Engineering Structures 34 (2012) 163–172

Contents lists available at SciVerse ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Fatigue behavior of welded coverplates treated with Ultrasonic Impact Treatment and bolting

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ARTICLE INFO

Article history:
Received 6 April 2010
Revised 23 February 2011
Accepted 4 September 2011
Available online 4 November 2011

Keywords:
Fatigue
Bolts
Welds
Cracking
Rehabilitation
Retrofit
Ultrasonic Impact Treatment
Cover plate
Steel bridge

ABSTRACT

Damage due to traffic-induced fatigue is a common problem in welded steel girder bridges. Engineers tasked with the duty of repairing fatigue-damaged bridges face difficult decisions about the choice of repair method to implement. In some instances different repair methods are used in combination, under the assumption that the combined effects of two techniques that have been shown separately to improve fatigue life will result in greater improvement. This study evaluated the interaction that may take place between different repair methods for a particular type of fatigue vulnerable detail. The detail that was chosen for the study was a welded connection between a plate and a coverplate, often used in older bridges. Specifically, this study investigated the fatigue life enhancement afforded by three retrofit methods: post-installation of tensioned bolts behind the weld, application of Ultrasonic Impact Treatment (UIT) to the weld, and a combination of the two techniques.

Results of 15 fatigue tests showed that UIT was a highly effective technique to enhance the fatigue life of coverplate end details. Weld treatment with UIT resulted in an improvement in fatigue life over control specimens by a factor of 25. This translated into an improvement in fatigue life from that of an AASTHO fatigue Category E detail to that of an AASHTO fatigue Category A detail. The bolting procedure, as implemented in this study, had a negligible effect on fatigue life. The combination of the two methods was found to be less effective than using UIT alone due to stresses induced by the bolt on the untreated portion of the weld.

1. Introduction

Numerous aging steel highway bridges are currently developing cracks due to traffic-induced fatigue. Many of these bridges were designed at a time when little was known about the causes of fatigue crack initiation and propagation in steel structures. As a result, structural connection details having fatigue–vulnerable combinations of geometric discontinuities and large stress ranges were used in these structures. Many of these details are now recognized as undesirable and are no longer constructed. However, state Departments of Transportation (DOTs) must repair existing fatigue cracks and retrofit susceptible connection details. Due to the escalating costs of bridge replacement coupled with the large number of aging steel bridges with fatigue-susceptible details across the United States, means to efficiently extend the useable life of fatigue–prone steel bridges are critically needed.

Welded connections in steel bridge girders account for a large percentage of fatigue critical details in the national inventory. Welds are particularly susceptible to fatigue cracking because of planar or volumetric discontinuities often present in the weld or base metal, such as porosity, slag inclusions, lack of fusion, and undercut [1]. Additional factors such as geometry-induced stress concentrations, residual stresses, and distortion tend to decrease the fatigue strength of welded connections. This is particularly worthy of consideration given that many common steel bridge girder connections utilize welded connections in a wide range of applications, including cover plates, transverse and longitudinal stiffeners, connection plates, flange transitions, and web-to-flange connections.

Welded cover plates are of especial concern because this is a common detail particularly vulnerable to fatigue damage. Although welded coverplates are no longer commonly used to increase bending resistance of bridges, this was not the case 40 years ago. Many existing bridges were retrofitted with welded coverplates to increase their capacity as traffic loads intensified over time. It has since been found that welded cover plates tend to be particularly susceptible to fatigue crack initiation in the welds at cover plate terminations, and for this reason have been

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doi:10.1016/j.engstruct.2011.09.009

Nomenclature

$\sum$	stress, MPa (ksi)	A	constant for a particular AASHTO fatigue detail category, MPa^3 (ksi^3)
c	distance from the neutral axis to an extreme fiber on the cross-section, mm (in.)	N	number of fatigue cycles to failure
I	bending moment of inertia, mm^4 (in.^{4})	ΔF_{TH}	stress range corresponding to infinite life of a particular fatigue detail category, MPa (ksi)
δF_n	stress range, MPa (ksi)		

subsequently classified among the worst performing AASHTO fatigue Categories E and E′ [2–4].

Improved practices have since emerged for retrofitting susceptible welded coverplates and for installing new cover plates with better performing fatigue details. One mechanism for improving performance of cover plates is to extend the coverplate into a region of compressive stress or to an inflection point, where tensile stress ranges are negligible. Another method is to remove end welds and develop the full moment capacity of the cover plate through a bolted connection. The detail resulting from the latter technique is now classified as an AASHTO fatigue Category B detail [7].

Another accepted method for improving fatigue performance of welded connections that has been successfully applied to coverplates is Ultrasonic Impact Treatment (UIT) [8–10]. Ultrasonic Impact Treatment has been shown to reduce the likelihood of fatigue cracks in weldments by relaxing tensile residual stresses introduced during welding, and by smoothing imperfections on the surface of the weld. Both effects are achieved through application of ultrasonic stress waves at the surface of the weld. The stress waves induce plastic deformations, which leave a residual compressive stresses on the order of the yield strength of the weld metal near the surface of the weld. Because fatigue cracks form primarily at imperfections in regions subjected to high tensile stress ranges, introduction of large compressive stresses and the smoothing of the surface greatly retard and may eliminate formation of fatigue cracks at the location of treatment. Since UIT is generally performed at regions having the greatest tensile stress concentrations, usually weld toes and weld discontinuities, the regions most prone to fatigue crack growth benefit the most from induced compressive stresses. When UIT treatment is performed at the toe of a fillet weld, the change in shape of the zone of plastic deformation also reduces the concentration of stress at the weld toe, as the treated surface has a larger radial shape than does an untreated weld toe.

2. Research significance and objective

The objective of the study was to investigate the effectiveness and interaction of various repair methods on the fatigue life of a commonly used fatigue–vulnerable connection detail. The specific repair methods evaluated were Ultrasonic Impact Treatment (UIT) of the weld, installation of tensioned bolts behind the weld, and the combination of UIT of the weld and installation of tensioned bolts. A cover plate detail was chosen for study because of the prevalence of this detail in aging steel bridges, its simplistic geometric configuration and design, and its poor fatigue performance.

Installation of bolts in an existing welded coverplate as a fatigue strengthening method requires removal of the weld at the coverplate ends so that load transfer can take place through the bolts instead of the weld. Improvements in fatigue life due to post-installation of bolts coupled with weld removal are well documented in studies by Yamada and Albrecht [3] and Simon and Albrecht [4]. In the present study, rather than expand on the fatigue related benefits of post-installing bolts in cover plates, the welds were left in place to study the interaction between post-installed tensioned bolts and welded connections treated with UIT. For example, fatigue cracks were observed in a bridge in Kansas at connections between gusset plates from cross-bracing and girder flanges [5,6]. These connections developed a prying effect due to deformations imposed by the cross brace on the girder flange that caused fatigue cracks. Bolts were post-installed to counteract the prying effect, but questions remained about the beneficial effects of treating the welds with UIT.

3. Experimental program

Fifteen welded steel specimens, each representative of a girder flange with a welded cover plate, were fabricated using Grade A36 steel. Of those 15 specimens, six were control specimens receiving no treatment (designated CONTROL), three were treated with UIT along the weld toe at the cover plate ends (designated UIT), three had tensioned bolts installed near both ends of the coverplate (designated BOLT), and three had both UIT and tensioned bolts installed near both ends of the coverplate (designated UIT/BOLT). The 15 specimens were fabricated in two batches: the first batch was comprised of 12 steel specimens, after which a second batch comprised of three additional control specimens was fabricated.

3.1. Steel specimen design and testing program

A schematic of the steel specimens is provided in Fig. 1. A bar with dimensions PL $25.4 \times 114 \times 1270$ mm (PL $1.00 \times 4.50 \times 50.0$ in.) was chosen for the plate representing the girder flange, and a bar with dimensions PL $25.4 \times 76.2 \times 660$ mm (PL $1.00 \times 3.00 \times 26.0$ in.) was chosen for the coverplate element. The coverplate element was chosen to be as wide as possible while still allowing ample flange surface on each side to accommodate the fillet weld, while the length was chosen considering shear lag effects and St. Venant's Principle. Shielded metal arc (SMAW) 7.94-mm (0.313 in.) fillet welds were used to connect the coverplates to the flanges, with the weld applied all-around the coverplate element. This weld size and configuration are commonly used for welding bridge coverplates because it is the largest size fillet weld that can be laid in a single pass. The primary purpose of the experimental program was to compare fatigue behavior of treated and untreated specimens. Although not essential to the outcome, AASHTO detail categorization is presented here to provide a frame of reference for the results of the study. To account for the fact that the neutral axis of the cross-section was within the flange plate (rather than far above the weld toe, in the web or top flange), nominal stresses were calculated directly at the weld toe to reflect the normal bending stress at that specific location. Therefore, a stress range reported as 138 MPa (20.0 ksi) implies that this was the nominal tensile bending stress value calculated for a bare steel specimen at the toe of the weld.

After the steel substrate specimens were fabricated, tensioned bolts were post-installed at both ends of the coverplate for six of the specimens. For each coverplate retrofitted with bolts, a 25.4-mm (1.00-in.) diameter ASTM A325 carriage bolt was installed at both coverplate ends. The bolts were tightened using a calibrated pneumatic wrench to have a minimum bolt tension of 227 kN (51.0 kips), the standard minimum bolt tension specified for this