondet and Garcia; Chaudhary, 2014; Jha and Duyne, 2010; Langenbach, 2006; McWilliams and Griffin, 2013; Reconstruction and Authority, 2006; Sofronie, 2004). However, while seismic isolation of buildings or ground improvement have been extensively studied, optimised and implemented in developed countries, few works on geotechnical-based methods have been published, as the equilibrium between effectiveness and low-cost feasibility is difficult in developing countries for this techniques to become a real alternative or complement. For that matter, some promising lines of work are:

- Adaptive post-yield structures (McCormick et al., 2008; Wagg et al., 2008) and shape memory devices (Castellano et al., 1999): the design for post-critic structures,

- Seismic isolators:
  - Rubber bands and scrap tire pads (STP) devices (De Luca et al., 2001; Kidokoro, 2008; Melkumyan, 2008; Yamaguchi et al., 2008b)
  - Rock-friction supports (Yamaguchi et al., 2008a; Yamaguchi et al., 2008b)
  - Fibre-reinforced elastomers (Konstantinidis and Kelly, 2012)
- Biological soil reinforcements (Burbank et al., 2011; DeJong et al., 2013; DeJong et al., 2010; Kavazanjian Jr and Karatas, 2008; Lee et al., 2012; Montoya et al., 2013)
- New foundation materials:
  - Rubber-soil mixing (Foose et al., 1996; Tsang, 2008; Xiong and Li, 2013; Xu et al., 2009)
  - Post-tensioned cement stabilised soils (Barros and Imhoff, 2010)
  - Fibre-reinforced soils (Ibraim et al., 2010; Ibraim and Fourmont, 2007) (Wang and Brennan, 2013)
  - Adapting EPS geofoam embankments solutions to develop new foundation supports and panels for low-rise buildings (Elragi, 2000; Riad and Horvath, 2004; Zarnani and Bathurst, 2007)
- Liquefaction-buoyant structures: a new line of research by the authors puts forward a new design of floatable foundation geometries combined with low-density, resilient back fill materials or recycled resources specifically for low-rise houses on shallow liquefactable sands.

Conclusions

The terrible loss of lives due to recent earthquakes should be definitive wake-up call for the society as a whole in the search for real, sustainable world-wide politics of turning vulnerable non-engineered buildings into a seismic resilient stock. The adaptation of vernacular housing to earthquake-resistant forms while preserving the aesthetical, historical and anthropological value should also be a main theme of new retrofitting techniques. Finally, working not only *for* the local communities but *with* them should be always required to permit new designs to become a reality and not a simple theoretical but impractical idea. Some promising works on geotechnical retrofitting, at different stages today, can become feasible, low-cost alternatives tomorrow to provide safer dwellings.

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