Enhancement of Welded Steel Bridge Girders Susceptible to Distortion-Induced Fatigue

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Executive Summary

A large number of steel bridges within the national inventory are affected by distortion-induced fatigue cracks. Repairs for this type of failure can be very costly, both in terms of direct construction costs and indirect costs due to disruption of traffic. Furthermore, physical constraints inherent to connection repairs conducted in the field sometimes limit the type of technique that may be employed. The goal of the proposed research is to investigate the relative merit of two different repair techniques for distortion-induced fatigue cracks: drilling undersized holes subsequently treated with Ultrasonic Impact Treatment (UIT) or bolt interference, and stiffening the connection with a layer of composite materials through Chopped-Fiber Spray Lamination. These techniques were selected because they can be implemented with limited or no disruption to traffic, and because it is possible to use them in areas with restricted space within bridge structures.

Project Personnel

The proposed research will be carried out by a group of faculty from the University of Kansas in partnership with practicing professionals from the private and public sectors with expertise in the areas of fracture and fatigue, bridge maintenance, strengthening, and repair. The Fracture and Fatigue Research group at the University of Kansas is led by Dr. Stanley Rolfe (Civil, Environmental, and Architectural Engineering Dept.), who has vast experience in the field of fatigue and fracture. Professor Rolfe has published over 70 technical articles in fatigue and fracture of steel structures, and is a recipient of the ASTM Fracture Mechanics Medal. Dr. Adolfo Matamoros (CEAE Dept.) and Dr. Caroline Bennett (CEAE Dept.) have extensive experience in linear and nonlinear finite-element analyses, as well as field and laboratory experimental testing. Dr. Ron Barrett-Gonzalez (Aerospace Engineering Dept.) is an expert on the use of composite materials and applications. External partners include Dr. John Barsom (President of Barsom Consulting Ltd.) who is consultant in the area of fracture mechanics and failure analysis. He has authored more than 80 technical papers on fracture, fatigue, steel and weld metal properties, and performance of structural connections. Dr. William Clawson (Vice President of HNTB Corp.) will serve as consultant with expertise in design and retrofitting of steel bridges. The research group will work in close collaboration with John Jones and Kenneth Hurst, engineers from the Kansas Department of Transportation, and Ron Bruce (President of Builders Steel) who will be the fabrication partner throughout the research effort.

Problem Statement and Objective

Distortion-induced fatigue cracks constitute a serious national problem given the large number of steel girder bridges constructed before 1985 that are affected by this type of failure. It is estimated that 90% of all fatigue-related cracks in bridges have arisen due to out-of-plane distortion (Connor and Fisher 2006). Finding, repairing, and potentially preventing fatigue cracks at details susceptible to out-of-plane distortion represents a significant expense to State DOTs. This problem is exacerbated by the fact that many of the affected bridge structures carry large traffic loads, or their geographical location is such that temporary closure would cause significant disruption to the economic activity of the local residents. While a number of repair and retrofit methods have been shown to be effective in addressing this problem (Roddis and Zhao 2001; Roddis and Zhao 2003;

Stallings et al. 1999; Connor and Fisher 2006), these strategies can be time-consuming, expensive to implement, and often require temporary bridge closures. There are also instances in which these methods cannot be implemented due to lack of space in the affected region of the bridge. In those cases, the use of new and/or combined techniques may present a viable method for fatigue life extension.

The main objective of the proposed research is to ***explore the use of composite materials and hole treatments (ultrasonic impact treatment and bolt interference) to develop new retrofitting techniques aimed at extending the fatigue life of bridges with connection details susceptible to distortion-induced fatigue.*** The techniques that will be studied were selected because they are relatively inexpensive, easy to implement, and can be carried out without significant disruptions to traffic.

Background

Distortion-induced fatigue cracks develop near or at connections between girders and out-of-plane elements (Figure 1). Prior to 1985 it was common practice to assume that stresses induced by the out-of-plane elements on bridge girders were secondary effects, and therefore negligible. Two common scenarios in which out-of-plane elements induce significantly high stresses on girders, making the distortion problem more pronounced, are: (1) skewed and/or horizontally curved girder bridges, in which the distance from a given station to the support is significantly different for two adjacent girders, and (2) bridges in which the superstructure is comprised of two or three deep girders. Due to the lack of redundancy in the latter case, a large fraction of the traffic load acting on the superstructure is transmitted directly to a single girder. In both cases, out-of-plane stresses are induced by differential deflections between adjacent girders.

For either of the two scenarios, secondary stresses caused by differential girder displacements often have the most detrimental effect at the junction of a connection plate welded to the girder web, usually near the top flange of the girder. Prior to 1985, the AASHTO Standard Specifications for Highway Bridges (AASHTO 1982) did not require any connectivity between connection plates and the top flanges of girders. Therefore, a large percentage of the steel girder bridges built before 1985 lack this connection and are at risk of sustaining significant fatigue damage. Figure 1(a) shows a girder without a connection between the top flange and the connection plate.

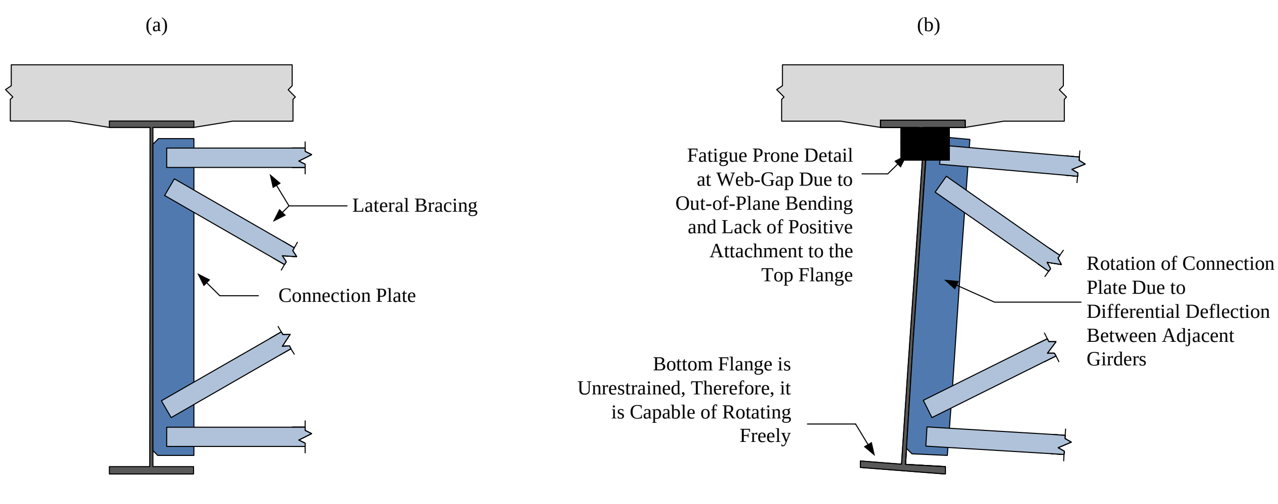

Figure 1: (a) Girder Cross-Section before Differential Displacement
(b) Girder Cross-Section after Differential Displacement

The aforementioned connection detail is particularly vulnerable because the top flange is restrained from rotating and displacing in the horizontal direction by the concrete deck. The out-of-plane flexural stiffness of the web is increased significantly by the connection plate, leaving a very short, relatively flexible region in the gap between the connection plate and the bridge deck. Equilibrium in the horizontal direction dictates that the out-of-plane loading must be transferred from the top of the connection plate to the top flange through this flexible web section, causing a significant out-of-plane distortion (Figure 1(b)). The short length of unstiffened web between the top flange and the connection plate is commonly referred to as the "web gap" region. Because the bottom flange is relatively unrestrained and it is able to rotate freely, the effects of distortion are significantly less at that location.

Successful retrofit strategies used in the past have been aimed at changing the out-of-plane stiffness of the connection. One such strategy (Figure 2) consists of providing an alternate load path for the lateral loads by introducing a mechanical connection between the plate and the girder flange (Roddis and Zhao, 2001). This strategy results in a significant increase in the stiffness of the connection. A different strategy relies on increasing the length of the web gap, which has the effect of decreasing the stiffness of the connection. While the effects of these two approaches are opposite on the lateral stiffness of the connection, both have been shown to be effective in reducing the stress range in the web-gap region (Roddis and Zhao 2001). Other strategies rely on disconnecting adjacent girders by removing lateral bracing or diaphragms (Stallings et al. 1999), allowing the girders to deflect independently without suffering damage from stresses due to out-of-plane loads. The main drawback of these techniques is their cost, and in some cases, complications associated with the use of field welds. These practices may require access to the full thickness of the girder top flange to install bolts, which can require removing portions of the concrete bridge deck. This type of work is difficult to perform without disruption to traffic. If the connection is to be stiffened using a welded retrofit, field welding must be performed in the least desirable positions, and in very tight conditions. An ideal solution to this problem should be inexpensive and easy to implement, should minimize traffic disruptions, and should be effective at mitigating future fatigue cracking. The proposed study will investigate retrofit techniques that meet the aforementioned characteristics.

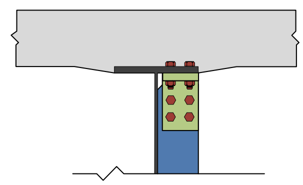

Figure 2: Bolted Angle Retrofit Technique for Stiffening of Web-Gap Region

Two techniques that have separately shown great promise as fatigue improvement methods are (1) the addition of bolts to provide an alternate load path, and (2) ultrasonic impact treatment (UIT) of welds to improve fatigue life of the welds (Wright 1996; Fisher et al. 2001). A study is currently under way at the University of Kansas to examine the effects of combining repair techniques to extend the fatigue life of a simple, two-dimensional, category E detail. The specimens used in the study (Figure 3) consist of two-plate assemblies representative of a bottom flange and a welded cover plate loaded in three-point bending. A total of fifteen specimens are being tested to evaluate the increase in fatigue life obtained by using the two retrofit measures separately and in combination.

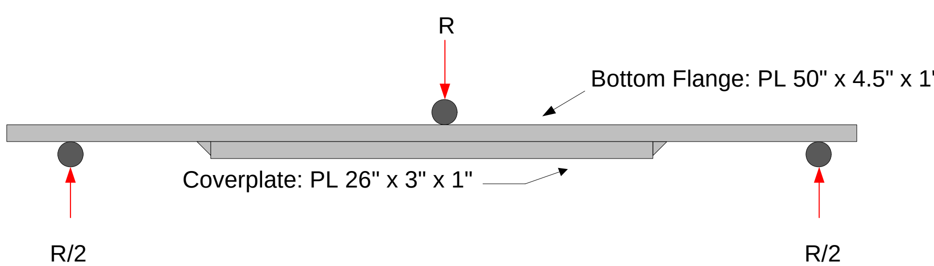

Figure 3: Fatigue Specimen in Three-Pt. Bending

A third retrofit measure currently being evaluated at the University of Kansas in a study sponsored by the KU Transportation Research Institute (TRI), is the attachment of composite materials to the specimens shown in Figure 3, with the primary goal of providing an alternate load path. A secondary goal of the KU TRI project is to explore the use of composites as fatigue life indicators, or "fuses". Figure 4 depicts the fatigue specimens outfitted with the composite doublers.

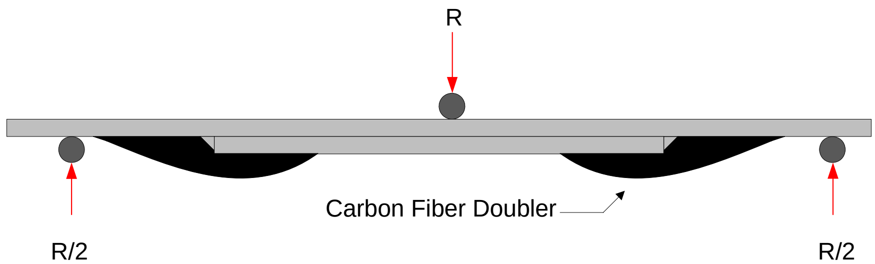

Figure 4: Fatigue Specimen with Composite Application

The KU research group is preparing to perform another preliminary study on flat plate specimens with undersized drilled crack "stop holes" treated with UIT and bolt interference. A method commonly implemented to arrest fatigue crack propagation is to drill holes at the end of an existing crack. Hole drilling changes the crack geometry from being "infinitely sharp" at the crack tip to having a well-defined radius at its end. If the drilled hole radius is sufficiently large, it will completely halt crack propagation. The equation describing the required radius to halt crack propagation was developed by Barsom and McNicol (1974) and later extended by Fisher (Fisher et al. 1980), and is well-established. Due to tight geometry in regions such as the one pictured in Figure 1, it is not always possible to drill a stop-hole with a large enough radius to arrest crack propagation. For this reason, it would be highly beneficial to develop repair methods for crack arrestment that require hole diameters smaller than those dictated by the equation developed by Barsom and McNicol (1974). The combination of an undersized hole and additional treatment may be effective in reducing the diameter of the hole needed to arrest cracking. Treatment of the perimeter of the hole to induce residual compressive stresses has been shown to extend fatigue life in aerospace applications (Lanciotti and Polese 2005). This study will examine the effect of treatments on the performance of undersized holes drilled to stop the propagation of cracking on two-dimensional specimens. Sixteen flat plate specimens will be tested in fatigue to study the effect of hole treatments on crack propagation.

Preliminary research at the University of Kansas has yielded valuable information about the use of the aforementioned techniques to improve fatigue life. The proposed pooled fund research program will leverage this experience and use it to develop improved retrofit measures for distortion-induced fatigue cracks.

The composite material layers used in the TRI study currently underway at the University of Kansas consist of carbon fiber reinforced polymers. While this type of composite material has significant advantages in terms of stiffness, it shares many of the same constructability drawbacks that existing retrofit measures for distortion-induced fatigue suffer from. A more viable alternative in terms of cost and constructability is the use of chopped-fiber spray lamination. Chopped-fiber spray lamination takes advantage of low-cost fabrication techniques to build up a protective jacket of fiber reinforced plastic (FRP) around complex joints. This technique of FRP application has been used for decades in the creation of consumer goods, but also has promise in the bridge engineering arena. The technique relies on a gravity-fed spray gun, which mixes resin and chopped fibers at the nozzle. The user sprays the FRP mixture onto the piece being reinforced, eliminating many of the problems associated with conventional wet lay-up techniques.

The chopped-fiber spray laminations will be used to provide positive connectivity between the top flange and connection plate, as well as to reduce the severity of the stiffness change in the web gap region. Both of these effects have been shown to improve the fatigue resistance of complex joints that suffer from distortion-induced effects. Furthermore, this process may be used as an indication technique for detection of pending fatigue problems.

Proposed Research

The proposed study will investigate innovative techniques for improving the fatigue life of steel girder bridges, specifically focusing on the urgent and ubiquitous problem of distortion-induced effects. The project will include computational and physical simulations of girder assemblies to evaluate the effectiveness of various retrofit techniques.

Test Set-Up: The proposed experimental configuration is shown in Figure 5. The test set-up is comprised of a reaction frame and specimens consisting of one simply-supported bridge span with three I-girders connected through lateral bracing. A reinforced concrete deck will be cast on top of the girders to properly model the effects of the axial and flexural stiffness of the deck.

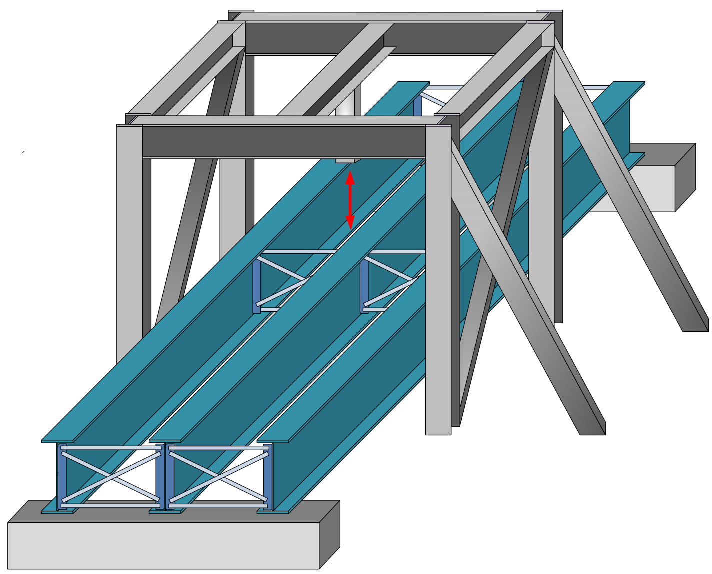

Figure 5: Test Set-up for Loading Girder System

The center girder will be loaded vertically at midspan causing a relative displacement between the center and exterior girders. The exterior girders are expected to be subjected to out-of-plane displacements, as illustrated in Figure 1(b).

The girders will be reduced-scale models of typical slab-on-girder systems. It is anticipated that a scale in the range of 25% - 50% of the actual girder size will be implemented. A span length of approximately 25 ft will be utilized. A scaled concrete slab will be constructed over the portion of the system being loaded; it will not be cast continuously over the entire span due to access and monitoring considerations. The concrete slab will span all three girders for a length of approximately 6 ft.

The retrofit techniques to be examined alone and in combination are (1) UIT and interference-fit fasteners and (2) Sprayed Chopped Fiber Composites.

UIT and Bolt Interference: In the repair of bridge structures there are instances in which it is not possible to drill a hole large enough (Barsom and McNicol 1974) to prevent re-initiation of fatigue cracks. In these cases the use of a smaller hole with treatment of the interior perimeter may be sufficient to extend fatigue life, or at least to provide a viable measure until a better solution can be implemented. The use of UIT on welds has been examined by the KU Team on two-dimensional specimens. Application of UIT to the inner surface of crack-stop holes is being studied on two-dimensional flat plates, and will be investigated on three-dimensional connections to determine its effectiveness as an additional treatment when full-diameter stop holes cannot be drilled. Another potential method for arresting crack propagation is the use of interference-fit fasteners, which introduce a compressive stress field that emanates outward from the interior of the bolt hole. Bolt interference has been previously studied in the aerospace field as means for improving the fatigue lives of aluminum structures (Lanciotti and Polese 2005); this study will apply that technology to steel bridges.

Chopped-Spray Lamination Retrofit: The second technique to be examined is chopped-fiber spray lamination. Susceptible bridge details will be coated with chopped-fiber polymers, applied using a gravity-fed spray gun. The effects of this FRP on fatigue performance will be investigated. In previous work, it was shown that although the material stiffness of fiber reinforced plastic (FRP) is lower than steel, a build-up method can easily make the flexural stiffness of the FRP lamination much greater than the adjacent steel parts to be supported. As part of the chopped fiber lamination portion of this study, the investigators will also develop an indication technique aimed at helping inspectors detect fatigue failure. A method of indication is being developed at KU that would be refined as part of this project, and will be discussed in more detail in a full proposal.

Test Sequence: The test sequence described in the following list will be performed to investigate the effects of different retrofit techniques on the fatigue life of steel girder systems.

- Two systems with no treatments
- Two systems with previously-studied, conventional retrofit techniques (bolted and/or welded angle techniques)
- Two systems with out-of-plane fatigue-prone details treated with UIT and undersized-diameter holes
- Two systems with chopped-fiber spray composites applied to the fatigue details
- Two systems with UIT, undersized-diameter holes, and chopped-fiber spray composites applied to the fatigue details

Analytical Investigation: A comprehensive finite element study will be carried out using the commercial finite element modeling package, ABAQUS. The goals of the finite element analysis are: (1) To corroborate and explain the behavior observed in the experimental study, and (2) to perform numerical parametric studies to investigate different connection configurations and retrofit measures. Additionally, the development of accurate baseline finite element models will enable the researchers to better model the effect of adding chopped-fiber spray composite layers.

Deliverables

The KU Fatigue and Fracture Research Group will produce recommendations concerning the proposed retrofit techniques, including (but not limited to) application techniques, expected levels of fatigue performance, methods of fatigue life indication, and implementation costs. The researchers will produce a Final Report, as well as quarterly reports. The researchers intend to publicly disseminate results in public forums through such avenues as peer-reviewed publications and conference proceedings.

Project Schedule

The proposed schedule of work for this project is shown in Table 1. Each year has been broken into quarters.

Table 1: Schedule of Project Tasks

	Year 1 (’07-‘08)				**Year 2 (’08-‘09)**				**Year 3 (’09-‘10)**			
Task Description	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**
1. Extensive Literature Review	■	■										
2. Review of proposed connection details with external review group.	■	■										
3. Bridge System Design	■	■	■									
4. Design of Test Frame	■	■	■									
5. Fabrication and Erection of Test Frame			■	■								
6. Fabrication of Test Specimens			■	■	■							
7. Full-Scale Finite Element Modeling		■	■	■	■	■	■	■	■			
8. Experimental Testing of Girder Systems					■	■	■	■	■	■		
9. Data Reduction of Recommendations										■	■	■

Budget Considerations

KU has been in continuous contact with the Kansas Department of Transportation (KDOT) throughout the process of preparing this proposal. KDOT has committed funds to design and fabricate the test frame in the amount of $75,000. KDOT is committed to participation in a pooled-fund study.

In addition to the KDOT grant for construction of the test set-up, the KU team is seeking funding support from the KU Transportation Research Institute (TRI) for testing of an initial girder assemblage. Preliminary discussions have taken place to establish a partnership with the American Institute of Steel Construction. The goal of the investigators is to secure partial funding from these sources, reserving pooled funds for specimen fabrication and experimental testing.

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