Inspection of Seismic Damage and Conservation Conditions in Modern School Buildings in Chile

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Abstract. The present study describes the procedures and results of inspections carried out in public school buildings constructed in Chile between the 40s and 80s. These buildings constitute part of the country's modern heritage. The aim of the study was to empirically analyze – through documentation, in-situ observation and measurements with non-destructive testing – the state of damage and deterioration of school buildings, taking into account that these buildings continue functioning as before, even surpassing their useful life by more than 30 years, with minimal or no maintenance processes. Further to normal wear, tear and aging of materials, Chile's frequent exposure to earthquakes has added lesions and structural damages. This study compares the behavior of buildings constructed with reinforced masonry from an early period (from the 40s to 60s) to the modular buildings constructed with industrialized systems and elements from a later period (from the 60s to 80s), considering the country's seismicity and climatic diversities. In both cases the designs meet standards and regulations for quality and resistance. Pathological processes in structural and enveloping elements were recorded through direct observation. In addition, the instruments used (thermography, metal detector, humidity meter, Hammer test and laser level) enabled further analysis of the building's constructive features. They account for possible causes of damage, monitor structural resistance conditions and measure constructive durability parameters.

Keywords: Structural monitoring · Seismic behavior · Construction pathology School architecture · Modern architecture · Modular building

1 Introduction

Over the past decades, there has been keen academic interest in the preservation problems regarding 20th Century architecture, in particular when built with concrete, since fast processes of damage have been observed in these constructions [1] – especially those that depend on public resources for their maintenance and preservation. This is the case of municipal public schools in Chile.

R. Aguilar et al. (Eds.): *Structural Analysis of Historical Constructions*, RILEM Bookseries 18, pp. 504–512, 2018.
https://doi.org/10.1007/978-3-319-99441-3_54

It can be observed that the damage processes in modern architecture are mainly related to design features, experimentation with new materials and construction systems, heterogeneous use of material in one same building, and project execution. Part of the problem with these buildings is related to the use of various materials with detrimental behavior, resistance and processes, which were hard to predict [2, 3], causing a decrease in their useful life.

"It has become apparent that modern buildings generally require initial (medium level) repair within half the time of more traditionally constructed buildings" [4], this is mainly due to the introduction of an architecture with formal changes that separate enclosures from structure, forming independent units that reduce sections and diversify use of materials.

Further to natural wear, tear, and aging of materials, Chile's frequent exposure to earthquakes has added structural damages, reducing their useful life. Based on these premises, the present study compares the behavior of modern school buildings located in an earthquake-prone and environmentally aggressive area – the Chilean Pacific Coast.

The present paper seeks to demonstrate – through instrumental measurement and monitoring – that buildings located in an earthquake zone are more heavily affected by mechanical damages than by physiochemical damages due to environmental exposure. Logically, the influence of these variables will depend on the constructive and structural typologies of the buildings examined. This is necessary to determine proper conservation methods for school buildings that are not only part of modern national heritage (how especially show in top row of Fig. 1) but also remain in use, and therefore must meet high safety standards.

Fig. 1. Samples of the educational establishment examined. Top row: Eduardo Frei School (Arica), República del Salvador School (Valparaíso), Paula Jaraquemada School (Iquique). Bottom row: Ljubica Domic School (Antofagasta), Flor del Inca School (Iquique), Instituto Superior de Comercio (Valparaíso).

2 Methodology of Inspection and Research

This paper gives partial results from ongoing research addressing school buildings located in desert cities from Atacama (Arica, Iquique and Antofagasta) and a central area (Valparaiso); a total of 18 cases to analyze. The above-mentioned cities have suffered frequent earthquakes of different magnitudes over 7.0 Mw, with salty environments, high environmental humidity and exposure to strong winds. Their main differences are rainfall levels and extreme temperatures (Table 1).

Table 1. Seismic and environmental conditions of the case of study (Centro Sismológico Nacional y Dirección Meteoro de Chile).

1	Educational establishment	Year	Useful life (years)	N° of earthquakes above 7,0 Mw	Environmental conditions			
					Humidity	Winds	Rainfall	Temperature
Arica	Eduardo Frei School	1955	62	6	75% annually	Max. 27.8 Km/h	1.5 mm	Minimum 5.8° Maximum 31.5° Average 21.1°
	Liceo Octavio Palma Perez	1963	54	4				
	Pedro Lagos Marchant School	1970	47	4				
	Liceo Antonio Varas	1981	36	3				
Iquique	Esc. Paula Jaraquemada School	1940	77	8	71% annually	Max. 25.9 Km/h	1.0 mm	Minimum 7.0° Maximum 31.6° Average 18.8°
	Instituto Comercial Baldomero W.	60´	57+	4				
	Especial Flor del Inca School	70´	47+	4				
	Alte. Patricio Lynch School	70´	47+	4				
Antofagasta	Liceo Mario Bahamondes	1947	70	9	77.3% annually	Max. 27.7 Km/h	3.4 mm	Minimum 3.0° Maximum 31.8° Average 16.9°
	Armando Carrera School	1958	59	5				
	Romulo Peña School	1970	47	4				
	Ljubica Domic School	1979	38	4				
Valparaíso	República de el Salvador School	1938	79	7	76.1% annually	Max. 55.6 Km/h	372.5 mm	Minimum -3.6° Maximum 31.9° Average 17.5°
	Alemania School	1944	73	6				
	Liceo Matilde Brandau	1945	72	6				
	Liceo Eduardo de la Barra	1971	46	4				
	Diego Portales School	1972	42	4				
	Instituto Superior de Comercio	1976	41	4				

The selected educational establishments were built from 1937 to 1987 by *Sociedad Constructora de Establecimientos Educacionales* (SCEE) as a government policy for State modernization. In the works performed by them, two stages can be distinguished regarding architectural models (Fig. 1), the first one (1937–1965) uses singular building sites constructed with solid Reinforced Concrete (RC) structures and reinforced masonry with bricks [5]. The second (1965–1987) uses serial, modular and prefabricated sites with steel and concrete. All the works meet the seismic standards existing in Chile from 1930.

From a methodological point of view, this paper sets three different correlated methods of analysis: site natural conditions, constructive-structural morphologies, and pathological processes. Thereafter a comparative analysis of cases was performed between the two types of architectural design previously mentioned.

For sample selection, the seismic and environmental conditions of the different cities and geographic zones of the country were characterized. Subsequently, a search for constructive information in files, planimetry and original technical specifications of projects was undertaken, a work that proved more fruitful with second period projects.

During fieldwork, we performed quality observation of formal, structural and constructive features of the buildings; regarding damages, this process was recorded through referenced photography. Simultaneously, quantity data was collected through measurements with non-destructive devices, which determine constructive features, structural resistance and humidity conditions. Functionally, all measurements was carried out with non-invasive checking used basic tests.

Thermic differences between materials allowed us – using a thermographic camera – to identify non-visible structural elements in walls and roof covers (Fig. 2). This allowed us to differentiate concrete pillars and beams inside the mass walls, revealing its confined masonry construction instead of fully reinforced concrete (RC). This is corroborated by the pachometer, which indicates the areas where there are effectively steel bars of RC. Using this camera on roof covers allowed us to differentiate RC slabs and wooden trusses. The camera was not effective for damage detection or non-visible lesions.

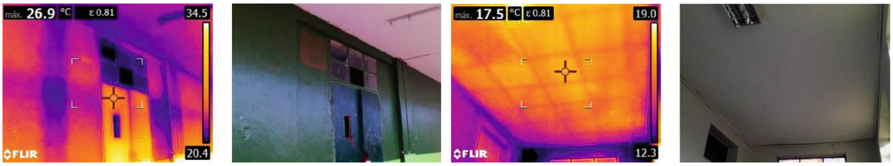

Fig. 2. Element containment display in masonry walls and wooden roof structures.

The Hammer Test Sclerometer was used according to recommendations by [6, 7], under a nine-strikes Protocol for each assessment area, applying it in three minimum sectors from each level. In some cases, filler and paint accumulation have required new measurements.

Measurements of superficial humidity in walls in socle, underground or first level floors (with a height less than 60 cm) were taken. In the same way, humid areas on higher levels and the façade were measured when they presented seepage problems. Carbonation testing was not performed since the concrete was painted and did not present symptoms that required its application.

The information collected has been arranged in a graphical sheet. For our analysis, the behavior of structural elements facing seismic activities was compared with façades and roof covers facing environmental conditions, although we found cases in which both situations combined.

3 Inspection Results

3.1 Structural and Constructive Characterization

Through technical documentation, field inspection and measurements, we classified school buildings based structural and constructive features into four groups:

Of these four types, the first two belong to traditional buildings from the first stage from SCEE and the second pair to the second stage of design, which sought to construct building faster in response to massive educational demand. Buildings from Group 1 (Table 2) belong to the oldest period, with higher static loads (greater number of floors), yet at the same time have a basic slenderness relation in walls (h/e: 9.7–13.6), less than the subsequent buildings. Those with higher structural slenderness (h/e: 11.6–18.6) have fewer levels and static loads, designed with a unique RC structure and better seismic behavior.

Table 2. Structural and constructive characterization of school establishments.

	Structural system	Constructive system	Dimensions	Levels
Group 1 1937–1960	Walls, slabs or trusses	Mixed, reinforced brick masonry, reinforced concrete. Roof cover slabs or truss	Wall thickness: 25–35 cm Height 3.4 m on first level	Socle plus 3 top levels
Group 2 1940–1965	Walls and slabs	Reinforced concrete	Wall Thickness: 15–30 cm Height from 2.8 to 3.5 m on first level	2 levels
Group 3 1970–1985	Rigid frame, buttresses and slabs	Reinforced concrete. Truss partition timber walls in sections. Windows, masonry and panels in enclosures	Type 510, distance module up to 7 m, flying buttress heights 2.4 m	Up to 3 levels
Group 4 1965–1985	Rigid frames and slabs	Reinforced concrete at first level and metallic frames at second level	Type 606: distance module at 3.0 m between frames and 6.0 m between pillars	2 levels

3.2 Structural Damages and Faults

Comparative analysis of damages in school buildings of mechanical origin (due to seismic activity) shows that although they meet acceptable functional and stability conditions, Group 1 buildings are more vulnerable to seismic conditions. They present higher moderate-severity fault frequency related to forces of in-plane shearing, torsion and differentiated movements. Damage severity is estimated in relation to resistance and structural stability losses, as well as possible risks of construction elements falling during the evacuation of children. The main lesions observed were:

(a) ***Diagonal cracks in walls:*** These faults have moderate severity in relation to seismic resistance in school buildings, and are observed in first period premises, mainly in transversal pavilion walls. These walls must resist in-plane shear stress with regard to perpendicular pushes on pavilions. Their length is short (they divide classrooms) and frequently with smaller sections than longitudinal walls. They are repeated faults since there is evidence of previous repairs. In most cases, the cracks cross walls, which lose constructive continuity due to working tensions that exceed admissible tensions for masonry, and even concrete. According to the observed, due to the height of levels, brick masonry enclosure elements do not fulfill the conditions set in NCh 2123 [8] regarding "maximum area of in-plane wall" (12.5 m^2).

(b) ***Expansion joints:*** Detachments in coating mortar, broken concrete, etc. have been produced in joints (Fig. 3). This is a fault in every school building; its severity lies in possible mortar falls since joints pass through corridors and aisles. They constitute repeated poor practice that has led to successive repairs and interventions to avoid rainwater leaking. With regard to seismic activity, structural displacement has been greater than estimated in joint designs (less than 50–55 mm separation) and volumes have probably moved unevenly or with torsion.

(c) ***Cracks from edges in spans:*** These faults are produced in weak areas of the walls such as door and window spans in buildings from Group 1. Due to in-plane shear force, angular distortions are produced in spans with stress that masonry walls do not support. Also frequently observed are vertical cracks that belong to constructive joints between different material types.

Fig. 3. Faults in expansion joints in all buildings in the sample

Concrete elements of second period buildings, according to our measurements with a sclerometer, have homogenous resistance results for surface compression (mean: *fc* 320–340 kWh/cm^2). These results are lower than measurements performed in older buildings (mean: *fc* 230–400 kWh/cm^2). However, frames and slabs do not present structural problems, only micro-fissures in external concrete coating that is exposed, and some transversal cracks in slabs and cantilevered beams in corridors. These show that pillar and beam flexibility (with lights up to 7.0 m), like the rigidity of the knots in these frames, effectively resist the loads and dynamic forces. Nevertheless, most of these buildings present enclosure panel fractures, caused by the children striking or knocking partition materials, mainly chipboard.

3.3 Observation of Physicochemical Damages

Similar environmental humidity conditions (Table 1) in each city have produced gradual deteriorating processes in all the buildings studied, regardless their period of construction. However, educational establishments in Antofagasta have undergone more frequent maintenance processes, and as a consequence there was little evidence of damage of this type.

(a) ***Coating mortar detachment:*** In façade walls of schools from the first period in Valparaiso (high rainfall, humidity and salt levels), there were fissures or cement mortar losses, caused by steel bar corrosion.

(b) ***Stains, efflorescence, peeling paint:*** As shown in [9] common lesions are caused by humidity of diverse origins (Fig. 4). In desert cities there was humidity in socle or underground retaining walls due to absorption by capillarity. Moreover, in Valparaiso damage rainwater leakage was evident in roofs and walls, generally in horizontal concrete roof slabs with poor drainage, as well as a lack of barriers against humidity. Thus, every school building in Valparaiso and the oldest in Arica presented peeling paint under slabs and in exposed elements that retain humidity. Humidity measurements presented higher levels in areas of increased humidity; levels were lower in higher areas, probably due to evaporation.

Fig. 4. Stains, efflorescence and peeling paint because of humidity. Absorption by capillarity in retaining walls (Arica) and rainfall leakage (Valparaiso), environmental humidity from morning fog (Antofagasta).

(c) ***Metallic structure corrosion:*** Deterioration in metallic structures exposed to winds in a maritime environment with high sodium chloride levels, which accelerate corrosive processes in steel (Fig. 5). These damages were observed in schools from group 4 only. Permanent paint avoids oxidation.

(d) ***Xylophagous insects:*** Termite bore holes and feces can be observed in the timber carpentry and secondary elements, probably Porotermes Quadricollis [10], diminishing the interior section. Severity is lower since no school building has a timber structure. However, there are some chipboard panel dividers that have been attacked by termites.

Fig. 5. Corrosive processes in metallic structures with different protection levels (paint).

4 Conclusions

It is proved that first period buildings, constructed in a traditional manner with solid structures, have suffered greater damages as a result of seismic shear forces than buildings built from the 70 s onwards. The only mechanic-origin fault observed in more recent buildings is expansion joints, as with traditional buildings, indicating a sub-dimensioning problem of structural design.

The results of resistance measurements (*fc*) must be considered together with material and morphologic variables, since they may contradict the observed damage levels. It seems that traditional buildings have greater compressive resistance (due to concrete age or greater wall thickness), whereas mixed systems are more fragile. Similarly, the long pavilions model is more vulnerable to torsion and cutting forces than the square model of new buildings.

In general, the school buildings presented good constructive quality, especially concrete buildings from the second stage, which were originally designed to remain exposed. The older buildings (from 54 to 79 years) have resisted between 4 and 9 earthquakes over 7.0 Mw (Table 1) and have presented acceptable seismic behavior, in spite of the aforementioned damages (localized), maintaining stability against static loads and repeated earthquakes (according to standards in NCh 433 [11]). Nevertheless, they present a certain level of vulnerability, for according to this regulation, educational use has an increased degree of importance, and therefore it must meet higher safety standards.

Physicochemical-origin deterioration as a result of environmental conditions was greater in Valparaiso, due to an aggressive weather environment in relation to rainfall and wind speeds. With respect to schools located in desert areas, flat roof covers with slabs presented leakage problems in unexpected rainfall events, a consequence of climate change. Lack of maintenance is directly related with physicochemical lesions that degrade materials, which may decrease its resistance capacity. Second stage school buildings require frequent maintenance to protect roof covers and façade structural elements, since elements are designed with smaller sections and concrete without additional protection mortars.

Acknowledgments. This study was financed by Comisión Nacional de Investigación Cientifica y Tecnológica, CONICYT, Chile.

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