Eduardo Torroja: The Alloz Aqueduct

EDUARDO Torroja Miret graduated as an engineer in 1923. That same year, after a bloodless coup d'état, General Primo de Rivera assumed the control of government in Spain and launched a modernizing economic program clearly based on infrastructure: development of the telephone network, modernization of ports, tramway system expansion, creation of 800 km of railroads, extension and paving of over 15,000 km of roads...

By Carlos García Vázquez

SPANISH engineers faced the challenge from very conservative positions, educated as they were in the harsh canons of the Madrid *Escuela de Caminos y Canales* (Civil Engineering Faculty), founded in 1802 and which had inherited the strictly technicist, regulatory and economistic spirit of the *École de Ponts et Chaussées* in France. Many of them despised reinforced concrete, both technically and aesthetically. Hennebique's patent had been introduced in Spain in the late 19th century by José Eugenio Ribera, engineer and owner of Hidrocivil. Certainly, the monolithic system of the patent's frames did not leave much creativity leeway. Other obstacles also had to be taken into account: first, the precariousness of calculation systems (the resolution to a surface structure involved tens of equations with tens of unknown factors to be solved without using computers), and secondly, the absence of structural testing centers in Spain (the smallest design heterodoxy involved making expensive models). Under these circumstances, experimentation did not deal with reinforced concrete.

This bleak scenario was abruptly diluted in 1930. A systematic research process led to the application of photoelasticity in numerical calculation, the marketing of strain gages, the appearance of inductive sensors, the development of movement and deformation measuring methods... This series of innovations sparked two revolutions: pre-tensioned concrete and concrete shells. The first was patented by engineer Eugène Freyssinet in 1928, although it was not definitely recognized until 1934, when it was applied to the consolidation of the Maritime Station in Le Havre. Conceptually it was very different from reinforced concrete because the reinforcement bars bore the tensile stress while in pre-tensioned concrete rebar was previously tensioned to induce compressive stress to concrete, preventing tensile stress afterwards.

Eduardo Torroja was the leading figure of the second revolution, that of concrete shells. His contribution consisted in replacing the Hennebique beam and pillar porticos with a very thin shell of up to 1/600 of slenderness. A radical conceptual upturn emerged affecting the basis of architectural composition: slabs supplanted the classic duality between structure and building enclosure in favor of a continuous and enveloping veil which exerted both functions at the same time. This also opened a new horizon for concrete, one that had always been latent but remained unexplored due to technical difficulties: moldability.

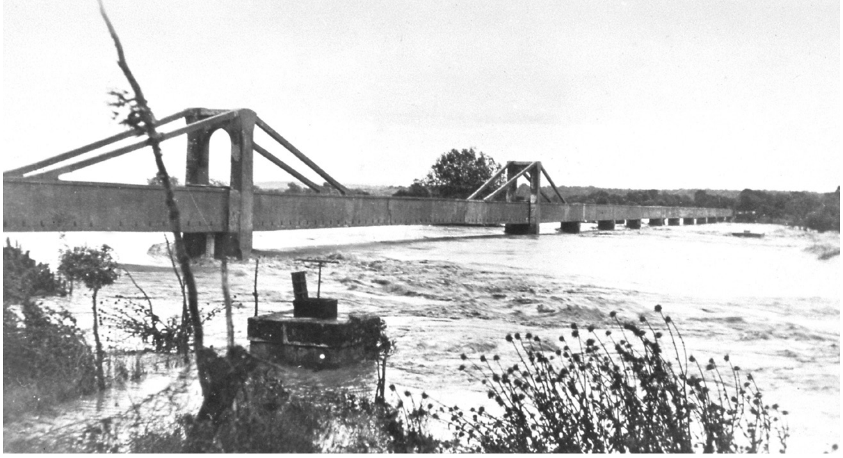
The works of Freyssinet and Torroja—and also those of engineers Robert Maillart and Pier Luigi Nervi—were essential to the popularization of concrete use between architects. The Plougastel Bridge (Freyssinet, 1930), the Salginatobel Bridge (Maillart, 1930), the hangars in Orvieto (Nervi, 1935) and the Recoletos *pelota* court (Torroja, 1935) transferred the poetics that had been fascinating architecture and avant-garde art for decades to engineering; the poetics of evanescence. This explains the huge international prestige that Torroja enjoyed at that time. Sigfried Giedion detected in his plates the "way to proceed" and Frank Lloyd Wright called him "the greatest living engineer."

His masterpieces had been erected between 1927 and 1936, in collaboration with the best Spanish architects: the so-called *Generación del 25*, precursor of Modernity. He built the Algeciras Market (1933) with Manuel Sánchez Arcas, the *Frontón de Recoletos* (Madrid, 1935) with Secundino Zuazo, and the Zarzuela Hippodrome (Madrid, 1935) with Carlos Arniches and Martín Domínguez. The brilliance of all these works lay in the use of concrete shells designed by Torroja.

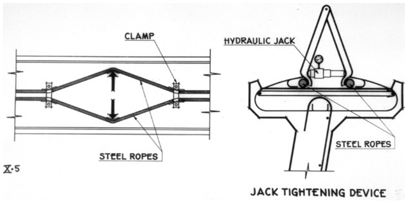
However, the projects on which we will focus on in this article were related to the other great structural success of that moment: pre-tensed concrete. Freyssinet stated that Torroja had never understood its conceptual essence. He had proclaimed that, despite its greater sophistication, it was not better than reinforced concrete (agreeing with Maillart and Nervi), and he used it in an unorthodox way (we do not know whether by choice or due to the country's technological shortcomings).

The first time Torroja experimented with something similar to pre-tensioned concrete was in the Tempul Aqueduct, built in 1927 over the Guadalete River, which had

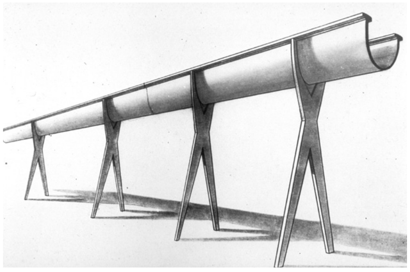
< The Alloz Aqueduct by **Eduardo Torroja**, built in 1939.



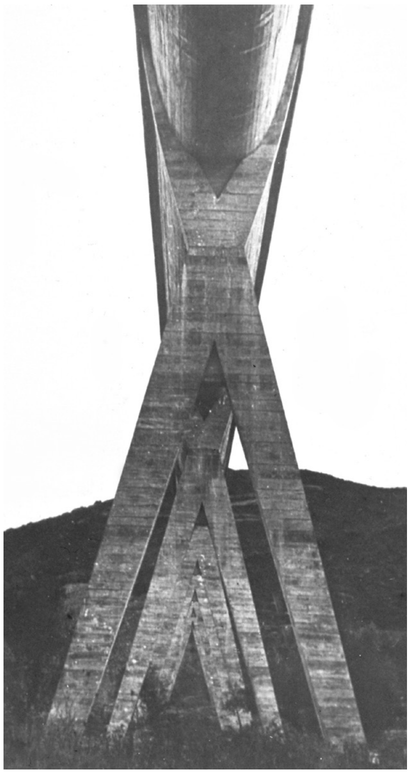
The Tempul Aqueduct during a flash flood.



Alloz Aqueduct jack tightening device.



Alloz Aqueduct drawing.



The Alloz Aqueduct piers and channel.

to supply water to Jerez de la Frontera. Water circulated through two 280-meter-long pipes housed inside a reinforced concrete box. The initial project planned to settle them on top of four piers, two located on the riverside and two on the riverbed, but the poor soil made Torroja remove the latter. He resolved the 60-meter-suspended deck span over the river by using two cable-stayed cantilevered decks connected to the riverside piers using a helical arrangement of 37-high-strength steel cables stranded together.

To avoid the high elongation that would occur in these 55-meter-long struts when put under stress, he used what we could call a "pre-technological" pre-tensioned system. He supported both stays on saddles on top of the piers, allowing them to move and behave independently. Once the concrete was poured and solidified, he raised them with hydraulic jacks to get the proper tension. He then proceeded to pour the concrete into the gap between the saddles and the tower-heads (the stays were also concreted in place to avoid corrosion). With this rather traditional system, Torroja became familiar with the concept of pre-tensed concrete.

More than a decade later he would use this system again. The Alloz aqueduct was built in 1939 over the Salado River in Navarra. Unlike in Tempul, in this case water was not going to circulate through pipes but on a concrete open-topped channel, which meant dealing with the essential risk of all aqueducts: leakage or, in other words, fissures. Torroja attempted to settle the problem by subjecting the inside part of the channel (which would be in contact with water) to a bi-directional compression. To achieve it he complemented his pre-tensioned proposal with a supportive design. The channel, which has a parabolic cross-section (form that ensures a good hydraulic profile), was supported on a cruciform structure similar to compass-shaped piers. Its 450 m length was segmented into 40 m sections supported by two separate pillars which stood 20 m apart with a cantilever of 10 m at each end. This established a longitudinal negative or null bending moment diagram in which no part of the viaduct was in sagging, and hence the bottom edge of the channel was always in longitudinal compression, avoiding cracking where water's pressure was stronger.

To achieve the same result in the upper part, Torroja decided to longitudinally post-tension the edges. He carved a recess in each one and placed a pair of twisted cables similar to those used in Tempul. To anchor them to the concrete, he separated the filaments and bent the ends into a hook form. The pre-tensioned system was also somewhat artisanal as he introduced transverse jacks between the pairs of cables, and by jacking the cables apart, lengthened and hence stressed the cables. By using this system he submitted the outer face of the channel to a longitudinal compression in all the cross sections. Finally, to ensure the transverse compression on the inside, Torroja connected the parabola's top flanges with bars placed at roughly 4 m intervals on top of the water. By tightening turnbuckles on the bars and drawing the two flanges slightly together, the inner face of the channel became compressed towards the bottom part (again, where it is most needed).

The result was a totally compressed piece, in all its length and both inside and outside, a simple and inexpensive piece which never cracked nor presented leaks. It is also a beautiful piece, a centipede with giant and delicate legs which seems to tiptoe over the territory.

The Alloz Aqueduct gives evidence of Torroja's peculiar engineering ideas, his consideration that the ultimate goal of structures is aesthetic and not functional: "works are not built to withstand [...] their resistance is a key condition, but it is not the only ultimate purpose, not even its primary purpose." In another occasion he claimed: "the creation of form is the result of a great flash of inspiration, the epilogue to a drama." This chaste engineer liked to skirt the abyss of irrationality, sensitiveness, subjectiveness; his radically technical training saved him from succumbing to it.

Architects intellectualized Torroja's difficult to define universe. Frank Lloyd Wright said "of all the engineers I know, Torroja has expressed the principles of organic construction better than anybody else." Pedro Miguel Sosa, referring to his structures, said "he does not design them to withstand gravitational actions in a passive or inert way but, instead, he handles their geometry and causes, in an active way, forces or deformations so that materials support appropriate tensions according to their resistance behavior."[1] This essentially organicist attitude turned structures into expectant beings, beings which are "in a permanent state of alert, not inert to gravity, but in constant response to the need for balance and endurance."[2]

Torroja's intense engineering sensitivity was enough to shape his beauty aspiration. According to his structural plexo–tensional definition, the aim was to "incorporate to our spirit, as a second nature, the intuition of resistance phenomena, and, trying to capture the essence of physical phenomena, that is, make tensions visible, materialize them so that intuition becomes easier."

Only somebody like him could assume such a challenge, endowed as he was with a remarkable ability to assimilate the principles of tension in structures. It was as if, in the case of the Alloz Aqueduct, he had felt the water friction, the channel deformation, the stretching of the edges, the bending of the supports and the compression of the pillars in his own body—a tension distribution feeling which he was able to defuse just before the infrastructure was put under stress, but which he also showed because he was shaping it as a "living" artifact, condemned to survive in permanent challenge with a flow of tensions.

Torroja's brilliant career was cut short with the Spanish Civil War (1936–1939). The architectural quality of his work declined swiftly after the war although his activities as a government employee (*Jefatura de Puentes* of the Ministry of Public Works), teacher (School of Civil Engineering in Madrid), researcher (*Instituto de la Construcción y del Cemento*) and writer (he was the author of *Razón y ser de los tipos estructurales*, published in 1957 and immediately translated into English and German), allowed him to continue leading the efforts to overcome the craftwork culture and to incorporate construction to the country's industrialization process.

Eduardo Torroja died in 1961, at the beginning of the decade that marked the definitive decline of reinforced concrete shells as a result of a more expensive labor cost.

Notes

1. VV.AA. *Eduardo Torroja, la vigencia de un legado*, Valencia, Universidad Politécnica de Valencia, 2002, 167.
2. Tarragó, Salvador, *La modernidad en la obra de Eduardo Torroja*, Madrid, Ediciones Turner, 1979, 36.

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All images from *Las Estructuras de Eduardo Torroja*, Madrid, *Ministerio de Fomento*, 1999.
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