A Comparison of Cable-Stayed vs. Extradosed Bridges

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ABSTRACT

Cable-stayed bridges have been firmly established as the most efficient and cost effective structural form in the 500-ft to 1500-ft span range for most applications. The cost efficiency and the signature visual quality of the cable-stayed bridge have led to its widespread popularity around the world, with increasingly longer spans being planned and constructed. The concept of extradosed bridges, introduced in late 1980s, is gaining popularity in the span range between traditional girder bridges and cable-stayed bridges. In this span range of about 400-ft to 600-ft, extradosed bridges offer several key advantages over girder solutions as well as traditional cable-stayed bridges. The paper discusses the key differences in the behavior and design approach, and provides a comparison between an extradosed and a traditional cable-stayed solution for the lower span range.

1. INTRODUCTION

The cable-stayed bridge form has evolved considerably since the 1950s, when the Stromsund Bridge, widely regarded as the first modern cable-stayed bridge, was built in Sweden. It had a main span of 600-ft (183-m) and two symmetrical back spans of 245-ft (75-m) each with only two cables on each side of the tower, anchored to steel I-shaped edge girders. The structural efficiency and constructability advantages of cable-stayed bridges make them the most cost effective solution for the 500-ft (150-m) to 1500-ft (460-m) span range. This cost efficiency and the general satisfaction with their aesthetic aspects has propelled this span range in either direction, with both increasingly shorter and increasingly longer spans being designed and constructed at the present time.

Extradosed bridges look remarkably similar to cable-stayed bridges and could best be described as an adapted version or a variation of the cable-stayed form. They utilize considerably shorter towers and considerably flatter cable angles that give them a classic visual form. Technically, they can be considered a pre-stressed girder bridge, in which the pre-stressing tendons over the main piers are brought out of the girder and arranged as external tendons. This places the tendons at a higher eccentricity, considerably enhancing their effectiveness in resisting negative moments. Thus, the primary role of cables in an extradosed concrete bridge is to provide pre-compression to control the stresses within the concrete section.

In literature on extradosed bridges, it is generally reported that the concept was first introduced by Jacques Mathivat in 1988 with the first extradosed bridge ever constructed

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being the 400-ft (122 m)span Odawara Blueway Bridge in 1994 ([1], [2]). The Odawara bridge superstructure consists of a pre-cast concrete haunched box girder varying in depth from 7'-2 ½ " (2.2 m) to 11'-6" (3.5 m). The cables are anchored onto a tower that extends 35-ft (10.7 m) above the roadway (Figure 1 - photo by Takagi, Ryo).

Figure 1: Odawara Blue Way Bridge, Japan (Photo by Takagi, Ryo)

The 571-ft (174 m) main span Ganter Bridge designed by Christian Menn and completed in 1980 in Switzerland (Figure 2) is remarkably identical in concept to the modern concrete girder extradosed bridges. However, the Ganter Bridge is often classified as a cable-stayed bridge in literature.

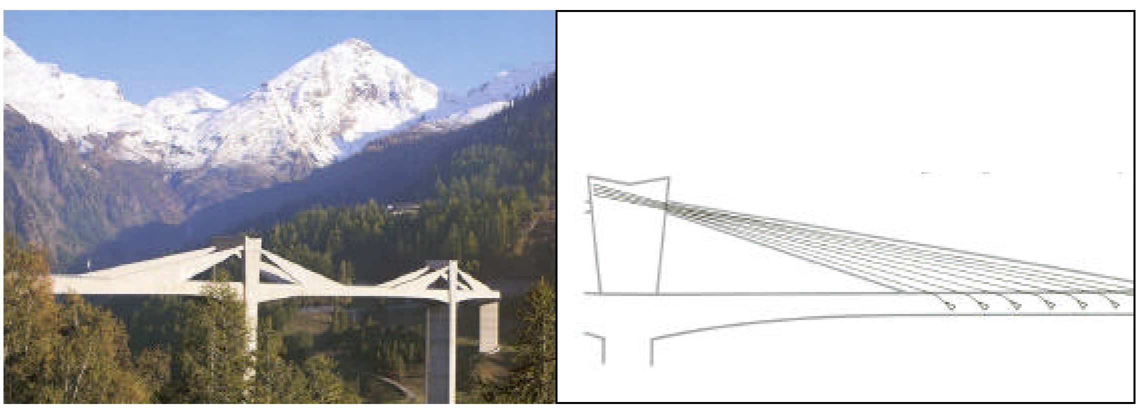

Figure 2: Ganter Bridge, Switzerland (from Bridges by David J. Brown)

Extradosed bridges provide many advantages in the span range too small for a traditional cable-stayed bridge but where a girder solution would result in a very deep, heavy superstructure. There are over 25 extradosed bridges around the world already constructed or in the planning stages since the above pioneering structures in this category. The special advantages of extradosed bridges include:

1. Reduction in the superstructure girder depth where a girder solution may not provide the necessary clearance requirements

2. Reduced tower height in situations where the traditional cable-stayed bridge towers may exceed project specific height limitations

3. A more structurally efficient, visually fitting solution to the 400-ft to 600-ft span range than a girder solution or a cable-stayed bridge

4. Higher permissible stresses in cables due to reduced fatigue stress levels

5. More efficient tower and cable anchorage designs – providing cost and inspectability advantages

6. Signature bridge form that provides an enhanced level of driver experience due to the tower & cable elements than a girder solution

These advantages have led to development of this bridge type beyond the concrete girder superstructures of the early designs. Two composite designs feature a steel girder section at mid-span joined to concrete sections at the piers as in Ibi River & Kiso River Bridges in Japan [3]. For the Pearl Harbor Memorial Bridge in New Haven, Connecticut, USA [2] two designs, one in post-tensioned concrete and the other in traditional steel girder composite concrete deck, are to be competitively bid for construction. If selected for construction, the latter is reported to be the first of its kind.

The use of steel girder/concrete deck composite superstructures in extradosed bridges brings out newer design issues that must be addressed as well as other possibilities that could be explored. These include:

1. For the concrete extradosed superstructures, the cable pre-compression acting at the enhanced eccentricity provided the major design benefit. For composite construction, while the pre-compression would help controlling stresses in the deck slab, for longitudinal steel girders, the pre-compression is not necessarily a design advantage.

2. The fatigue stresses with lighter superstructures

3. It appears that steel-composite extradosed bridges are considerably more amenable to incorporating the possibility for future complete deck replacement into the initial design than traditional cable-stayed bridges or pre-stressed girder bridges.

2. CABLE STAYED VS. EXTRADOSED - CASE STUDY

Figure 3 is a cross-section of a highway crossing over a shallow river with a bank to bank distance of about 400-ft. It is desirable to minimize the number of river piers due to cost and environmental impact issues. A signature cable-supported bridge is desired for the location for its aesthetic and cultural value, but the cost efficiency of the design is also important to the bridge owner as well as the funding agencies. The bridge is a part of a new highway development with a complex interchange on one side and tie-in elevations are critical. There is also an existing railway that passes under the bridge needing critical clearances to be maintained, and thus the structure depth is an important factor. The scale of the bridge is also required to be proportional and suited to the site, and not to overpower the surroundings.

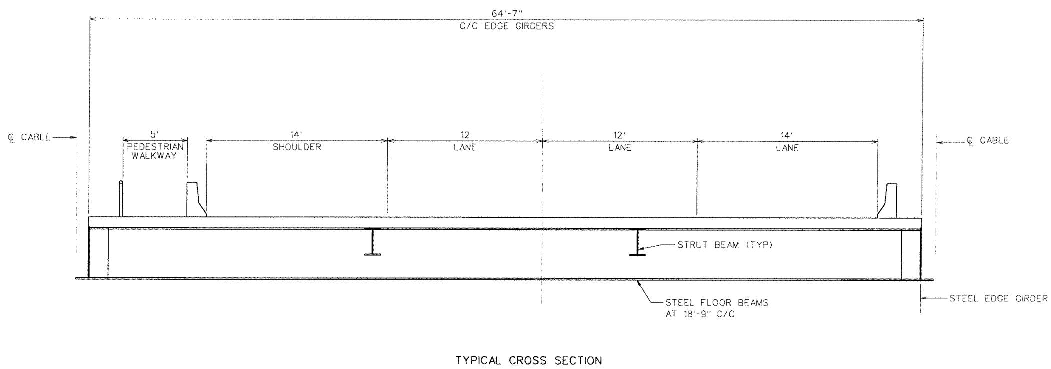

Figure 3: Deck Cross Section

A 450-ft long two-span main unit with a constant superstructure width and a 230-ft long two span approach unit with a variable superstructure width (to accommodate the additional lanes for the interchange) was selected as this appeared to provide the best overall span solution. Figure 4 show two possible cable-supported bridge layouts for this site, one a traditional cable-stayed bridge with a tower height of about 125-ft above the roadway and the other an extradosed bridge with a tower height of about 45-ft above the roadway. The key differences in the two systems include:

1. Towers: The lower tower height of the extradosed bridge allows the use of a compact tower section as the tower slenderness does not impact the design. As the cables can be easily accessed from a man-lift placed in the shoulder area, internal tower access is not needed. This allows the tower leg section of the extradosed bridge to be reduced to a 6-ft x 7-ft section with the 6-ft dimension being the transverse width. The cable-stayed tower design follows traditional cable arrangement where the cables are anchored inside the hollow tower with internal access provided for the inspection and maintenance of the cable anchorages. Furthermore, as the tower design is controlled by transverse slenderness, a minimum tower section of 7-ft x 10-ft is required at the deck level where the 7-ft dimension is placed in the transverse direction.

2. Foundations: One of the key foundation issues at this site is the skewness of the flow to the bridge axis. The tower footing for the cable stayed option becomes relatively large due to the need to keep the footing oriented along the direction of flow. The tower legs for the extradosed option on the other hand can be brought back to minimize the foundation size, helping this situation considerably.

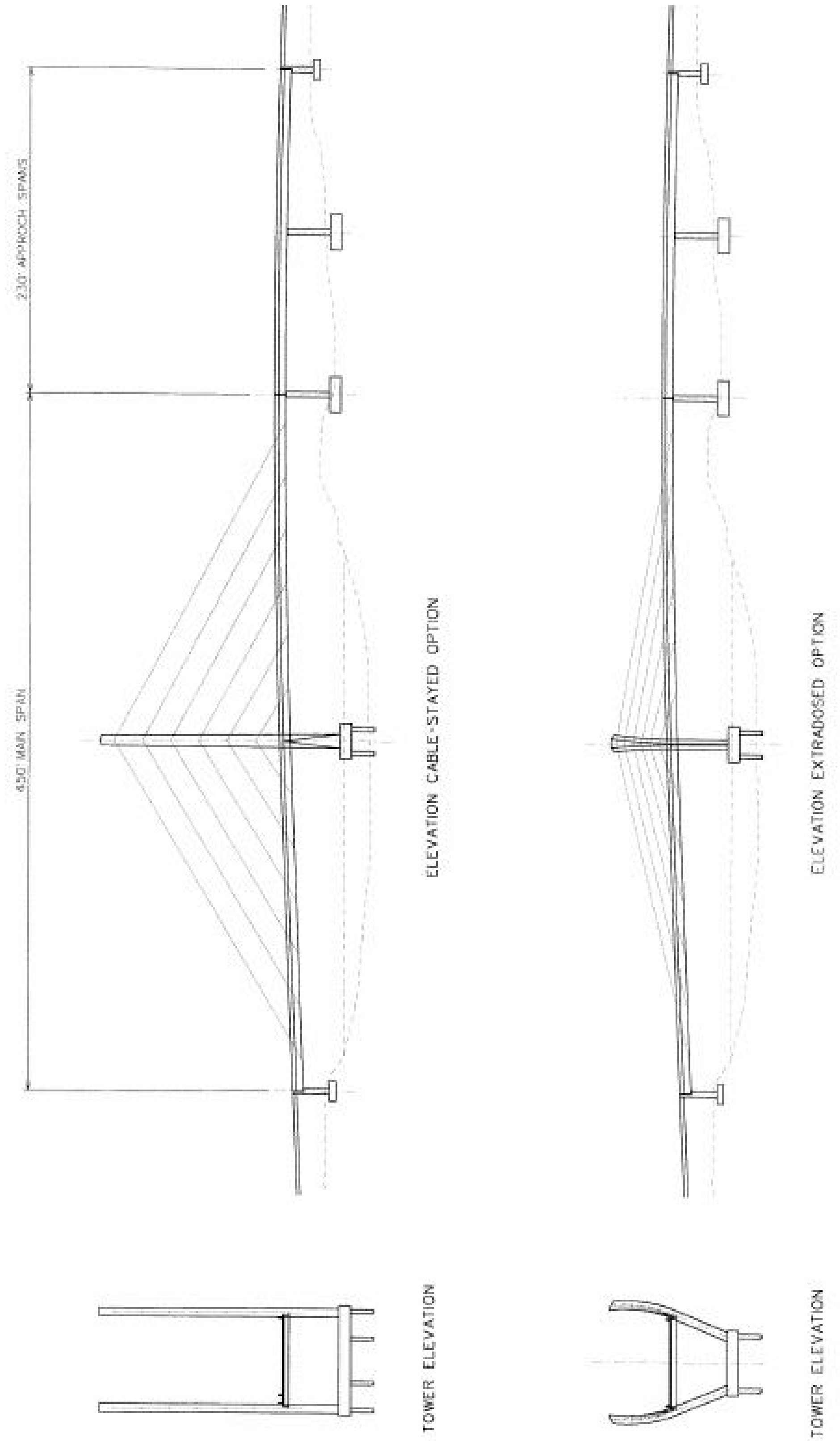

Figure 4: Bridge Layout Options

3. Cables: Saddle type tower cable anchorages are proposed for the extradosed option. This is more cost effective and facilitates faster construction given that internal access is not required for regular inspection and maintenance. For the cable-stayed option however, traditional anchorages are assumed. Furthermore, due to the significant reduction in the cable fatigue stresses in the extradosed bridge option, a higher allowable stress of 0.55*GUTS is used[5] for AASHTO Group I service loads where as the traditional 0.45*GUTS is used for the cable-stayed option.

The designs are still under development, and the following discussion on design issues is based on results to date.

3. KEY DESIGN ISSUES

Cable Fatigue Stresses: Following is a tabulation of cable fatigue stresses for the cable-stayed and extradosed options. Fatigue stresses were obtained using the 1993 PTI Guide Specifications as well as the 2001 PTI Guide Specifications, which uses an LRFD approach.

Table 1: Cable Fatigue Stresses

Evaluation Criteria	Extradosed	Cable-Stayed	PTI Allowable Range
PTI 1993 Guide Specifications	9.86 ksi	17.43 ksi	18 ksi
PTI 2001 Guide Specifications	4.21 ksi	7.61 ksi	8 ksi

The fatigue stresses for the extradosed bridge option is considerably less than that for the cable-stayed. Similar results are reported by Steven Stroh et al [2]. Thus, the use of a higher allowable stress for cables is justifiable. However, this is an issue that PTI should probably address in future editions to ensure uniformity of application.

Global Design Optimization: Figure 5 shows the service level design moments for the cable-stayed layout. The optimized dead load condition was obtained by adjusting cable forces to reduce the peak negative moment demand at the tower location as shown in Figure 6. Parallel data for the extradosed option is shown in Figures 7 and 8. It can be seen that the peak negative live load moment demand for the extradosed option is about twice that for the cable-stayed, making the dead load optimization for this option more important for design than for the cable-stayed.

[5] Same as that reportedly used on Pearl Harbor Memorial Bridge [2]

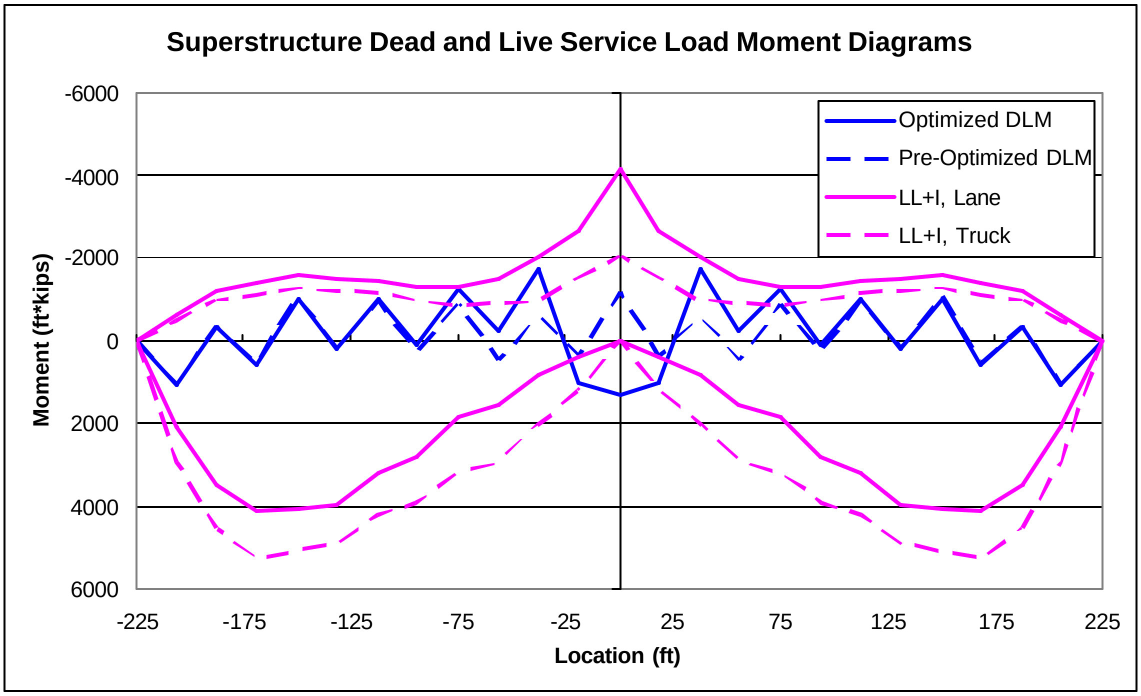

Figure 5: Cable-Stayed - Service Level DL and LL Moment Diagrams

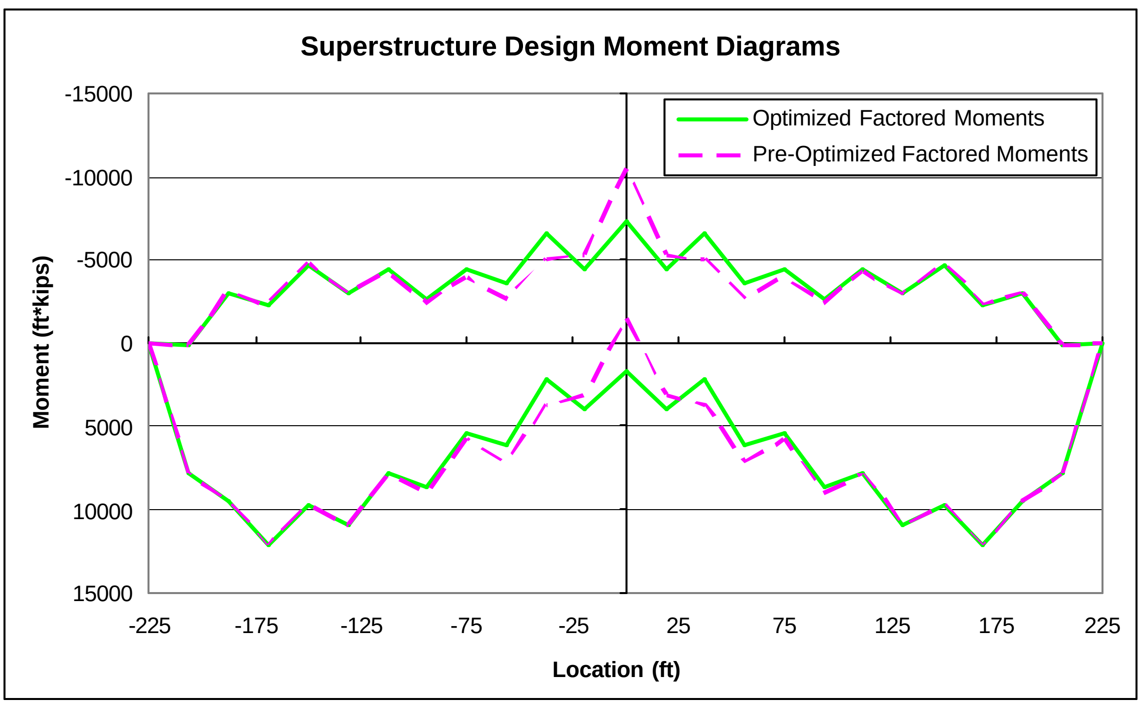

Figure 6: Cable Stayed - Superstructure Design Moments

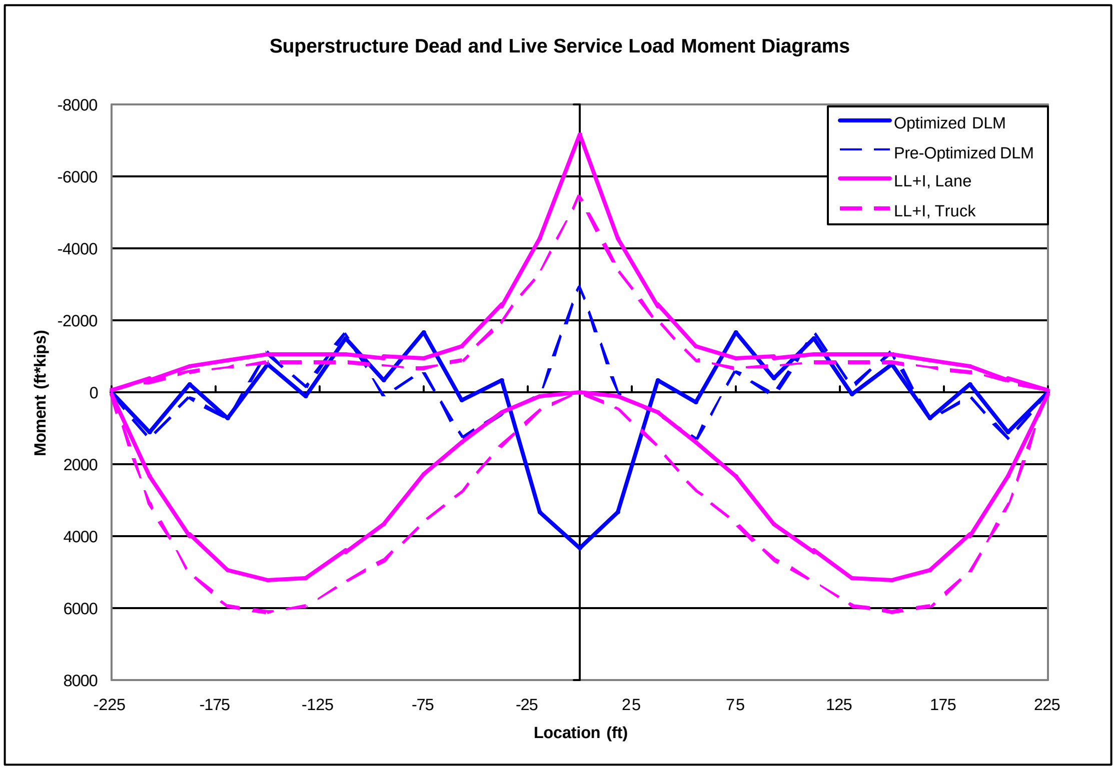

Figure 7: Extradosed - Service Level DL and LL Moment Diagrams

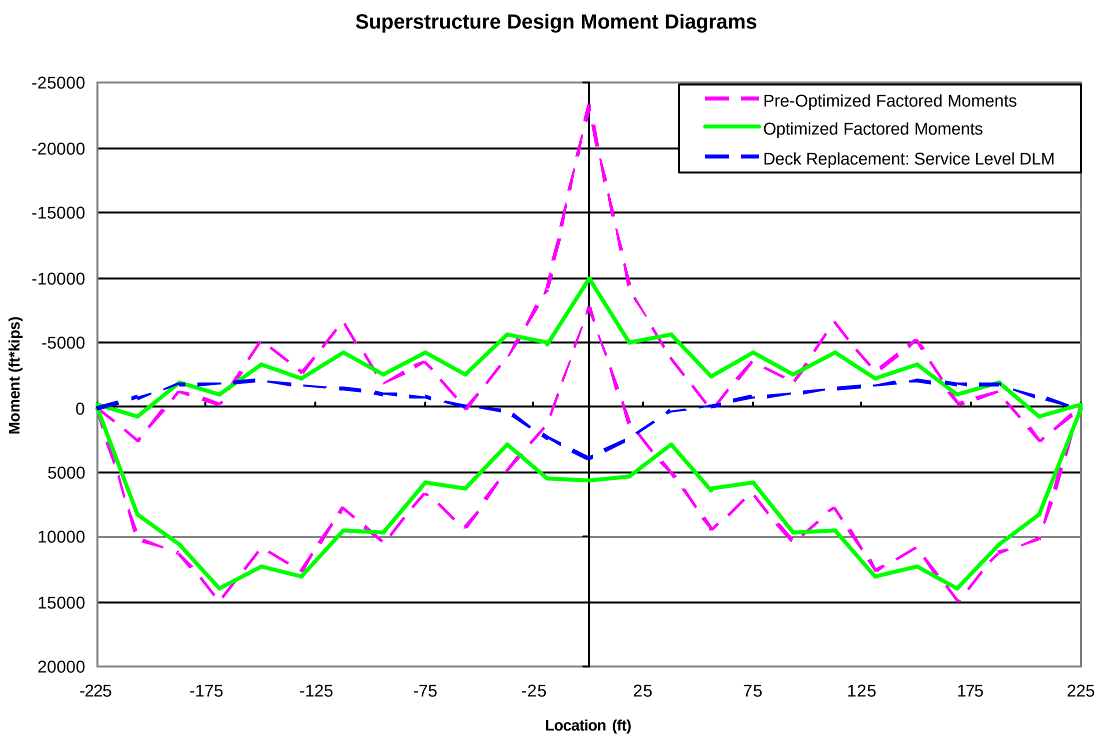

Figure 8: Extradosed - Superstructure Design Moments

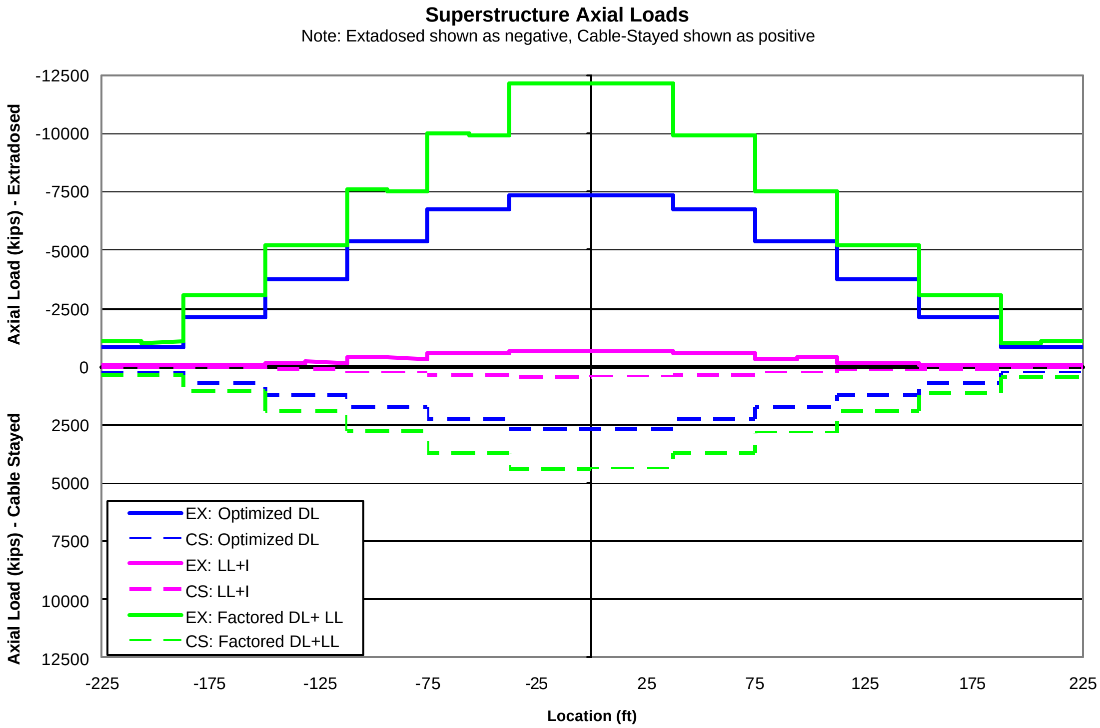

Figure 9: Extradosed vs. Cable-Stayed - Superstructure Axial Loads

Superstructure Axial Loads: Superstructure axial load diagrams for the extradosed and cable-stayed options are shown in Figure 9. For the purpose of showing cable forces for the two options on the same graph, forces for the extradosed option are shown above the horizontal axis (negative) and those for the cable-stayed option are shown below the horizontal axis (positive). The axial loads are compressive for all cases regardless of the sign as shown in the above graph. The dead load axial force for the extradosed option is about three times that for the cable-stayed option. While there is no great benefit to be gained in the design of edge girders by the increase in axial loads, it helps considerably in controlling tension in the deck slab, leading to a significant reduction in the deck post-tensioning required.

Deck Replacement: Figure 8 shows the girder moments induced due to replacement of the deck slab in 16-ft wide strips (4 stages). It can be seen that the momeents are well within the capacity of the girder. The maximum girder deflection due to this loading is less than about 12”. This indicate that replacement of the deck of an extradosed bridge is considerably less demanding than on a cable-stayed strcture.

Cable Forces: The cable forces for the two bridge options are shown in Figure 10. In this figure, cable 1 is the longest cable and cable 6 is the shortest cable closest to the tower. Again, for the purpose of showing cable forces for the two options on the same graph, forces for the extradosed option are shown above the horizontal axis (positive) and those for the cable-stayed option are shown below the horizontal axis (negative). The cable forces are tensile for all cases regardless of the sign as shown in the graph.

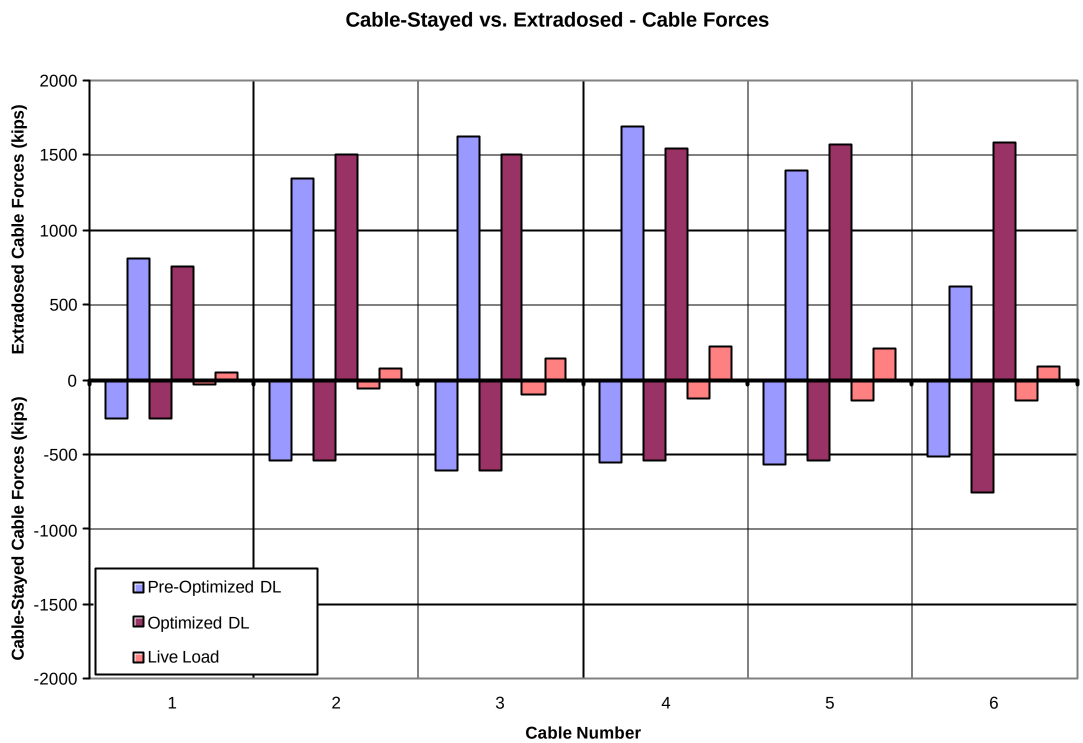

Figure 10: Extradosed vs. Cable-Stayed - Comparison of cable forces

4. COMPARISON OF CABLE-STAYED VS. EXTRADOSED

Cable fatigue stresses: Extradosed bridge cable fatigue stresses are about 50% of the cable-stayed bridges and this justifies using a higher service level allowable stress in cable design

Superstructure design: The factored design moments for dead and live loading for the Extradosed bridge superstructure is about twice that for the cable stayed option. However, the increased axial load appear to compensate for the increased bending in the deck slab and also help reduce the girder steel quantities slightly.

Deck replacement: The study results indicate that the deck replacement of the extradosed option is feasible within the original design capacity of the girder if done in four stages involving 16’ wide strips. In the worst case, some additional steel may be required to strengthen the girder for this future possibility.

Cost Efficiency: Extradosed option requires about 80% more cable steel than the cable stayed. There are major cost savings to be gained in the simpler tower design. However, about 60% of the cost savings in the tower is consumed by the additional cable steel required. There are additional savings in the simpler foundations (See table 2)

Table 2 below outlines preliminary quantity and cost differentials between the two options. The common elements for the two options are not shown in the table. It can be seen that for the case study options, the savings in the smaller tower for the extradosed option is negated to a large extent by the increase in cable steel. However, the extradosed option appears to be the more cost effective option based on the results of this initial study.

Table 2: Cable-Stayed vs. Extradosed – Preliminary Quantity Differentials

Preliminary Quantity Differentials							
Element	Item	Quantity		Unit	Unit Price	Differential (CS - EX)	
		Cable-Stayed	Extrados		$	Quantity	Cost
Tower	Tower Concrete (6000 psi)	580	340	CY	2000	240	$ 480,000
	Tower Reinforcement	270,000	146,000	LBS	1.00	124000	$ 124,000
	Tower Anchorages						$ 50,000
Cables	0.6" Diameter Strand	61,000	110,000	LBS	6.00	-49000	$ (294,000)
Superstructure	Deck Post-Tensioning	41,500	34,500	LBS	6.00	7000	$ 42,000
	Steel Edge Girder	415,000	410,000	LBS	2.50	5000	$ 12,500
Foundations	Footing & Drilled Shafts						$ 150,000
			Total Estimated Cost Differential				**$ 564,500**

REFERENCES

[1] The Tsukuhara Extradosed Bridge Near Kobe *by* Atsuo Ogawa, Tetsuo Matsuda and Akio Kasuga, Structural Engineering International (IBASE), V 8, No 3

[2] First of Its Kind *by* Steven Stroh, William Stark and Joseph Chilstrom, Civil Engineering (ASCE), August, 2003.

[3] Bridges, Three Thousand Years of Defying Nature *by* David J. Brown, Toppan Printing Co (1993)

[4] High Tech Twins by Akio Kasuga, Bridge Design & Engineering, V5, No 17, 1999.

[5] PTI Guide Specification (2001). Recommendations for stay cable design, testing and installation. Post-Tensioning Institute Committee on Cable-Stayed Bridges, 4th edition.

[6] PTI Guide Specification (1993). Recommendations for stay cable design, testing and installation. Post-Tensioning Institute Committee on Cable-Stayed Bridges, 3rd edition.