BEHAVIOUR OF LAP SHEAR RIVETED CONNECTIONS WITH CONSTRUCTIONAL IMPERFECTIONS

A. Milone¹, A. De Martino²

¹Department of Structures for Engineering and Architecture, University of Naples “Federico II”, Via Forno Vecchio 36, 80134 Naples, Italy; aldo.milone@unina.it

²Department of Structures for Engineering and Architecture, University of Naples “Federico II”, Via Forno Vecchio 36, 80134 Naples, Italy; attilio.demartino@unina.it

Abstract

Riveted connections are the most common structural details of existing steel bridges. Due to the increase of traffic loads as respect to the conditions at their erection time, existing riveted bridges are usually characterized by structural deficiencies and prone to fatigue damages. Moreover, the structural inadequacies are often magnified by the presence of peculiar constructional defects (i.e. shank misalignment, forged head distortion), which induce local stress concentrations that further reduce the service life.

In this paper, the behaviour of riveted lap shear connections under static and cyclic actions is investigated by means of finite element (FE) simulations. The investigated connections are representative of typical geometries of the details of actual existing railway bridges. FE models were calibrated against the results of former tests drawn from literature. In addition, the FE models allowed at investigating the influence of constructional imperfections on the ultimate static and fatigue resistance and of the connections. In order to widen the parametric study, the following parameters are varied, namely: (i) number of rivets, (ii) diameter of rivet shank, (iii) thickness and width of the plates.

Keywords: Lap shear connections, Fatigue, Riveted connections, Existing Steel Bridges, Finite Element Analysis.
1 INTRODUCTION

Riveted steel bridges represent the most common type of existing railway bridges in Italy \[1\]. The diffusion of this structural typology mainly developed between the XIX\textsuperscript{th} century and the first half of the XX\textsuperscript{th} century, after which the usage of hot-driven rivets gradually diminished owing to the introduction of high-strength bolts \[2\]. Therefore, existing riveted railway bridges in Italy are often characterized by an exceptionally long service life. This condition, in conjunction with the increase of traffic loads through the years, inevitably exposes such kind of structures to critical fatigue issues.

Moreover, the adopted technology for the implementation of hot-driven rivets (i.e. heat forging) can lead to peculiar structural imperfections which further reduce the structural service life. Indeed, the heating process brings the rivet base material to a plastic state which enables the realization of an on-field head by means of a pneumatic hammer. This semifluid consistency also leads to a diameter dilatation due to the hammering, leaving no gaps among the rivet shank and the relative plate holes, differently from bolted connections. However, if involved plates are not correctly aligned, the forging operation will result in a distorted shank which presents several superficial discontinuities acting as critical stress amplifiers.

It should be remarked that current provisions for fatigue design of steel structures (EN:1993-1-9 \[3\]) only provide a single detail category for riveted connections (\(\Delta\sigma_{c} = 71\) MPa) which does not account for the actual riveted joint, although the influence of joints detailing on the cyclic behavior of steel structures is widely recognized in literature \[4-16\]. Moreover, the presence of the aforementioned structural imperfections is completely overlooked.

Therefore, in this paper the actual static and fatigue behavior of common types of riveted connections is parametrically investigated by means of numerical analyses.

The present work is divided in three parts. In the first section, the main features of investigated riveted connections are presented; the most relevant modeling assumptions are reported in the second part, with particular attention to damage modeling and fatigue load protocol derivation. Finally, the results of numerical analyses are discussed, highlighting the influence of the investigated parameters on both the static and cyclic response of considered riveted joints.

2 DESCRIPTION OF INVESTIGATED RIVETED CONNECTIONS

Four different types of lap shear riveted connections were tested in order to evaluate the influence of (i) rivet diameter, (ii) plates width and thickness and (iii) number of rivets on both static and fatigue behavior of these joints. Each adopted configuration is representative of typical details adopted in existing railway bridges.

Among the different typologies of possible constructional imperfections, in this paper only the shank distortion due to plates misalignment is considered. According to the Sustainable Bridges report \[17\], such kind of misalignment is considered acceptable for an existing riveted connection (i.e. connection repair or substitution is not required) if the ratio between the shank eccentricity \(e\) and the rivet diameter \(d\) does not exceed 0.15.

In order to account for possible difficulties in on-field eccentricity measuring, a maximum value of \(e/d\) equal to 0.20 was considered.

A proper nomenclature \(L-D-T-N-E\) was introduced to label each investigated joint, where:

\(L\) is the considered load condition;
\(D\) is the rivet diameter;
\(T\) is the plate thickness;
\(N\) is the number of rivets;
\(E\) is the shank eccentricity.
In order to reproduce the actual technique for on-field eccentricity measuring, the parameter $e$ has been defined as the distance between the shop head and the heat forged head of the rivet in the direction of the applied loads, as depicted in Figure 1. A total of 40 finite element analyses (FEAs) were conducted accounting for the variation of each introduced parameter (see Tab. 1).

<table>
<thead>
<tr>
<th>Joint Typology</th>
<th>Load Conditions</th>
<th>Rivet Diameter D [mm]</th>
<th>Plate Thickness T [mm]</th>
<th>Number of Rivets N</th>
<th>Eccentricity $E$ [e/d]</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-16-10-1-E</td>
<td>S (Static)</td>
<td>16</td>
<td>10</td>
<td>1</td>
<td>0.00</td>
</tr>
<tr>
<td>L-19-10-1-E</td>
<td>or</td>
<td>19</td>
<td>10</td>
<td>1</td>
<td>(No Imperfections)</td>
</tr>
<tr>
<td>L-19-12-1-E</td>
<td>F (Fatigue Cyclic)</td>
<td>19</td>
<td>12</td>
<td>1</td>
<td>to 0.20</td>
</tr>
<tr>
<td>L-19-10-2-E</td>
<td></td>
<td>19</td>
<td>10</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Main features of investigated joint configurations.

3 MODELLING ASSUMPTION

Finite element models (FEMs) were developed using ABAQUS 6.14 [18]. In order to reduce the computational effort, riveted connections have been modelled considering their geometrical and mechanical symmetry. Static and fatigue behavior of each connection has been investigated imposing monotonic and cyclic displacement histories at the plates tip, respectively. The adopted boundary conditions are reported in Figure 2.

All elements were discretized using solid C3D8 element type (i.e. 8-node linear brick). The mesh density was defined on the basis of preliminary sensitivity analyses; therefore, a mesh size of 1 mm was set for the connection zone, while a value of 20 mm was adopted for the plates ends, which were expected to remain in their elastic range.

Steel yielding was modelled using the Von Mises criterion. Yield stress for both rivets and plates was calibrated against experimental trials carried out by D’Aniello et al. [2]. Both kinematic and isotropic hardening were implemented by means of material parameters. Ductile damage formulation was introduced to reproduce the material degradation due to plasticization under triaxial stresses. According to Yang et al. [19], the following analytical expression for triaxiality curves was considered:

$$\varepsilon_{pl,eq,\eta} = \varepsilon_{pl,eq} \exp\left(-\frac{3}{2}(\eta - \frac{1}{3})\right)$$  \hspace{1cm} (1)

where $\varepsilon_{pl,eq,\eta}$ is the equivalent plastic strain (PEEQ) at damage initiation for a given stress triaxiality, $\varepsilon_{pl,eq}$ is the equivalent plastic strain at damage initiation under uniaxial stress and $\eta$ is the stress triaxiality, defined as the ratio between the mean pressure $\sigma_m$ and the equivalent Von Mises stress $\sigma_{eq,VM}$ at a given point. Adopted values of $\varepsilon_{pl,eq}$ were calibrated against the aforementioned experimental tests on real riveted joints. The assumed values of mechanical parameters are reported in Table 2. “Surface-to-Surface” interactions were introduced to model contact among rivets and plates.
An “Hard Contact” formulation was considered for the normal contact behavior, while a penalty formulation was used to model the tangential behavior (with friction coeff. = 0.30).

<table>
<thead>
<tr>
<th>Investigated Joint</th>
<th>Plate Yield Stress [MPa]</th>
<th>Rivet Yield Stress [MPa]</th>
<th>Rivet Damage Strain [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-16-10-1-E</td>
<td>298</td>
<td>385</td>
<td>0.54</td>
</tr>
<tr>
<td>L-19-10-1-E</td>
<td>298</td>
<td>461</td>
<td>0.53</td>
</tr>
<tr>
<td>L-19-12-1-E</td>
<td>298</td>
<td>414</td>
<td>0.60</td>
</tr>
<tr>
<td>L-19-10-2-E</td>
<td>298</td>
<td>350</td>
<td>0.32</td>
</tr>
</tbody>
</table>

Table 2: Adopted material parameters for the investigated riveted joints.

3.1 Derivation of the fatigue load protocol

In order to reproduce fatigue loads which could affect real riveted connections comparable with the investigated ones during their service life, a cyclic protocol was developed starting from the structural analysis of an existing railway riveted bridge situated in Italy (Bridge over Gesso Torrent, see Figure 3a). The investigated bridge, which is composed by three identical simply-supported spans, has a reticular structure with two main external longitudinal trusses and two supplementary internal girders supporting the overlying embankment. Longitudinal trusses are connected by means of X-shaped braces in both the transversal and horizontal direction [1]. The whole structure was modeled using SAP2000 v.21 [20] (see Figure 3b) and subjected to fatigue load trains borrowed from current Italian provisions for fatigue design of railway bridges [21]. The main features of the load models considered are reported in Table 3.

Figure 3: Overall view of riveted bridge over Gesso Torrent (a) and relative structural model made with SAP2000 (b).
“Moving Load” command was used to reproduce the effect of transient train loads, thus obtaining the variation of nodal actions through time. Among the various existing connections, the one linking the most stressed diagonal to the tension side of the truss was chosen.

The resulting loads history relative to a single rivet was finally used as load protocol for the fatigue analysis of investigated riveted connections (see Figure 4).

<table>
<thead>
<tr>
<th>Load Train</th>
<th>Total Load [kN]</th>
<th>Number of Axles</th>
<th>Train Length [m]</th>
<th>Daily Passages</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>9400</td>
<td>60</td>
<td>385.5</td>
<td>7</td>
</tr>
<tr>
<td>4</td>
<td>5100</td>
<td>30</td>
<td>237.6</td>
<td>6</td>
</tr>
<tr>
<td>8</td>
<td>10350</td>
<td>46</td>
<td>212.5</td>
<td>1</td>
</tr>
<tr>
<td>9</td>
<td>2960</td>
<td>24</td>
<td>134.8</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 3: Main features of the load trains adopted according to [21].

4 RESULTS OF NUMERICAL ANALYSES

4.1 Static behavior of investigated joints

The static behavior of each investigated joint in terms of shear strength-eccentricity and ultimate displacement-eccentricity is reported in Table 4. One can notice that the peak resistance of each investigated joint does not change significantly as the shank eccentricity $e/d$ increases. This outcome is consistent with the failure mechanism related to all analyzed specimens (i.e. rivet shear failure for each investigated joint). Indeed, the shear resisting section of the distorted rivets is not actually influenced by the holes misalignment due to the diameter dilatation.

However, the effect of shank distortion can be appreciated in terms of both ultimate displacement and damage concentration. Due to the loss of in-plane symmetry, the material damage develops unevenly among the shear planes, as depicted in Figure 5. This leads to a reduction of joint ductility which becomes more consistent with increasing eccentricity $e/d$.

Moreover, this tendency is more pronounced for low values of “rivet slenderness” ratio $t/d$. (i.e. S-19-10-1-E specimen, $t/d = 0.53$) due to the higher influence of second order bending moments caused by distorted geometry. Nevertheless, the influence of these effects on the static behavior of examined riveted joints can be considered negligible within the investigated range of defects amplitude. Indeed, as reported in Table 4, the loss of shear resistance with respect to undistorted specimens is extremely low. This outcome is in consistency with tolerances on eccentricity suggested by Sustainable Bridges Report [17].

4.2 Fatigue behavior of investigated joints

The fatigue behavior of each investigated joint in terms of maximum damage initiation parameter-eccentricity is reported in Table 5.

![Figure 4: Cyclic protocol adopted for the fatigue analysis of the investigated riveted connections.](image)
Figure 5: Distribution of scalar damage parameter at failure in absence (S-16-10-1-0.00, a) and presence (S-16-10-1-0.20, b) of imperfections.

Table 4: Shear strength and ultimate displacement for all investigated joints in static conditions.

<table>
<thead>
<tr>
<th>Investigated Joint</th>
<th>Shear Strength [kN]</th>
<th>Ultimate Displacement [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>e/d [%]</td>
<td>e/d [%]</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>S-16-10-1-E</td>
<td>149.6</td>
<td>149.2</td>
</tr>
<tr>
<td>S-19-10-1-E</td>
<td>211.9</td>
<td>203.0</td>
</tr>
<tr>
<td>S-19-12-1-E</td>
<td>215.9</td>
<td>215.8</td>
</tr>
<tr>
<td>S-19-10-2-E</td>
<td>354.1</td>
<td>340.0</td>
</tr>
</tbody>
</table>

In all cases a sharp increase in damage parameter can be noticed for increasing values of shank eccentricity. Moreover, for higher values of e/d fracture spots relocate nearby shank discontinuities, while rivet heads are the most damaged components for undistorted specimens (see Fig. 6). In analogy with static analyses, joints with low “rivet slenderness” t/d (i.e. F-19-10-1-E specimens) are the most affected from constructional imperfections. The worst scenario is represented by F-19-10-2-E specimens in which have low t/d ratio and are further penalized by the presence of two distorted shanks, which both act as stress and damage amplifiers. Indeed, the maximum damage parameter for e/d = 0.20 is 8.6 times higher with respect to undistorted joint.

Table 5: Damage initiation parameter for all investigated joints under cyclic actions.

<table>
<thead>
<tr>
<th>Investigated Joint</th>
<th>Damage initiation Par. (· 10^3) [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>e/d [%]</td>
</tr>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td>F-16-10-1-E</td>
<td>2.25</td>
</tr>
<tr>
<td>F-19-10-1-E</td>
<td>0.71</td>
</tr>
<tr>
<td>F-19-12-1-E</td>
<td>1.17</td>
</tr>
<tr>
<td>F-19-10-2-E</td>
<td>0.59</td>
</tr>
</tbody>
</table>

Figure 6: Distribution of damage initiation parameter after the cyclic protocol in absence (F-16-10-1-0.00, a) and presence (F-16-10-1-0.20, b) of imperfections.
5 CONCLUSIONS

The static and fatigue behavior of four different kinds of lap shear riveted joints has been studied by means of numerical analyses. The influence of constructional imperfections on the joint’s response was investigated introducing hole misalignments up to 20% of rivet diameters. A proper cyclic load protocol was derived from the structural analysis of an existing riveted railway bridge situated in Italy.

From results of FEAs the following conclusions can be drawn:

- The static behavior of each investigated joint is not consistently influenced by the presence of constructional imperfections, with a maximum shear strength loss of about 5% with respect to undistorted specimens.
- However, a small difference can be noticed in terms of ultimate displacements, which decrease with increasing values of shank eccentricity; a modification of the damage mechanism is also observed due to distorted geometry.
- Ductility reduction increases for low values of “rivet slenderness” t/d due to higher second order stresses which promote damage evolution.
- The fatigue behavior of joints is highly dependent from shank eccentricity; increasing values of e/d lead to higher damages and develop of fracture spots nearby shank discontinuities.
- Similarly to the static scenario, low “rivet slenderness” t/d has a consistent influence on fatigue damage as well.
- The parametrical study will be further extended considering unsymmetrical joints, different kinds of imperfections and using standard cyclic protocols provided by EN:1993-1-9 [3].

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