Strut Failure Investigation of Paseo Suspension Bridge in Kansas City, MO

A proposal submitted to Missouri Department of Transportation

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Introduction

The Paseo Bridge in Kansas, MO, is a self-anchored suspension bridge, see Fig. 1. The total length of the main bridge is 1232 ft, including one main span of 616 ft and two side spans of 308 ft. At each end of the bridge, two stiffening girders are independently tied down to a bridge pier with two vertical hangers as shown in Fig. 2. Each hanger consists of a lower and an upper link connected with bolts by a strut (24I120 or S24×120). The links are connected with the stiffening girder and the bridge pier by two 11-inch diameter pins, respectively. Both flange and web of the strut is coped at two ends.

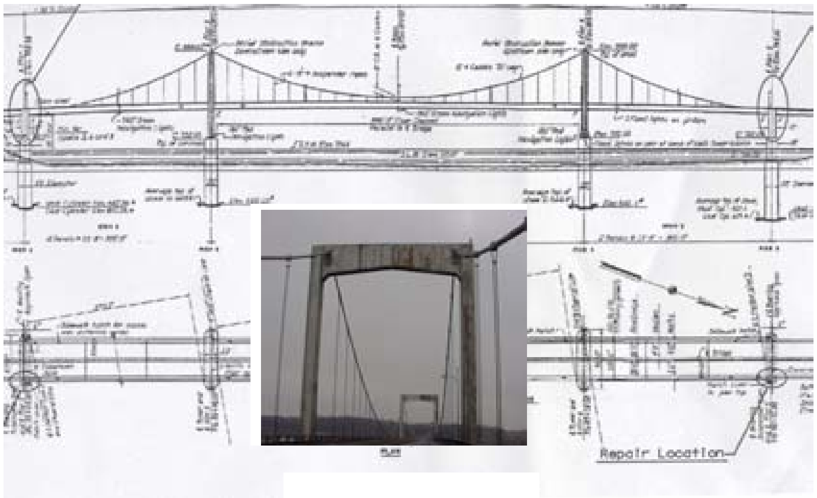

Fig. 1 Overview of the Paseo Bridge (Elevation and Plan)

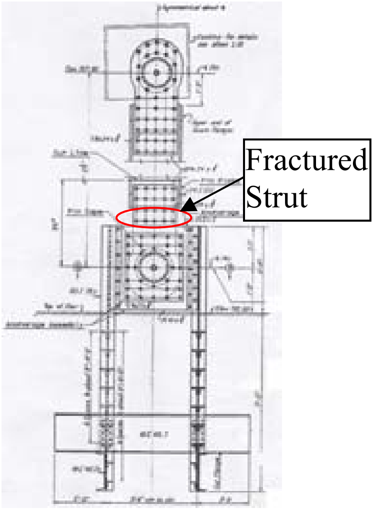

Fig. 2 Link Anchorage Details

The construction of the bridge began 1952. Currently, the bridge supports Interstate I-29 and I-35, and US Highway 71, and carries about 94,000 vehicles every day. On January 22, 2003, the Paseo Bridge was hurriedly closed to traffic during the Wednesday afternoon rush hours when a pronounced gap between sections of the bridge's deck sparkled fears about the span's safety. At the time, temperatures hit a record low of 9 below zero and windchills approached 25 degrees below zero. As shown in Fig. 3, the bridge deck of the southern side span raised about 8 inches above the approach deck. Next day, it was found that the strut (web) in the southeastern link anchorage assembly was fractured, see Fig. 4. A closeup view is presented in Figs. 5 and 6. Before the strut was completely fractured, several rivets were sheared off as seen from Fig. 7. Also seen from Fig.7 is a view of the fractured surface, indicating a brittle failure. Based on the discussions with field inspectors, the lower pin in the southeastern hanger was frozen and it does not allow for free rotation of the superstructure, which could be a key factor contributing to the fracture of the strut. This can be seen from the comparison between two pins (east vs. west side) in Fig. 8. The surface condition of the pin on the east side is severely corroded. Decision was made to replace all four hangers of the bridge including the fractured one. When the strut on the southwestern hanger was removed, it was also found to have been cracked, see Fig. 9. However, careful inspection by engineers reported that this crack is due mainly to overstressing as a result of fracturing of the southeastern strut.

Fig.3 Bridge Deck Rise of the Southern Side Span

Figure 4 Point of Strut Failure

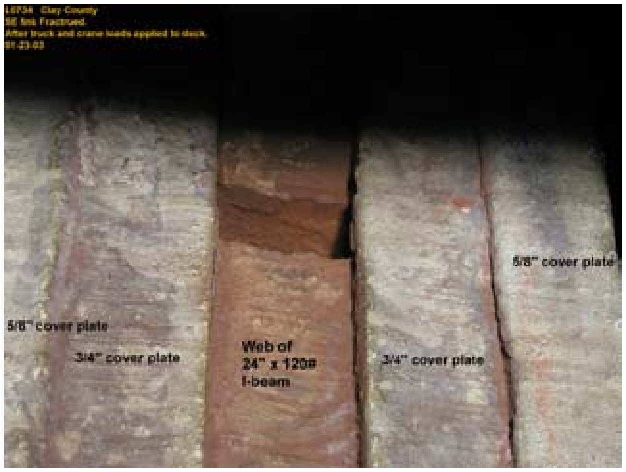

Fig. 5 Web Detail

Fig.6 Lower Link Anchorage

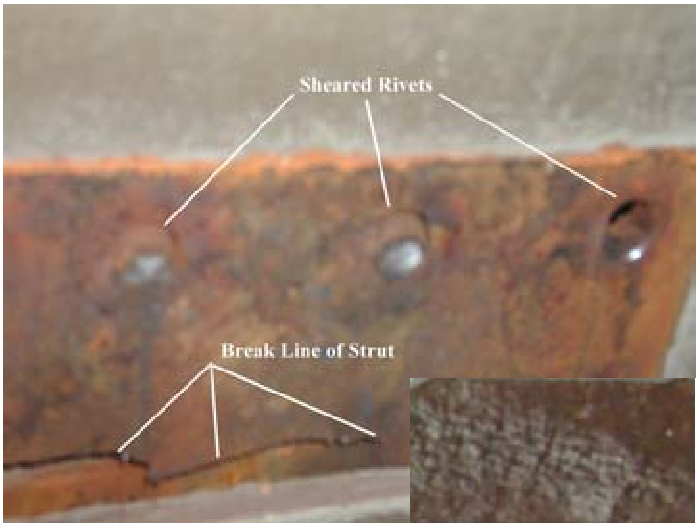

Fig. 7 Shear Damage of Rivets and Fracture Surface

(a) East Side (b) West Side

Fig. 8 Comparison of Pin Conditions

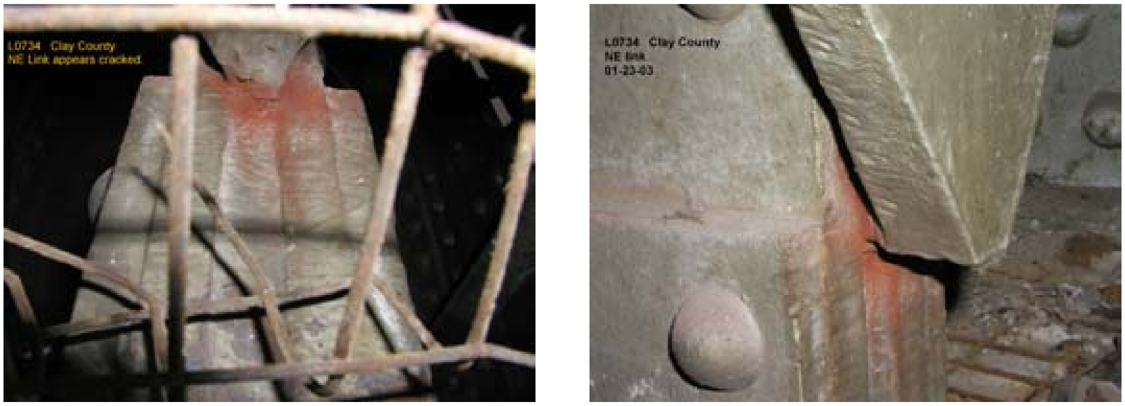

Fig. 9 Crack on the Southwestern Strut

As a result of the frozen condition in the southeastern pin, the strut is subjected to both tension/compression and bending. The damage of the strut is likely caused by one of the following reasons or their combination: overstressing, thermal expansion/contraction, fatigue, and reduction in fracture toughness associated with low temperatures.

After reviewing the AASHTO Specifications (1949) or the Steel Construction (AISC, 1941), the struts in the hanger links were likely made of A7-46 Structural Carbon Steel, though there is no detailed information available. In this proposal, A7-46 will be considered in the design of various test programs. In the event that the type of material is found different from A7-46 based on tension tests, necessary modifications will be made in fracture and fatigue characterization tests.

Objectives

The objective of this project is to understand the plausible reason(s) why the southeastern vertical strut of the Paseo Suspension Bridge in Kansas City, MO, fractured on January 22, 2003 after nearly 50 years of service. The load on the strut will be estimated from three sources: the payload used on the bridge deck during repairing to reposition the raised deck, the calculation of load rating from previous inspections and from the recent emergency design, and thermal effects on the failed strut as a result of a frozen pinned condition. The fatigue strength and fracture resistance will be determined with a series of characterization tests of the materials from the failed strut.

Project Design and Methodology

The scope of the proposed work is summarized in eight tasks and each task is detailed as follows:

1. Determine basic material properties,
2. Establish a stress-cycle (S-N) curve for crack initiation life estimation,
3. Establish the relation between fracture toughness (K_{IC}) and temperature,
4. Establish the crack growth rate data for crack propagation life estimation,
5. Estimate the average dead plus live load, range and number of cycles of live load,
6. Establish a detailed finite element model,
7. Simulate the strut failure process,
8. Disseminate the results and findings.

Task 1 Determine basic material properties

A total of five tension specimens will be made following ASTM Standard. They will be cut and machined from the fractured strut. Each specimen will be tested under the MTS880/810 loading machine at room temperature. The stress-strain curve of the materials used in the fractured strut will be established from a series of displacement-controlled tests. In particular, the modulus of elasticity, yield stress and ultimate stress will be determined.

Task 2 Establish a stress-cycle (S-N) curve for crack initiation life estimation

To understand the fatigue strength of the materials, six sets of standard (rectangular) tension specimens will be fabricated. Each set of specimens will be tested at one stress level (room temperature) so that an S-N curve can be developed for low and high stress levels. Identical tests of five specimens are used to ensure the validity of test data.

Under usual circumstances, the fatigue (S-N) data is used to estimate the so-called initiation life. This is the number of cycles to failure (crack initiation) if the component had no prior loading history. The Paseo Bridge has been in service for many years. As such the specimens cut out from its structure do not represent virgin materials. The S-N data to be generated from these samples could only be used to predict the residual life rather than the total initiation life. With this understanding, constant amplitude fatigue tests will be conducted on the MTS810 machine according to the ASTM standard E606-92 both at low and high cycle fatigue regions to obtain fatigue constants $(K', n', \sigma'_f, \varepsilon'_f, b, c)$ that are needed to estimate the crack initiation life (Bannantine et al., 1990). The stress-strain and strain-life relations in this approach are given in Eqs. (1) and (2).

$$\frac{\Delta\varepsilon}{2} = \frac{\Delta\sigma}{2E} + \left(\frac{\Delta\sigma}{2K'}\right)^{1/n'} \tag{1}$$

$$\frac{\Delta\varepsilon}{2} = \frac{\sigma'_f}{E}\left(2N_f\right)^b + \varepsilon'_f\left(2N_f\right)^c \tag{2}$$

where $\Delta\varepsilon$ and $\Delta\sigma$ respectively denote the cyclic strain and stress ranges on the specimen, E is the modulus of elasticity of the tested materials, K' and n' represent the cyclic strength coefficient and the cyclic strain hardening exponent, respectively of the material, and $2N_f$ is the number of reversals to failure.

Task 3 Establish the relation between fracture toughness and temperature

Literature has been consulted in terms of fracture and fatigue behavior of ASTM A7 steel. There is no data specifically on A7. However, comparing the yield stresses σ_{ys} and looking at a comparable material (σ_{ys} in the range of 33-36 ksi), the fracture toughness K_{IC} for A17 could be in excess of 200 ksi√in. Such a combination of σ_{ys} and K_{IC}, would require a prohibitively large thickness for facture toughness test specimens, following the ASTM E399 Specification.

Instead of determining K_{IC} using standard plane strain fracture toughness testing, Charpy impact tests will be conducted on 30 V-notched specimens. The Charpy Impact Tests will be done at six temperatures in the range of room temperature to -10°F. Six pre-cracked specimens will also be tested using this method (three tests at two temperatures). With the empirical relations between Charpy energy and K_{IC} for low strength alloys, that are available in literature, the plane strain fracture toughness will be related to temperature. The static properties required for this conversion at various temperatures will be experimentally determined. The goal of this exercise would be to determine the maximum flaw size at the design stress as a function of the operating temperature using the fracture criterion $K_I = K_{IC}$.

Task 4 Determine the crack growth rate in Paris Law for crack propagation life estimation

To study the crack growth and propagation in the fractured strut, crack growth rate data will be generated to determine the constants *C* and *m* in Paris Law (Bannantine et al., 1990):

$$\frac{da}{dN} = C(\Delta K)^m \tag{3}$$

in which da/dN is the crack growth in one cycle and ΔK is the stress intensity factor range. It is expected that the minimum and maximum stress ratio of the fractured strut is between 0 and 0.5. The effect of the stress ratio will be taken into account using the concept of "effective ΔK". A total of five compact tension specimens will be made with a machined notch and fatigue pre-crack as shown in Fig. 10. They will be tested on the MTS810 machine according to ASTM Standard E647-95a at room temperature. The crack length during stable growth will be determined with an unloading compliance method.

Task 5 Estimate the average dead plus live load, range and number of cycles of live load

The load on the fractured strut will be estimated from three sources: the payload used on the bridge deck during repairing to reposition the raised deck, the calculation of load rating from previous inspections and from the recent emergency design, and thermal effects on the failed strut as a result of a frozen pinned condition. Dead and live loads as well as thermal effects will be considered in this study. Traffic flow records and temperature change data in the bridge area will be collected to estimate the number of stress cycles due to their effects acted upon the strut. Depending upon how much information made available by the Missouri Department of Transportation, an idealized cable structural model may be developed for structural analysis of the main bridge to facilitate the determination of dead and live loads on the strut. Such a model may also be needed to understand the stress variation in the strut induced by traffic or temperature fluctuations.

The stress on the new and old struts will be determined analytically and compared. Effort will also be made to search for the fatigue properties of the materials used for the new struts and use them to approximately estimate the service life of the new struts.

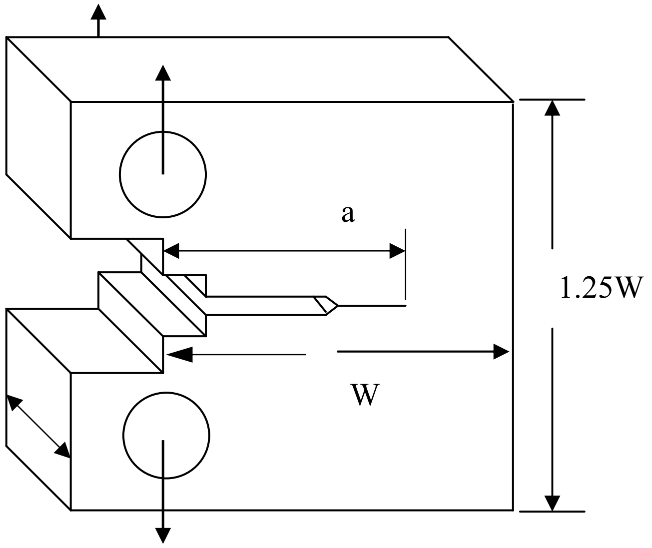

Fig. 10 Compact Tension Specimen

Task 6 Establish a detailed Finite Element Model

A detailed finite element model will be established for lower part (min. 4 rows of rivets) of the failed strut to study stress concentration at its connection and the stress intensity factor as a function of crack length. Three-dimensional solid elements will be used to model the lower link anchorage system and a refined mesh will be considered in the coped flange and web area of the failed strut. Based on recent experiences gained from the mast arm failure investigation, it can be assumed that the life of crack initiation governs the total fatigue life. The model will therefore be calibrated with the fatigue life (crack initiation life) of the failed strut in terms of initial flaw size. This assumption will be validated in Task 7. Attempts will be made to take into account the effect of deformed rivets on the stress distribution in the failed strut, which will affect the fracture line of a strut. Friction between the web of the strut and other plates will be neglected at the ultimate load since it is expected relatively small in comparison with ultimate capacity of the strut. However, due consideration of friction effect will be given if warranted at lower stress levels. Further inspections on the web surface of the failed strut will be conducted to see any indication of significant friction during fracturing of the strut.

Task 7 Simulate the strut failure process

To fully understand why the southeastern strut fractured, reverse engineering is exercised in this task. The goal is to reproduce the failure process that is well constrained with field observations and material properties. Since the material properties are limited to those under pseudo-static loads, the failure process will be simulated statically in an incremental fashion. The time allowing for the evolution of cracking will be determined from the number of cycles corresponding to an incremental crack length. Stress redistribution will be investigated with the finite element model as a crack grows or propagates for each increment. The stress concentration factor will be updated at the same time. The failure process will be developed based on the redistributed stress field and the crack growth model established in Task 4.

Assume that a small defect (e.g., 0.05 inch) exists at the end of strut flange(s). The strut can still support the external loads until the defect propagates through the most web section of the strut so that fracture of the remaining section occurs suddenly. Crack propagation life is defined as the number of stress cycles (or converted into time in years) the propagation of the defect completes. For development of an incremental crack length, the number of stress cycles that the strut can take is determined based on the Paris Law. If variable amplitude stress cycles are concerned, the Root-Mean-Square model will be used to determine their equivalent effect as if they were of constant amplitude.

Whether cracking of the fractured strut propagates in one direction (from one end of the strut web to the other) or in two directions (from two ends to the center of the strut web) will significantly change the failure process. Inputs from field inspectors will be solicited to see if any evidence indicates that the strut cracked from both ends of its web and which web end of the strut is near the main bridge. Based on the fracture line of the failed strut, see Fig. 11, it is likely that crack initiated from one end of the web in an approximately 30° angle and propagated about one third of the web before sudden fracture occurred over the remaining section.

Fig. 11 Line of Strut Fracture

For propagation of a crack from one side of a strut web, the stress intensity factor can be determined by (Broek, 1984):

$$K_I = 1.12\sigma\sqrt{\pi a[1 - 0.2060\frac{a}{w} + 9.397(\frac{a}{w})^2 - 19.34(\frac{a}{w})^3 + 27.06(\frac{a}{w})^4]} \tag{4}$$

in which a is the crack length, w is the web width, and σ is the stress applied on the web. They are illustrated in Fig. 12.

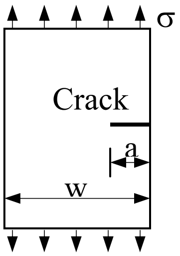

Fig. 12 One-Side Crack: Mode I

Task 8 Disseminate the results and findings

The results and findings from this study will be summarized in a final report that will be submitted to the Missouri Department of Transportation. Intermediate results will also be submitted to the annual transportation research board meeting for discussions and publication.

Project Schedule and Management

Due to the time consuming nature of fatigue tests, the proposed project requires 18 months to complete all tasks delineated above. Specific timelines of the proposed study are established in Table 1. Dr. Genda Chen will be responsible for managing the project and ensuring that the project be completed on time within the budget constraint. A post doctoral fellow or two graduate students will work on the project full time. Drs. Lokesh Dharani and Genda Chen will supervise the technical aspects of the project.

Table 1 Project Timeline

Task	Month	3	6	9	12	15	18
1		→					
2		──	──	→			
3		──	──	→			
4			──	──	→		
5		──	→				
6			──	──	→		
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