Fatigue crack initiation in riveted railway bridge connections

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The objective of the investigation presented in this paper was to identify and rank in terms of damage, fatigue-critical locations on a typical riveted stringer-to-cross-girder connection used in railway bridges using the finite element method. The results were derived in the form of Miner’s damage under the passage of a typical freight train. Through this ranking and by considering different damage scenarios, including rivet defects, loss of clamping force in a rivet and loss of a rivet, it was found that the most damaging effect was caused by the presence of clearance between the rivet shank and the hole or by the loss of a rivet. The damage at the angle-fillet and the rivets connecting the angle to the stringer web was found not to be affected considerably by rivet defects. In contrast, the rivet clamping force appeared to affect fatigue damage around the angle holes and on the rivets to a considerable extent. The effect of the manner of hole preparation was not considered in this investigation.

Keywords: Riveted wrought-iron connections; fatigue damage; finite element analysis

1.0 Introduction

Though characteristic of older construction practice, riveted railway bridges are still in use in many parts of Europe and North America. On the whole, the performances of these bridges appear to be rather satisfactory provided that the deterioration due to corrosion has been kept in check. However, due to their large number as well as their age, which in many cases exceed 100 years, their fatigue safety has become an issue of some concern. This has led to research efforts to determine whether these bridges can continue to perform in a satisfactory manner or whether wide-spread fatigue damage should be expected in the near future. The global problem, which is associated with the identification of members and connections most likely to sustain fatigue damage, is not readily related to the next step which aims at identifying the particular locations on these members and connections (e.g. holes, rivets, connection angles) more likely to experience fatigue cracking. This is of concern to bridge owners who need to formulate efficient and effective inspection plans. The complexity of the problem is further exacerbated by the variety of structural forms encountered in riveted bridges and the unique features associated with each bridge. In many cases, conclusions regarding fatigue damage are structure-specific and, therefore, cannot easily be extended to cover a wider bridge network.

The research carried out so far on the fatigue performance of riveted bridges, which was largely in the form of fatigue tests of built-up riveted girders (Out et al. 1984, Fisher et al. 1987, Brühwiler et al. 1990, Åkesson 1994, Adamson and Kulak 1995, Xie
et al. 2001), has shown that in the absence of fabrication errors, poor detailing, or extreme corrosion, the damage on these bridges has a slow propagation rate and can be detected before it affects the load-carrying capacity. The low level of stresses experienced by the primary bridge members (Fisher et al. 1987, Åkesson 1994) and the inherent redundancy of built-up riveted members (Sweeney 1979) are important factors in reducing their criticality with respect to fatigue failure.

Reemsnyder (1975) carried out full-scale tests on riveted truss members under constant and variable amplitude loading in order to study the effect of replacing rivets with high-strength bolts as a repair or strengthening method. Two to six times increase in fatigue life of the tested specimens was observed as a result of replacing the rivets with high-strength bolts showing the beneficial effect of clamping force. Other tests on riveted members have shown that the method of rivet hole preparation and the surface condition of these holes influence the fatigue strength of these members (Zhou et al. 1995, Kulak 1997). Riveted members with punched holes have been found to result in lower fatigue strength compared with members with drilled holes. The effect of hole preparation is considered in the American Railway Engineering Association (AREA) code by suggesting a more onerous S-N curve for the case of having punched holes (AREA, 1996).

The majority of the fatigue damage in riveted railway bridges has been reported in riveted connections and in particular stringer-to-cross-girder connections (Fisher et al. 1987, 1990, Al-Emrani 1999). Typically, fatigue cracks have been found in the past in connection angles, rivets and around rivet holes. The damages observed in these connection details have been largely attributed to their restraint against rotation, which typically results in locally elevated stresses in the connection angles and the rivets (Al-Emrani 2005). These connections always possess some rotational fixity (stiffness), which was most probably ignored during their design. It must be mentioned that estimation of the rotational stiffness of the connection is not an easy task as it depends on a large number of variables such as clamping force in the rivet, thickness of the angle, etc.

Experimental works carried out on stringer-to-cross-girder connections are rather limited. One of the few full-scale testing programmes was carried out in Sweden on parts extracted from an old riveted railway bridge (Al-Emrani 2005). The assembly consisted of four stringers and three cross-girders. The moments that were carried by the stringer-to-cross-girder connections were estimated to range between 56 to 67% of the corresponding fixed-end moments. Four-point bending fatigue tests of the assembly resulted in fatigue cracking of the connection angles near the fillet and of the rivets at the head-to-shank junction. However, the propagation rate of these cracks was found to be very slow. The same investigators also carried out finite element (FE) analyses of a simple stringer-to-cross-girder connection (Al-Emrani and Kliger 2003). In their analyses, the cross-girder was modelled as a rigid surface whereas the stringer was modelled using shell elements. The leg of the connection angle and the rivets connected to the cross-girder web were also included in the model. Loading consisted of two point loads applied to the stringer representing train axle loads. The angle-fillet and the junction of the rivet head-to-shank were identified as the most stressed regions of the connection, which was in agreement with the experimental observations. The clamping force in the rivets was found to have a more pronounced effect on the rivet stresses rather than the angle stresses.

Newly manufactured full-scale specimens consisting of a stringer and a cross-girder bolted together using two double-angles were fatigue tested by Abouelmaaty et al. (1999). The moment developed at the stringer-to-cross-girder connection was found to
be equal to 9% of the corresponding fixed-end moment. The fatigue damage was concentrated on the cross-girder and stringer webs and on the bolts. Similar damage patterns on the cross-girder web were also observed previously in other full-scale tests on parts extracted from a bridge in Germany (Mang and Bucak 1990). The specimens tested by Abouelmaaty et al. were modelled using the FE method (Jones et al. 1997). Shell elements were used for the stringer and the connection angles, whereas the cross-girder was modelled using solid elements. The bolts were not modelled explicitly and instead were represented by rigid links and constraint equations. Good agreement between the analytical and the experimental results was observed by the authors.

A three-dimensional FE analysis of a stringer-to-cross-girder connection was carried out by DePiero et al. (2002). Their model consisted of a stringer, part of the cross-girder and a connection angle, all of which were modelled using brick elements. The root of the angle-fillet at the top part of the connection was the most stressed.

Previous studies carried out by the present authors, in the form of FE analyses of an entire short-span, riveted, railway bridge, indicated that the most fatigue-critical connections were the inner stringer-to-cross-girder connections (Imam et al. 2005). The connections in the global model were represented by simply tying the bridge members together, thus assuming full connection fixity. This assumption was found to result in the maximum damage in the stringer-to-cross-girder connections (Imam et al. 2004). In the study presented in this paper, the previous global model of the bridge was enhanced at the location of the most fatigue-critical stringer-to-cross-girder connection by modelling the full connection geometry. A typical freight train was traversed over the bridge and the fatigue-critical locations (‘hot spots’) of the connection were identified. In doing so, the effects of the rivet clamping force and the different assumed damage scenarios on the fatigue damage of the connection were investigated. Where appropriate, comparisons between the present refined bridge model and the previous global model (Imam et al. 2005) are made in this paper.

2.0 Finite element analysis

2.1 Description of the bridge and the finite element model

The wrought-iron bridge considered here carries two-way traffic, has a 9.6 m clear span and is 7.6 m wide. The superstructure consists of three riveted, built-up main girders and four rows of built-up stringers, interconnected with built-up cross-girders (figure 1). This bridge may be considered as being representative of a large number of riveted bridges constructed in the UK and North America in the second half of the 19th century. The members comprise plates whose thicknesses range between 6.4 and 15.9 mm, whereas the connections throughout the structure comprise 76×76×12.6 mm equal angles and 19 mm rivets. Clearly, these are all converted to SI units from the original Imperial units. Furthermore, for the purposes of the FE analysis, all built-up members were transformed into equivalent I-sections having the same depth and the same second moment of area.

The bridge structure was modelled using the commercial FE-package ABAQUS 6.5 (2004). The global finite element model of the riveted bridge and its relevant dimensions are shown in figure 1. As mentioned previously, this model consisting entirely of shell elements was presented elsewhere (Imam et al. 2005). A Young’s Modulus of 200 GPa (Moy et al. 2004), Poisson’s ratio of 0.3 and linear elastic material behaviour was assumed. The individual members were tied to each other at the locations of the connections, which assumed full connection fixity. Stiffeners at 1200 mm
spacings on the three main girders were also modelled. The bridge was assumed to be
simply supported at the ends of the three main girders.

Figure 1 Bridge global FE model and relevant dimensions.

The refined model of the riveted bridge is shown in figure 2 and will be referred to as
the ‘global-local’ model. In this model, the location of the most fatigue-critical stringer-
to-cross-girder connection, as identified by previous FE analyses of the global model
(Imam et al. 2005), was further refined by using brick elements and taking into account
the full connection geometry. The stringer-to-cross-girder connection consists of four
angles, each riveted to the stringer and the cross-girder webs using two and three rivets,
respectively. In contrast to the global model of figure 1, wherein a simplified
representation of the riveted connections was used, the global-local model permitted
investigation of the fatigue damage of the individual elements of the connection (angles,
rivets). The model also allowed the local flexibility of the connection to be accounted
for. Thus, in the model shown in figure 2, part of the cross-girder and the stringer as
well as the connection angle and the rivets were modelled by using 8-noded brick
elements with full integration. The entire FE model consisted of approximately 67000
brick elements and 20000 shell elements. A close view of the refined connection is
shown in figure 3. A shell-to-solid interface was used in the FE model for the transition
from the 8-noded shell elements to the 8-noded brick elements.
Figure 2 Global-local FE model of the riveted bridge.

Figure 3 Close-up view of the global-local FE model at the stringer-to-cross-girder connection location and rivet-hole nomenclature.
Contacts between the individual parts of the connection (angle-to-stringer web, angle-to-cross-girder web, rivet-to-hole, stringer-to-cross-girder) were modelled using contact pairs and the master-slave algorithm of ABAQUS (2004). A Coulomb friction model with an assumed coefficient of friction of 0.3 was considered for all contact pairs. The surfaces of the rivet head that were in contact with the angle were modelled using the *NO SEPARATION option of ABAQUS (2004) in order to ensure that these surfaces remained in contact throughout the analysis. The pre-tension force in the rivets was modelled using the *PRE-TENSION SURFACE option of ABAQUS (2004) at the mid-length location of the rivets. Application of the rivet clamping force was carried out prior to application of any external load.

2.2 Loading and damage calculation

The bridge was loaded with the heaviest of the BS 5400 (1980) medium traffic trains. This freight train, which is referred to as train No 7 in the BS 5400, has a maximum axle load of 25 t. It consists of an engine car in front followed by ten two-axle wagons. For the purposes of the analysis, the train was traversed in 1 m steps over one track of the bridge (left track in figure 2) up to the point of loading repetition, which was caused by the passage of the same wagons. In total, the analysis comprised 43 static load steps. The axle loads were applied directly to the top flange of the stringers neglecting the benefit of any load spread due to the rails and sleepers. The self-weight of the bridge members and the superimposed dead load due to the sleepers and rails were taken into account in the FE model.

The damage caused by the single passage of the train was calculated by first converting the irregular stress histories into stress range blocks through rainflow counting followed by the use of Miner’s Rule (Miner 1945). Two-slope S-N curves were used as suggested by the BS 5400 (1980) and the UK railway assessment code (Railtrack 2001) for variable amplitude loading. The change of slope from \( m \) to \( m+2 \) takes place at \( 10^7 \) cycles which corresponds to the fatigue limit. The investigation was carried out for the riveted stringer-to-cross-girder connection.

In the case of the global model (Imam et al. 2005), these connections were classified as either Class B with the use of the appropriate stress concentration factor (2.4) or Class D according to BS 5400 (1980). The former, which will be referred to as modified Class B, can be used to represent the case of having low or no clamping force in the rivets, whereas Class D can be regarded as being representative of connections with normal or high clamping force. A wrought-iron riveted detail class (WI-rivet), as proposed by the UK railway assessment code (Railtrack 2001), was also used to classify the connection. This detail is used for rivet holes in wrought-iron riveted connections and implicitly takes into account any stress concentration effects. A far-field stress value, which is independent of stress concentrations, is used in conjunction with all of the above detail classes. In the case of the global model, stress history outputs were obtained at a cross-section located at a distance of 250 mm from the stringer-to-cross-girder interface as shown in figure 3. At this distance, stress concentration effects were found to diminish considerably (Imam 2006). Along the section’s depth, stresses were reported at a 50 mm distance from the bottom flange of the stringer (point P in figure 3), which coincided with the location of the angle clip edges. This location was chosen since previous investigations by the authors revealed that the bottom part of the stringer-to-cross-girder connections was the most damaged (Imam et al. 2005).

In the case of the global-local model, where the full connection geometry was taken into account and hot spots for fatigue crack initiation were identified, a different
wrought-iron riveted detail class from the one described previously was used for classification (WI-plain). This detail class is suggested by the UK railway assessment code for plain wrought-iron material (Railtrack 2001). This detail class was used in combination with principal stresses as it is suggested by the BS 5400 (1980) for potential crack locations. The S-N curves of all the relevant fatigue classes together with their slopes are shown in figure 4.

The fatigue damage for a single train passage is given as

\[ D = D_1 + D_2 \] (1)

and

\[ D_1 = \sum_{i=1}^{k} \frac{n_i}{10^2} \left( \frac{\Delta \sigma_i}{\Delta \sigma_0} \right)^m \text{ if } \Delta \sigma_i \geq \Delta \sigma_0 \] (2)

\[ D_2 = \sum_{i=1}^{k} \frac{n_i}{10^2} \left( \frac{\Delta \sigma_i}{\Delta \sigma_0} \right)^{m+2} \text{ if } \Delta \sigma_i \leq \Delta \sigma_0 \] (3)

where \( k \) is the number of different principal stress ranges \( \Delta \sigma_i \) obtained from the passage of the train over the bridge, \( n_i \) is the number of applied stress ranges \( \Delta \sigma_i \) and \( \Delta \sigma_0 \) is the fatigue limit of the detail class considered.

![Figure 4](image)

**Figure 4** S-N curves for two BS 5400 (1980) fatigue classes and the two WI classes (Railtrack, 2001).

### 2.3 Damage scenarios

The effects of the different rivet clamping forces and the various damage scenarios on the stresses and the accompanying fatigue damage of the connection are discussed in the following. The rivet and hole numbering used throughout is shown in figure 3. The effects of various rivet defects associated with bad fabrication or corrosion are examined. Two rivet clamping stress values of 100 MPa and 200 MPa were considered. The former is a typical value observed in riveted bridges, while the latter can be
considered as an upper bound (Åkesson 1994). The effects of the loss of clamping force in the top rivet connecting the angle to the cross-girder web (rivet 1 in figure 3) and of the loss of the entire rivet 1 were also studied. Rivet defect scenarios that were examined also included the case of having a smaller rivet head than normal, the case of an offset rivet head and, finally, the case of having a small clearance between the rivet shank and the rivet hole. All the above scenarios were considered for rivet 1 since field observations had shown that fatigue damage was more likely to occur in either the top or the bottom rivets of the connection (Al-Emrani 1999). The effect of the method of hole preparation was not considered in this investigation.

A small rivet head can come about through fabrication error or poor pressing during the riveting procedure. In these cases the press does not apply the correct amount of pressure for the formation of a normal-sized rivet head. On the other hand, a rivet head can also become smaller due to material loss resulting from corrosion. For the purposes of the present study, a smaller rivet head of 12 mm radius, as compared with the 16 mm radius of the original rivet head, was modelled for rivet 1. This can be assumed to be equivalent to a uniformly distributed corrosion of 4 mm on the rivet head.

Clearances between the rivet shank and the rivet hole are not uncommon, especially in cases of long rivet shanks (Baron and Larson 1953, Vasishth 1960). During the riveting procedure, the diameter of the hole is usually drilled approximately 1 to 2 mm larger than the rivet shank diameter. The rivet head is formed through forging, using a pneumatic hammer or press. As the rivet head is formed, the shank of the rivet expands laterally resulting in an increase of its diameter, and the rivet material ideally fills the hole. In some cases, however, a clearance between the rivet and the hole can remain due to insufficient heating and/or punching. In this study, the case of a 0.5 mm clearance between rivet 1 and its corresponding hole was examined.

An offset in the rivet head can result from eccentric punching or hammering. Several cases of rivet head misalignment were reported for rivets extracted from girders (Xie et al. 2001). For the purposes of this study, a 3 mm offset of the rivet 1 head towards the outer edge of the connection angle was assumed.

Finally, the effect of the complete loss of rivet 1 was also examined by removing the rivet from the FE model. This type of damage can happen through fatigue failure of the rivet.

3.0 Results and discussion

The fatigue damage of various parts of the stringer-to-cross-girder connection due to a single passage of the BS 5400 train 7 and under different damage scenarios are presented in this section. The more likely locations of fatigue crack initiation (hot spots) were identified using principal stress histories and the findings are summarised in figure 5. Points ‘A’ are located on the angle, at the root of the fillet. Points ‘B’ and ‘C’ are located on the edges of rivet holes, at the interface of the connection angle with the cross-girder and stringer webs, respectively. Points ‘D’ and ‘E’ are located on the rivet shank-to-head junction. In the following, the results of the global-local FE analyses and the reasoning leading to fatigue-criticality of the various hot spots are presented.

3.1 General connection behaviour

Analyses of the global-local FE model, carried out under train loading, identified several regions of high stress concentration in the connection. The positions of these highly-stressed regions varied with time as the train traversed over the bridge. For example, at one time instance, the most highly-stressed region was at the top part of the
connection angle and at a different time instance the most critical region shifted to the middle or the bottom part of the connection angle. In general, these highly-stressed regions were located along the fillet root of the connection angle, along the circumferences of the rivet holes on the surface of the connection angle which were in contact with the cross-girder and the stringer webs, and on the rivets around the circumference where the rivet shank met the rivet head. It should be noted that during the fatigue process, the most important parameter is the stress range experienced at a location, rather than the stress level itself. Therefore, the region with the highest stresses in a stress history is not necessarily the most fatigue-critical.

![Figure 5](image_url)

**Figure 5** Hot spot locations at different parts of the stringer-to-cross-girder connection.

Figure 6 shows the stress distribution along the fillet root of the connection angle during a particular load step for two different clamping force values in the rivets. Both the axial stress i.e. stress $\sigma_{11}$ at the edge of the fillet in the leg of the angle connected to the stringer web, and the bending stress i.e. stress $\sigma_{33}$ at the edge of the fillet in the leg of the angle connected to the cross-girder web are presented. The bending stress resulted from the out-of-plane flexure of the leg of the connection angle attached to the cross-girder web. The out-of-plane flexure also caused axial and bending stresses in the rivets connecting the angle to the cross-girder web. It can be seen in figure 6 that for this particular load step, the top part of the connection angle was subjected to a high tensile stress whereas the bottom part locally experienced compression. The stress $\sigma_{11}$ was concentrated at the locally stiffer level along the first rivet line. This was due to the higher restraint along the rivet line provided by the clamping force from the rivet, which attracted a larger portion of the stresses. The level of clamping force was found to have a small effect on both the axial and the bending stresses with the maximum difference between the clamping stresses of 100 MPa and 200 MPa being approximately 20% for
this particular load step. All the above observations were in agreement with the FE analysis results of Al-Emrani and Kliger (2003).

Figure 6 Axial (stress component $\sigma_{11}$) and bending (stress component $\sigma_{33}$) stresses in the connection angle along the fillet root.

The bending stress profiles through the thickness of the connection angle and at the level of the first rivet line (see figure 6) are shown in figure 7 along three different paths. The results are shown for clamping stresses in the rivets of respectively, 100 MPa (labelled as C100) and 200 MPa (labelled as C200). Path 1 is situated at the location where the edge of the rivet head met the connection angle (point P1). Path 2 is located at the start of the angle-fillet (point P3) whereas, path 3 is located at hole 1 (see figure 3), starting under the rivet head (point P5) and ending at the point where the angle contacted the cross-girder web (point P6). As can be seen, the bending stresses at points P1 and P5 were compressive since they were located under the rivet head and were under the effect of the rivet clamping force. On the other hand, the bending stress at the angle-fillet (point P3) was found to be predominantly tensile and of alternating nature under the passage of the load train. Indeed, this location has been identified as fatigue-critical and, over the years, cracks starting from this region were found in stringer-to-cross-girder connections (Fisher et al. 1987, Al-Emrani 1999). Cracks are also likely to originate from the rivet hole on the side of the connection angle in contact with the cross-girder web (point P6 for example) where the bending stresses are of tensile nature as well.

It is evident from figure 7 that the leg of the connection angle abutting the cross-girder behaves as a partially-fixed beam, restrained by the rivet head along P1-P2 and by the angle-fillet along P3-P4. With the exception of path 1 (P1-P2), the rivet clamping force did not have a significant effect on the magnitude of the maximum bending stress. Furthermore, by reducing the value of the clamping stresses from 200 MPa to 100 MPa in this particular load step, the bending stresses increased and decreased by approximately 15% respectively, at points P3 and P6. On the other hand, a higher clamping force resulted in a higher bending stress at point P2 near the rivet. Similar
behaviour was also observed by Al-Emrani and Kliger (2003) in a stringer-to-cross-girder connection having a different geometry.

![Figure 7](image-url)  
**Figure 7** Bending stress profile through the angle thickness and along various paths for two different rivet clamping forces.

The effects of the clamping force on the bending stress histories at points P3 and P6 are shown in figure 8. The stress histories are shown up to the point of repetition of loads due to the passage of similar train wagons. It can be seen that for point P3 the stress history was not affected significantly by the clamping force. On the other hand, at point P6 further analysis demonstrated that the stress ranges were considerably reduced, although a higher clamping force generally resulted in higher stress at this location. As a result, fatigue damage at this location should be reduced with increased rivet clamping force. The behaviour of points P3 and P6 are similar with the same number of cycles experienced at both the locations.

Figure 9 shows the history of the principal stress at the shank-head junction of rivet 3 (point D8, figure 5) for two values of rivet clamping stresses (100 MPa and 200 MPa). The stress histories are shown for the passage of the entire train. The positive effect of a higher clamping force in reducing stress ranges and hence fatigue damage is evident from the stress range histograms shown in the same figure. Although the case of a clamping stress of 200 MPa resulted in higher stresses when compared with the case of a clamping stress of 100 MPa, the most frequent and damaging stress range in the former case (113 MPa) was found to be about 40% lower than the most frequent stress range associated with the latter case (157 MPa).

### 3.2 Fatigue damage under different scenarios

Fatigue ranking of the different parts of the connection (connection angle-fillet, rivets, holes) with respect to the different assumed damage scenarios is presented in this section. The hot spots of the connection that are identified below are shown in figure 5.
Figure 8 Effect of clamping force on bending stress history (stress component $\sigma_{33}$) at points P3 and P6 (see figure 7).

Figure 9 Principal stress history and stress range histogram at shank-head junction of rivet 3 (point D8, figure 5) for two clamping stress values.

3.2.1 Effect of rivet clamping force. Figure 10 shows the fatigue damage at various hot spots of the connection, calculated through equations (1)-(3), for two different values of rivet clamping stresses (100 and 200 MPa). In the same figure the hot spot locations where fatigue damages were reported (with respect to Figure 5) are also indicated.
As shown in figure 10, with the exception of the angle-fillet location (point A1, figure 5), an increase in the rivet clamping stress from 100 MPa to 200 MPa resulted in a decrease in the fatigue damage by a factor ranging between 2 and 22 in the case of the holes, and between 2 and 3 in the case of the rivets. At point A1, the damage increased slightly with an increase in the clamping stress from 100 MPa to 200 MPa. Nevertheless, figure 10 shows the beneficial effect of a high clamping force in delaying or even preventing fatigue crack initiation at the holes and the rivets. Points C1 and C3 in the angle holes 4 and 5 on the side of the stringer web were found to be the most damaged in the case of a clamping stress of 100 MPa, whereas points C2 and A1, respectively on the angle hole 5 and the angle-fillet, were found to be the top two damaged locations in the case of a clamping stress of 200 MPa. It is evident that as the clamping force of the rivets increase, the fatigue life of the angle-fillet becomes critical.

It should be noted that overall, the higher damage observed at the angle holes on the side of the stringer web (points C in figure 5) as compared to the damage at the angle holes on the side of the cross-girder web (points B in figure 5), can be attributed to the lower number of rivets used on one side (two vs. three). A higher number of rivets on the stringer side would have resulted in lower forces being carried by each rivet and hence lower fatigue damage.

Table 1 shows ranges of the ratios of the fatigue damage (Miner sum under the passage of a single train estimated through equations (1)-(3)) calculated using the global-local model for a rivet clamping stress of 200 MPa, to the fatigue damage calculated at the connection using the global model according to different detail classifications. If the connection is assumed to be of steel material, the BS 5400 Class B (plain material without the use of stress concentration factor) can be used for the global-local model in conjunction with modified Class B or Class D for the global model. It can be seen from table 1 that excluding the case of holes 4 and 5, the global model is unconservative by a factor of up to 5. The greater variation observed between the global...
and the global-local models in the case of holes 4 and 5 may be attributed, as mentioned previously, to the lower number of rivets used on the stringer side of the connection. If a wrought-iron connection is assumed and a Class WI-plain is used for the global-local model in conjunction with Class WI-rivet for the global model, the discrepancies between the two models are considerably higher. Notwithstanding the results associated with holes 4 and 5, the global model may be seen to be unconservative by a factor of up to 20. The difference in the above factors between the steel and the wrought-iron connections shows that the fatigue life estimates are sensitive to the quality of the S-N characterisation of the detail. It could be argued that the S-N curves pertaining to a steel riveted detail (modified Class B or Class D) are a better match with a plain metal (Class B) curve used in conjunction with a global-local model than their wrought-iron counterparts (Class WI-plain and Class WI-rivet). This may be attributed to the higher uncertainty in the fatigue properties of wrought-iron when compared to steel and the limited fatigue test results available for the former.

Table 1. Comparison of fatigue damage between global and global-local models.

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<tr>
<th></th>
<th>Modified Class B</th>
<th>Class D</th>
<th>Class WI-rivet</th>
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<tr>
<td></td>
<td>Holes 1-3</td>
<td>Holes 4-5</td>
<td>Rivets</td>
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<tr>
<td>Class B</td>
<td>0-3</td>
<td>5-10</td>
<td>0-2</td>
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<tr>
<td>Class WI-plain</td>
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3.2.2 Effect of loss of clamping force and loss of rivet. The fatigue damage associated with the possible scenarios of the loss of clamping force in rivet 1 and the loss of the same rivet entirely can be seen in figure 11. By way of comparison, the damage in the case of a clamping stress of 100 MPa in the rivets is also presented in the same figure.

As can be seen, the effect of the loss of clamping force in rivet 1 was to increase the fatigue damage in the connection, in some cases. A slight decrease in damage was observed at points B5, C3, A1 and E6 (see figure 5). The largest increase in fatigue damage was associated with the region where the loss of clamping force took place (hole 1 and rivet 1). More specifically, the increase in damage was 25% for hole 1 (point B2) and 160% for rivet 1 (point D3). Consequently, fatigue cracking is more likely to occur at these locations. As in the case of a clamping stress of 100 MPa in all the rivets, the fatigue-critical locations were holes 4, 5 and 1.

Figure 11 shows that loss of rivet 1 led to an increase in fatigue damage in most parts of the connection, excluding points C1 (hole 4) and E6 (rivet 5). The increase in fatigue damage was found ranging between 20% and 240% depending on the location. Since rivet 1 was removed from the FE model in this scenario, its fatigue damage is not shown in figure 11. It can also be seen that the fatigue damage of the hole, from which the rivet was removed (hole 1, point B3), reduced to almost negligible levels. This can be attributed to the absence of the bearing of the rivet on the hole after it was lost, which is a major reason leading to stress concentrations at holes. The most damaged location of the angle-fillet shifted from point A1, when the rivet was present, to point A2, when the rivet was lost. In this scenario, the most fatigue-critical region of the connection was found to be point B4 of hole 2.
3.2.3 Effect of rivet defects. The effect of various rivet defects associated with poor detailing and fabrication errors is shown in figure 12. As was mentioned previously, these include having a smaller rivet head than normal, having an accidental offset of the rivet head and having a certain clearance between the rivet shank and the rivet hole. All these cases considered a clamping stress of 100 MPa in all the rivets.

A 0.5 mm clearance between rivet 1 and hole 1 was found to have a profound effect on the damage of the rivet. On the other hand, the effect on the fatigue damage of hole 1 was small but its effect on holes 2 and 3 was considerably more pronounced, with the fatigue damage increasing by a factor of 2.5. In terms of fatigue criticality, hole 2 was ranked first.

A 4 mm reduction in the head diameter of rivet 1 resulted in a small overall reduction in damage excluding at points C3, D1 and E6. The decrease in fatigue damage was up to about 40%. On the other hand, increase in fatigue damage was found to be about 20%. Figure 12 shows that a reduction in the size of the rivet head resulted in a reduction in the fatigue life of the rivet itself rather than the rivet hole. Reduction of the size of the rivet head led to reduction in the surface through which the force could be transferred between the rivet and the connection angle. This was accompanied by an increase in the stress concentration present at the rivet head-shank junction.

Finally, the offset of the head in rivet 1 by 3 mm towards the side of the angle edge was found to result in an increase in the fatigue damage of the rivet itself (point D5) by over 50%. An accompanying increase in the damage of hole 1 (point B2) by about 20% was also observed. The remaining regions of the connection, excluding hole 5 and rivet 5, were associated with a decrease in damage that ranged between 5% and 30%, the maximum being at the angle-fillet (point A1).
By comparing figures 11 and 12 it can be seen that the most damaging scenario is the presence of a clearance between the rivet 1 and the hole 1. The second most damaging effect is found to be the loss of rivet 1. In both the cases the hole 2 was the most affected region.

As the relative damages recorded in figures 11 and 12 demonstrate, the defect in one of the rivets resulted in changes that were mostly localised. Therefore, these changes appear to be less significant in the angle-fillet and rivets/holes 4 and 5.

It should be noted that the conclusions regarding the effects of various scenarios on the fatigue damage of the connection are drawn for this specific connection geometry. Criticality of different regions in other types of connection may be different from the one reported here. However, given the wide-spread use of this connection in the UK and the bridge typology studied here, fairly general conclusions may be drawn that can help in future inspections.

Identification of the various hot spots of the connection has provided some insight on the locations where crack initiations are likely to occur. The Fracture Mechanics (FM) approach can subsequently be used in order to study the behaviour of existing cracks at various locations of the connection.

4.0 Conclusions

In this paper, fatigue damage results obtained from the finite element analysis of a typical riveted railway bridge under the passage of a single freight train were presented, taking into account the full stringer-to-cross-girder connection geometry. The leg of the connection angle connected to the cross-girder web was found to behave as a partially-fixed beam at the locations of the angle-fillet and near the rivet head. The rivet clamping force was found to have a more pronounced effect on the bending stresses near the rivet rather than near the angle-fillet.
Damage scenarios such as loss of clamping force in a rivet, presence of clearance between the rivet shank and the rivet hole, loss of rivet, reduction in the volume of the rivet head and rivet head offset were investigated and hot spots were identified and ranked according to their fatigue damage. The effect of the manner of hole preparation was not considered. The more damaging cases drawn for this specific geometry were found to be the presence of clearance between the rivet shank and the rivet hole and the loss of a rivet. Accordingly, damage was found to be predominantly localised in the hole and in the rivet. The rivets and holes on the side of the stringer web were not considerably affected by the assumed damage scenarios in the top rivet connecting the angle to the cross-girder web.

The next step of the work presented here will be to investigate initiation of new cracks or propagation of already existing cracks at the hot spots identified in this paper, using the Fracture Mechanics approach.

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