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Analysis of Eduardo Torroja's Tempul Aqueduct an important precursor of modern cable-stayed bridges, extradosed bridges and prestressed concrete

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ABSTRACT

This paper describes a study of the Tempul Aqueduct, one of the first structures designed and built by Eduardo Torroja. At a time when computers did not exist, Torroja's courage and innovation were outstanding. He was in no way constrained by a lack of theoretical knowledge, inadequate materials and the contemporary doubts about cable-stayed structures. In fact, he was able to build one of the world's first prestressed concrete structures, and a precursor to modern cable-stayed and extradosed bridges. This paper briefly reviews the history of the Tempul Aqueduct, gives the results of the analysis of this structure by several Finite Element Models (FEMs), and compares the FEM results to those obtained by Torroja himself. The FEM results confirm the validity of Torroja's conceptual design. The paper also contains a detailed analysis of the influence of the structural system on the behavior of the bridge and the effect of removing the live loads with the aim of providing a better understanding of the context and behavior of the Tempul aqueduct.

1. Introduction

Cable-stayed bridges figure among the most challenging, structural efficient and aesthetic man-built structures. According to Strasky [1] "the beauty of these structures comes from their clear and clean structural function, which determines their architectural expression." In the last decades, the development of materials, construction techniques, simulation methods as well as the economic boom propitiated a huge increase in the construction of cable-stayed bridges worldwide. Nevertheless, these modern structures cannot be understood without the precursor cable-stayed bridges, which form the basis of this typology.

Stayed elements in tension have been widely used in structures in general and in bridges in particular since ancient times. In the first bridges, the tension elements were made of flexible materials, such as bamboo or liana [2], although the reduced lifespan of these natural materials greatly limited primitive bridges span and durability. Since the primitive stayed structures, cable-stayed bridges have evolved with time, enabling longer spans. Unlike other typologies (e.g. suspension bridges), the rapid development of cable-stayed bridges did not take place until practically the twentieth century, thanks to the works of Roebling, Gisclard, Armodin, Torroja and Dischinger. According to Podolny and Scalzy [3], this delay was attributed to a lack of technical knowledge in dealing with the difficulty of analyzing stayed-structures and the lack of suitable materials for stays. In fact, as timber or iron chains could not be prestressed, the use of these materials was discarded, as substantial deformations of the superstructure were required for the stays to remain in tension. According to Billington and Nazmy [4], the fact that the eminent engineer Navier was against cable-stayed bridges was a major issue that delayed the development of this typology. Navier's objection to cable-stayed bridges was based on facts (the collapse of structures such as the Dryburgh Bridge [3] and the Brighton Chain Pier Bridge [5]). He also had: (1) social reasons: he considered that stayed bridges did not have any economic advantage over suspension bridges and (2) symbolic reasons: he rejected the typology because the first designs came from an architect (Poyet in 1823) rather than an engineer. Billington and Nazmy [4] claim that if Navier had dedicated his talent to the development of cable-stayed bridges, this typology would probably have been developed faster.

However, despite the lack of theoretical knowledge, less than adequate materials and the experts' doubts, many cable-stayed bridges were designed up to the beginning of the 1960s. Table 1

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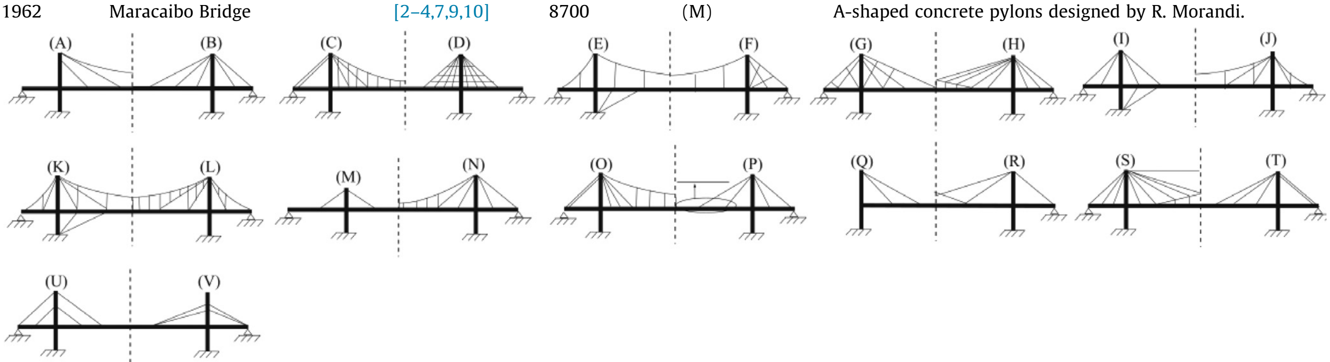
Table 1
Evolution of cable-supported bridges.

Year	Name	References	Span (m)	Staysystem	Notes
1600s	Pont Ferreus	[2]	–	(A)	Heavy pylons instead of backstays
1700s	Ponte Dell'Arsenalle	[2]	–	(Q)	Drawbridge.
1784	Leocher'sdesign	[2,3,9]	32	(B)	Timber bridge designed by a carpenter
1817	King's-Meadows Footbridge	[2,9]	33	(B)	Demolished in the 50 s.
1817	Dryburgh Bridge	[2,3,9]	79	(C)	Collapsed due to wind vibrations
1821	Poyet-type Bridge	[3]	–	(D)	Designed by architect Poyet
1821	Brighton Chain Pier Bridge	[12,13]	308	(E)	Stays to stiffen the girder, wind collapse
1823	Menai Straits proposal	[4]	–	(F)	Proposed by T. Telford with stays only in the backspan
1824	River Saale Bridge	[2,3,9]	78	(G)	Collapsed due to overweight
1837	Tiverton Bridge	[2]	–	(G)	Vertical hangers from stay cables.
1840	Gischlard-Arnodin Bridge	[3]	–	(H)	Two stay systems with masonry pylons
1840	Hatleychain Bridge	[3]	–	(G)	Chain stays in a parallel configuration
1846	Monongahela. Bridge	[5,13]	459	(I)	Stay cables were used to stiffen the structure.
1850	Lewiston-Queenston Bridge	[13]	306	(J)	Stay cables were used to stiffen the structure.
1855	Niagara Falls Bridge	[2,3,5,9,13]	250	(K)	Stay cables were used to stiffen the structure.
1860	Allegheny Bridge	[5]	–	(K)	Stay cables were used to stiffen the structure.
1867	Cincinnati Bridge	[5,13]	322	(J)	Stay cables were used to stiffen the structure.
1868	Franz Joseph Bridge	[2]	146	(L)	In the proximities of the pylon hangers do not hang the girder
1868	Rock Island Bridge	[14]	168	(J)	Stay cables were used to stiffen the structure.
1868	East Rockport Bridge	[14]	168	(J)	Stay cables were used to stiffen the structure.
1869	Union Bridge	[14]	229	(J)	Stay system counterbalances 45% of the loads
1869	Lowelville Bridge	[14]	145	(J)	Stay system counterbalances 35% of the loads
1870	Waco Bridge	[14]	189	(J)	Guys for storm protection
1871	Newcastle Bridge	[2]	73	(M)	Rigid bar as stay cable.
1871	Jones Mill Bridge	[14]	92	(J)	Stay system counterbalances 16% of the loads
1872	Albert Bridge	[3,9]	122	(J)	Girder stiffness enables notable stay separation
1879	Saint-Ilpize Bridge	[2]	68	(N)	Arnodin's design
1883	Lamothe Bridge	[2]	115	(O)	Arnodin's design
1883	Brooklyn Bridge	[2,3,5,7,9]	483	(J)	Stayed system to reduce deformability
1888	Midi Bridge	[2]	127	(N)	Arnodin's design
1890	Barton Creek Bridge	[15]	–	(P)	Patented prestressing twisting device
1899	Bridge of Cassagne	[9]	156	(H)	Development of economic and rigid hangers
1899	Bluff Dale Bridge	[15]	43	(P)	Patented prestressing twisting device
1900	Aramon Bridge	[2]	274	(J)	Arnodin's design
1903	Leamington Spa Footbridge	[2]	30	(R)	Gisclard's design
1904	Bonhome Bridge	[2]	163	(N)	Arnodin's design
1911	Tres-Cases Bridge	[2]	—	(S)	Horizontal cables to avoid axial forces in girder.
1924	Lazardrieux	[2,9]	112	(T)	Girder compression to counterbalance horizontal forces.
1926	**Tempul Aqueduct**	[2,3,6,9,10]	56	(M)	First Modern cable-stayed bridge [10]
1938	Elbe Bridge	[3,9]	497	(O)	Precursor of Stromsund Bridge design
1952	Donzère canal Bridge	[2,10]	81	(B)	Actual modern bridge but considered precursor [2].
1953	Quinault River Bridge	[9]	72	(B)	Collapsed due to a stay failure.
1956	Stromsund Bridge	[2–4,6,9,10]	183	(B)	Precursor [1], First modern cable-stayed bridge [3,6,9]
1957	Benton City Bridge	[2,9]	52	(M)	Precursor of modern cable-stayed bridges [2]
1958	North Brücke Bridge	[2–4,7,9,10]	476	(U)	Bridges built over the Rhine after the Second World War.
1960	Severin Bridge	[2–4,7,9,10]	452	(U)	Bridges built over the Rhine after the Second World War.
1961	Schiller-Steg Footbridge	[3]	93	(B)	Light structure sensitive to vibrations.
1962	North Elbe Bridge	[2–4,7,9,10]	300	(V)	Bridges built over the Rhine after the Second World War.
1962	Maracaibo Bridge	[2–4,7,9,10]	8700	(M)	A-shaped concrete pylons designed by R. Morandi.



shows the stay cable system, the span and some features of some of the most important of these bridges, among which it is easy to find several precursors of modern cable-stayed bridges (characterized by high strength steel wires and large pretension forces). Nevertheless, bridge designers and historians do not agree on which one was actually the first modern cable-stayed bridge. On the one hand, a significant number of researchers (such as [3,6–8]) state that the first modern cable-stayed bridge was the Stromsund Bridge built in Sweden in 1956. This structure was strongly influenced by the work done by Dischinger in the 1930s [4]. On the other hand, the Tempul Aqueduct, also known as the San Patricio Bridge, built in Spain in 1925 by Eduardo Torroja is considered by Virlogeux [10] and Arenas [11] as the first modern cable-stayed bridge. However, Fernández-Troyano [2] is of the opinion