The Chilean Building and the Earthquake-Proof Building Standards

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Keywords: *Chilean building, Chilean Seismic Design Code, architecture, structural engineering, empiric construction*

ABSTRACT

The article inquires into the notion of Chilean building as a structural standard based on reinforced concrete walls as a seismically efficient resource. The theory and practice of this convention are contrasted with the Chilean Seismic Design Code through three local architecture projects built within the 70's decade and the year 2009. Finally, the significance of this convention is discussed, proposing a conceptual expansion of the Chilean building from an architectural perspective.

1985 AND 2010 EARTHQUAKES AND THE CURSE OF THE CHILEAN BUILDING CODE

In general, the nature of every construction code, and of building in particular, is grounded on the need to establish limits and restrictions in the pursuit of one or more objectives. More specifically, earthquake codes seek mainly to provide "safety coefficients (...) with the aim of reaching a reasonable degree of protection against the risk of construction flaws" (Vásquez, Riddell, Cruz, & Lüders, 1993, p. 191). However, the earthquakes proof buildings codes operate in uncertainty field – ruled by the unpredictability of seismic phenomena –, where probabilities offer ranges of approximation towards a certainty that is, as such, utopian (Jacobsen, 1956).

On the other hand, the architectural and structural design may be valid as abstract and theoretic exercises and processes. As an architectural piece gets built, it becomes prone to be evaluated in regard to parameters such as its seismic performance. Thus, the architectural development in Chile can be understood through this key fact, whose production has been marked by huge and devastating earthquakes, as well as by consecutive adjustments to the code.

From this perspective, some of the most important recent earthquakes in Chile are San Antonio (1985, 8.0 Mw) and Cobquecura (2010, 8.8Mw) (Centro Sismológico Nacional, n.d.). The damages observed in both cases derived in building code adjustments (NCh443 Of.72 and NCh433 Of.96). The first case showed structural damages mainly in mid-height masonry buildings related to "conceptual errors in design, poor execution and incomplete projects" (Flores, 1993, p. 172). While reinforced concrete high-rise buildings were mostly undamaged (Vásquez et al., 1993). The main code adjustments, instead, resulted in a seismic zoning of the continental territory, with values of acceleration differentiated according to the proximity to the coastal border and divided into three strips from north to south: coast, center, and mountain (NCh 433 Of.96); in addition with the inclusion of edge structural elements standards design (Music & Ponce, 2014), among others. This code also incorporated the static and dynamic methods, and some considerations related to the building shape and use, security, gravity axial center, between others. Those of them took from the 1972s code.

The 2010 earthquake, instead, lead to a critical revision of standards related to the type and quality of the soil, design spectrum, values for the lateral shift of roofs, and seismic calculation margins based on reinforced concrete walls with edge structural elements (Music & Ponce, 2014). Other factors such as irregular and convex building configuration (Arnold & Reitherman, 1982) were also revealed as damage causes, as structural irregularities and axial loads in reinforced concrete buildings.

A strong quake may be useful not only for critical analysis based on an empirical approach but also to understand building seismic behavior efficiency. Thus, architectural and structural models can be tested empirically. Then, architectural and structural design, theory and practice, merge into a unique instance crossed by an earthquake event. Or, in other words, a kind of a natural laboratory that in the Chilean case has been crucial for earthquake-proof building design advances (Flores, 1993), not only for any building typology but also for a reinforced concrete high-rise.

In fact, in the aftermath of the 1985 and 2010 earthquakes, it could be determined that, besides some few cases, most of them reported high seismic performance standards (Bonelli, 1993; Lagos et al., 2012; Riddell, Wood, & De La Llera, 1993; Vásquez et al., 1993) despite the strong motion reached in both events.

THE CHILEAN BUILDING. FROM THE IDEA TO THE PRAXIS

The Chilean building, as a concept, doesn't have an explicit definition in the academic milieu, despite some authors relate it with a structural practice referring to high-rise buildings based on high-density concrete walls (A. Arias, 1993; Bonelli, 1993; Riddell et al., 1993) which are categorized into two types: "sheer walls, [and] rigid walls or seismic walls in reinforced concrete" (A. Arias, 1993, p. 173). It is also not clearly defined when did this practice begin to take hold. Flores suggests that the 40's buildings, design just under some basic structural rules, were based on two main basic principles: symmetry and "arrangement of continuous load-bearing elements from the base up, with thicknesses and framings decreasing according to height" (Flores, 1993, p. 169), starting from which, the essential feature took hold of the local building characterized "by highly dense walls" (Flores, 1993, p. 169). Conversely, Arias embraces the thesis by Monge, Moroni and García (1986), who attribute its massification to the Chilean standard code NCh429 Of.57, in which "is defined shear tension limits applied for different kind of concrete, under which sheer-resistant frames design may not be necessary" (A. Arias, 1993, p. 177). Yet, it is a characteristic feature fairly accepted and widespread whose "result is typical of our high-rise buildings" (A. Arias, 1993, p. 176). Arguably, the main contribution of this structural typology may be found on its seismic efficiency medium and high-rise buildings tested during strong motion quakes – occurred in the past – without exceeding by doing so the prescribed margins of safety. It is a practice that has been assimilated gradually into the local seismic culture.

If building codes supposed to limit architectural and structural design in order to establish some stability margins, then de Chilean building, as an extended practice, must be seen as an implicit convention, albeit not necessarily one derived from the regulatory framework. Moreover, the structural criteria behind the Chilean building have been validated in the practice and seismic experience. In this context, it is worth asking to what extent the Chilean building has provided tools equally efficient and operative in the field of local architecture, taking into account its requirements (such as architectural program, space, function and shape problems), usually related with demands of a different nature. Or, from an opposite point of view, to what extent the density of the walls in which the Chilean building is based on has extended or rather limited the architectural possibilities of high-rise buildings in the country.

SEISMIC RESISTANCE AND TECTONIC CONVERGENCIES

Although the type of structuring based on reinforced concrete walls – in its two modalities – has been validated in the engineering discipline in Chile, its application in the field of architecture and its acceptance as a convention does not seem so clear, at least in a tacit manner. Among other reasons, because the walls – as a structural and architectural element – imply an increased rigidity of the skeleton, but also a resource that can tend to fall into a compartmentalization of a given space in a not always desirable way, as in flexibles programs and spaces requirements (A. Arias, 1993). They can also generate an impact in spatial and aesthetic decisions tending to favor isolated and svelte structural elements, like columns. A problem is thus presented that is tensioned by architectural explorations and structural solutions that not always converge towards a common formal solution. The bottom issue lays, in any case, rather than in the disciplinary disagreements, in particular convergences that, by means of articulated operations, allow the emergence of architectural proposals that embody structural interpretations capable of permeating the boundaries between both disciplines. This reinforces the notion that architecture "is the rightful owner of creation and the splendor of adequate forms (...) and [which] need [likewise] to rely on scientific knowledge and technical power" (Rojo, 1969, p. 130). From this perspective, the Chilean building should be understood from a broader perspective that incorporates also the architectural dimension.

By examining some given cases, it is possible to understand to what extent does the Chilean building allow variants that take its resistance to the limit and synthesize, at the same time, structural concepts intertwined with an architectural, spatial and aesthetic conception. Three works built within the last five decades will be examined, all of them cut through by modification processes in the Chilean code and great earthquakes. The examination visits the works in inverse chronological order, starting with a recent work and concluding towards the 70´s decade. They will allow to precisely understand the diverse structural variants interpreted architecturally.

The first case corresponds to the Cruz del Sur office building (Izquierdo Lehmann Architects, 2009). In it, a structural-architectural solution is developed that makes of the built object a form of expression that tells about the transmission of the gravitational loads of the building (Izquierdo, 2012), through an inverted trapezoid (Figure 1). The building is monolithic and is composed of a vertical core made of double parallel walls (Figure 2), perimetral frames that configure the façade and the slabs for each floor. In turn, the framed system unfolds freely from the closing planes, acting autonomously and making of the structural grid an element that aesthetically defines the volume (Izquierdo, 2012). The regularity in the continuity of structural elements is taken to the extreme at the ground floor, where all perimetral support is dispensed of. The central core becomes the vertebral column of the body, as it goes through all the levels while receiving the loads of the sloping planes in the façade through a network of branching beams that converge into structural nodes housed in the walls (Figures 1, 2 and 3). Apart from its monolithic character, the piece establishes an order ruled by two supporting systems which, combined, enable the existence of free floors (solving the program requirement). The structural demands in this case reveal a double dimension. On the one hand, to support the internal tensions of the building (its own mass and weight, deformations, joints); and on the other, to oppose resistance to seismic effects within the ranges established in the code. It differs in this case from the Chilean structural model not so much in the density of the walls, but in the way they are distributed. Indeed, instead of assuring a layout that covers a great portion of the floors in each level, the decision was to concentrate them, without compromising by doing this its stability or its seismic resistance, but rather achieving a singular work that reinterprets the matrix notion of the Chilean building *supported in the prevalence of wall-like facings.*

A different variation of the high-rise building that moved in the same direction is the Centro Santa Maria tower (Alemparte & Barreda Architects), designed and built between 1978 and 1980. Flanked by the footings of the Metropolitan Park and the Mapocho river, the volume is resolved in a vertical prism with a square footprint (25.80 m on each side), pure, regular and without any discontinuities in its 30 stories. Reliant on the 'tube within tube' structural building scheme (S. Arias, 1985), the tower establishes a formal resolution based on the combined use of reinforced concrete walls and columns cast in the site, and prefabricated slabs and girders (Monge et al., 1986). Steel frames were also included, confined to the ground floor so as to avoid "beams of excess height over the wide openings in the accesses (...) [and whose columns] are supported by the walls in the first basement level" (Monge et al., 1986, p. 115). The particularity of the case is solved through a traditional variant of the rigid portico that allowed the characterization of the exterior of the building and the generation of free floors. This variant consisted of shifting columns and beams out of plumb, and displacing the latter towards the inside so that, preceded by the glass enclosing, they are invisible from the exterior. By doing so, the vertical grooves that conform the sequence of pillars (in foreground) and the glass enclosing (in the background) are exposed in the exterior. This architectural strategy enabled to enhance the height and geometric purity of the building (Figures 4 and 5), as well as shifting the interpretation of the Chilean building *towards one of the endemic architectural problems in the local milieu: the svelteness of the building and its structural components.*

The third work examined here is the Empresa Nacional de Electricidad (ENDESA) corporate building. Designed by Luis Larraguibel, Jorge Aguirre, Gastón Etcheverry, Emilio Duhart and Roberto Montealegre (1961–1968) and built before the formalization of the building code NCh433 Of.72 (Larraguibel, 1969), the architectural piece had to comply with the regulatory contents in force at that time, that is, the Ordenanza General de Construcciones y Urbanismo (General Ordinance for Construction and Urban Design) of 1949. Despite this, the architectural and structural design methods used anticipated some contents included later in the 1972 building code.

The scheme that orders the tower is constituted by a rigid vertical column, rigid exterior porticos and pre-tensioned reinforced concrete beams and slabs ('ENDESA', 1969), responding in this manner to a structural criteria "based on rigid frames and simple or coupled rigidity walls" (S. Arias, 1985 p. 45). The particularity of the ENDESA building lays in "the simplicity that governs the spatial and structural order (...) in the unity of the supporting elements, the continuity in the transmission of vertical loads or in the rigidity of the porticos that surround the facades" (Barrientos, 2018, p. 12). At the ground floor level (Figure 6), the walls are distributed in a regular pattern around the geometric center, in a double core disposition ('ENDESA', 1969), while the exterior perimeter is characterized by a sequence of hexagonal section columns (Barrientos, 2016) that carry the upper loads axially to the ground (Figure 7). The key that relates ENDESA's corporate headquarters with the Chilean building *lays (together with the concentration of rigid walls) in the progressive diminution (in ascending* *order) of the sections of columns and beams (Barrientos, 2018), bringing together in this manner the continuity at the base and the reduction of thicknesses in ascending order (Flores, 1993).*

CHILEAN BUILDING. *REREADING FROM ARCHITECTURE*

The high level of seismic performance of high-rise buildings made of reinforced concrete in Chile is due to a multiplicity of factors, among them stand out the inclusion of high-density walls, along with other types of solutions. Although the beginning of this practice in architecture and engineering hasn´t been established precisely in the country, it has been gradually assimilated as a convention, understood as a structural criterion that contributes significantly to seismic resistance. The Chilean building *is not a single model or matrix for designing structures. Rather it responds to monolithic buildings based on the use of walls that are perpendicular among them, distributed in such a way in the plan that they respond adequately to seismic forces. Rather than a model, it is a structural type that offers multiple combinatory alternatives, although always confined to a realm restricted by seismic action. Materially, such possibilities are viable through reinforced concrete as technical and building resource characterized by its 'adaptive-resistant' condition, and with mechanical properties where "steel endows stone with fiber (...) [and] concrete endows steel with mass" (Torroja, 2010, p. 67).*

That the Chilean building *emerged in the practice rather than from the codes does not mean, however, that it may distance itself from the criteria, methods and design parameters established in them. On the contrary, it has served as a complement, contributing – initially indirectly – to the critical evaluation of damages identified in buildings after a major earthquake.*

From an architectural perspective, though, the Chilean building *has become, before anything else, a morphologically flexible form of convention, with possibilities of handling and expressing material aesthetics and open to combination with complementary and solidary structural systems, in part tending to achieve greater svelteness, both in the supporting elements as in the built body itself. The cases examined here are the reflection of the spatial alternatives that emerge from the relative resistance offered by* seismic walls *(A. Arias, 1993). But, above all, of the architectural ideas that have managed to shift, together with structural ingenuity and under the auspices of building codes, the boundaries that separate seismic resistance from destruction. In their way, these three works embody theoretical architectural and structural approaches based on the* Chilean building *– of which they also are part – and that suggest a field of exploration expanding rather than limited.*

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