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論文題名（外国語の場合は、その和訳を併記） Thesis Title（foreign language title must be accompanied by Japanese translation）
Evaluation of seismic performance of residential buildings in Lima, Peru: a case study of buildings constructed with thin RC walls and confined masonry walls ペルー・リマ市における建物耐震性評価に関する研究 ー薄壁式構造物と枠組みレンガ造構造物を対象としてー

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－薄壁式構造物と枠組みレンガ造構造物を対象として－

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Summary

According to a report presented by Guha-Sapir et al. (2011), 1888 people died due to the occurrence of 22 big earthquakes in 2009 in the world. That report also showed that the number of casualties by the 25 big earthquakes in 2010 was 226,735 and caused 46.2 billion US dollars worth of damage. It have been observed that despite the fact that there has not been an increase in the number of big earthquakes over the last years, the damage to several infrastructures (e.g. residential facilities) and the loss of human lives have increased, especially in the developing countries like Peru. In addition, it can be said that the disasters caused by seismic events are long lasting and often paralyzes the economy of the countries.

The recent earthquakes around the world occurred in this century have showed the vulnerability of buildings to this natural phenomena. For example, a 7.0 magnitude earthquake occurred on January 12th, 2010 in Haiti caused severe damage to approximately 300,000 dwellings and more than 300,000 people were killed (DesRoches et al., 2011). But, It is widely known that earthquakes don't kill people, buildings do, which is particularly true in case of countries where the damage is a result of a combination of lack of design codes and poorly constructed structures. There are some agreements for the disaster risk reduction (e.g. Yokohama Strategy (IDNDR, 1994) and Hyogo Framework (ISDR, 2005)). These agreements have proposed a paradigm change from post-disaster relief efforts towards pre-disaster planning. The principles of international disaster risk reduction also recognize the need to focus risk reduction strategies in the developing countries. It has been a significant effort in the last decade towards developing seismic risk assessment and management programs with a more global focus. Because of the uncertainties related to the nature of earthquakes, the damage risk assessment in the pre-disaster planning is related to the vulnerability or fragility of structures using the called vulnerability or fragility functions (Porter, 2003).

Recently, a comprehensive research project for the earthquake and tsunami disaster mitigation in Peru under the framework of "Science and Technology Research Partnership for Sustainable Development (SATREPS)", sponsored by Japan Science and Technology Agency (JST) and Japan International Cooperation Agency (JICA) is carried out (Yamazaki et al., 2012). Among the outputs of the project, we have the evaluation of structural seismic resistances and the estimation of earthquake disaster losses. Based on this outputs, the present thesis aims to provide a set of fragility functions for thin reinforced concrete wall buildings and confined masonry wall dwellings. After that, using the constructed fragility functions, the evaluation of the seismic performance of those residential facilities in Lima, Peru was carried out.

Lima, which is the capital and the largest city of Peru, is located in the valleys of the Chillón, Rímac and Lurín rivers, in the central coastal part of the country, overlooking the Pacific Ocean. Together with the seaport of Callao, they form a contiguous urban area known as the Lima Metropolitan Area. The number of population is approaching approximately 9 million. The urban area of Lima covers about 800 km^2. It is located on mostly flat terrain in the Peruvian coastal plain. For its location in the world, Lima is located in a seismic-prone region belonging to the Pacific Ring of Fire where earthquakes are generated by subduction process between the Nazca plate and the South American plate. The history of Lima has shown that earthquakes of major magnitude have hit the city being the last recorded in 1974.

In Lima city, there are many types of dwellings and buildings. Since 1940, most of the low-rise dwellings are constructed using clay bricks and reinforced concrete confining elements. According to the National Institute of statistics and informatics of Peru (INEI), the number of this type of dwelling has been increasing over the years.

In the 80’s, some buildings with reinforced concrete bearing walls were made because of the low price of concrete and steel. The thickness of the walls was 15 cm or more. In the 90’s, due to the increase in the cost of steel and labor, the construction of these buildings stopped.

Since 1998, the relative low costs of steel, concrete, labor and financing enabled the community of Peruvian engineers to resume the construction of buildings with reinforced concrete walls. The companies that produce concrete and steel, in coordination with designers and builders achieved to construct a building based on thin reinforced concrete walls which was fast to construct. The result was an appropriate economic building to cover the housing deficit in the medium and low-medium sector. For 2003, many of these buildings had been built without specific design standards. Initially, in 1998, this structural system was used in low-rise and mid-rise structures but then the number of stories increased (8, 10 floors). Because of the lack of design standards, the College of Engineers of Peru form a committee to discuss this issue and develop specific rules for design and construction. In December 2004, the National Training for the Construction Industry (SENCICO) incorporated specific provisions for design and construction in the seismic design standard E.030 and reinforced concrete design standard E.060.

Based on the facts previously presented, it is important to know and understand the current behavior of thin reinforced concrete wall buildings and confined masonry wall dwellings in order to take some countermeasures of mitigation. With that, the life, the material and the economical looses can be avoid during future seismic events.

The objective of the present thesis is to evaluate the seismic performance of confined masonry wall dwellings and thin reinforced concrete wall buildings. To reach this objective, fragility functions were constructed considering calibrated numerical models based on test results. The seismic performance was evaluated by considering the probability of been in various damage states at three seismic hazard levels, and also with respect to a weighted mean damage.

The thesis was divided into six chapters that can be grouped into four sections. The first section is composed by chapter one which deals with an introduction to the research. The next two chapters (chapters 2 and 3) are concerned with the calibration of a hysteretic model for thin reinforced concrete walls based on test using a trial and error method, and the generation of analytical fragility functions to evaluate the seismic performance of thin reinforced concrete walls buildings. The following two chapters (chapters 4 and 5) deal with the calibration of a hysteretic model for confined masonry walls using a genetic algorithm procedure and the evaluation of seismic performance of confined masonry wall dwellings using numerical fragility functions. The last section composed by chapter six shows the conclusions and further research for evaluation of seismic risk in thin reinforced concrete wall buildings and confined masonry wall dwellings. The next paragraphs describe each chapter in further detail.

Chapter 1 makes an introduction to the research developed. First, some facts about earthquakes and the damage caused by them are presented. Then, the general characteristics of the place of study (Lima city) are presented. A small revision of the evolution of dwellings and building in Lima used as residential facilities is also presented. After that, the principal goal of the thesis was stated as follow: contribute to the reduction of seismic risk of the Peruvian residential buildings. To achieve this general goal, some specific goals were defined: identify and evaluate the main structural characteristics of thin reinforced concrete walls and confined masonry walls, define and calibrate numerical models to reproduce the in-plane structural behavior of thin reinforced concrete walls and confined masonry walls, generate fragility functions for mid- and high-rise thin reinforced concrete wall buildings and low-rise confined masonry dwellings and, finally evaluate the seismic performance of for mid and high-rise thin reinforced concrete wall buildings and low-rise confined masonry dwellings in order to assess their vulnerability. Some previous studies on seismic assessment using fragility functions in Peru were reviewed. It was found that the study related to Peruvian buildings in Lima using fragility functions is referred to reinforced concrete frame structures used as school or offices. In case of analytical fragility functions, the numerical modeling of the structural elements didn’t have an experimental support. In case of fragility functions for residential buildings based on thin reinforced concrete walls, they are generated based on expert opinions. The disadvantage of this procedure is that the reliability of the functions depends on the individual experience of the experts. Finally, there was no report about the generation of fragility functions for dwellings based on confined masonry walls for Lima city.

Chapter 2 presents the test results of seven full-scale thin reinforced concrete walls subjected to cycling loading carried out at Japanese Peruvian Seismic Research Center and Disaster Mitigation (CISMID). The objective of these experiments was to evaluate the use of electro-welded wire mesh as the main reinforcement instead of a conventional reinforcement. Six walls were equipped with the electro-welded wire mesh, which is made of a non-ductile material, and one wall was reinforced with conventional bars, which are made of a ductile material. A single layer of main reinforcement was used in both directions. The edges of all walls were reinforced with conventional bars. The structural behaviors are examined in terms of structural parameters such as strength, stiffness, dissipated energy, and equivalent viscous damping. The “Three-parameter Park hysteretic model” was calibrated in order to reproduce the behaviors of the thin walls reinforced with the conventional reinforcement and electro welded-wire mesh.

In chapter 3, an analytical approach was adopted to construct fragility functions for mid-rise, thin reinforced concrete wall buildings, whose vertical and lateral resistance systems are thin reinforced concrete walls. This type of Buildings has typically been constructed in this fashion in Lima, Peru, since 1998. The geometrical model of mid-rise building used in this study was constructed based on the result of statistical analyses of actual buildings. The numerical model was defined based on the experimental results. The fragility functions for the buildings were constructed assuming that the damage ratios follow a lognormal distribution. The seismic performance was evaluated by considering the probability of being in various damage states at three seismic hazard levels, and also with respect to the weighted mean damage.

Chapter 4 analyzes the experimental results of four full-scale confined masonry walls subjected to cycling loading. These tests were carried out at Japanese Peruvian Seismic Research Center and Disaster Mitigation (CISMID) in 2003. Confined masonry walls are widely used in low- and mid-rise buildings in Peru to take the vertical and lateral loads. The objective of these experiments was to evaluate the cyclic behavior of confined masonry walls constructed with handmade bricks and lime mortar. In the experiments, the dimensions of all the walls were kept constant in all specimens, but the reinforcement ratios of the confining elements (bond beam and tie-columns) were changed. The structural behaviors were examined in terms of strength, lateral stiffness, dissipated energy, and equivalent viscous damping. Finally, an equivalent macro model based on an equivalent strut approach with smooth hysteretic model was calibrated and validated in order to reproduce the behaviors of the confined masonry walls using a genetic algorithm procedure.

In Chapter 5, an application of an analytical approach was followed to elaborate fragility functions of confined masonry wall dwellings located in Lima in order to evaluate their seismic performance. This kind of dwellings has been typically used since 1940. The numerical model was calibrated in the previous chapter. Due to the characteristics of these structures, a single wall was used to evaluate the seismic response to real and synthetic records. The lognormal distribution was considered to correlate the damage ratios with the earthquake intensity. The fragility functions are created for each limit state in terms of Peak Ground Acceleration. Finally, a suggestion for retrofit of 2-story dwellings is presented in order to reduce their vulnerability and its effectiveness is evaluated.

The general conclusions are drawn in the final chapter (Chapter 6) and it also provides discussions and future perspectives of researches.

It was found in the chapter two that even thought the thin reinforced concrete walls presented different main reinforcement (in amount and type of reinforcement), they presented similar tendency in terms of structural characteristics. This fact can indicate that the in-plane behavior of the walls is dominated for the edge reinforcement that remained constant in all walls. Considering the parameters that define the three-parameter Park hysteretic model, it was found that the walls present extreme unloading stiffness degradation, severe strength degradation based on ductility, no strength degradation based on energy and mild pinching effect.

In Chapter three, it was found that fragility functions depend on the spectral characteristics of the earthquake ground motion. This finding supports the idea that the set of records to be used must reflect the seismicity of the region where the structure will be located. It was also found that the use of electro welded wire mesh as main reinforcement instead of conventional rebars produce a small variation of the probability of damage for mid- and high-rise buildings. The reduction of reinforcement ratio of electro welded wire mesh as main reinforcement didn't produce a variation of the probability of present a light and moderate damage for mid- and high-rise buildings. The estimation of the weighted mean damage showed that mid- and high-rise buildings will suffer a reparable damage. These findings suggest that the use of electro welded were mesh is acceptable with respect to seismic performance.

In Chapter four, it was found that although the walls presented different amount of reinforcement in the confining elements (i.e. bound beam and tie-columns), they presented similar tendencies in their strength, stiffness degradation, energy dissipated and equivalent viscous damping. This finding indicates that characteristics of the masonry panel control the in-plane behavior of the specimens. Following a genetic algorithm procedure, twelve parameters that define the hysteric behavior of the panels were estimated. For this purpouse, an error function was defined considering the relative error of the structural characteristics. It was observed that some parameters had small influence on the structural charateristics.

Finally, in Chapter five, again, it was observed that the variation of input ground motion have an influence on the statistical parameters that define the fragility functions as it was observed in Chapter three. The evaluation of the fragility functions for dwellings in Lima at three hazard levels (i.e. occasional, rare and very rare earthquakes) reveal that one-story dwellings will not suffer damage. Two-story dwellings have a 36% probability of severe damage for occasional earthquakes and less than 5% of collapse for rare earthquakes. Finally, three-story dwellings will suffer extensive damage even under occasional earthquake. The weighted mean damage also revealed that two- and three-story dwellings would suffer irreparable damage. A retrofitting procedure involving the use of electro welded wire mesh was evaluated numerically. It was found that this simple procedure reduced the expected damage of two-story dwellings.