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"IRON CAGES." TECHNICAL DISCUSSIONS AFTER THE 1906 VALPARAÍSO EARTHQUAKE AND RECONSTRUCTION WITH NEW TECHNIQUES AND MATERIALS

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Abstract. *A few months after the San Francisco earthquake and fire in April 1906, the prosperous and cosmopolitan city of Valparaíso (Chile) suffered a similar catastrophe, sparking the forerunner application of new materials and construction systems. After the earthquake, reports, and articles were produced analysing the characteristics of the earthquake and its effects on the built environment, emulating at a more basic level those emanating from the ad hoc commissions created to analyse the earthquakes in San Francisco and Messina (1908). At the theoretical level, solutions for reconstruction were discussed between reinforced concrete and steel structures, and the applications of these new materials, structural systems, and constructions in the world were closely observed. The solutions used for reconstruction ranged from proven inefficiencies prior to the earthquake to new techniques and materials. In this area, the use of steel with imported pre-manufactured systems as well as local solutions stands out. The need to reconstruct public and private buildings in Valparaiso with a reliable and fast system leaned the choice at the beginning towards the use of pre-manufactured metal structures. The article will expose and analyse the discussions of the time regarding construction systems and materials from a seismic-resistant point of view, complemented with the description of three emblematic cases of metal medium height construction in Valparaiso, after the earthquake: the Hucke Factory, Cardonal Market and the "Jabonería La Estrella" Factory.*

1 INTRODUCTION

On August 16, 1906, a few months after the earthquake and fire in San Francisco, the prosperous and cosmopolitan port of Valparaiso suffered a similar catastrophe, detonating the pioneering application in Chile of new construction systems and materials for the local area. The Valparaiso earthquake along with the San Francisco earthquake of the same year[1] and the Messina earthquake of 1908 was a turning point for seismology and seismic engineering, setting the end of the so-called historical earthquakes, with the transition in the approach to seismic engineering from one based on empiricism to another based on science. After the San Francisco earthquake, detailed reports made on the effects of the quake as regards the built environment and seismological aspects [1]. Lawson's work, one of them, focuses on describing earthquake effects on rural areas, buildings, drinking water, and railway networks. In Italy, Engineer Mario Baratta and a team also prepared a detailed report with injury surveys, and damage planimetry in the main cities [2] and a committee of experts analyzed, evaluated and proposed dynamic seismic calculation formulas and new regulations [3]. After the Valparaiso earthquake, some reports and articles arose, analyzing the characteristics of the quake and its effects on the built environment, quoting in one of them the reports and scientific articles of the San Francisco earthquake [4]. Chile also published a series of articles analyzing the San Francisco earthquake that had considerably more ground information than the local earthquake [5-7]. Discussions among specialists reveal the heterogeneous flow of knowledge and the freedoms given to architects, engineers, and builders in the absence of national building regulations and weak local ordinances, a weakness that has persisted for almost three decades[2].

The solutions used for reconstruction ranged from the proven inefficiencies before the earthquake, to new techniques and materials. On a theoretical level, reconstruction solutions were discussed between the use of reinforced concrete and steel structures, looking closely at the applications of these new materials in the world. The need to rebuild public and private buildings in Valparaiso with a reliable and fast system, at first favored the choice of prefabricated metal structures. Both the speed of assembly and the seismic-resistant characteristics of the steel structural systems influenced this choice, as did, to a not lesser extent, the origin of the owners and principals of the buildings. In the analysis of the material choice, it should take into account that Chile did not have local steel production until 1924, with a brief and failed attempt in 1910 at the Altos Hornos de Corral [8, 9].

2 THE ASSESSMENT OF THE EARTHQUAKE'S EFFECTS

Five days after the earthquake, in New York, 8,200 kilometers away, The New York Times interviewed Chilean engineer Juan Tonkin [10]. According to Tonkin, the destruction in Valparaíso had not been as high as indicated by different sources, affirming his belief that the earthquake damage reports were exaggerated. We are not clear who Tonkin's informants were. Yet, the information he received was incorrect, as the earthquake for Valparaiso was a catastrophe, and for a sector of the city called El Almendral, the ruin [11]. Despite this error, Tonkin's comments regarding the characteristics of the construction in Valparaíso, its possible problems, and the projections for the reconstruction are understandable. Tonkin was clear that the area most affected by the earthquake had been the land reclaimed from the sea, the sector of El Almendral, characterized by uncontrolled sand and artificial fillings. Another relevant factor was that it had been years since Valparaiso had suffered an earthquake of magnitude, with buildings constructed without the necessary provisions, stone, and brick buildings that did not have the required flexibility to withstand an earthquake. In the interview, Tonkin declared his preference for lightweight partitions and steel structures, due to the advantages in their behavior against earthquake and fire, arguing how convenient it was to build buildings of up to 8 or 10 floors of steel, thinking how limited was the space of the city plan.

After the earthquake, the Chilean government appointed an ad hoc commission to analyze the quake, headed by geographer Hans Steffen. Steffen, aware of the importance of on-site observation used in his explorations, applied the observer method for earthquake analysis [12]. However, these methods had long since fallen into disuse. The magazine of the Chilean Institute of Engineers published the report's results [13]. Within the analysis line of the seismological phenomenon, there is also the article by Luis Zegers [14]. Although we found a series of published works on seismology, such as those mentioned above, the analysis of the earthquake effect in Valparaiso on the built environment and the rest of the affected cities is limited. It is in contrast to the series of articles published in Chile analyzing the San Francisco earthquake[3].

The first report published on the earthquake effects on the built environment was by Prussian engineer Carlos Koning [15], Director of Public Works and founder of the Materials Resistance Laboratory of the Universidad de Chile. In his article, Koning describes the effect of the earthquake on commercial construction to learn lessons for future buildings, assessing the problems in masonry and possible solutions. Undoubtedly the most interesting analysis of the earthquake is that of the young engineer Hormidas Henríquez, who published in the newspaper La Unión de Valparaíso a scientific article in six editions gathered under the title "The earthquake of Valparaíso under its constructive aspect." [16]. The article was published in a book and also in two well-known Spanish magazines[4]. They contrast the knowledge of seismic engineering of Henriquez, a newly qualified engineer, with that of Koning, an experienced engineer. Henríquez had up-to-date knowledge about seismic engineering; he knew Lawson's report on the San Francisco earthquake and the work of Milne in Japan, one of the pioneers of seismology worldwide. Koning sought to position "well-executed masonry" alongside iron and reinforced concrete masonry. On the contrary, Henríquez proposed the abandonment of masonry, judging the "detestable brick." Henríquez cites a series of articles in Engineering Record magazine about the effects of the earthquake and the suggested solutions. One of the cited articles is that of the engineer Edward Boggs [17], who postulates that "Steel Frame" is the best solution to earthquakes for high-rise buildings, as the Claus Spreckels building. Other engineers also cited shared this position[5]. Henríquez was debating himself between the reinforced concrete systems and the metallic structures. The entry of reinforced concrete into Chile was delayed after the disastrous collapse of the Casa Prá building in 1904, built with the Cottancin system [18].

3 « VALPARAISO OF THE FUTURE »

Before the earthquake, in Valparaiso, iron, and steel were used in building construction as insulated parts (i.e., columns, beams) and reinforcements (i.e., hardware, inserts), just as in the early days of iron use in Europe [19]. These pieces and reinforcements were inserted in traditional masonry models, resulting in some cases detrimental to their seismic performance. The deficiencies of mass construction systems in seismic behavior were exposed, after the catastrophic consequences of the earthquake, leading to a debate among professionals who proposed various solutions for reconstruction. Most of them based on construction models used abroad, considering the use of steel structures among them.

A few months after the earthquake, the illustrated current affairs magazine Sucesos published a report entitled "Valparaíso of the future," with photographs of a metal structure building under construction, in a central area of the city (figure 1). The architect and director of the work Antonio Lafoglia designed the building in question, the metal structure assembled by Alejandro Beltrami, and the masonry by C. Pirazzoli, all of the Italian origin. The building, designed before the earthquake, was originally a masonry structure. Nevertheless, the experience of the catastrophe made it necessary to rethink the construction system, replacing the weighty masonry walls with an "elegant iron cage." Note the term "elegant," perhaps related to the lightness of the construction system's appearance, a symbol of modernity. Since the building construction started before the earthquake, the plinth was made of masonry, and the metal structure mounted on it. The steel and concrete building is advertised in the news report as a fire-resistant building rather than an earthquake-resistant building. In contrast to "Valparaíso of the future," the same magazine publishes in another edition the "Valparaíso of the Past," a photograph of the Valparaíso Theatre under construction, a building with masonry walls and a wooden structure on the roof that did not finish due to the earthquake. Lafoglia's work can be seen as a relevant milestone in the constructive transition from mass systems to metallic systems. This building is positioned as an example of replacement of the traditional systems, making possible the construction of more slender buildings, with a greater number of floors and free of the ornamentation that predominated in the masonry buildings.

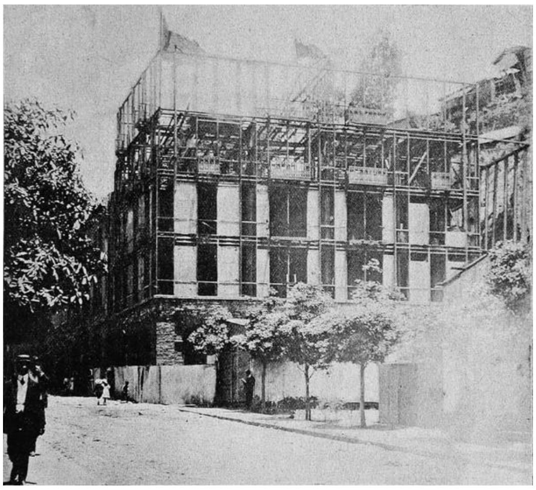

Figure 1: Construction of the metal structure building by architect Antonio Lafoglia, San Agustín slope, Valparaíso (Revista Sucesos 1907, No. 227, January 10, 1907).

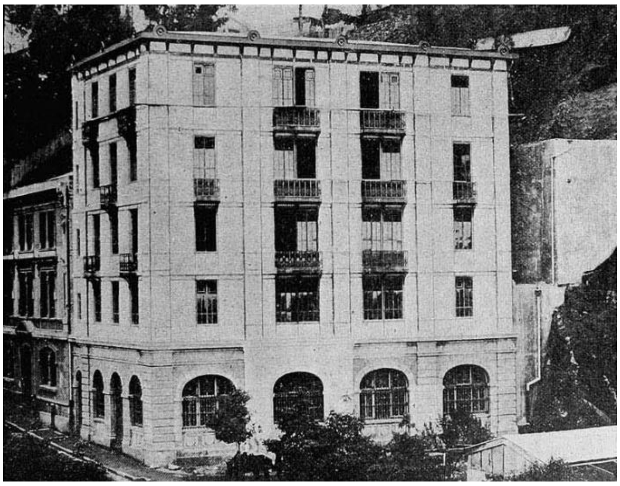

Figure 2: Building with a metal and concrete structure resistant to fire and earthquakes, San Agustín slope, Valparaíso (Revista Sucesos 1907, No. 251, June 28, 1907).

Concerning the architectural aspect, but also structural construction, there are two possibilities for integrating the metal structures and their filling: expressing the steel framing in its facade or hiding it. The latter will not be discussed in this article as they are seen as a precedent for reinforced concrete systems. Among the first we will analyze three emblematic cases of metal construction in Valparaíso after the earthquake: the Mercado El Cardonal, the

Hucke Factory, and the Jabonería La Estrella[6]. In the studied buildings, of compact geometry, walls' filling is placed between the steel profiles, keeping them visible both towards the outside and inside. The three analyzed buildings correspond to the Steel Frame system, a metal grid with infill walls, whose first exponent as a medium height building with an iron structure is the Chocolaterie Menier by Jules Saulnier built-in 1872 near Paris. However, the analyzed structures differ from the building of the chocolate factory in two significant aspects. In the studied cases, laminate steel predominates, as a construction material, and the configuration of the bracing elements are cross-linked beams and columns, not a net as in the Menier factory.

4 EL MERCADO EL CARDONAL

Mercado El Cardonal building occupies an entire block. Before occupying the land, the market was located in an adjacent block, under the name of "Recova del Cardonal," built-in 1855 by the American builder Alexander Livingstone [20]. The masonry building had two floors with a central courtyard.

As with other buildings in El Almendral, the earthquake and subsequent fire destroyed the Market. In the first instance, a temporary facility called "El Mercado de las Delicias" was built while waiting for a project for the new market. Then, there were a series of proposals, such as the one from the municipal official Abelardo Arriagada, influenced by the European markets of the 19th century. Also, the one from the well-known architect Eugenio Joannon, who finally became the architect of a project, whose authorship is still unclear. Eduardo Feureisen Harms, a Civil Engineer, graduated from the Universidad de Chile in 1903.

In 1912, the works of the new Mercado building began, a steel and concrete block structure imported by the Municipality of Valparaíso through the company based in Valparaíso, Vorwerk y Co., representative of the German company specialized in steel constructions, Aug. Klönne from Dortmund (figure 2). In mid-1914, the new Mercado de El Cardonal opened. According to a publication for the 50th anniversary of the company, El Mercado was one of the projects of Aug. Klönne abroad. The 1,000-ton building was manufactured, moved, assembled, and delivered on a turnkey basis [21]. The company had specialized departments for the integral development of steel projects.

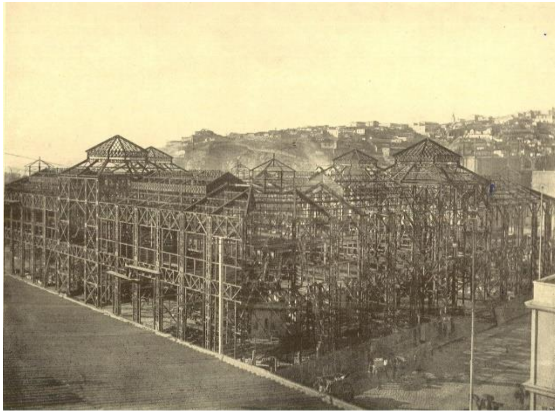

Figure 3: Construction of Mercado el Cardonal in 1913 (Source: Aug, K., Aug. Klönne Dortmund 1879-1929. 1929, Dortmund: Krüger GmbH)

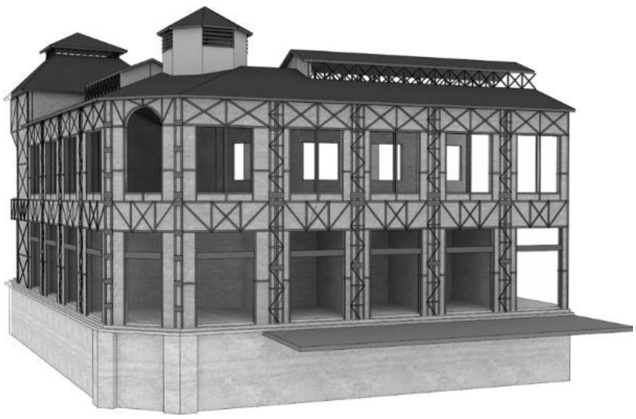

Figure 4: Exterior facade of El Mercado (drawing: Katherine Cabezas).

4.1 Building description

Mercado El Cardonal is a trapezoid-shaped building whose sides measure 67, 54, 68, and 60 meters, and its corners are octagonal. The building has a compact appearance and occupies the entire surface of the block, with two floors plus a basement (Figure 3).

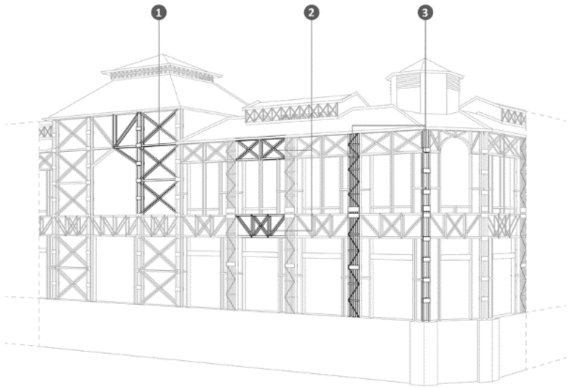

Figure 5: Components of the structure of the exterior facade of El Mercado. 1) braced walls 2) lattice beams 3) simple composite column and bracing (drawing by Katherine Cabezas)

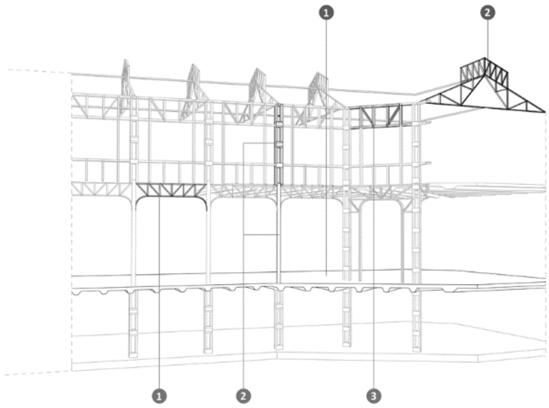

Figure 6: Components of the internal structure of El Mercado. (top) 1) rigid diaphragm 2) cross-linked truss (bottom) 1) lattice beam 2) column 3) bracing (Katherine Cabezas drawing).

A perimeter ring and a central piece shape the building, both separated by a double-height space that makes them structurally independent. Both the perimeter ring and the central piece are structured based on flexible steel frames, achieving free floors on each of their levels. As an enclosure of the building and also its interior partitions, the metal structure was filled with concrete blocks, giving the structure greater rigidity. The metal framework consists of single-section, cross-linked pillars, and beams, on the outside and part of the inside of the building (Figure 4). The cylindrical pillars inside the first floor are cast-iron pieces. In the underground, only its interior skeleton is exposed, leaving the metal structure embedded in a concrete wall on the perimeter, thus avoiding the oxidation of the metal parts. The roof structure is composed of exposed steel trusses and turnbuckles with a corrugated zinc plate covering. The latticework of its exterior facade stiffens the building. The façade made up of two lattice beams that extend along its entire length and of pillars made up of triangular and plain profiles, which make up the building's frames. The interior facade is made up of trusses with few diagonals on the upper level and a lattice beam on the first floor. The rigid diaphragm is a slab ribbed by a succession of steel beams that rest on pillars and intermediate walls of the building in a perpendicular direction to the perimeter axes (Figure 5).

5 HUCKE COOKIE FACTORY BUILDING

The Hucke factory[7] is a particular case in this selection, with a building inaugurated in 1901 with two floors, built with brick perimeter walls and a wooden interior structure. The building resisted the earthquake with minimal damage, restoring normal factory operations within a few weeks. However, three months later, a fire destroyed the entire factory[8]. First Ernst Hucke and after his death his brothers, Otto and Georg, traveled to Germany to observe on-site the buildings and facilities of the most important factories. In Germany, they contracted at the German steelworks Burbacher Hütte in Saarbrücken a prefabricated steel structure for a five-story, 10,000 square meter building [22]. Fourteen months after the fire, and under the direction of the architect-engineer Otto Andwanter, the building was inaugurated (Figure 6). Its height and aesthetics positioned it at the time as the tallest and most modern building in Valparaiso.

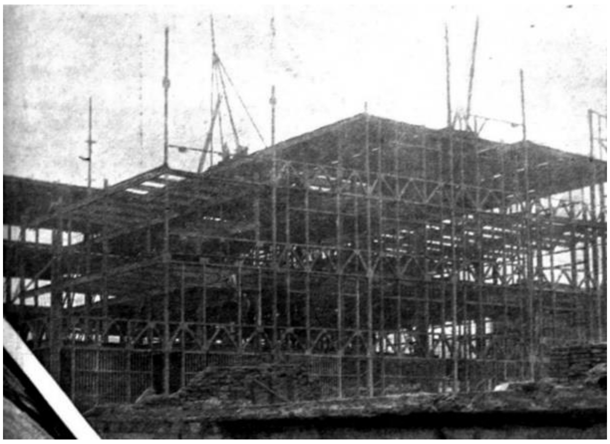

Figure 7: Construction of the new Hucke factory in 1908 (Source: Resurgence of Valparaíso, 1908, August 16, Zig-Zag Magazine No. 182).

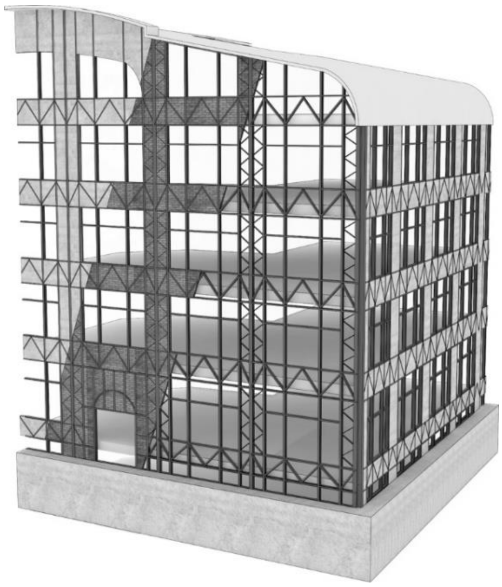

Figure 8: Structure of Hucke factory facade (drawing by Katherine Cabezas).

5.1 Building description

The Hucke factory building occupies the end of an elongated block, with three facades facing the street and a dividing wall adjacent to the reinforced concrete construction of the sugar refinery built years later, designed by architect Karl Mönch. The factory is a compact trapezoid-shaped volume with sides ranging from 38 to 40 meters and a maximum height of 30 meters, divided into a basement, five floors, and the mansard. Inside, it housed large and heavy machinery for the production of its products. The interior luminosity of the building is possible thanks to its structure, which in addition to reducing the mass, allows for larger openings in its walls compared to masonry buildings.

The first bay next to the façade absorbs the difference between the plant’s perimeter irregularity and the interior structure regularity. The interior distribution in each one of its floors resolved in a free level divided into seven crossings of 5.70 meters wide by 40 meters long and six transversal to these of similar measures. The widths of the bays are variable on the facades: one goes from 5.20 meters to 1.70 meters and the other from 5.30 meters until it disappears at the other end. The height of each floor is, on average, 3.70 meters between the slab and main beam and a maximum of 4 meters between slab and vault. From the underground level, the floors are vertically connected by an inner courtyard that adapts to the frames of the primary structure, located off the central axis of the building. The metal skeleton is mainly made up of nine uniformly spaced frames, which are transversally tied by eight main beams in each of their slabs. At the same time, the perimeter of the structure acts as support against lateral forces as it is made up of lattice beams and columns (Figure 7). In the basement, the perimeter walls in reinforced concrete and in the upper floors in brick masonry.

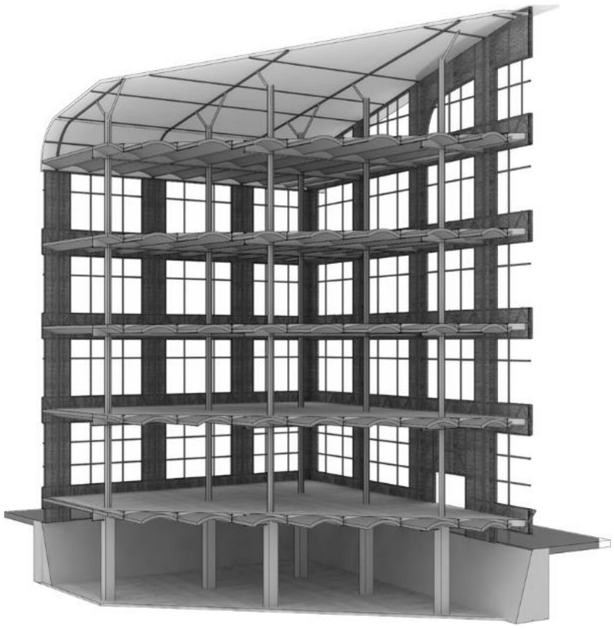

Figure 9: Interior structure of the Hucke factory (drawing by Katherine Cabezas)

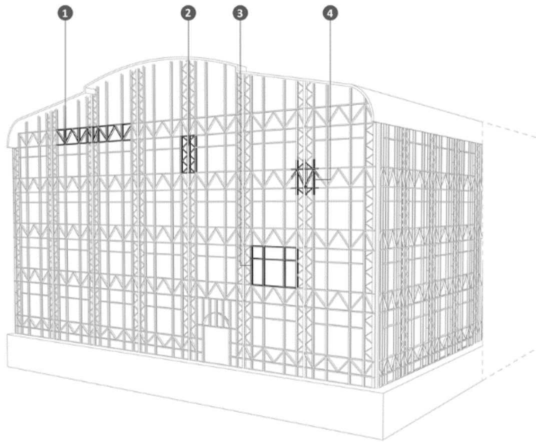

Figure 10: Structural components of the Hucke factory facade. 1) lattice beam 2) structural panel 3) span reinforcements 4) meeting of lattice beam with structural panel (drawing by Katherine Cabezas)

Inside the building, the horizontal structure is constituted from the basement to the fourth floor by a secondary steel beam that supports masonry vaults and that are arranged transversely to the main beams, transferring the loads to the vertical structure. The vaults are covered with concrete, leaving an approximate thickness of 50 centimeters. As for the internal vertical structure, it consists of pillars made of simple laminated steel profiles joined by plates, stiffeners, and rivets, obtaining vertical continuity through connecting plates. On the fifth floor, this structure changes by creating branched support for the roof structure. The joints between the vertical and horizontal structures use angle plates and bolted or riveted gussets (Figure 8). It should be noted that the general structure of the case is mainly supported by a rigid perimeter and center, which in the building can be recognized as the exterior façade and the interior façade towards the inner courtyard, concentrating in them all the bracing systems (figure 9).

6 LA ESTRELLA SOAP FACTORY

John Deichert founded the candle and soap factory in 1866, with experience in the business in his own factory in Kassel [22]. His son, John William, who studied at one of Brunswick's leading soap factories, took over the factory in 1899. The soap factory before the earthquake was located on a central street in Valparaiso in a colonial building. After the earthquake, the building was in ruins, and the factory moved to another lot in the city where they built a shed. In September 1910, the shed was burnt down, and in October of the following year, the new building with metal and reinforced concrete structure was inaugurated, a building specially built for its functions (Figure 10). In the Municipal Archives, the current lot of the factory has the entrance of a building project of metallic structure similar to the existing one, the first semester of the year 1908; the construction of a new building was already in the horizon.

Figure 11: Interior of La Estrella soap factory (Source: German progress in America, 1924).

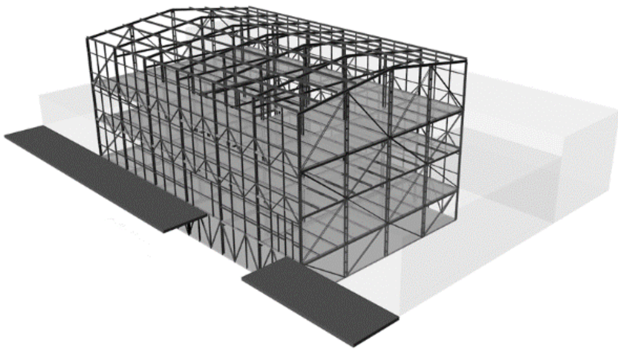

Figure 12: The steel structure of the soap factory (drawing: Katherine Cabezas)

6.1 Building description

"La Estrella" factory is a rectangular-shaped volume with three blindsides and a façade facing the street, measuring 33 by 22 meters at the base and 19 meters high from its underground level (figure 11). Structurally, the building's interior is regularly divided into six bays on its longest side and four cross bays, while its height is made up of three open-plan floors plus a basement level, with the upper levels connected by a large central void that served as ventilation and natural lighting system (figure 12). The factory is structured by steel elements from the underground level to the roof, with reinforced concrete enclosures in the whole of its perimeter walls. Additionally, brick masonry is used as a lining for the metal elements located in the underground, as a strategy for protection against moisture and to provide greater strength. The metallic skeleton is made up of seven frames that cross the smaller side of the volume, composed of five pillars each and intersected in the same direction by main beams and a transversal framework of eleven secondary beams that tie up the set of structural elements. The perimeter of the building has stiffening elements, which in its smaller walls, are made up of V-shaped braces that intercalate their orientation between floors, from the basement to the roof (Figure 13). As for the larger walls, stiffening is based on the formation of two lattice beams at the height of the slabs and a V-shaped bracing in the basement wall, embedded in the reinforced concrete.

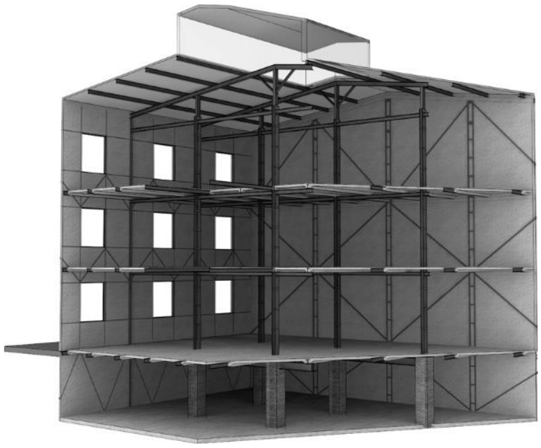

Figure 13: The internal structure of the soap factory (drawing: Katherine Cabezas).

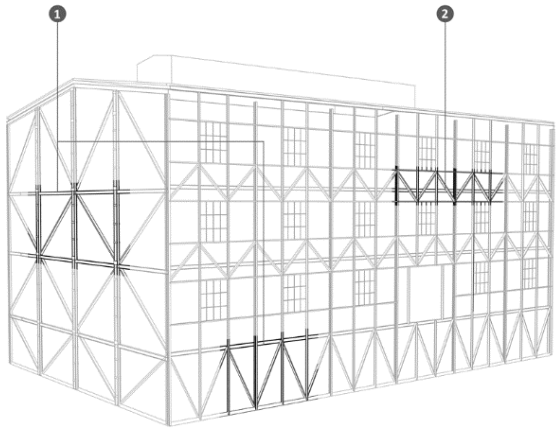

Figure 14: Structural components of the factory facade. 1) braced wall 2) lattice beam (drawing by Katherine Cabezas)

7 CONCLUSIONS

The use of metal construction systems in Valparaíso had an unprecedented application after the earthquake, an expression of its capacity for reconstruction and its booming industry, in a cosmopolitan city that was economically projected in the Pacific due to its potential as a commercial exchange port. The fact that it was a port allowed the fast-import of new technologies and construction materials from North America and Europe (e.g., cement, steel beams, pipes, wood, etc.). Thus, the origin of the structural components of at least two of the three cases is German steel companies - Mercado el Cardonal and Hucke Factory -, and the Soap factory certainly as well. It should be noted that at that time, there were no steel mills in Chile that supplied iron or steel parts; however, there were central-workshops capable of assembling a structure based on imported standard profiles.

The excellent performance of the metallic structures in the San Francisco earthquake earned it a good reputation among the engineers and architects of Valparaiso, in addition to the similar characteristics of the soil.

According to the seismic-constructive strategies, a configurable relationship is established between the traditional construction models of mass and steel frames, where both distribute a large part of the stiffening elements in the structure perimeter. For the study cases, the elements are braced columns, structural panels, lattice beams, and complete wall bracing, distributed symmetrically with respect to the main structural axes of the buildings. On the other hand, in some cases, the filling of the metal structure through a hidden reinforcement contributes to the stiffening of the steel framework avoiding deformations. About the structural elements, these are mainly U-section, double T-section, flat and angular profiles, while for the joints, riveted and bolted gussets and connecting plates are used.

Finally, as a general conclusion, it is argued that the 1906 earthquake considerably accelerated the process of architectural transformation that had begun in the mid-19th century, positioning steel trusses as the most reliable and fastest system for reconstruction. However, the close link with international technical and technological development means that the use of reinforced concrete will soon replace this system.

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[1] On January 31, 1906, the Esmeraldas earthquake occurred between Ecuador and Colombia, with a calculated magnitude of 8.8 Mw. Despite the magnitude, the impact of this earthquake was less than that of Valparaíso and San Francisco because it did not affect urban centers (Moncayo, M., et al., *Terremotos mayores a 6,5 en escala Richter ocurridos en Ecuador desde 1900 hasta 1970*. Ingeniería, 2017. **vol. 21**(n° 2): p. 55-64).

[2] The General Law and Ordinance on Construction and Urbanization promoted after the 1928 Talca earthquake, published in 1936. The law dedicates a section to the calculation of building stability to achieve *the assimilation of the constructions.*

[3] As an example the following articles: Hoerning, Cárlos. 1907. "El terremoto de San Francisco de California sus efectos y la reconstrucción (will continue)." *Anales del Instituto de Ingenieros de Chile* año VII (n° 4): p. 168-180; (n° 5):p. 197-284. Calvo Mackenna, Domingo, and G. H. del Canto. 1907. "El Terremoto de San Francisco de California sus efectos y la reconstrucción (Continued)." *Anales del Instituto de Ingenieros de Chile* año VII (n° 7):p. 374-375; (n° 8):p. 391-407.

[4] Henríquez, Hormidas. 1907. "El Terremoto de Valparaíso bajo su aspecto constructivo." *Arquitectura y Construcción*. Año XI (n° 177):p. 119-127; (n° 178):p. 147-156. Henríquez, Hormidas. 1907. "El terremoto de Valparaíso bajo su aspecto constructivo." *La Construcción Moderna* (n° 7): p. 116-119; (n° 8): p. 130-137; (n° 9): p. 146-151; (n° 10): p. 165-170.

[5] Phillip E. Harroun, Maurice C. Couchot, W. C. Ambrose, profesor Frank Soulé y Carl Leonardt.

[6] At present the Market building continues to fulfill the same functions, the Hucke factory houses the Faculty of Engineering of the Universidad de Valparaíso and the La Estrella soap factory the Labor Court of Valparaíso. Both factories have been subjected to reinforcement works of their structure due to their excessive flexibility.

[7] The Hucke cookie factory in this period achieved great success both locally and internationally, reaching a position as the largest factory in the entire Pacific coast (Sucesos Magazine n°s 208-225, 1906).

[8] On November 17, 1906, a fire in the biscuit ovens destroyed the factory in two hours (Sucesos Magazine n° 208-225, 1906).