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Executive Summary
RP 930-307

FATIGUE OF DIAPHRAGM-GIRDER CONNECTIONS

Sponsored by

The Alabama Department of Transportation
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16. Abstract

Distortion-induced fatigue cracking has occurred at hundreds of diaphragm-girder connections in multi-girder steel bridges in Birmingham, Alabama in recent years. The research goal was an improved maintenance strategy for repair and maintenance of the bridges so the potential for future cracking is minimized. The investigation included field measurements of distortion-induced stresses at connections, field measurements of the effects of removing diaphragms from two in-service bridges, structural evaluations of typical bridge designs, Finite Element Method analyses of typical bridge designs, and laboratory testing of bolted connections.

Results indicate interior diaphragms can be removed from many existing bridges without significant negative effects. Guidelines for evaluating candidate bridges were developed for both simple spans and continuous spans. A bolted connection was designed, installed in the field, and tested. Tests confirmed the new design performed better than the original design.

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SUMMARY

Construction of the interstate highway system through downtown Birmingham began in the late 1960's, and multi-girder steel bridges were used extensively. In most bridges, rolled W-shapes were used for girders and rolled channels for the diaphragms. The diaphragm-girder connections were typically made of a flat plate shop welded to the girder web and field welded to the diaphragm. The diaphragm connection plates were not attached to the girder flanges because welding to a tension flange was discouraged in common design practice at that time.

Over the last six years bridge inspectors have discovered distortion-induced fatigue cracks in the welds, connection plates, diaphragms, and girder webs at hundreds of the diaphragm-girder connections in the Birmingham bridges. Repairs included removing cracked welds, drilling holes at crack tips, and replacing welded connections with a bolted angle connection. Subsequent bridge inspections revealed that holes drilled at crack tips were ineffective at some connections and fatigue cracks had initiated in many of the bolted connection angles after only two years in-service.

The project goal was to develop an improved maintenance strategy for repairing diaphragm-girder connections and maintaining the bridges so that the potential for future cracking is minimized. The following options were investigated: continued use of holes drilled at the tips of web cracks, removal of interior diaphragms to eliminate diaphragm-girder connections, and redesign of the bolted connection angle to improve the fatigue life. The investigations included field measurements of distortion-induced stresses at connections, field measurements of the effects of removing diaphragms from two in-service bridges, structural evaluations of typical bridge designs, Finite Element

Method analyses of typical bridge designs to evaluate the effects of removing diaphragms, and laboratory testing of bolted diaphragm-girder connections.

Results of the research indicate interior diaphragms can be removed from existing bridges without significant negative effects. Guidelines for evaluating candidate bridges were developed for both simple spans and continuous spans. Evaluations of five typical designs were performed which indicate that all interior diaphragms can be remove from the (two) simple span bridges investigated and approximately half the interior diaphragms can be removed from the (three) continuous span bridges investigated.

The cause of the fatigue cracking in the original bolted connection angles used in repairs was identified, and a new design was developed. Laboratory tests and field measurements confirmed that the fatigue performance of the new design was better than that of the original design. The new design is proposed for use at connections where diaphragms are not removed.

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BACKGROUND

Multi-girder steel bridges are common along the state and interstate highway systems throughout the United States. The steel girders span in the direction of traffic flow from bent to bent and serve as the primary load carrying members. The structural system is tied together by a reinforced concrete deck slab and transverses steel members, or diaphragms, that are connected to the girders. Diaphragms at the girder supports provide resistance to transverse traffic and wind loadings. Interior diaphragms stabilize the girders during construction and placement of the deck, and also serve to some extent to distribute traffic loads transversely among the girders.

Construction of the interstate highway system through downtown Birmingham began in the late 1960's, and multi-girder steel bridges were used extensively. Primarily rolled W-shapes were used for girders and rolled channels for the diaphragms as shown in Figure 1.1. The diaphragm-girder connection in the original construction typically consisted of a plate field welded to the channel diaphragm and shop welded to the girder web. A typical connection is shown in Figure 1.2. Some connections were made using an angle welded to the girder web instead of a flat plate. The diaphragm connection plates were not attached to the girder flanges because welding to a tension flange was discouraged in common design guides at that time.

Over the last six years bridge inspectors have discovered fatigue cracking in the welds and base metal in many of the welded diaphragm-girder connections. Cracks have been discovered in the welds connecting the diaphragm to the connection plate,

Figure 1.1. Typical Lines of Channel Diaphragms

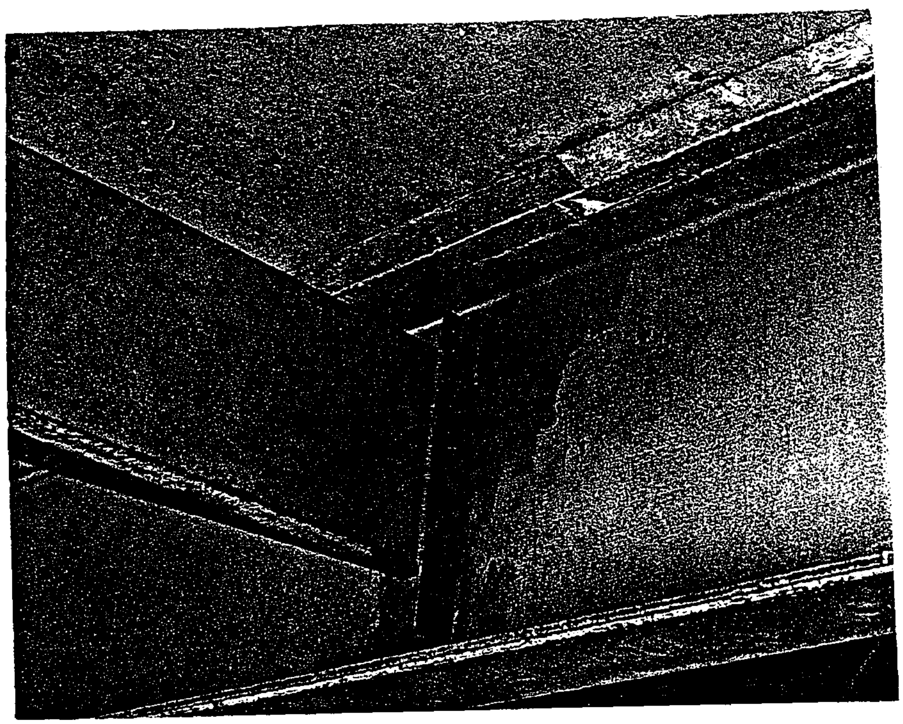

Figure 1.2. Welded Plate Diaphragm-Girder Connection

in the welds connecting the connection plate to the girder web and in the girder web. Cracking in the girder web, as illustrated in Figure 1.3, poses the greatest threat to the longevity of the bridges. Fatigue cracks develop at diaphragm-girder connections due to secondary live load forces created by differential deflections between the girders. These secondary live load forces cause out-of-plane distortion of the girder web which leads to distortion-induced stresses in the web and in the welds of the connection.

In the past the Alabama Department of Transportation (ALDOT) used three basic techniques to repair fatigue cracking at diaphragm-girder connections. Short cracks in welds were removed by grinding. More extensive weld cracks and cracked connection plates were repaired by removing the original welded connection and installing an angle bolted to the diaphragm and girder web as shown in Figure 1.4. Subsequent bridge inspections revealed cracking in many of these angles, as illustrated in Figure 1.5, due to bending of the angle leg bolted to the girder web. Distortion-induced cracks in the girder web were repaired by drilling a 19 mm to 25 mm diameter hole to remove the crack tips. This was ineffective at some locations as illustrated in Figure 1.6 by the fatigue cracks which have extended beyond the holes. Connections with significant weld cracks and web cracking were repaired by a combination of drilling holes in the web at crack tips and replacing the connection with a bolted angle connection.

Total repair costs for fatigue cracking at diaphragm-girder connections were approximately $8 million at the time this research project started. This large maintenance cost resulted from fatigue cracking at hundreds of connections. The cost of repairs, recognition that hundreds of additional connections may experience similar

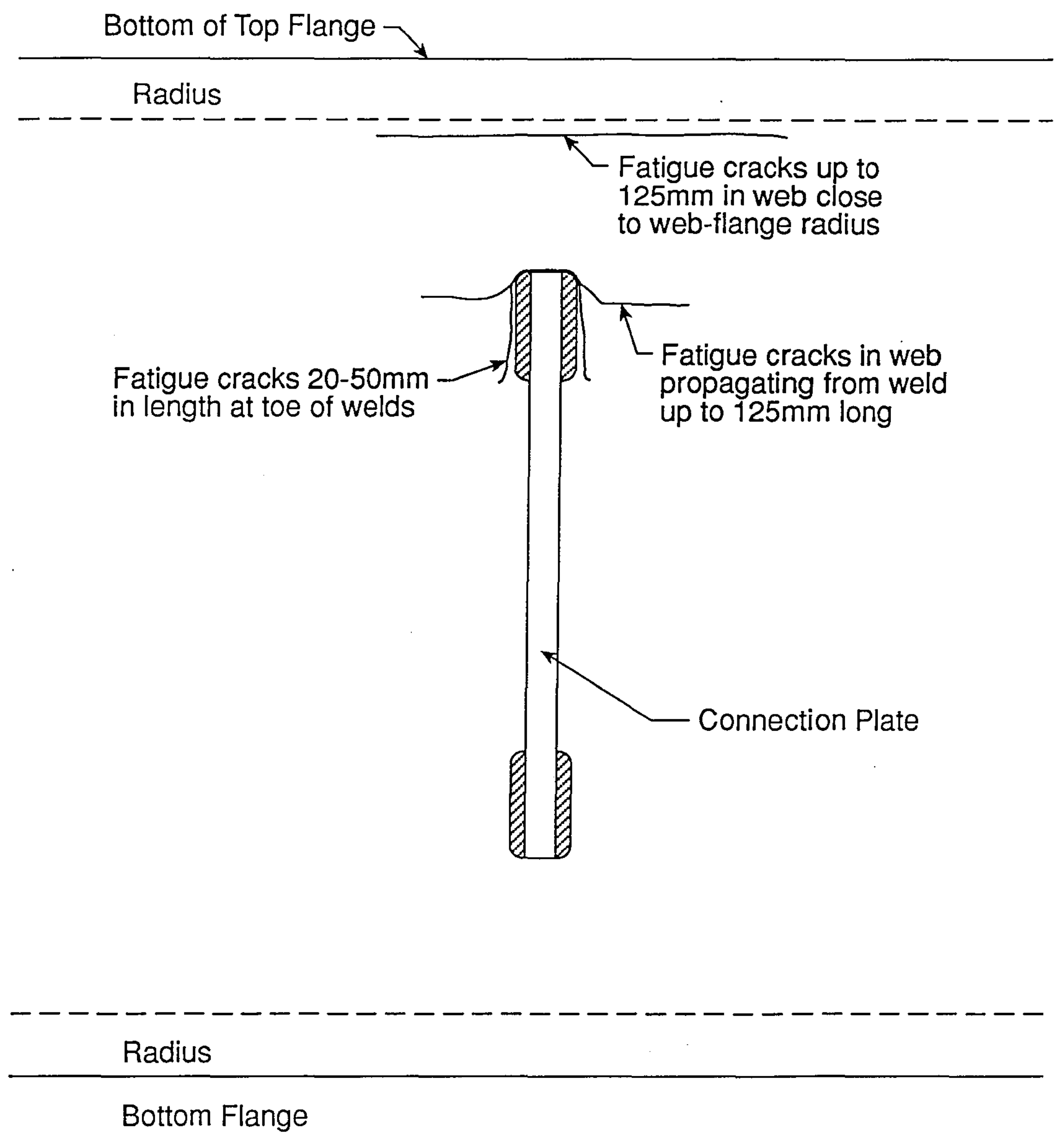

Figure 1.3. Typical Web Gap Cracks

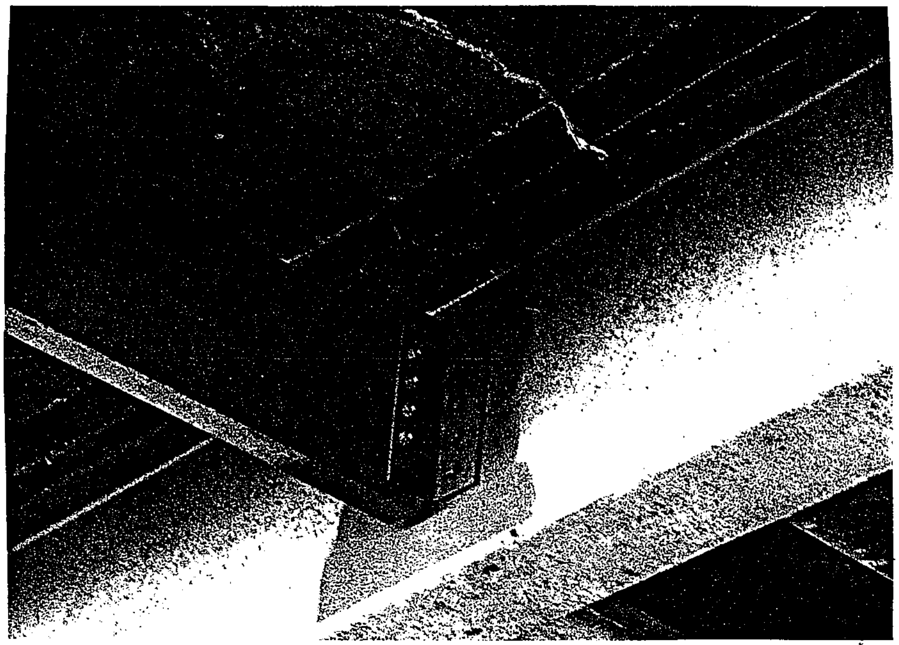

Figure 1.4. Bolted Angle Connection

Figure 1.5. Typical Fatigue Crack in Existing Bolted Connection Angles

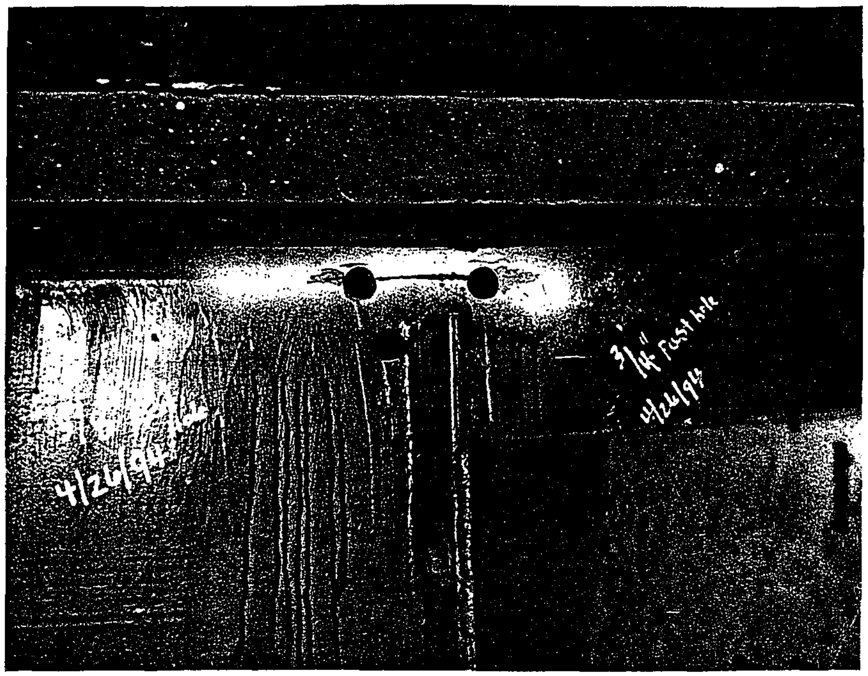

Figure 1.6. Web Cracks at Welded Plate Connection
with Drilled Hole Repair

problems, and concern that the repairs being performed were not permanent provided motivation for this research.

PROJECT OBJECTIVES

The overall goal of this project was to develop a maintenance strategy for repairing fatigue cracking at diaphragm-girder connections and maintaining the bridges so that the potential for future fatigue cracking is minimized. Specific objectives were to investigate the following maintenance options: complete or partial removal of interior diaphragms, continued use of hole drilling to repair web cracks, and relocation and/or redesign of bolted connection angles. A description of the options is given below along with the methodology used to evaluate each one.

Holes Drilled at Crack Tips

Past laboratory tests by Fisher et al. (1990) indicate that drilling a hole at the tip of a distortion-induced fatigue crack is an effective repair under certain stress conditions. Inspections of bridges in Birmingham just prior to the start of this project revealed cracks propagating beyond the holes at approximately five percent of the connections where holes were drilled. This could result from missing the crack tip when the hole was drilled or from re-initiation of the crack as a result of very high distortion-induced stresses. One objective of this project was to use field measurements of stresses at several connections to evaluate the potential for successful permanent arrest of distortion-induced web cracks. The evaluation was performed using field measurements of distortion-induced stresses at 13 different welded connections in various bridges around the Birmingham area.

Diaphragm Removal

Diaphragms have been required in multi-girder steel bridges at a spacing no greater than 7.6 m since 1944 by the American Association of State Highway and Transportation Officials' *Standard Specifications for Highway Bridges* (1944). The 7.6 m limit was apparently an arbitrary limit which was possibly based on construction requirements. Early experts such as Newmark (1948) recognized that diaphragms had only a small effect on the performance of a bridge after the concrete deck was completed.

The goal here is to identify conditions where diaphragms can be removed from existing bridges to eliminate diaphragm-girder connections where fatigue cracking is a problem. By eliminating the connection, the fatigue problem is solved.

Several parallel efforts were undertaken to investigate the effects of diaphragm removal. Structural evaluations were performed for five typical bridges. These evaluations included a load rating analysis, wind load analysis, and a lateral-torsional buckling analysis for continuous span bridges. The results of the evaluations illustrate the effects of diaphragm removal with standard engineering calculations. The structural evaluations provide a methodology for evaluating other bridges where diaphragm removal is desirable and provide example calculations.

Effects of diaphragm removal were also investigated by field tests. Load tests were performed on two bridges, a long simple span and a three span continuous bridge, before and after all the interior diaphragms were removed. To extend the investigation beyond the practical limits of field tests, Finite Element Method (FEM) analyses were performed on eight bridges which cover a wide range of typical bridge geometries.

Relocation of Diaphragms and Redesign of Bolted Connections

The possibility that complete diaphragm removal may not be feasible for all bridges was recognized before the project began. Results early in the project illustrated that complete removal was not always possible. Logical alternatives include moving the diaphragms to locations where the potential for cracking is minimized and redesigning the connections to improve the fatigue life. Trade-offs between the costs of moving lines of diaphragms and expected improvements in the fatigue life of proposed new connections narrowed the focus of the research to improving the performance of bolted diaphragm-girder connections.

Field observation of numerous cracked connection angles, such as the one shown in Figure 1.5, indicated that the fatigue crack initiated at the outside surface of the angle in front of the bottom bolt. Fatigue cracks were observed to initiate at the edge of an indentation created by the nut or bolt head during tightening as shown in Figure 1.7, or a short distance in front of the bolt as shown in Figure 1.8. The fatigue crack propagated inward and lengthwise along the angle as illustrated by the shape of the fatigue crack in Figure 1.8. The inward crack propagation resulted from a tensile bending stress at the outside face of the angle caused by the diaphragm pushing on the bottom of the angle. Subsequent field and laboratory test data confirm this conclusion and show this is possible due to the existence of a gap between the inside face of the angle and the girder web as shown in Figure 1.9. The width, or size, of the gap limits how much the diaphragm can push the angle to close the gap, and places a limit on the maximum possible magnitude of the tensile stress range which causes fatigue cracking.

A truck crossing a bridge can cause the diaphragm to push or pull on the bottom of a connection angle based on where the connection is relative to the loaded traffic lane. Generally, all connections undergo some pushing and pulling from truck traffic distributed among the traffic lanes. Field measurements of stresses in angles of the original design show that very heavy trucks pull (or pry) on the bottom of the angle sufficiently to cause yielding in front of the bottom bolt. This yielding results in a permanent increase in the width of the gap between the angle leg and the girder web which accelerates fatigue crack initiation.

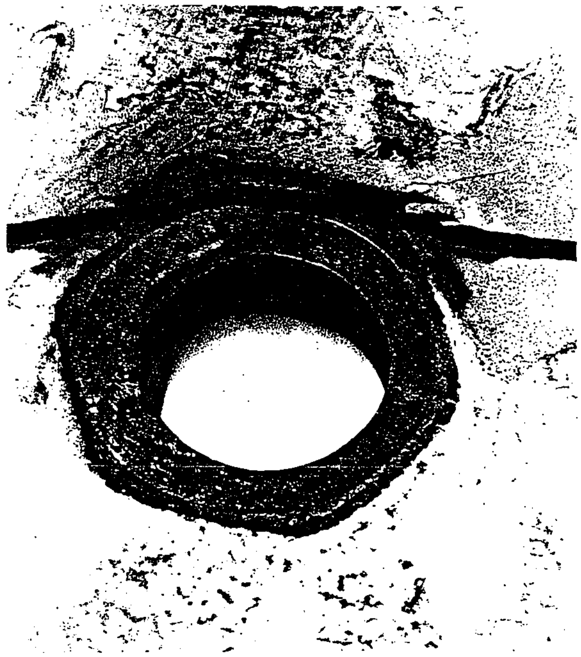

Figure 1.7. Fatigue Crack at Indentation Caused by Bolt Head

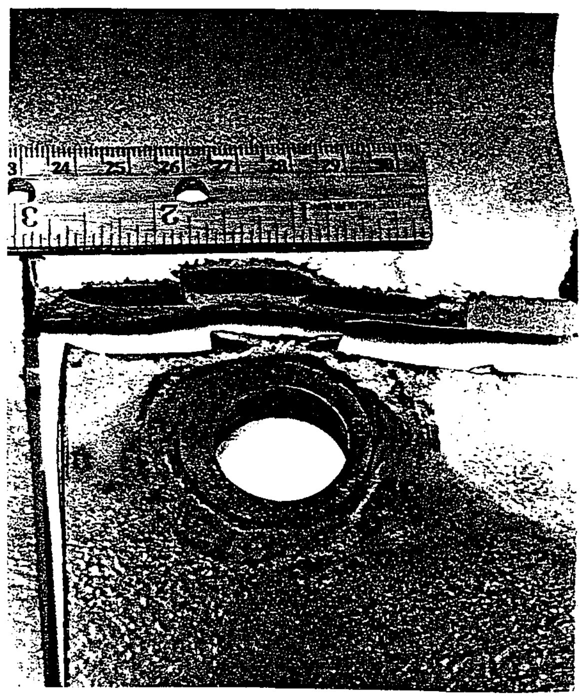

Figure 1.8. Fatigue Crack In Front of Bolt

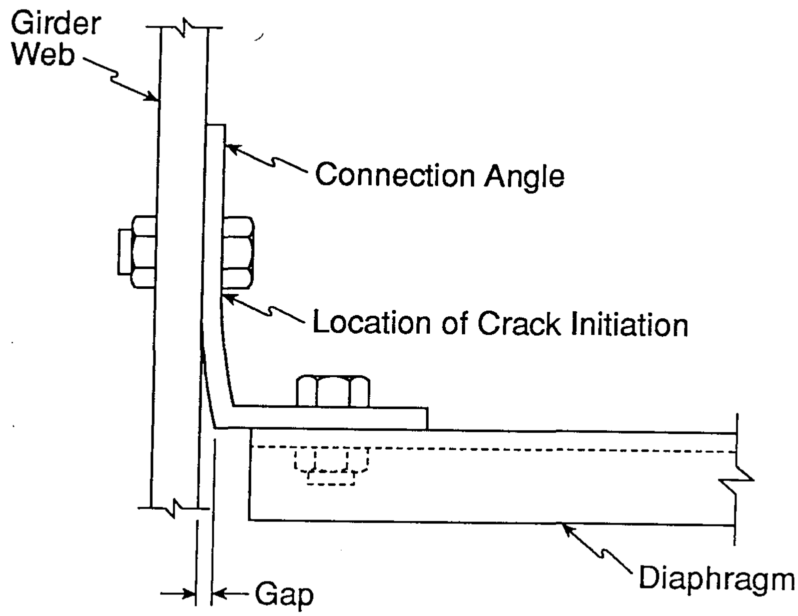

Figure 1.9. Gap Between Connection Angle and Girder Web

Based on the observed causes of the cracking and preliminary field and lab test results, a proposed new connection angle design was chosen. The angle leg bolted to the girder web was lengthened to decrease the stress in front of the bottom bolt. The yield strength of the angle was increased from 36 ksi to 50 ksi to limit the size gap that can be created by yielding of the angle. And, a specific installation sequence was developed. By tightening the bolts on the girder web first the gap width between the angle and the girder web is minimized. Tightening the bolts between the diaphragm and the angle first can create a significant gap when the bolts connecting the angle to the girder web are tightened. Subsequently, field and laboratory tests were performed as part of this project to evaluate the performance of the new angle relative to former designs.

CONCLUSIONS

Field measurements of distortion-induced stresses were made at welded diaphragm-girder connections typical of the original bridge construction. The measured stresses were compared with laboratory test results of other researchers. These comparisons indicate the stress ranges at most connections are high enough that fatigue cracking is expected at additional connections and reinitiation of fatigue cracking is expected at some connections where hole drilling alone is used to repair fatigue cracks in the girder webs.

Fatigue cracking of bolted connection angles used to replace original welded connections was found to be strongly influenced by the gap between the leg of the connection angle and the girder web. The gap results from fit-up error, the installation procedure, and yielding of the angle due heavy trucks. A new angle design and installation procedure was proposed and tested in the laboratory and in the field. The new design performed better in the laboratory and field tests than the angle design most commonly used by ALDOT in previous repairs. The test results indicate that the likelihood of fatigue cracking of the new angle design is reduced but not eliminated. The new installation procedure was used to install four lines of diaphragms in an existing bridge, and the procedure appears practical.

Field installation and tests were performed using new diaphragms and connection angles installed at two different distances below the top girder flanges (web gap lengths). No significant difference resulted from the two different distances. Hence, exiting holes in the girder webs for connection angle bolts drilled during previous repairs can be used for installing angles of the new design.

Removal of all interior diaphragms to eliminate fatigue damaged diaphragm-girder connections from composite simple span bridges is feasible. Field tests and Finite Element Method (FEM) analyses confirm that the increase in interior girder stresses resulting from complete diaphragm removal is approximately ten to 15 percent. Removal of all interior diaphragms from continuous span non-composite bridges is not feasible. For the bridges investigated, one line of diaphragms on each side of the interior supports is required for bracing against lateral-torsional buckling. The increase in stresses in typical interior girders is found to be approximately the same as for simple span bridges and does not represent a significant increase.

Changes in the live load stresses in the exterior girders due to removing diaphragms in both simple and continuous span bridges are insignificant. This observation is important because the wind loading stresses on exterior girders are significantly increased by removal of interior diaphragms. Wind loading is not critical for the bridges investigated; however, the research results do show that a structural evaluation including loading combinations with wind loading must be investigated before removing all diaphragms from an existing bridge.

The increases in deck slab bending moments due to removing diaphragms are slightly greater (5 to 7 percent) than the stress increases experienced by the girders. From FEM analyses of a typical simple span bridge, the transverse positive bending moments midway between the girders increased approximately 15 to 20 percent. The negative transverse moments over the girders decreased. These results are corroborated by theoretical results presented by Newmark (1946). Increased positive moments may shorten the remaining life of the deck, but are judged not to have a significant effect on the interstate highway bridges in Birmingham.

RECOMMENDATIONS

The following strategy for maintaining fatigue damaged diaphragm-girder connections in multi-girder bridges with rolled section girders and channel diaphragms is recommended based on the results of the research.

Removal of interior diaphragms (not at supports) is recommended to eliminate unnecessary lines of interior diaphragms. Diaphragms at supports are necessary to resist transverse horizontal loads and should not be removed for any reason. The first line of diaphragms on each side of interior supports of continuous span girders are necessary for bracing against lateral-torsional buckling and should remain in-place. A structural evaluation should be performed on a candidate bridge to verify that combined dead load, live load and wind load stresses on the exterior girders are acceptable with the diaphragms removed. If these combined stresses are found unacceptable, removal of only some lines of diaphragms and/or all interior diaphragms except those between the exterior girder and first interior girder should be investigated.

Removal of only selected connections and diaphragms is desirable because maintenance costs are avoided, or delayed, at some connections. Removal of complete lines of diaphragms is not required. To repair fatigue cracking in parts of the connection other than the girder web, an individual diaphragm can be removed to eliminate the affected connection. To repair distortion-induced fatigue cracks in the girder web, the diaphragms on both sides of the affected girder should be removed.

The fatigue cracks in the girder web should be repaired by drilling a hole at the crack tips as in previous repairs.

Fatigue damaged connections at necessary lines of interior diaphragms should be replaced with a bolted connection of the new design proposed here. The connection angles should be installed by bolting to the girder web first then to the diaphragm to avoid creation of a gap between the connection angle and girder web. Connection angles should be installed with approximately a 90 mm gap between the top of the connection angle and the bottom of the top girder flange. This will allow existing holes from previous connection replacements to be utilized. Connections at both ends of an individual diaphragm should be replaced at the same time to avoid misalignment of the diaphragm. Fatigue cracks in the girder webs should be repaired by drilling a hole at the crack tips (as performed in previous repairs) before installing the new connections.

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