THE SAN FRANCISCO-OAKLAND BAY BRIDGE: INNOVATION OR BLUNDER?

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Abstract: The project started as a more attractive option than just repairing the 1989 Loma Prieta earthquake-damaged eastern span of the San Francisco – Oakland Bay Bridge. A decision to make the span tougher to seismic challenges than the 1930's existing one led to a long public debate on the kind of a bridge the San Francisco Bay area, the home of the world famous Golden Gate Bridge deserves. The initial engineering voices (most notably that of T.Y.Lin, a leading U.S. bridge designer of the 2nd half of the 20th Century) advocating cable stayed bridge were slowly drowned in the debate between politicians, public media, and beauty experts. The revolutionary design of self-anchored suspension bridge was supposed to cost some $120 mln more than the $1.5 bln cable-stayed design, a difference not sufficient for the decision makers to abandon the experimental design. The final price at opening of the bridge in 2013 was $6.3 bln and the meter continues ticking as tens of millions in repairs and retrofits are being spent on keeping the bridge as safe and as long-lasting as promised. With this example, the paper discusses the issue of innovation, economy, and professional responsibility when it comes to public service structures built with public funding.

Keywords: bridges; self-anchored suspension; cable-stayed; retrofit; cost analysis.

1. Introduction

The theme this paper tries to address is the duty of engineering professionals to forward the state-of-the-art while at the same time ensuring his or her efforts are not resulting in an excessive safety, reliability, or financial risk to society. Certainly, many projects carried out with public funds could be an example of the design being too experimental to satisfy the above requirements thus leading to major undesirable consequences, including severe cost overruns and extensive delays. The newly constructed span of the San Francisco–Oakland, California bridge (Bay Bridge) could serve as a good example in that fine-line debate.

The Bay Bridge serves as a transit link between Oakland and downtown San Francisco. The bridge opened for traffic in November of 1936, has two major spans: one "East" span between Oakland and Yerba Buena Island and one "West" span between Yerba Buena Island and San Francisco. The original design and construction consisted of a cantilever truss bridge for the East span and a suspension bridge for the West span [1]. An aerial photograph of the old (the truss structure) and new (forefront) East spans are shown in Fig. 1.

In October 1989, a magnitude 6.9 earthquake (commonly referred to as "Loma Prieta") struck the Bay Area [2]. The earthquake caused significant damage to the East span, by collapsing the top deck of the cantilever portion onto the lower deck (Fig. 2). The fatalities were limited to one person being killed, although the earthquake occurred during rush hour, and immediately before an important baseball game time. The suspension (western) span was largely undamaged

After Loma Prieta, the Bay Bridge was closed to traffic for approximately one month for emergency repairs. However, a long-term solution needed to be sought in order to prevent significant damage from a future major earthquake, one predictably much more severe than the Loma Prieta earthquake. After much discussion, engineering, and political discourse, it was decided that the cantilever-type East span of the Bay Bridge would be *replaced* by a revolutionary, self-anchored suspension bridge and that the suspension-type West span would simply be retrofitted. The replacement of the East span is the subject of this paper where the initial estimate of $1.3 billion soared to a construction total of over $6.3 billion at the time of completion [3]. The validity of the chosen replacement versus retrofit is examined and leads one to consider the crux of this paper: Does the cost borne by taxpayers for a state-of-the-art bridge replacement represent the price of innovation or financial mismanagement?

Fig. 1 Aerial Photograph of the Bay Bridge East span (courtesy T.Y. Lin International)

Fig. 2 Photograph of Bridge Deck Collapse (1989) [1]

2. Historical Perspective: Pre-1989

In 1929, the California State Legislature approved the creation of the California Toll Bridge Authority; whose mandate was to construct a bridge connecting San Francisco and Alameda County (Oakland). It was further decided that in order to build an economically feasible link, the bridge must go through Yerba Buena Island which was owned by the United States government as a U.S. Naval base. In 1931, the United States Congress gave permission to use the island as an anchor point for the East and West spans of what would become the San Francisco-Oakland Bay Bridge [1]. The bridge's innovative, preliminary design was overseen by the Chairman of the Board of Consulting Engineers, Mr. Ralph Modjeski. In fact, it was originally Modjeski's idea to link the two suspension spans of the West span through a concrete anchorage pier [6]. A sketch of the original design from 1930 is shown in Fig. 3.

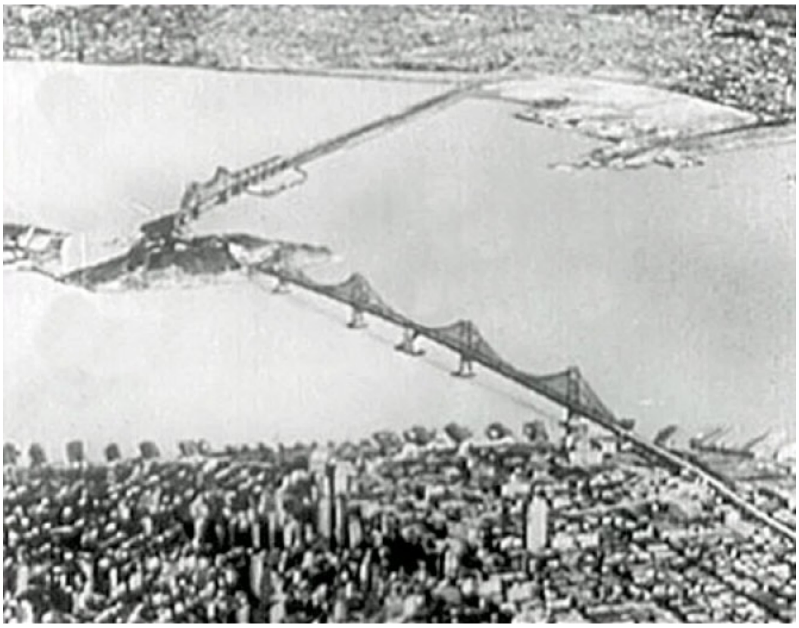

Fig. 3 Original Bay Bridge Design circa 1930 [1]

Construction began on the bridge in 1933 and was completed in 1936 at a total price of \$77 million, which was \$6 million under budget [1]. If the total cost is related to today's dollars, it would amount to roughly \$1.4 billion when calculated based on the consumer price index (CPI) or using a more appropriate measure, \$4.9 billion when calculated based on the differential in skilled labor costs between 1933 and 2015 (This will be noted as "labor adjusted" for the remainder of this paper) [7]. Monetary comparisons based on the skilled labor rate are used exclusively henceforth as the labor rate is often considered the most appropriate predictor for large-scale civil works projects.

3. Making the Case for a New Span

The Loma Prieta earthquake which struck the Bay Area in October of 1989, caused damage to many of the region's bridges, including a partial collapse of East span of the Bay Bridge as shown in Fig. 2. Original estimates issued by a team of researchers from the University of California, Berkeley in September of 1992 suggest that the East span of the bridge could be retrofitted for \$150-\$200 million and that a new span would likely cost around \$1 billion [8]. A series of events and considerations led from a mere retrofit to the construction of the largest self-anchored suspension bridge in the world.

Option 1: Retrofit of the Existing East Span - After UC Berkeley's report in 1992 estimating a retrofit cost for $150-$200 million, California voters approved Proposition 192 in 1996 authorizing retrofit of the entire Bay Area bridge system for $650 million, of which a portion would be attributed to the East Span of the Bay Bridge [8]. However an argument questioning the wisdom of retrofit was made based on the remaining useful life and seismic characteristics of the 56 year old East span.

Option 2: Replacement of the East Span - In the summer of 1995, the California Department of Transportation, Caltrans, recommends replacement of the East span with a new bridge. Subsequently, various reports estimate that a new cable-stayed bridge will likely between $843 million and $1.7 billion [8]. The Governor of California, Pete Wilson, decides that a new East span shall be constructed in lieu of the retrofit option [8]. Next, in August 1997, state Senator Quintin Kopp introduces Senate Bill 60 (SB 60) which avows "that replacement of the span will be safer, stronger, and more cost-effective to maintain than completing a seismic retrofit of the current east span." Furthermore, the cost is estimated at $1.3 billion, which includes the costs of a "more expensive [single tower] cable suspension bridge [9]."

At this point, it is important to consider the difference between a self-anchored-suspension (SAS) bridge and a cable-stayed bridge. A SAS bridge is similar to a typical suspension bridge (e.g., the Golden Gate Bridge), except that the support cables are not anchored into the piers, but are anchored into the bridge deck itself, creating a compression force in the bridge deck. Additionally, tension cables hang from the main, suspended catenary cables to vertically support the deck. A cable-stayed bridge has a similar compression tower, but supports straight tension cables in lieu of a catenary cable. These straight tension cables support the deck vertically and transfer compression into the deck structure of the bridge. A comparison of the force diagrams for a SAS and a cable-stayed bridge is shown in parts (a) and (b) of Fig. 4, respectively. Generally, suspension bridges gain an advantage where long spans are required, whereas cable-stayed bridges are appropriate up to moderate span ranges. While traditional suspension bridges are a common occurrence all over the world and numerous cable-stayed bridges are also in operation, only a few SAS bridges have been constructed to-date in regions of high seismicity.

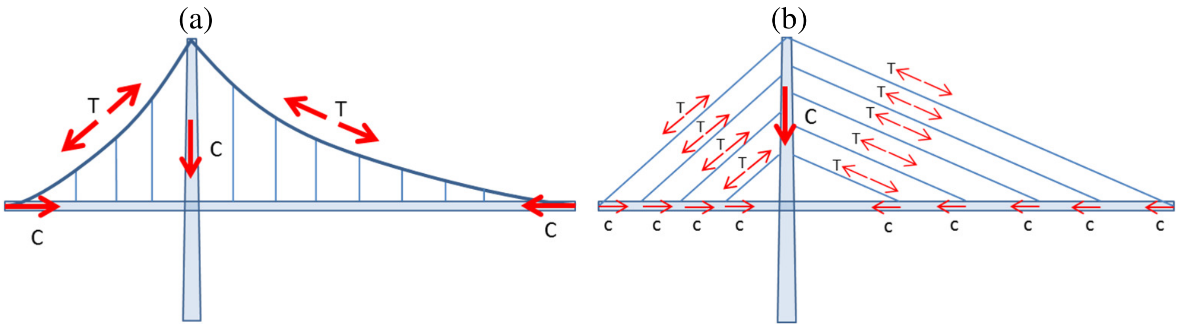

Fig. 4 (a) SAS and (b) cable-stayed force diagrams

Starting in 2001 and over the next several years, the California legislature passed AB 1171 (2001) and AB 144 (2005) which increased replacement budgets to $2.6 billion and then to $5.49 billion with an additional contingency fund of $900 million, respectively [3]. AB 144 also created the Toll Bridge Program Oversight Committee (TBPOC) which was entrusted with reigning in the ballooning costs of the project [3]. To date, the cost of change orders approved by TBPOC alone total over $1.4 billion [8].

One important item of engineering interest is the number of deficiencies found to-date in the construction of the new East span. The main construction defects observed include [10]:
– Several high-strength, galvanized anchor rods and bolts as shown in Fig. 5 have broken, potentially due to hydrogen-induced corrosion,
– Steel guardrail attachments to the bridge deck have allowed water leakage, potentially permitting corrosion of the deck,
– Numerous weld inspections have indicated substandard weld quality and potential weld cracking, and
– The misalignment of deck sections led to in-situ retrofits which may lead to poor performance during a seismic event.

Despite these engineering concerns, the Bay Bridge has been deemed safe for use while Caltrans engineers design appropriate solutions to these construction defects.

Fig. 5 Evidence of corrosion around Bay Bridge bolts (photo courtesy of SF Chronicle)

Determined to Construct a SAS Bridge

The socio-political powers of the San Francisco Bay Area exhibited in the competitive nature of the Oakland-San Francisco relations played a significant role in the decision of a one-of-its-kind and esthetically unique solution, the SAS bridge, being selected for the East span replacement. This solution was chosen despite a number of independent review panels throughout the project indicating that a SAS bridge may not be the most efficient. Below are a few comments counter to the construction of an SAS East span [8]:
– Jan 2000 – A UC Berkeley professor calls for retrofit and claims the "new design is not earthquake safe."
– Aug 2002 – California State Auditor finds that the Bay Area "chose a more expensive design in the SAS."
– Nov 2004 – Federal Highway Administration Peer Review Team recommends a cable-stayed bridge.
– Dec 2004 – Peer Review Team concludes that a SAS bridge has the highest risk for cost overruns and delays.

Despite the mounting number of dissenters, the policy makers continued pushing for the SAS bridge over the least-invasive and least costly retrofit or even over the cable-stayed structure. The arguments of seismic performance, serviceability, and esthetics were combined into a neat package called: innovative solution.

4. The Price of Innovation

To compare the relative costs of other innovative projects, several examples of other large-scale, one-of-a-kind projects are shown to facilitate the discussion on the price of innovation. *The Big Dig – Boston, MA, USA* – The Big Dig was one of the most ambitious highway tunneling projects ever attempted, consisting of a 8-10 lane highway that was tunneled beneath the streets, several iconic bridges, and significant addition of street-level green space all in highly congested downtown Boston, Massachusetts. A before/after photo of the Big Dig is shown in Fig. 6. The following are the costs associated with the innovative Big Dig project [7] [11]:
– Estimated Construction Cost: $2.6 billion in 1982 (Labor adjusted = $6.04 billion)
– Final Construction Cost: $14.8 billion in 2007
– Ratio of Final to Estimated: 2.45x initial estimates

Arthur Ravenel Jr. Bridge – Charleston to Mt. Pleasant, SC, USA - The Arthur Ravenel Jr. Bridge was the largest span, however based on significant world-wide experience, cable-stayed bridge in the world at time of completion (in 2005). The bridge is famous for being one of the first design-build bridges of that scale and for being completed under budget [12]. A photo of the Ravenel Bridge is shown in Fig. 7. The following are the costs associated with this innovative bridge project:
– Estimated Construction Cost: $690 million in 2005
– Final Construction Cost: $540 million in 2005
– Ratio of Final to Estimated: 0.78x initial estimates

Stadiums in Europe - Sports stadiums in Europe are often financed from public budgets. One such example is the National Stadium in Warsaw. It is the largest stadium in Poland, with an attendance capacity of around 58,000 [13]. A photo of the National Stadium is shown in Fig. 8. The costs associated with developing this publicly funded project are [13] [14]:
– Estimated Construction Cost: 1.5-2.2 billion PLN in 2008
– Final Construction Cost: 2 billion PLN
– Ratio of Final to Estimated: 1.33x-0.91x initial estimates

Fig. 6 Boston's Big Dig – Before and After [15]

Fig. 7 Arthur Ravenel Jr. Bridge [12]

As discussed previously, the costs for replacement of the East span of the San Francisco-Oakland Bay Bridge are:
– Estimated Construction Cost: $1.3 billion in 1997 (Labor adjusted = $2 billion)
– Final Construction Cost: $6.3 billion in 2013
– Ratio of Final to Estimated: 3.15x initial estimates

The comparison of ratio of the initially estimated cost to the final cost of the above public works projects to that ratio of the Bay Bridge' East span (1.33 or 0.78 or 2.45 versus 3.15) begs the question: Why is this the case? Is it purely due to the novel nature of the new East span?

Fig. 8 National Stadium in Warsaw [13]

5. The San Francisco-Oakland Bay Bridge – Innovation or Public Money Mismanagement?

An engineering professional is bound to be an advocate for public safety as well as for economy of the project. To be true to that goal an engineer needs to advance the state-of-the-art by promoting new design methods or technologies. The fiduciary duty can be expounded through a Venn diagram depicted in Fig. 9 in which Safety, Innovation, and Economy need to overlap to create a true quality project. Should the engineer entertain a choice of only two of those elements overlapping?

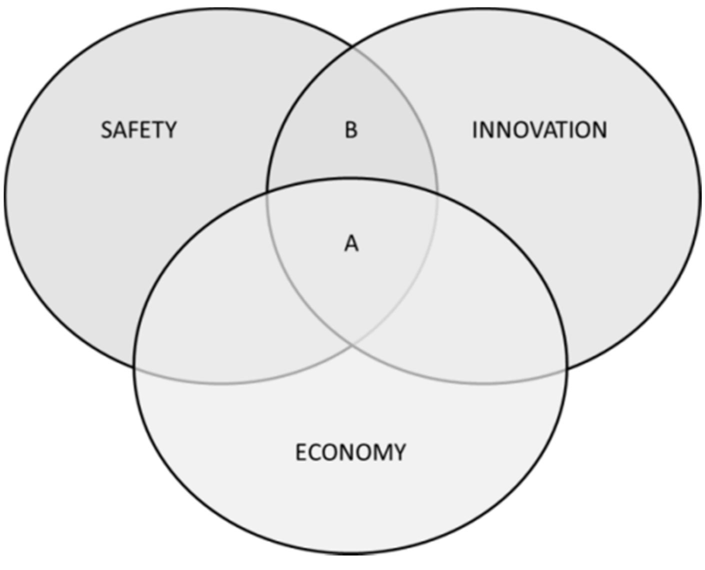

Fig. 9. A Designer's Venn Diagram

To no-doubt, many different approaches could have been pursued to provide an equally safe, reliable, and esthetically pleasing alternative to the new East span while maintaining better cost control, e.g. a cable-stayed bridge, as was suggested by numerous independent panels; a retrofit of the existing bridge for the proposed $200 million which would have bought many years in which to adequately plan a cost-effective means to replace the bridge, where several independent reviews and competitive bids could be sought; a design-build process similar to the Ravenel Jr. Bridge as opposed to the design-bid-build employed for the East span.

Conclusion

Public projects of significant service and/or esthetic impact on the society are a great opportunity to advance the state-of-the-art through bold, innovative solutions. However, as shown with the example of the replacement of the East span of the San Francisco-Oakland Bay Bridge, fiduciary responsibility should not and cannot be waived when such huge amounts of public money are at stake.

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