Stress analysis in upper fillet and rail-end bolt hole at rail joint

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Abstract
Rail joint between two adjacent rail ends in the transportation of railway track structure is one of the weakest components leading to defects and failures. In this study, the rail joint components such as rail, joint bars, bolts, and sleeper are modelled by 3D Abaqus/CAE software and Finite-element method are used to investigate stress distribution in rail under static wheel load condition. The wheel load positions and bolt-hole locations vary as a parametric study. The results show that the critical stress occurs at the upper fillet rail end and at the edge of the rail-end bolt hole (1st hole from the rail end). The wheel load position affects stress only in case of the rail-end bolt hole located at 80 mm from the end. In addition, overall trends for the effect of rail-end bolt hole positions are similar in which the stress decreases when the distance from rail end to the rail-end bolt hole increases. Taken together, these findings suggest stress distribution is the basic information that helps understand the failure mechanism.

Keywords: Rail-end bolt hole, Upper fillet, Wheel-load positions, Bolt hole positions, Von-Mises stress distribution

1. Introduction
A rail joint is a system connecting two rails end cross-sections to provide a smooth-running surface of the rail to reduce the risk of derailment. A large number of repetitive operating cycles, on the rail joint region, was found that lead to the railhead end edge damage and bolt hole fracture, in the rail web area, because geometric discontinuities and different mechanical properties were induced by high impact loads [1, 2]. A large and growing body of literature has investigated rail joints, based on different theories and finite element software. Up to now, far too little attention has been paid to the measurements data of stresses and strains of the rail joints. Although some research has been carried out on the replacement of the rail joint gap in continuously welded rails to reduce rail end defects, no studies have been found which the rail joint is now still used in rail transit and curved track system.

Zhu et al. [1] estimated fatigue life of rail-end upper fillet with three crosstie support configurations for the joint sitting under various wheel load factors. Zhu et al. [2] analyzed the stress distributions in rail the end bolt hole and rail-head-to-web fillet from bolted joint bars and considered five crosstie support configurations under static loading by using finite element models: their model considered elastic material by evaluation with severe impact wheel load factors. Two types of rail design (100-8, 115RE) and four types of longer and thicker joint bars were modelled in ABAQUS and simulated under
load applied for two positions [2]. By drawing on the results of this study, Zhu et al. [2] has been able to show that the longer joint bars did not enhance the performance, thicker joint bars noticeably reduced deflection at the rail joint. Zhu et al. [3] investigated the stress distribution in the upper fillet rail end and rail-end bolt hole by using a finite element model and considered the effect of bolt loading and missing-bolt configurations when the load directly applied on the fourth bolt hole. Their study was done with the six bolts rail joint. The maximum von Mises occurred in the contact area between the upper fillet rail end and the joint bar top and the fourth rail end bolt hole, because the load is directly applied on it. The result found that the rail end upper fillet stress is decreased when the bolt loading increased. Ding and Dhanasekar [4] used a 3D finite element model of the bonded bolted butt joints, due to bolt looseness, without considering rail shape details. Under severe loading, the loss of bolt tightness critically influenced the joint performance and life expectancy, due to increased length of the contact surface. Samantaray et al. [5] evaluated the structural integrity and joint bar deflection under static load and investigated the stress distribution in joint bars and bolt shank region under loadings. They simulated the effect of loose nuts and bolts and structure deformation behaviors by using finite element software of ANSYS and ABAQUS, for validation of the analysis results.

To date, several studies have linked the stress analysis in the rail-end bolt hole and upper fillet rail end with the rail designs of 100-8 and 115RE under static loading conditions [2]. However, the influence of the applied load positions on the railhead for UIC60 rail design and analyzed the stress in the rail-end bolt hole and upper fillet has remained unclear [5]. Therefore, this prospective study was designed to investigate the use of UIC60 rail, joint bar, bolt and nut and sleeper in ABAQUS/CAE FE software. The rail joint structure is simulated by variation in the applied load positions and variations in the distance from the rail-end bolt hole center to the rail end (65 mm and 80 mm). Consequently, the simulation results were analyzed for the stress distributed in the rail-end bolt hole and upper fillet for observation of the critical parameters which may lead to the initiation of the crack in the rail joint under loading conditions.

2. Finite element model

To study stress distribution in the rail-end bolt hole and upper fillet rail end, the components of rail joint structure such as rail, bars, bolts and sleepers are modelled in ABAQUS/CAE. Three parts of the bolt, nut and washer combination are simplified, as one component, to reduce computational cost [2]. The profile of the rail design UIC 60, joint bars and bolt were modelled by using the design of Samantaray et al. [5]. The rail joint gap between the two rail ends was 5 mm. Each solid rail element was 2.6 m long, 148 mm wide, 172 mm height and the adjacent sleeper center-to-center is 600 mm [5]. Also, the bolt hole diameter in joint bars and rail was 28 mm. The 65 mm and 80 mm distances from the rail end to the center of the rail-end bolt hole are parametric study, for verification the stress distributed in the rail-end bolt hole and upper fillet. The rail joint is placed between two adjacent sleepers as suspended crosstie support configuration. The assembly of the rail joint structure is shown in Figure 1.
The current study assessed the stress distribution in the rail-end bolt hole and upper fillet because the stress influencing is a critical factor affecting rail web fracture in the rail joint region. The simulation steps are shown in Figure 2. From this data, we can see that the component mechanical properties are based on a linear elastic material model (see Table 1). All components were customized steel except the concrete sleepers. Each mechanical property is applied to the parts of the rail joint structure.

![Figure 2. Steps for finite element simulation.](image)

| Parts                  | Modulus of elasticity-E (GPa) | Yield Strength (MPa) | Poisson’s ratio | Density (kg/m^3) |
|------------------------|-------------------------------|----------------------|-----------------|------------------|
| Parts                  | 210                           | 540                  | 0.3             | 7850             |
| Rail (UIC 60)          | 210                           | 540                  | 0.3             | 7850             |
| Joint bar              | 207                           | 540                  | 0.3             | 7800             |
| Nut and bolt           | 30                            | 46.6                 | 0.18            | 1265             |

In the interaction module, Surface-to-surface contact (Standard) of element type is used in-between Contact Pairs condition for all contact components. Then, the friction coefficient between rails and fishplates (bars), between bars and bolts, between bolts and rails are chosen as 0.3 to ensure tangential behavior in the penalty formulation [6]. Likewise, the normal behavior of component contact surfaces is selected as the default “hard” contact. According to this simulation, tie constraints were used between rail and sleeper and the analysis did not consider the sleeper effects, i.e., the bottom of sleeper surface was rigidly fixed in every direction [7].

Two loading steps are created for the rail joint structure simulation: bolt preloading and applied static load on the railhead from wheel load. In the first step, the bolt is preloaded to reduce the contact surface and length of separation from a loose of bolts tightness under static load condition [4, 5], following the pretension method [3-6, 8]. The preloaded bolt load was

\[ P_b = \frac{T}{K_b D} \]  

where \( P_b \) is the bolt load evaluated from the bolt torque, \( D \) is the bolt diameter and \( K_b \) is the coefficient of the bolt torque moment. The bolt load is used a preload 184 kN and based on an M27 bolt [3-5]. The second step is the vertical wheel load, acting on the railhead surface. As Figure 3 shows, the load is 200 kN, is applied on the rail end and rail-end bolt hole when varying the distances of rail-end bolt hole center to the rail end were 65 mm and 80 mm. The wheel load applied area is considered as the contact area from wheel to rail, following with Zhu et al. [2] model.

The applied-load positions are very important to analyze crack initiation in the rail joint since the load is on the rail end and the stress has reached a maximum in the rail end upper fillet area. Similarly, the load is applied above the rail-end bolt hole when the stress distribution around the bolt hole reaches its maximum [2]. To study the stress distribution in the rail joint, the tested distances from the rail-end bolt hole center to the rail end and the applied load positions was used (see Figure 3).

The mesh size at the contact locations is chosen as the fine mesh, while the other regions are used coarse that is allowed by the software for accuracy. Using a linear hexahedral mesh, the total number of elements and nodes in the rail, bars, bolts and sleepers was 602436 elements and 701956 nodes. The
structure elements are applied by using the ABAQUS `C3D3R’- an eight-node fully integrated tri-linear brick reduction - to ease integration for computational effectiveness and use hourglass control.

After the successful simulation, the results can be visualized for analyzing the stress distribution in the vicinity of the upper fillet and the rail-end bolt hole and for checking the likely service life of the rail joint.

3. Discussion findings of simulation
The current study found that the stress distribution of a rail in a rail joint is evaluated using the finite element method. As can be seen in Figure 3, it showed the stress analysis is performed only on the left rail due to the symmetry of rail joint structure. From the data in Figure 4, we can see that there is a stress distribution in rail when load of 200 kN is applied for each condition. It is apparent that higher stresses are located in the areas of fillets and around the holes. Further analysis showed that there is a tendency of stress values of upper fillet are higher than that of lower fillet under the conditions of load applied on rail end (see Figure 4(a and c)) and load applied on top of rail-end bolt hole (see also Figure 4(b and d)).

From this data, we can see that stress values around rail-end bolt hole (1st hole from the rail end) are larger than that of 2nd hole. The maximum stress measured from upper fillets, lower fillets, rail-end bolt holes and 2nd holes for each condition are summarised in Table 2. Interestingly, this correlation is related to the maximum stresses in upper fillet and rail-end bolt hole that are more critical when compared with the lower fillet and 2nd bolt hole. Therefore, the detail examination on FE analysis was concerned with stress distribution at the upper fillet area and around the rail-end bolt hole of the rail.

Figure 4. Von-Mises stress contour of a left rail in the rail joint for each condition.
Table 2. Maximum of Von-Mises stress (MPa) measured from upper fillets, lower fillets, rail-end bolt holes and 2nd holes for each condition.

| Maximum Stress (MPa) | Load applied at rail end | Load applied on the top of rail-end bolt hole |
|----------------------|--------------------------|---------------------------------------------|
|                      | 65 mm | 80 mm | 65 mm | 80 mm |
| Upper fillet         | 269.2 | 210.2 | 268.9 | 102.3 |
| Lower fillet         | 215.1 | 80.9  | 219.2 | 99.6  |
| Rail-end bolt hole   | 173.1 | 134.3 | 172.2 | 184.4 |
| 2nd bolt hole        | 130.1 | 96.1  | 129.2 | 166.4 |

3.1 Stress in upper fillet region

Figure 5 represents the critical stress in the upper fillet region typically occurs at the rail end. This finding is consistent with those of other studies confirms the upper fillet crack initiates at rail-end of the rail joint leading to head-web separation failure mode [1, 3]. The influence of positions of wheel-loading and a rail-end bolt hole on stress distribution in upper fillet was also investigated. Figure 6 compares the results obtained of a single case of the local stresses along with the upper fillet, and it starts from rail end toward the bolt-hole side. Figure 7 provides the effect of position of the rail-end bolt hole (65 mm or 80 mm) on Von-Mises stress along the upper fillet. The results indicate that the local stress values reduced when the distance from the rail-end to the rail-end bolt hole (1st hole) is longer from 65 mm to 80 mm in both cases of applied loading. In particular, the reduction is higher when a load is applied on the top of the rail-end bolt hole (see also Figure 7(b)).

Figure 5. Von-Mises stress distribution in the upper fillet in each condition.

Figure 6. The local stress along the upper fillet.

The effect of wheel-load positions (applied at rail-end and the top of the rail-end bolt hole) on the upper fillet stress are shown in Figure 8. In case of rail-end bolt hole located at 65 mm from the end (see Figure 8(a)), the local stresses along the upper fillet are identical both when wheel-load is applied at the rail end and above the hole. These results suggest that the distance of 65 mm is too narrow to see the influence of location change. On the other hand, in case of rail-end bolt hole located at 80 mm, the stresses of a load applied on the rail end are higher than those of a load applied above the bolt hole. These results reflect those of Zhu et al. [3] who also found that the upper fillet stress reaches its maximum when the wheel load is at the rail end. In Table 2, there is a clear trend of increasing of 80 mm of the maximum stress of 210.2 MPa when the load applied at the rail end. However, there is a steady trend in case of 65 mm the maximum stress (~269 MPa) when the load applied at the rail end or on the top of the bolt hole.
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Figure 7. Effect of position of rail-end bolt hole on Von-Mises stress along the upper fillet when wheel load applied (a) at the rail end (b) on top of the rail-end bolt hole.

Figure 8. Effect of wheel load position on Von-Mises stress along the upper fillet when rail-end bolt hole located at (a) 65 mm (b) 80 mm from the rail end.

3.2 Stress around the rail-end bolt hole

Figure 9 presents the stress distribution around the rail-end bolt hole for each condition. The maximum Von-Mises stress of the rail-end bolt hole is located at the edge of the hole as set out in the red dot in Figure 9. These results corroborate the ideas of the defect or failure in rail joint in which bolt-hole crack commonly initiates at the very end bolt-hole and at an angle that is approximately 45° to the neutral axis of the rail [9]. The maximum stress of the rail-end bolt hole is probably dependent on the position of wheel load and position of the rail-end bolt hole. The effect of the wheel load applies on the rail-end bolt hole is similar to on the upper fillet in which the change of wheel load does not affect to the stress in rail-end bolt hole with a case of 65 mm; maximum stresses are 173.1 MPa and 172.2 MPa when the load applied at rail end and on top of the bolt hole, respectively. However, at 80 mm distance, there is a difference in stress when the load applied at rail end (134.3 MPa) and when load applied on the top of the bolt hole (184.4 MPa). In other words, the stress around the rail end bolt hole in case of 80 mm distance reaches the maximum when the load is applied on the top of the bolt hole.

Figure 9. Von-Mises stress distribution around the rail-end bolt hole.
4. Conclusion
The purpose of the current study was to determine the performance of the FE method and to investigate the stress distribution of the UIC 60 rail in the bolt-rail joint under static loading of 200 kN with the parametric study of two positions of the applied wheel load (at the rail end and on the top of rail end bolt hole) and two rail-end bolt hole locations (65 mm and 80 mm). The summarize of FE results are shown as follows:

1) The critical locations of the bolt-rail joint are on the upper fillet rail end and the edge of the rail-end bolt where the maximum stresses are generated.

2) The wheel load position is not affected by the stress in upper fillet and rail-end bolt hole with a case of rail-end bolt hole located at 65 mm from the rail-end. However, in case of the distance from the rail end to the bolt hole is 80 mm, it is found that the stress value of upper fillet reaches the maximum when the load applied at the rail end whereas rail-end bolt hole reaches the maximum when the load applied above it.

3) Overall trends for the effect of rail-end bolt hole position are mostly similar in upper fillet and rail-end bolt hole where the Von-Mises stress of distance of 80 mm is lower than that of 65 mm except stress in rail-end bolt hole when the load applied above the hole.

These findings contribute in several ways to our understanding of stress distribution and provide a basis for stress distribution which can lead to a better understanding of structural failure.

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