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Stress distributions and crack growth in riveted lap joints fastening thick steel plates

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ABSTRACT

Single shear lap joints have been a common method to fasten steel plates in railroad bridges and can be highly susceptible to fatigue cracking under the cyclic loading bridges experience. To better comprehend the fatigue process of these connections, it is important to understand the stress state near the rivet hole. While the fatigue behavior of these riveted connections has been studied, few have been carried out on stress distribution and crack formation in riveted lap joints fastening *thick* steel plates. This study is to provide information regarding the stress distributions developed in a single shear lap joint connecting plates of varying thicknesses. Results from the stress contour analysis are utilized to detect possible regions for fatigue crack nucleation under cyclic heavy axle loads. The study also provides information regarding the fatigue crack geometry typically found in single shear lap joints.

1. Introduction

Rivets were widely used as mechanical fasteners in railroad bridges constructed after the 1900's through the 1960's, when the introduction of high strength bolts replaced the use of rivets [1]. These riveted railway bridges were not originally designed taking into account fatigue [2], furthermore, if fatigue was taken into account, it was based on limited understanding and knowledge of the phenomenon [3,4]. This was due to many reasons: first, fatigue cracking in these early structures was infrequent [5,6]. Second, axle loads in train configurations prior to the 1960s rarely exceeded 20 tons (40,000 lbs), creating an almost negligible effect on the fatigue damage of railroad bridges [7]. Finally, the fatigue phenomenon was only intensively investigated after the second half of the 20th century [2], were welding began to be used as the preferred method for fabrication of steel bridges.

There are a large number of old riveted railroad bridges that are still in operation today. The average age of these riveted railway bridges is reaching 100 years old [7]. Moreover, as the railroad industry increase their carloads, these bridges are subjected to increasing axle loads. Freight cars have increased from 85 tons, commonly used before 1960, to a range of 131.5 tons to 143 tons (263,000 lbs–286,000 lbs) used today [7]. Furthermore, in 2011 alone, it was reported that approximately 1600 railcars of 157.5 tons (315,000 lbs) were in service on Class I railroads [8,9]. With the ever increasing freight car weights, the old riveted railroad bridges are being subjected to larger and more frequent stress ranges that they were originally intended for. Since most of the riveted railroad bridges in service have passed the 80 years' service lifetime, the proper maintenance and remaining fatigue life of these bridges is a major concern. It is imperative to investigate the effect of heavy axle loads in fatigue damage of these structures.

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With the current fatigue provisions [10], the life of the components can be estimated by identifying the fatigue detail category and specifying the critical stress range it will experience during its lifetime. However, when utilizing a fracture mechanics approach, much more information regarding the stress state and crack (geometry and size) is needed; but it could also provide a more accurate fatigue life estimation. Current fatigue S-N curves are based on fatigue life of welded connections; experimental results have shown that fatigue life of riveted connections typically fall within Category C and D. The S-N curves can provide a robust estimation, however, in some cases, a more accurate calculation is needed.

2. Riveted lap joints

To understand the fatigue process within riveted lap joints, detailed knowledge of the stress state is required. Studies have demonstrated that clamping force is a principal variable influencing the fatigue resistance of riveted connections typical in old railroad bridges [11]. The presence of residual stresses resulting from rivet installation complicate the analysis of crack formation and propagation. In comparison with high strength bolts, the clamping stresses on rivets are generally lower in magnitude and not as predictable due to an increased variability in magnitude [2,3]. The use of different riveting techniques, either in-shop or on-site, may entail different clamping force magnitudes and variable load-carrying capacities in member and in joints [12].

The presence of clamping stress affects the nucleation location and the path of fatigue cracks at rivet holes. It will also dictate the magnitude of the compression stress between faying surfaces, this leads to transmitting a portion of the applied load by friction [13].

This study is to provide information regarding the stress state near the rivet hole due to thermal contraction during the installation. Additionally, it describes how the residual stress combines with external surface traction to yield the stress distribution typically found near rivet holes. The stress state near the rivet hole will be used to study fatigue crack propagation in this area.

2.1. Previous studies

Skorupa et al. [13] conducted fatigue tests on riveted lap joints, typically found in aircraft fuselages, to understand the effects of thickness and clamping stress of rivets on fatigue life, crack initiation and crack growth. It was found that cracks always initiate at the faying surface at the outer rivet rows and that the crack geometry and growth were affected by the clamping stress. Lower clamping stress produced quarter elliptical cracks which propagated through the rivet row, whereas higher clamping stress produced semi elliptical cracks that propagated away from the rivet row towards the edge.

Sanches et al. [14] performed a fatigue simulation of a double shear riveted joint. Both, crack initiation and propagation were accounted for. Effects of various variable model inputs such as friction, clamping stress, as well as the crack initiation size definition were assumed in the probabilistic form to generate S-N curves. For the investigated riveted joint, the fatigue crack initiation was the dominating damage mechanism. The proposed S-N curve did not show good agreement with the existing code-based S-N curves.

Skorupa et al. [15] analyzed the fatigue behavior in riveted lap joints and evaluate quantitatively the influence of several variables on the joint fatigue behavior. It was concluded that: fatigue cracks in riveted lap joint always start in one of the end rivet rows on the faying surface of the loaded sheet; sheet thickness, rivet type and clamping stress can have a significant impact on all aspects of the joint fatigue response; increasing the rivet clamping stress yields a longer fatigue life regardless of the sheet thickness; and that riveting imperfections can have a profound influence on the joint fatigue performance.

Zhou [16] conducted a study to measure the magnitude of clamping residual stress in riveted members from demolished bridges approximately 60 years of age. The measured clamping stress varied from 34 to 165 MPa (5 to 24 ksi), with an average of about 83 MPa (12 ksi) and a standard deviation of about 41 MPa (6 ksi). Zhou [16] also performed a two-dimensional finite element model to examine the distribution of normal and frictional stresses on the contact surfaces. The presence of a crack was not considered in the model. It was reported that a temperature change of 204 °C (400 °F) during the cooling process in the rivet caused a clamping stress of about 262 MPa (38 ksi).

Correia et al. [17] presented a comparison between two alternative finite element models to predict the fatigue strength of a single shear and single rivet connection. A finite element model using solid elements in its entirety is compared to a finite element model using a combination of shell elements for the plates, and solid elements for the rivet. Both steel plates and rivet were modeled as isotropic and elastic material. The simulations were performed using the Augmented Lagrange contact algorithm, and null gap between plates and rivet was considered. A through thickness crack was assumed and a stress ratio R equivalent to 0.1 was assumed. The study works with clamping stress ranging from 0 to 300 MPa. The research concluded that crack initiation phase is dominant for high cycle fatigue and that the numerical analysis assuming an initial crack size of 0.6 mm agreed well with experimental data. Correia et al. [17] based his finite element model in the studies presented by De Jesus et al. [2] and Correia et al. [18]. De Jesus et al. [2] proposed a methodology to generate probabilistic stress life data for a riveted shear splice, which can be applied into probabilistic fatigue assessments. Correia et al. [18] uses the same 3-D FE model of a riveted joint to assess the elastic stress concentration and the stress intensity factor to assess the crack initiation and crack propagation phases, respectively. This data was used to derive probabilistic S-N fields for riveted connections. The parameters in the analysis that were assumed in a probabilistic form were: clamping stress, friction, the initial crack size and the coefficient C of the Paris's Law.

All the above authors presented excellent work and insight into their finite element model. However, the stress distributions *per se* were not reported, as well as the effect of the plate thickness in the residual clamping stress. Additionally, this study investigates the effect of the plate thickness on the crack geometry developed due to cyclic loads.

Some authors, such as De Jesus et al. [19], Correia et al. [20], Lesiuk et al. [21,22,23] and Raposo et al. [24] have studied the mechanical properties of puddle irons/old mild steels as well as riveted connections used in old riveted steel bridges. De Jesus et al.