Seismic performance factors for wood frame buildings in Chile

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Doctor of Philosophy

under the supervision of Rijun Shrestha, Keith Crews, and Sardar Malek.

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CERTIFICATE OF ORIGINAL AUTHORSHIP

I, Xavier Estrella declare that this thesis is submitted in fulfilment of the requirements for the award of Doctor of Philosophy, in the Faculty of Engineering and IT at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise referenced or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of the requirements for a degree at any other academic institution except as fully acknowledged within the text. This thesis is the result of a Collaborative Doctoral Research Degree program with the Pontifical Catholic University of Chile.

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If I have seen further it is by standing on the shoulders of giants.

Isaac Newton, 1675

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ABSTRACT

Seismic performance factors are an engineering tool to estimate force and displacement demands on structures designed through linear methods of analysis. In Chile, the NCh433 standard provides the regulations, requirements, and factors for the seismic design of several structural typologies and systems. However, when it comes to wood frame structures, previous research has found that the NCh433 provisions are highly restrictive and result in over-conservative designs. Therefore, this project presents an experimental and numerical investigation aimed at proposing new, less restrictive seismic performance factors for wood frame buildings. Following the FEMA P-695 guidelines, this research embraced: (1) testing of materials, connections, and full-scale specimens, (2) developing of detailed and simplified nonlinear numerical models, (3) developing of a new FEMA P-695 ground motion set for subduction zones, and (4) analyzing the seismic performance of a comprehensive set of structural archetypes. 201 buildings were analyzed and results showed that changing the NCh433 performance factors from R = 5.5 & Δ_{max} = 0.002 to R = 6.5 & Δ_{max} = 0.004 decreases the average collapse ratio of wood frame structures by 13.3% but keeps the collapse probability below 20% for all the archetypes under study. Besides, it improves the cost-effectiveness of the buildings and enhances their competitiveness when compared to other materials, since savings of 40.4% in nailing, 15.9% in OSB panels, and 7.3% in timber studs were found for a 5-story building case study. Further analyses showed that the buildings designed with the new factors reached the “enhanced performance objective” as defined by the ASCE 41-17 standard, guaranteeing a neglectable structural and non-structural damage under highly recurring seismic events. Finally, dynamic results revealed that 87% of archetypes collapsed on the first and second floors, and that the minimum base shear requirement C_{min} of the NCh433 standard is somewhat restrictive for soil classes A, B, and C, leading to conservative results compared to archetypes where the C_{min} requirement did not control the structural design.

FACTORES DE DISEÑO SÍSMICO PARA EDIFICACIONES DE MADERA MARCO-PLATAFORMA EN CHILE

RESUMEN

Los factores de diseño sísmico son una herramienta ingenieril para estimar las demandas de fuerza y desplazamiento en estructuras diseñadas a través de métodos lineales de análisis. En Chile, la normativa NCh433 proporciona las regulaciones, requerimientos, y factores para el diseño sísmicos de varias tipologías y sistemas estructurales. Sin embargo, cuando se trata de estructuras de madera marco-plataforma, investigaciones anteriores han encontrado que las disposiciones de la normativa NCh433 son altamente restrictivas y resultan el diseños sobre-conservadores. Por lo tanto, este proyecto presenta una investigación numérica y experimental que apunta a proponer factores de diseño sísmico menos restrictivos para edificaciones marco-plataforma. Siguiendo la metodología FEMA P-695, esta investigación abarcó: (1) pruebas experimentales de materiales, conexiones, y especímenes a escala real, (2) desarrollo de modelos numéricos no-lineales detallados y simplificados, (3) creación de un nuevo set de registros sísmicos FEMA P-695 para zonas de subducción, y (4) análisis del desempeño sísmicos de un exhaustivo conjunto de arquetipos estructurales. Se analizaron 201 edificaciones y los resultados mostraron que cambiar los factores de diseño sísmicos NCh433 de R = 5.5 & Δ_{max} = 0.002 hacia R = 6.5 & Δ_{max} = 0.004 reduce el margen de colapso de estructuras marco-plataforma en 13.3% pero mantiene la probabilidad de colapso bajo 20% para todos los arquetipos analizados. Además, mejora la relación costo-beneficios de las edificaciones e incrementa su competitividad al compararlas con otros sistemas estructurales, ya que se encontraron ahorros del 40.4% en clavado, 15.9% en paneles de OSB, y 7.3% en pie-derechos para el caso de estudios de una edificación de cinco pisos. Análisis adicionales mostraron que las edificaciones diseñadas con los nuevos factores propuestos alcanzaron el "*enhanced performance objective*" definido por el estándar ASCE 41-17, garantizando un daño estructural y no estructural despreciable bajo demandas sísmicas de alta recurrencia. Finalmente, los resultados dinámicos revelaron que 87% de los arquetipos colapsaron en los pisos primero y segundo, y que el corte mínimo C_{min} requerido en el estándar NCh433 es algo restrictivo para tipos de suelo A, B, y C, llevando a resultados conservadores al compararlos con arquetipos donde el requerimiento de C_{min} no controló el diseño estructural.

PREFACE

TIMBER ENGINEERING: A NEW PARADIGM FOR MID-RISE CONSTRUCTION IN CHILE

The Chilean real estate market is mainly dominated by masonry for low-rise houses and reinforced concrete for mid- to high-rise buildings. Given the high seismic risk of the region, the local engineering community has developed a robust know-how regarding the seismic design of buildings employing these well-known materials. As a consequence, previous research has shown that the Chilean reinforced concrete buildings are capable of withstanding strong earthquakes with minor damage at the structural and non-structural level (Westenenk et al. 2012). Furthermore, during the last decades, the local industry has developed the mechanisms to provide good quality materials for the construction sector with an unbeatable benefit-cost ratio. In this context, an important question arises. Why moving towards timber construction? Three main points should be considered to answer this question: (1) local timber industry, (2) environmental footprint, and (3) engineering advantages.

The data provided by the Chilean Forestry Institute (INFOR 2016) shows that the local timber industry accounts for 2.6% of Chile's gross domestic product, and generates employment (direct and indirect) for more than 300,000 workers across the country (CORMA 2014), which is about 4% of the total number of people employed in Chile. However, recent research (INFOR 2017a) revealed that in 2016, only 30% of the wood sawn and produced in Chile was used inside the country, while the remainder was exported to countries such as China, the USA, Brazil, among others. The construction sector has a major role in this low level of timber domestic use. Recent data show that in Chile only 32% of the residential homes use timber, and at present, there is a ~0% of mid-rise timber buildings (Santa María et al. 2017), which is a relatively low figure when compared to rates in other countries such as New Zealand or the USA, where 90% of houses use timber as the main material (Ajay 1995; Buckett 2014). Therefore, pushing the growth of the timber construction industry will boost the internal use of wood across different sectors significantly contributing to the country’s economy.

In terms of environmental footprint, Chile has been struggling against pollution problems in several areas across the country in the past few years, as a consequence of highly populated cities and poor airflow through the high mountain ranges of the region. For instance, in 2016 the city of Coyhaique in the south of Chile was declared the most polluted city in Latin America (WHO 2016). Given the high demand for housing in the big cities, the timber construction sector may significantly contribute to mitigating this issue. For instance, studies have shown that the energy consumption of concrete houses is 60-80% higher compared to timber houses (Börjesson & Gustavsson 2000), and that the CO_2 production during the life span of a concrete building is 30-130 kg/m2 greater (Gustavsson, Pingoud & Sathre 2006). In countries with very marked seasons such as Chile, it has been calculated that a timber house consumes between 15% and 16% less energy for heating/cooling when compared to a concrete or steel house. Over a period of 100 years, it is estimated that a timber house could reduce the net emissions of greenhouse gases by between 20% and 50% when compared to traditional systems (Upton et al. 2008).

From an engineering performance perspective, it is universally acknowledged that timber structures have several engineering advantages that make them highly attractive when designing buildings in seismic prone areas (van de Lindt 2004). Their low seismic mass and high flexibility result in low design forces and economically efficient structures (Dechent et al. 2016; Follesa et al. 2018). Furthermore, their high capacity of inelastic deformation (ductility) allows them to achieve high performance levels when subjected to ground motions of low exceedance probability (Jayamon, Line & Charney 2017). This latter follows the current seismic design philosophy for earthquake-resistant buildings, which requires the structure to be able to withstand large inelastic deformations before collapse. Based on the information described above, although it would not be indisputable to affirm that timber buildings are the absolute solution for new constructions, it stands out that this structural system has several advantages over the others in terms of the local economy, environmental footprint, and engineering performance. Nevertheless, due to very conservative regulations, the growth of timber structures has slowed down over the last few years in Chile.

To tackle this issue, this thesis presents the results of a research project aimed at quantifying a new set of less conservative regulations for wood frame buildings in Chile. Following a rational methodology, the feasibility of employing a new R factor and elastic drift limit Δ_{max} is verified, aiming at improving the efficiency and cost of the wood frame buildings across the different zones of the country, and without compromising their safety during moderate and severe earthquakes.

HYPOTHESES AND OBJECTIVES

HYPOTHESES

GENERAL: It is possible to employ less conservative seismic performance factors when designing wood frame buildings in Chile in order to improve the cost-benefit ratio of such structures.

SPECIFIC 1: A new numerical model can be developed to efficiently compute the nonlinear response of 'strong' wood frame walls under lateral loads.

SPECIFIC 2: A continuous rod hold-down anchorage allows wood frame walls to withstand large lateral and overturning loads without showing a brittle or premature failure.

SPECIFIC 3: It is possible to develop a ground motion set for zones prone to subduction earthquakes keeping consistency with the guidelines provided by the FEMA P-695 methodology.

OBJECTIVES

GENERAL: To statistically prove the feasibility of employing less conservative seismic performance factors for wood frame structures in Chile.

SPECIFIC 1: To develop a new efficient numerical model to reproduce the nonlinear response of ‘strong’ wood frame walls under large lateral loads.

SPECIFIC 2: To validate the lateral response of wood frame walls with continuous rod hold-down anchorages through experimental tests.

SPECIFIC 3: To develop a new ground motion set consistent with the FEMA P-695 methodology and suitable to conduct dynamic analyses in areas prone to subduction earthquakes.

THESIS STRUCTURE AND ORGANIZATION

This thesis has been developed following an article-based format; therefore, each chapter of this document corresponds to published or publishable content. Besides, each chapter was designed to address one of the objectives proposed for this research project. Chapter 1 presents the overall project, methodology, and results, and Chapters 2, 3, and 4 present detailed support studies carried out to back up the main research in Chapter 1. This way, even though all the content of this thesis is strongly connected and interrelated, each chapter is self-contained and presents independent research that might be read and understood by itself. Aiming at achieving self-contained chapters, some concepts and explanations might be found more than once across this document for the sake of clarity. However, there is no research overlapped between chapters and sections. The content of this thesis has been organized as follows:

Chapter 1 addresses the General Objective proposed for this project. It presents the formulation of the project, background, methodology, and results of the new proposed seismic performance factors for wood frame buildings in Chile. Further analyses regarding the seismic response of wood frame structures are also presented in this chapter.

Chapter 2 addresses the Specific Objective 1. It presents a support investigation carried out to develop a new numerical model for wood frame walls. This new numerical model is employed in Chapter 1 to study the seismic response of mid-rise wood frame structures.

Chapter 3 addresses the Specific Objective 2. It presents a support experimental investigation that tested real-scale wood frame walls with continuous rod hold-downs. The results of this section fed the numerical models employed in Chapter 1 and provided a better understanding of the behavior of wood frame walls.

Chapter 4 addresses the Specific Objective 3. It presents the development of a new set of ground motions for subduction zones. This new set was employed as a dynamic input in the seismic performance analyses carried out in Chapter 1.

Chapter 5 presents the main findings and conclusions of this research project. In order to highlight the contributions to each field addressed in this thesis, conclusions were sorted out and grouped by chapters.

Finally, Appendixes A, B, C, and D present additional information about the structural archetypes analyzed in this thesis and their fragility functions for different performance levels.