Breakthrough

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Bridge Failure Points to Mechanically Frozen Pin

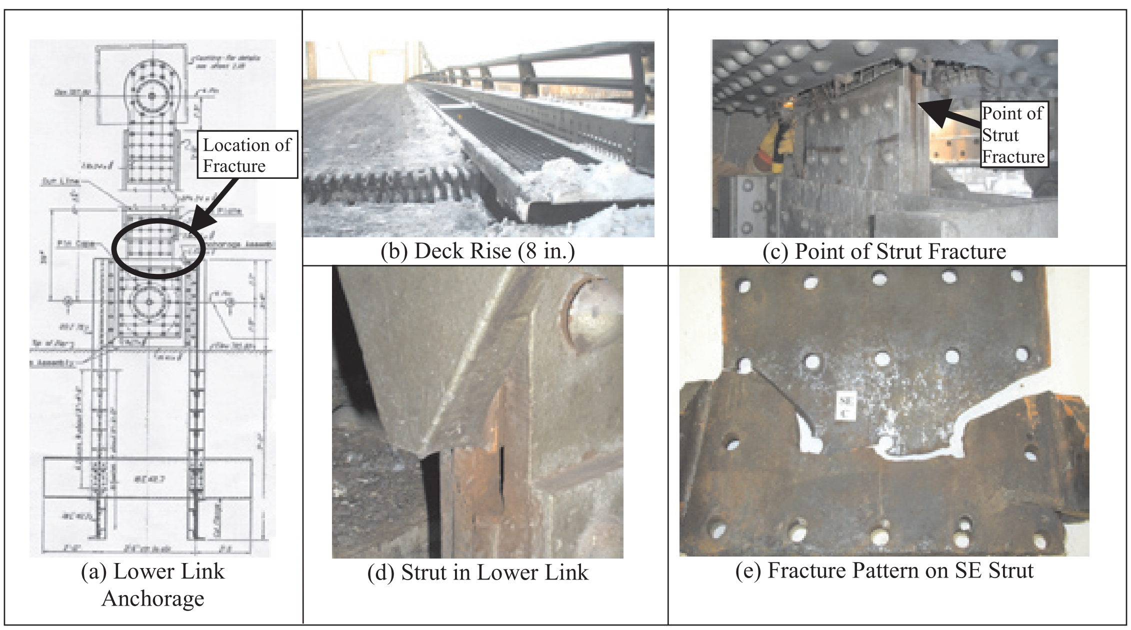
Business Issue

On January 22, 2003, the Paseo Bridge was closed to traffic when the bridge deck was raised by eight inches as indicated in Fig. 1(b). At the time, temperatures were reported to have hit a record low of -9˚F. During inspection the following day, the strut in the southeastern link anchorage assembly was found to be fractured as shown in Fig. 1(c, d, e). Field inspectors found the lower pin in the southeastern hanger was locked up and did not allow for free movement of the superstructure. As a result, the strut was subjected to both tension/compression and bending. Plausible reasons for the strut failure included overstressing, thermal contraction, fatigue, and reduction in fracture toughness associated with low temperatures. MoDOT needed to determine the actual cause and find a way to prevent similar failures in the future.

Background

The Paseo Bridge is a 1,232-feet long, self-anchored suspension structure spanning the Missouri River. Built in 1952, it supports Interstates I-29 and I-35 as well as US Highway 71 with an average daily traffic volume of 89,000 vehicles in 2003. At each end of the bridge, two stiffening girders are tied down to a bridge pier with two vertical hangers. Each hanger consists of a lower link, a strut, and an upper link. The links are connected with the stiffening girder and the bridge pier by two 11-inch diameter pins, as illustrated in Fig. 1(a).

Figure 1. Link Anchorage Details, Fracture Effects and Fracture Details



(a) Lower Link Anchorage

(b) Deck Rise (8 in.)

(c) Point of Strut Fracture

(d) Strut in Lower Link

(e) Fracture Pattern on SE Strut

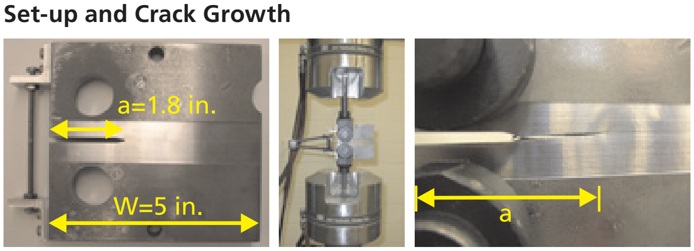
Approach

MoDOT teamed with the University of Missouri-Columbia to conduct a study[1] to understand why the southeastern vertical strut of the bridge fractured after 50 years of service. To achieve this objective, material and fatigue tests were performed on samples of the strut material according to several ASTM standards. The scope of this study included: (1) determining the basic material properties from static tensile testing; (2) estimating service loading conditions and number of cycles, (3) establishing a stress and cycles-to-failure (S-N) relation for crack initiation life estimation, taking into account mean stress effects; (4) establishing crack growth rate for crack propagation life estimation; (5) establishing the relation between fracture toughness and temperature; and (6) establishing a detailed finite element model and simulate the strut failure process.

Tension testing on five tensile specimens fabricated from the material of the fractured strut indicated that the material was A36 steel. The dead plus live load on the failed strut is 145 kips in tension only when the pin is free to rotate. With a frozen pin condition, the dead plus live load includes a tension force of 145 kips and a moment of 4,250 kip-in at a design temperature of 60ºF. The thermal effects amount the loads to a total of 200 kips in tension and 40,800 kip-in in bending moment, respectively, when the temperature drops to -10ºF. Each strut was subjected to approximately 230 cycles of live loading per day.

The fatigue constants necessary for the residual life prediction after 50 years of service have been determined with testing of 25 specimens. Fatigue tests on the failed strut material indicated an infinite life under normal service conditions when the strut were free to rotate, had no initial defects, or small cracks inherent to steel structures. However, initial defects often exist in steel members, especially around the coped flange of the fractured strut. Therefore, five compact tension specimens were tested as shown in Fig.2 to establish the Paris crack growth law. It was determined from the crack growth law that nearly 1,000,000 cycles (approximately 12 years) of 100% design loading or over 2,500,000 cycles of 50% design loading are required for an initial defect of 0.005 inches in the strut to propagate

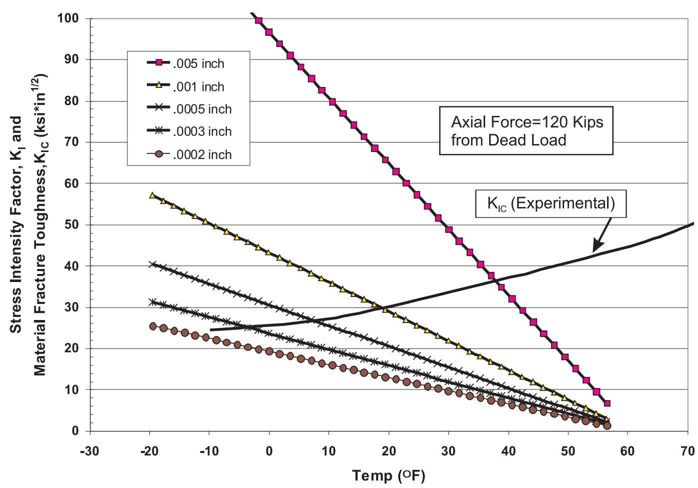
Figure 2. Crack Growth Test: Compact Tension Specimen, Set-up and Crack Growth



to a critical length (over 1.3 or 2.4 inches) causing sudden fracture under normal loading conditions if the pin were free to rotate. Since no visual cracks were recorded during the inspection two months prior to the failure, crack propagation was unlikely the reason for the failure. On the other hand, sudden fracture occurred as a result of the mechanically frozen pin condition at the lower link of the southeastern strut due to substantially increased bending stress as previously mentioned.

To investigate the effect of temperature on the strut failure, Charpy impact testing of 45 specimens was conducted at nine temperatures so that the critical flaw size at the design stress can be determined as a function of the operating temperature from -10º to 136ºF. The breaking energy of various specimens was related to the temperatures to which the specimens are exposed. The fracture toughness was then converted from the breaking energy with an empirical relation. It ranges from 24 to 110 ksi*in1/2, as shown in part in Fig. 3 for K_{IC}.

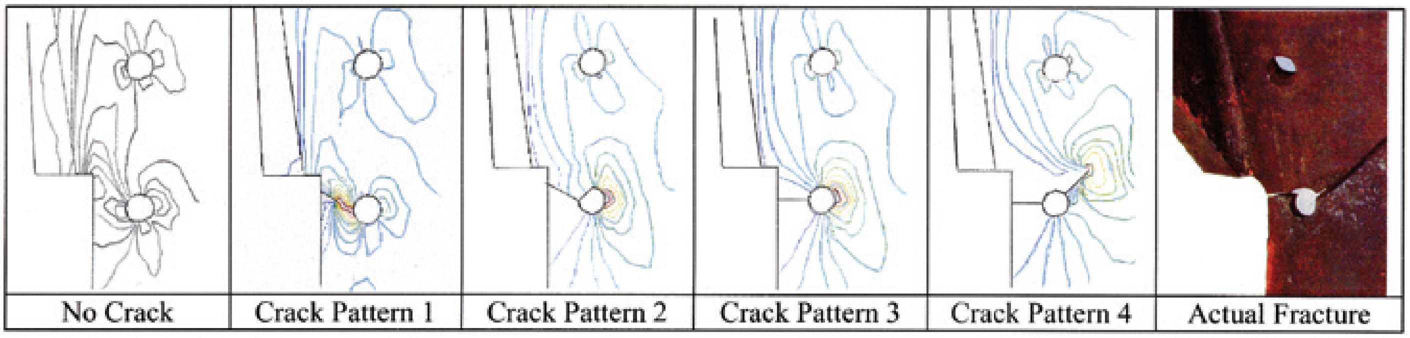
Figure 3. Prediction Chart for Fracture of the Southeastern Strut



When the fractured strut is simplified into an edge cracked plate subjected to tension and bending, the load-temperature relation established before can be transformed into the relation between the (elastic) stress intensity factor, K_I, and the temperature. The results are presented in Fig. 3 corresponding to each initial flaw size from 0.0002 to 0.005 inches. At a temperature of -10 ºF, the strut may fracture suddenly since K_I is larger than K_{IC} when an initial flaw between 0.0002 and 0.0003 inches is present. It must be noted that, on one hand, the conversion equations from the load to the stress intensity factor are a non-conservative estimate to the actual condition. On the other hand, consideration of plasticity around the root of a notch in actual conditions will reduce the stress intensity factors. Therefore, numerical simulations with computer

[1] Chen, Dr. G.D., University of Missouri-Columbia, (2005). Failure Investigation of the Steel Strut on the Paseo Suspension Bridge, Kansas City, MO.. Report RDT 05-008, Missouri Department of Transportation, Jefferson City, MO, USA.

Figure 4. Stress Contours for Crack Initiation Location Determination



software were conducted to mimic the actual geometry and take into account inelastic deformation.

Two finite element models of the strut, a global model for the entire strut and a local model for the cracked area, were developed to better understand the stress intensity factor at the location of flange coping, the area of crack initiation in the failed strut, and the process of failure. Simulation results indicated that the strut would never have fractured even at low temperatures and with a 0.005-inch initial defect if the pin in the lower link were free to rotate. Low temperature makes the strut material behave more brittle with low fracture toughness and is thus a secondary contributor to the fracture of the strut after the pin was mechanically frozen. The load transferred through the web of the strut is likely 50% of design loading as supported by the fact that the strut did not fracture under the combined dead plus live load and thermal effect at a temperature of higher than -10ºF during the bridge inspection in November, 2002. The initial defect (crack) in the coping flange area of the failed strut seems more than 0.001 inches.

To identify the location of crack initiation and propagation, a series of local models with various initial crack lengths were established. Each model was analyzed for the same load case. When there are no crack and cracks of various sizes (Crack Pattern 1 through 4), the stress contours are shown in Fig. 4. It is observed from Fig. 4 that crack is likely initiated near the flange coping area due to high stress concentration and propagated towards the closest hole. To further see the propagation of an initial crack, two additional models with a crack length of 0.5 in. for Crack Pattern 1 and 1.1 in. for Crack Pattern 2, respectively, were analyzed. As a result of the previous cracks, the maximum stress occurs in the opposite side of the hole near the flange coping area. To understand how sensitive the location of the maximum stress, the third crack pattern was introduced. By comparing Crack Pattern 2 and Pattern 3, one can see that the locations of the maximum stress identified from the two models are practically the same. To finish up the analysis for crack propagation, the fourth crack pattern was created. By comparing Crack Pattern 4 with the actual fracture pattern, also shown in Fig. 4, it is observed that the models accurately predict the crack initiation and propagation locations of the actual damage pattern.

Conclusion and Recommendations:

The root cause of the failure was overstressing of the vertical strut due to a locked up pin resulting from a bridge design that did not allow access for maintenance. The mechanical freezing of the lower link pin has been attributed to salt and sand accumulation in the lower link housing, discovered during the bridge inspection two months prior to failure. The overstressing, thermal contraction, fatigue, and reduction in fracture toughness associated with low temperatures were all real conditions, but they would not have caused the failure if the preventative maintenance had been allowed. Several relatively simple recommendations to prevent similar incidences to other bridges and the new struts installed on the Paseo Bridge include:

- Greasing the upper and lower pins during special pin inspections and maintenances to ensure continued free rotation of the struts. This would have prevented the freezing and allows for the free rotation. It is recognized that the design of the bridge had limited access to the lower link pin housing. Therefore, although the two cycles of inspection are adequate, special pin maintenance may be done over a longer time period such as every ten years.
- Partially sealing the lower housings to prevent salt and sand accumulation near the pins or using traps under the finger expansion joints to stop salt and sand debris from dropping to the lower link housing.
- Installing a problem alarm device at a cost of less than $10,000 to remotely monitor the rotation of all four vertical struts and immediately alert officials should the pins become mechanically frozen. In light of the limited access to the lower link area, greasing pins could be costly, and this recommendation may be a practical solution in some situations.

For More Information

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