The Alamillo Bridge: At the Interface of Structure and Art

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Introduction:

For some engineers and architects, as well as the general public, the use of concrete is merely utilitarian in nature. Its inherent strength, ease of use, and low cost lend it to a wide variety of applications, many of which are very low profile in nature. In areas where the amount of physical infrastructure is abundant, one can observe many fairly unattractive applications of concrete, including parking lots, roadways, and parking ramps. Furthermore, two very widely used applications of concrete, floor slabs and foundations, can never actually be seen by the majority of its users. This perception of concrete as solely being used in lackluster construction projects has been abandoned by Santiago Calatrava. Calatrava uses the properties of concrete in such a fashion as to create something that is both functional from an engineering standpoint and aesthetically pleasing. With concrete, Calatrava is able to design for structural elegance, meaning that the structure both serves the purpose of its namesake, i.e. it is structural, and also represents the form, or architecture, of the design. Perhaps the quintessential representation of using concrete for structural art is the Alamillo Bridge in Seville, Spain, with its incline pylon/cable stay design. This project proposes to evaluate the design and present an overall case study for the use of concrete in this application. It is significant because it is both an engineering marvel and highly visible in the public eye. More precisely, it presents a challenge to a person of expertise but is also identifiable for the layman.

This project will investigate the mechanics of the superstructure and how that relates to the choice of concrete as the load bearing material. Furthermore, it will identify characteristics at the material level. For example, research into the strength of concrete used, rebar configuration, and prestressing methods (if used), will be included in the analysis. Finally, a comparison and contrast of the use of concrete versus other engineering materials in terms of the basic engineering requirements: safety, cost, and user-interface, will provide a perspective on the use of concrete in civil engineering structures. The concepts proposed in this class- biaxial behavior, creep, shrinkage, and service load behavior- will be used to explore this design. Before exploring the technical details of the analysis, mechanics, and material characteristics, one must have a fundamental of the Alamillo Bridge both in terms of how the structure behaves on a most general level and why the bridge was built to begin with.

Background:

The Alamillo Bridge was built between 1987-1992 as a result of a commission for the Universal Exposition of 1992 in Seville, which coincided with the Barcelona Olympics, full membership in the European Union, and the quincentennial of the discovery of the Americas [Pollalis ix]. These extraordinary circumstances called for an extraordinary bridge design, out of which came this unique, inclined pylon design. The bridge has a total length of 250 m (820 ft), maximum span of 200 m (656 ft), and a mast height of 142 m (466 ft). Thirteen pairs of cable-stays support the bridge deck via a concrete-filled, steel caisson pylon inclined at 58^o [Frampton 55,58]. These details will be illustrated in greater depth later.

The bridge consists of four basic components: the deck, cable-stays, pylon, and foundation. The live and dead loads from the deck are carried via tension upward to the pylon, which in turn transfers loads through axial compression and bending to the foundation. Most cable-stay bridges rely on front- and back-stays to maintain equilibrium, and the pylon is primarily loaded axially [Podolny]. However, the Alamillo Bridge relies on the weight of the pylon, along with its incline, to resist the overturning moments produced by the cable tension. In an ideal case, the weight of the pylon will be in perfect balance with the deck loads, which would solely result in axial loads. It should be noted that the pylon will always experience minor bending moments because its self-weight is distributed, however the cable forces act at discrete locations [Pollalis 40]. Of greater importance is the fact that traffic loads are constantly changing, and since the incline of the pylon cannot be adjusted, a moment will ensue. This adds fairly significant design complexity when compared to a typical cable-stay structure, since the pylon has to be designed for large axial loads and moments. Also, there are tight deflection constraints, since deflection in the pylon will directly result in deflection in the deck, which is governed by current codes [AASHTO (1998)].

Perhaps an obvious question that arises from a discussion about the basic characteristics of the bridge is why concrete was used in the pylon design. The pylon of any cable-stayed structure has to be able to resist large compressive forces and stresses, especially near the base of the structure. Thus, a material with high compressive stress capacity is necessary. Furthermore, due to the above discussion, large bending moments can and will occur under the various loading conditions a bridge will experience. Only under one condition, the so-called “funicular loading” [Pollalis 41], will the pylon experience only axial action. Choosing the proper funicular loading scenario is not a trivial design consideration but is out of the scope of this project and will not be explored here. Regardless of this consideration, the occurrence of bending in the pylon is unavoidable and therefore a material resistant to the combined effects of axial loading and bending was necessary. A slightly more subtle design consideration is also related to funicular loading principle, and that is the distribution of weight in the pylon. Equally important to strength characteristics is the ability to maintain the balance of forces on the superstructure level. Under the geometric constraints chosen by the architect, a ratio of pylon weight to deck was calculated. Given a tower angle of 58 degrees and a cable angle of 24 degrees in the harp configuration [asdfasfd], the weight per unit length of the pylon should be 3.4 times that of the deck. A concrete pylon could provide the necessary weight along with the desired structural characteristics.

"The design requirement for a changing cross section of the pylon along its length, as well as details of the steel reinforcement, led to a composite design of steel caissons forming the outer surface of the pylon and reinforced concrete filling them" [Pollalis 52]. The concrete-filled caisson design serves the dual purpose of easing construction purposes as well as providing certain architectural features. Perhaps its greatest benefit is structural, however, since the steel encasement provides a constraint in plane with the cross-section. This essentially provides a biaxial state of stress when the section is under axial loading, which has been shown to be beneficial for concrete [Nilson, Darwin, and Dolan (2000)].

Analysis:

The Alamillo Bridge was designed using various design codes (Spanish Code OM, British Standard BS, and Swiss code SIA) in S.I. units, combined with proprietary methods, since the structure was highly innovative. This innovation calls for use of Finite-Element Modeling as well as dynamic wind tunnel testing on a scale model [Pollalis 77]. Professor Angel Aparicio of the Technical University of Barcelona used a comprehensive finite element model to analyze the bridge under applicable loading conditions and converge on an optimal design. This project will use the existing geometry with certain simplifications, along with American design code, to analyze the design and perform safety evaluation. Following is a description of the finite element model, the simplifications used for analysis, and the bases for these simplifications.

SAP2000 was used for the finite element model of the superstructure. The geometry is provided by numerous sources, and Spiro N. Pollalis' What is a Bridge? is referenced here. The cable attachment locations provide a convenient mesh length for both the bridge and the deck. For the pylon, one frame element was modeled between each cable connection, while in the deck two frames are used between each connection. As in any finite element model, increasing the number of elements will increase the accuracy of the analysis. However, using just one element between each element is optimal for several reasons. First, SAP2000 calculates internal forces at three discrete locations along the frame, at each end and at the center, and thus inherently provides twice the accuracy as one would assume from observing the mesh. Secondly, using fewer nodes increases the computational speed of the hardware, which is not a governing problem for this model but should be considered when using finite elements. The following is an illustration of the moment distribution under dead loads, which were taken from the final construction data. Notice that the magnitude of the moments are much lower in the pylon than in the deck, especially far away from the base of the pylon. This illustrates the concept of reducing the bending of the tower under funicular loading.

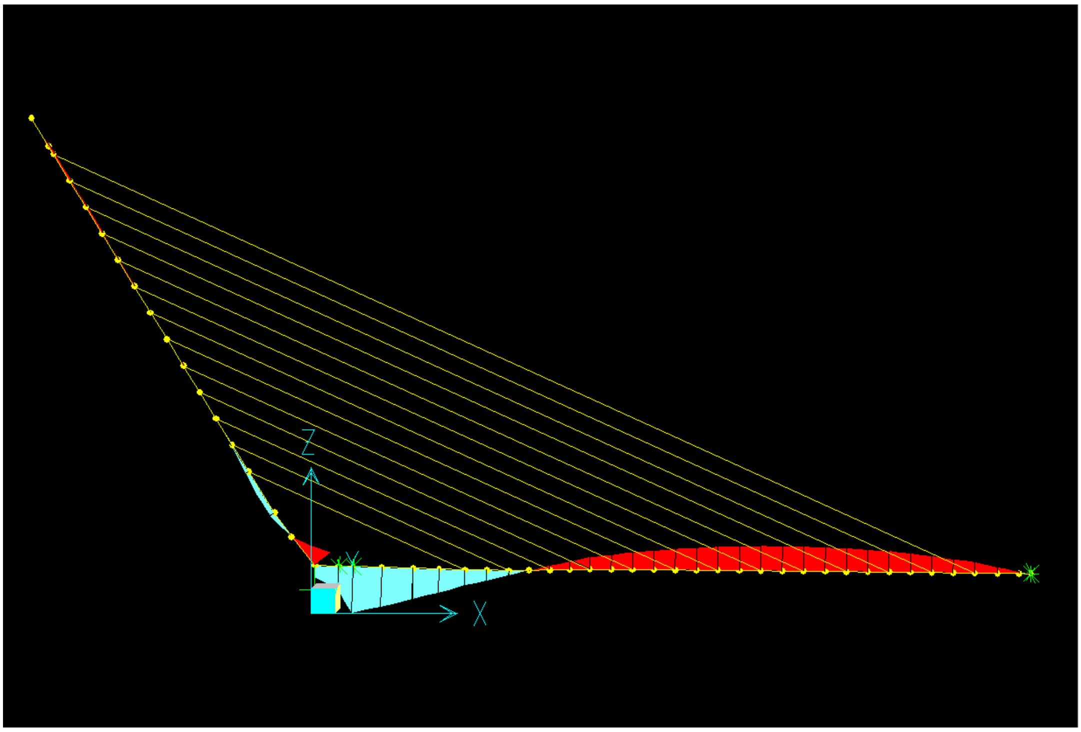

Figure 1: Finite Element Model-Moment Distribution

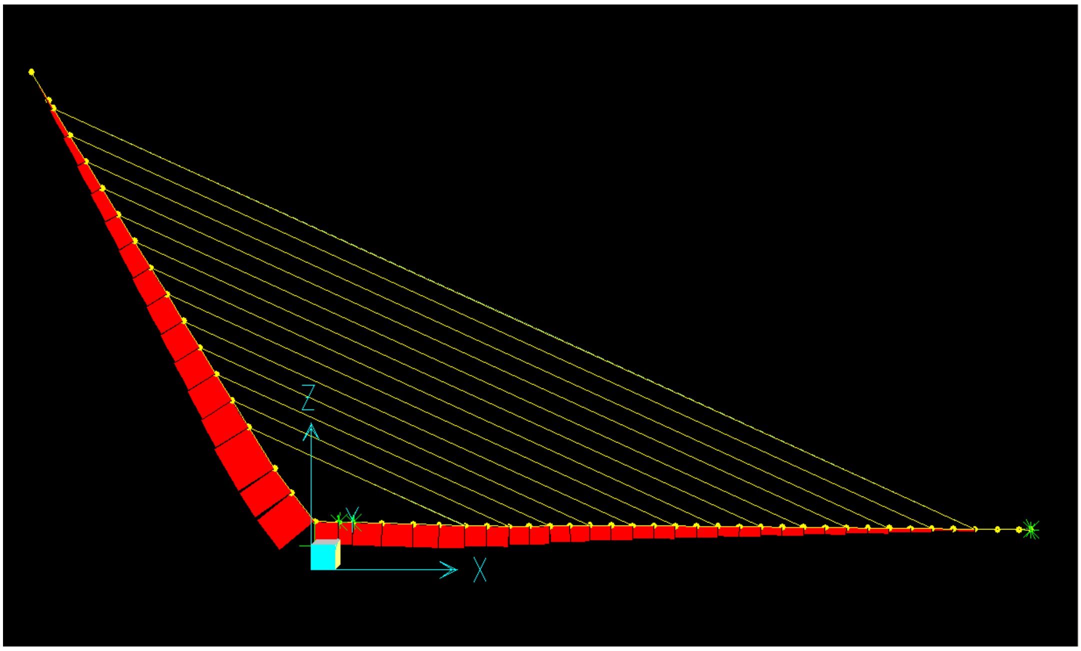

Figure 2: Axial Force Distribution

The properties of the deck and cables, i.e. moment of inertia, modulus of torsion, area, and dead load were taken from the final design documents [Pollalis 60-61]. As a basis for analysis, an equivalent section was used for the pylon. Figure 2 shows the final design section at mid-height of the pylon. This is a relatively complex geometry, which when combined with the rebar configuration and the steel caissons, makes analysis quite difficult. Therefore, the geometric simplifications shown in Figure 3 were used, combined with the concept of equivalent area. Reinforcement, caisson, and concrete areas were final design values.

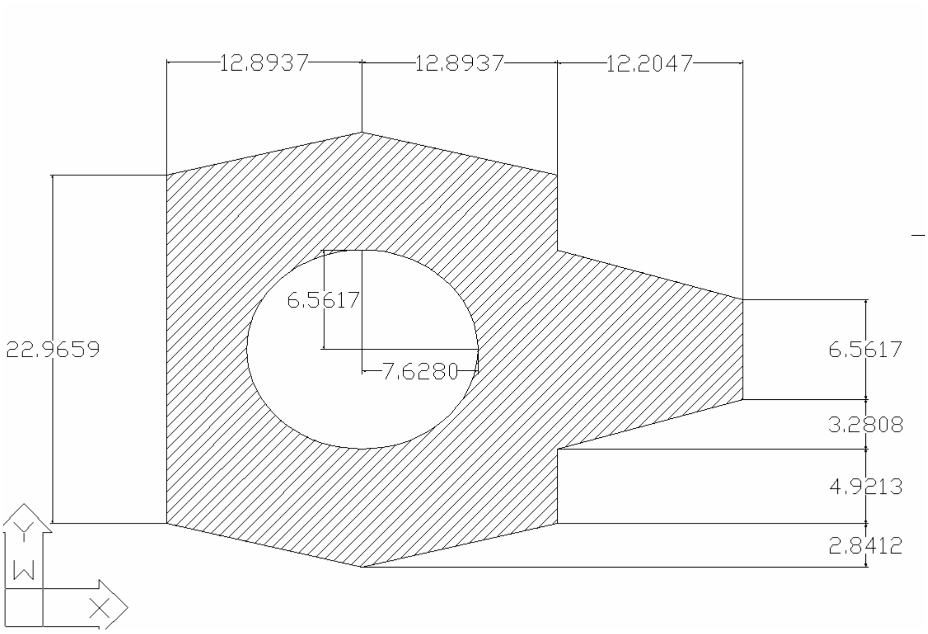

Figure 3: Equivalent Pylon Section

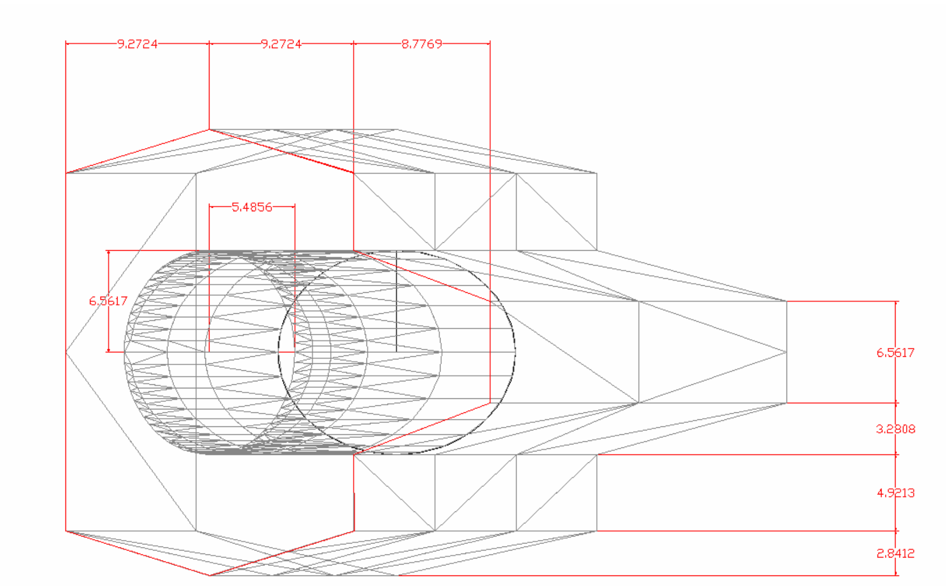

Figure 4: Section Dimensions Normal to Neutral Axis