A SIMPLE PROPOSAL FOR THE SEISMIC RISK ASSESSMENT OF WOODEN PATRIMONIAL STRUCTURES IN CHILE

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Abstract

The seismic risk assessment of patrimonial wooden structures constitutes a relevant issue not sufficiently considered in the current status of the seismic engineering community.

A simple proposal to evaluate the patrimonial seismic risk of wooden structures is presented, taking as study case the city of Valdivia, in southern Chile. The seismic risk is analyzed under three core aspects: vulnerability, hazard and architectural cost that considers the patrimonial variable.

The vulnerability assessment is considered by means of the vulnerability index method taking into considerations the most relevant parameters involved in wooden patrimonial structures. The seismic hazard considers both the uniform and local seismic conditions. The architectural cost considers the architectonic relevance, predominant styles, architectonic exposure and the territorial architectonic value.

Field measures were performed in order to obtain relevant information, taking as a study case the historic area in the city of Valdivia. Having defined the basic parameters, is created a computational platform, RIPAT, which calculates patrimonial risk, also establishing recommendations related to the intervention criterion.

As a result, the need to incorporate the patrimonial variable through the architectural assessment was found, generally becoming more significant than the other aspects. In these sense it´s important to understand that the seismic risk assessment of historic structures with the inclusion of the patrimonial variable is more than a structural or seismic evaluation only.

Keywords: Patrimonial structures; Wood; Seismic Risk; Chile

1. Introduction

The application of new technologies for controlling seismic risk affecting cultural heritage has led to important methodological changes in the preservation of heritage timber structures. This new approach is itemised in the aims of the International Council on Monuments and Sites (ICOMOS) [1], [2], which seeks to preserve the memory of historic buildings, promoting the application of technology in the assessment of monuments.

Chile is located on the Ring of Fire [3], which is the Pacific Ocean coastline characterized by the most important subduction zones in the world, resulting in intense seismic and volcanic activity in this area. However, Latin American countries located in places with high exposure to natural risks (e.g. those located on the *"Ring of Fire"*) [4], show lack comprehensive methodologies to manage the vulnerability of buildings and their exposure to external hazards, including quantitatively the cultural heritage value [3], [4]. In spite of the foregoing, some efforts have been made in Chile (Ministry of Housing and Urban Planning, Government of Chile and new Ministry of Culture, Arts and Heritage) to conserve cultural assets, although such efforts are currently only performed at sectorial level. To address these concerns, this paper aims to propose a new approach to decision-making for the development of preventive maintenance strategies [5], taking into account vulnerability, external hazards and architectural attributes in heritage buildings in Valdivia, southern Chile.

The city of Valdivia is an urban enclave located in southern Chile, far from the country's main urban centres (Fig. 1). As mentioned by [6], German culture in Chile (German immigration to Chile was promoted by the Chilean government) overlapped with prior Spanish colonialization. The Valdivia Germans adopted the features characteristic of architecture in their former homeland, albeit with adaptations in terms of the use of wood, as this was the locally available building material. The use of wood as the primary building material has a long history in southern Chile, particularly for building churches and other important structures [7]. In this sense, the Prochelle I House is an exceptional example of nineteenth-century German colonization, a standout building in the urban layout and in the city's current collective urban identity [8]. This heritage building is located in a Typical Areas and which are therefore protected under Chile's national Monument Law [9]. This construction is one of the oldest and most emblematic timber heritage houses in Valdivia, dating from 1902. In 1985, the house was declared a Historical Monument by the Chilean government. The building is protected by a territorial conservation plan drawn up by the city's authorities and the Ministry of Housing and City Planning [10]. This regional heritage timber structure has resisted many natural disasters, including earthquakes [11] such as the Valdivia's earthquake in 1960 (9.5MW - the most powerful earthquake ever recorded in the world) and the Concepción earthquake in 2010 (8.8MW). Fig. 2 shows the historical timber building studied here (Prochelle I House). It currently belongs to the municipality of Valdivia. The building has the following main construction characteristics [12].

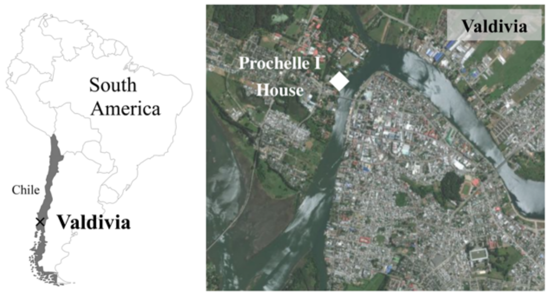

Fig. 1 - Location of the case study in Valdivia


Fig. 2 – Typical study case: Prochelle I House

2. Seismic vulnerability index in patrimonial structures

The seismic assessment of monumental buildings requires the consideration of safety and conservation objectives, both for the building and its cultural heritage assets. In this context, studies based on vulnerability indexes applied to wood structures in Chile are relatively scarce [7]. One initiative in this field is the Risk-EU Project. This methodology based on European experiences studies constructions with wooden structures located in Chile and was adapted by [13]. In this study, an index-based seismic vulnerability method adapted to Chilean typologies was presented and applied [14]. A total of three main variables were identified (heritage attributes, vulnerability and hazards) (Table 1).

Table 1 outlines the hierarchical structure of the system and the weighting of the inputs and intermediate variables involved. The seismic vulnerability method consists in a quantification of variables established by means of an expert survey. A total of 7 professional civil engineering, construction management and architecture experts were consulted during the model design stage [14]. This model was validated professionally and approved by the Reviewing Authority in the case studies of Nueva Imperial, Araucanía region, Chile [15].

Table 1 - Hierarchical structure and weighted variables of the seismic vulnerability method.

Input variables	*Weighting*	*Intermediate variables*	*Weighting*	*Intermediate variables*	*Output variable*
A11 - Territorial value	*0.20*	*A1 – Heritage significance*	*0.60*	*A - Heritage attributes*	*Seismic vulnerability index (RIPAT1.0)*
A12 - Architectural value	*0.20*				
A13 - Preservation value	*0.20*				
A21 - Architectural style - historical sequence	*0.15*	*A2 - Representativeness*	*0.30*		
A22 - Representative elements	*0.15*				
A31 - Typological classification according to use	*0.05*	*A3 - Exposition of the structure*	*0.10*		
A32 - Occupancy	*0.05*				
V1 - Effects of deterioration			*0.35*	*V - Vulnerability*	
V21 - State of conservation	*0.075*	*V2 - Structural problems*	*0.30*		
V22 - Columns risk level	*0.075*				
V23 - Overloads	*0.075*				
V24 - Density of divisions	*0.075*				
V31 - Quality of divisions	*0.002*	*V3 - Non-structural problems*	*0.10*		
V32 - Stairs	*0.002*				
V33 - Facades	*0.002*				
V34 - Cover	*0.002*				
V35 - Ceilings	*0.002*				
V41 - Asymmetry	*0.005*	*V4 - Structural skills*	*0.15*		
V42 - Corners	*0.005*				
V43 - Structures interventions	*0.005*				
V5 - Floor-Structure interaction			*0.10*		
H1 - Seismic zone			*0.33*	*H - Hazards*	
H21 - Seismic amplification	*0.167*	*H2 - Local hazard (site effects)*	*0.34*		
H22 - Dynamic expansion	*0.167*				
H31 - Geotechnical features	*0.167*	*H3 - Geological location*	*0.33*		
H32 - Construction skills	*0.167*				

The seismic vulnerability index method was selected [16] by means of the use of the tool RIPAT, developed at RiNA – Natural and Anthropogenic Risks Research Center [14]. This method orders, compiles and quantifies the evaluation of architectural value and seismic risk in a quick and easy manner. This methodology has been adapted and reviewed throughout research on timber heritage structures (buildings), including the analysis of groups of heritage buildings with similar construction features (Typical zone in cities - zones under historical protection in Chile) (Ministry of Housing and Urban Planning, Government of Chile). Three group of parameters were considered to define the seismic vulnerability model for the building evaluated: heritage attributes (A) (eq.1), vulnerability (V) (eq. 2) and hazards (H) (eq. 3). Table 2 explains the potential appraisals of each input variable of the method (from 0 to 1).

$$A = (0.60A_1 + 0.30A_2 + 0.10A_3) \quad (1)$$

$$V = (0.35V_1 + 0.30V_2 + 0.10V_3 + 0.15V_4 + 0.10V_5) \quad (2)$$

$$H = (0.33H_1 + 0.34H_2 + 0.33H_3) \quad (3)$$

Table 2 – Valuation of variables of the set of parameters for defining seismic vulnerability *(RIPAT1.0)*

Valued variables	*Description*	*Points (0-1)*
Heritage attributes (A)	*Building with no architectural significance and without exposure.*	*0*
	Building with remarkable architectural features and high exposure.	*1*
Vulnerability (V)	*No vulnerable structure.*	*0*
	Very vulnerable structure.	*1*
Hazards (H)	*Building with a very low seismic hazard and located on suitable ground.*	*0*
	Maximum seismic hazard, building located on very poor ground conditions.	*1*

Heritage attributes of buildings (A) are the most visible part of a country's history, reflecting a complexity of ideas and cultural ideals, conveyed over time [17]. Vulnerability of buildings (V) is defined as the degree of loss of performance as a consequence of the occurrence of a natural phenomenon of a given intensity and hazards [18]. In terms of hazards affections (H) , these correspond to the influence of external parameters, which seriously impair building performance [19].
Seismic vulnerability index (RIPAT1.0) (eq. 4) is the convolution of A, V, H. RIPAT1.0 varies between 0 and 1. Table 3 shows the quantitative and qualitative valuation of the output model [20], [16].

$$RIPAT_{1.0} = (A * V * H) \qquad (4)$$

Table 3 - Seismic vulnerability conditions for timber heritage structures

Conditions level	*Range*	*Seismic vulnerability affections*	Colour
Condition A	*RIPAT1.0 < 0.25*	*Building with a low seismic vulnerability*	
Condition B	*0.25 ≤ RIPAT1.0 < 0.5*	*Building with a medium seismic vulnerability*	
Condition C	*0.5 ≤ RIPAT1.0 < 0.75*	*Building with a high seismic vulnerability*	
Condition D	*RIPAT1.0 ≥ 0.75*	*Building with a very high seismic vulnerability*	

3. Results and discussion

This approach sought to estimate the seismic vulnerability index of extremely valuable heritage structures. To this end, it was necessary to evaluate the input parameters used in the methodology. The great advantage of this kind of technique is that it is a quick and very simple system for systematizing and computerizing, and also provides professionals and researchers with a knowledge framework for the assessment and conservation of heritage timber structures [21]. In this sense and regard to case study (Prochelle I House) (Table 4). Firstly, it was observed that the results for the three major aspects evaluated exceeded average values. This finding was quite reasonable given the noteworthy heritage features and high exposure of the building. Secondly, the analysis of the sample revealed some deterioration and structural problems, mainly associated with the state of conservation of the structure, as reflected in the numerical results of the method (eq. 5). Thirdly, although the building is located in a geological area highly suitable for the construction of buildings, it presents a high dynamic amplification and bearing in mind the seismic zone in which it has been erected adds above-average value from the seismic threat standpoint [14].

$$RIPAT_{1.0} = (0.668 * 0.694 * 0.625) = 0.289 \qquad (5)$$

Table 4 – Valuation of input and intermediate variables of the seismic vulnerability model for the study case analysed.

Inputs	*Value*	*Intermediate variable*	*Value*	*Intermediate variable*	*Value*	Output*
A11	*0.200*	*A1*	*0.550*	*A - Heritage attributes*	*0.668*	0.289
A12	*0.200*					
A13	*0.150*					
A21	*0.023*	*A2*	*0.050*			
A22	*0.028*					
A31	*0.038*	*A3*	*0.068*			
A32	*0.030*					
V11	*0.206*	*V1*	*0.206*	*V - Vulnerability*	*0.694*	
V21	*0.075*	*V2*	*0.214*			
V22	*0.056*					
V23	*0.045*					
V24	*0.038*					
V31	*0.020*	*V3*	*0.084*			
V32	*0.012*					
V33	*0.020*					
V34	*0.020*					
V35	*0.012*					
V41	*0.050*	*V4*	*0.150*			
V42	*0.050*					
V43	*0.050*					
V51	*0.040*	*V5*	*0.040*			
H11	*0.333*	*H1*	*0.333*	*H - Hazards*	*0.624*	
H21	*0.042*	*H2*	*0.167*			
H22	*0.125*					
H31	*0.083*	*H3*	*0.124*			
H32	*0.041*					

**NOTE: RIPAT1.0 = A*V*H*

The Prochelle I House, despite its relatively high architectural heritage value and prevailing vulnerability, the structure does not present an imminent risk of collapse and its architectural elements do not present major or irreversible problems [13]. The result (RIPAT1.0) obtained after the analysis of the model and application of the methodology was 0.289 points (eq. 5); it may therefore be classified within condition B (orange colour), namely a building with average seismic vulnerability.

After 2014, as part of the restoration process, the building underwent mayor improvements in the form of structural reinforcement through the incorporation of metal elements or the replacement of deteriorated wood elements, coupled with the improvement and restoration of non-structural elements such as coatings, stairs and façades [16].

Since this heritage building belongs to a group of historical monuments, improvement and restoration work was carried out with extreme care to ensure the original shape of the pieces was preserved so as not to alter its heritage value. Consequently, these maintenance actions allowed the structure to recover and substantially improved its performance conditions. The building is currently the headquarters of the Municipal Cultural

Corporation of Valdivia city. This initiative was of paramount importance because the conservation of cultural heritage is a crucial part of social and community wellbeing in Valdivia [17]. This study presents an innovative tool for organizing, compiling and quantifying the evaluation of architectural heritage and seismic risk in a quick and easy manner [22], [5], in order to develop global urban conservation strategies or preventive maintenance plans that can minimize damage to cultural heritage and reduce the cost of expensive interventions.

4. Conclusions

This innovative study represents one of the first attempts to assess the seismic risk index, considering the inherent heritage attributes of the building, its intrinsic vulnerability and the impact of external hazards to which it is subject. The outcomes achieved can be extremely useful for the organization of maintenance activities, since the conservation of heritage buildings is important in order to preserve the culture of modern societies. As example, this study assessed the seismic vulnerability of the Prochelle I House, as one of the most representative examples of architecture in the city of Valdivia, Chile. The analysis provided coherent results for timber structures houses. Information on strategies for managing historic buildings in South America is currently scarce; hence, this type of methodology makes a significant contribution to the state-of-the-art in terms of the development of preventive conservation strategies in timber structures in southern Chile. The experience gathered in this study marks a further step in the management and optimisation of maintenance work in heritage buildings, enabling experts to select the best moment to intervene and prolong the service life of buildings (decision-making processes in heritage building management) in the most cost-effective manner. This information can help public and private authorities to develop innovative heritage building preservation strategies for different types of constructions (e.g. masonry, concrete, etc.) in the northern-central regions of Chile.

In the future, the model may be adapted to other realities and contexts. The current model could be improved to make the system more versatile and applicable to new case studies focusing on other types of constructions and sets of buildings located in different climatic contexts.

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