A rail joint typically is one of the weakest elements of a track superstructure, primarily because of discontinuities in its geometric and mechanical properties and the high-impact loads induced by these discontinuities. The development of continuously welded rail has significantly reduced the number of rail joints, but many bolted joints remain installed in rail transit systems. Because of the unique loading environment of a rail transit system (especially high-frequency, high-repetition loads), defects related to bolted rail joints (e.g., joint bar failures, bolt hole cracks, and cracks in the upper fillet) continue to cause service failures and can pose derailment risks. Recent research in the Rail Transportation and Engineering Center at the University of Illinois at Urbana–Champaign has focused on investigating crack initiation in the bolt hole area around the neutral axis to save material but this modification did not significantly decrease the moment of inertia of the hole (9–11). Carolan et al. (14) found that, other than the number of bolts used in the joints, rail deflection and stress distribution were dependent mostly on the support condition, whereas Zhu et al. (15) concluded that the missing bolts condition affects stress distribution in the rail joint. Even though joint easement reduced contact stress when properly adopted, high contact pressure was still found in the area adjacent to the easement (14). Recent research has focused on studying rail joints with “standard” joint bar configurations; however, the performance of rail joints with nonstandard configurations—longer joint bars, thicker joint bars, and different bolt configurations—has not been studied thoroughly for the current loading environment.

Recent research performed by the Rail Transportation and Engineering Center at the University of Illinois at Urbana–Champaign No. 2607, 2017, pp. 33–42. http://dx.doi.org/10.3141/2607-06.
(UIUC) has focused on investigating the stress distribution around the rail-end bolt hole and upper fillet areas to better understand crack initiation and propagation. Preliminary results are presented in this paper from numerical simulations of bolted joints under a static transit loading condition with four joint bar types.

**OBJECTIVE AND SCOPE**

This study investigated the stress distribution around the rail joint area, specifically at the bolt hole and upper fillet areas of the rail, with the use of finite element (FE) modeling. For both 100-8 and 115RE rail, four types of joint bar (defined in the section on joint bar design) with five crosstie support cases (defined in the section on crosstie support configuration) were simulated in the parametric study under typical transit loading. Findings were interpreted to better understand the effects of joint bar length and thickness as well as the number of bolts and consequently to provide guidelines for alternative joint bar designs.

**NUMERICAL SIMULATION SETUP**

FE analysis is one of the most popular and powerful numerical simulation methods for solving complicated structural and mechanical problems. Commercially available Abaqus/CAE software was selected to perform the simulations. Figure 2 is an example of the numerical models in this parametric study, which consists of four major components: 115RE rail, standard joint bar, simplified bolt, and rail extension. The first three components were modeled as

![Figure 1: Early joint bar designs (2–4).](image)

![Figure 2: FE model of 115RE rail joint: (a) profile and plan views and (b) cross section](image)
three-dimensional (3-D) deformable solids and the rail extension as deformable wire.

More specifically, the 115RE rail component was meshed with 45,965 linear hexahedron elements, the standard joint bar component with 33,239 linear tetrahedron elements, the simplified bolt component with 2,576 linear hexahedron elements, and the rail extension component with 40 cubic beam elements. The rail extension was assigned the section properties of 115RE rail (i.e., rail cross-sectional area, moment of inertia, and location of the neutral axis). The coefficient of friction between all the components was set at 0.4 (16). The number of elements used may vary when simulating the 100-8 rail and other joint bar designs.

**Relevant Simplifications**

Like in a previous study, three simplifications were made to the bolted joint models to reduce computational cost for the parametric study (15). First, each rail modeled with 3-D deformable solid elements was only 36 in. (91.4 cm) long, and the remaining 180 in. (457.2 cm) of each rail was simplified by assigning rail section properties to beam elements. Second, the bolt, nut, and washer combination was simplified to a single component with a bolt preload of 22,000 lb (97.9 kN), and the bolt was assumed to be installed perfectly along the central axis of the rail bolt hole such that initially, no direct contact was captured between bolt shank and rail bolt hole (15). Third, the models were loaded only in the vertical direction so the crossties could be represented by vertical springs. Details of the simplifications are available in an earlier publication (15).

Even though all assumptions and simplifications affect the magnitudes of deflections and stresses calculated with FE modeling, the goal of this study was to compare different configurations. Laboratory experiments are under way, and results will be published in the future.

**Variables for Parametric Study**

Two rail types, four joint bar designs, five crosstie support configurations, and two wheel-loading locations were included in the parametric study. The variables are described in detail in the following subsections.

**Rails**

Two types of rail section are considered in this parametric study: 100-8 and 115RE, which are representative of rail typically used in heavy rail transit systems. The primary differences between standard joint designs for the two rails are illustrated in Figure 3: the contacting

![Figure 3](image-url)
area between the rail-end upper fillet and joint bar top of 100-8 rail is considerably smaller than that of 115RE rail, and the cross-sectional area and moment of inertia of 100-8 rail joint bars are noticeably smaller than those of 115RE rail joint bars (Figure 3, a and b); the locations of the inner four bolt holes also differ (Figure 3, c and d).

Joint Bar Design

Four types of joint bar are simulated for each rail section in the parametric study: standard joint bar [SB; 36 in. (91.4 cm)], longer bar with eight holes [LB-8; 48 in. (121.9 cm)], longer bar with six holes [LB-6; 48 in. (121.9 cm)], and thicker bar [TB; 36 in. (91.4 cm)]. Cross sections of the joint bar designs show that for LB-6, rail-end bolt holes are drilled but hidden behind the 48-in. (121.9-cm) joint bar and the inner two bolt holes of the joint bar are undrilled (Figure 4).

Table 1 shows three of the most critical joint bar design properties: thickness at bolt hole, joint bar cross-sectional area, and moment of inertia. The bolt hole is 135% thicker for the TB than for the SB or the LBs for 100-8 rail [1.469 in. (3.7 cm) versus 0.625 in. (1.6 cm), respectively] and 171% thicker for 115RE rail [1.692 in. (4.3 cm) versus 0.625 in. (1.6 cm), respectively]. For 100-8 rail, the cross-

<table>
<thead>
<tr>
<th>TABLE 1  Critical Properties of Joint Bars for 100-8 and 115RE Rail</th>
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<td>100-8 Rail</td>
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<tr>
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<tr>
<td>Thickness at bolt hole</td>
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<tr>
<td>Two joint bars cross sectional area</td>
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<td>Moment of inertia</td>
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FIGURE 4  Four types of joint bars studied: (a) profile views and (b) cross sections.
sectional area of the two joint bars is 49.4% greater [10.16 in.² (65.5 cm²) versus 6.80 in.² (43.9 cm²), respectively] for the TB than the SB or LBs, and the moment of inertia is 20.4% greater [9.75 in.⁴ (405.8 cm⁴) versus 8.10 in.⁴ (337.1 cm⁴), respectively]. For 115RE rail, the cross-sectional area of the two joint bars is 29.3% greater for the TB than the SB or LBs [13.84 in.² (89.3 cm²) versus 10.70 in.² (43.9 cm²), respectively], and the moment of inertia is 13.7% greater [26.51 in.⁴ (1,103.4 cm⁴) versus 23.30 in.⁴ (969.8 cm⁴), respectively].

Crosstie Support Configuration

Varying the support condition is a key area of study for this research. The five crosstie support configurations used in the parametric study are described here and illustrated in Figure 5:

- Case A. Nominal [rail joint is suspended in the middle of two crossties spaced 18 in. (45.72 cm) apart];
- Case B. Suspended [rail joint is suspended in the middle of two crossties spaced 22.5 in. (57.15 cm) apart];
- Case C. Supported (crosstie) [rail joint is supported by a crosstie immediately under the center of the joint];
- Case D. Supported (plate edge) [rail joint is supported by the edge of a plate, and center of the crosstie is 3.5 in. (8.89 cm) from the center of the joint]; and
- Case E. Broken plate [crosstie underneath the joint is 5 in. (12.70 cm) away from the center, with its plate broken or missing].

These five cases represent typical crosstie support configurations in the field or worst-case scenarios that might aggravate the material fatigue.

Track Stiffness and Wheel Loading

The track stiffness value adopted in this parametric study is 4,000 psi (27.6 MPa), obtained from field measurements collected on New York City Transit Authority (NYCTA) infrastructure during prior efforts. In addition, 4,000 psi (27.6 MPa) is close to the typical track stiffness measured in regular ballasted track [3,000 psi (20.7 MPa)]. The static wheel load of 16,500 lb (73.4 kN) per wheel also was obtained from NYCTA and is heavier than wheel loads for other heavy rail transit systems. However, the heaviest static wheel load among freight systems can be much higher at 32,000 to 39,000 lb (142.3 to 173.5 kN) per wheel.

The wheel load impact factor varies by condition (e.g., train speed, track stiffness at the joint, or irregularity in wheel or rail shape), especially at rail joints. For this paper, the impact factor was set as a constant of 3.0 on the basis of the current value in the Manual for Railway Engineering, which suggests a 200% increase over static vertical loads to estimate the dynamic effect of wheel and rail irregularities (17).

For the simulations conducted and analyzed in this paper, wheel load was applied at two locations: on top of the rail-end bolt hole and on the rail end (Figure 2a). These locations were selected according
configurations. The wheel load was applied on top of the rail end and 115RE rail with four joint bar designs and five crosstie support configurations. Maximum deflections at rail end are presented in Figure 8 for 100-8 vertical deflection at rail end, tensile stress around rail-end bolt hole, and critical outputs of the 100-8 and 115RE rail joint models (vertical deflection at rail end, tensile stress around rail-end bolt hole, and fatigue limit of 61.5 ksi (424.0 MPa)).

Model Optimization

Mesh sensitivity analysis was accomplished by comparing the maximum Von Mises stress values around rail-end bolt hole as the number of nodes around that rail-end bolt hole increased. In this sensitivity analysis, four mesh densities were tested by uniformly spreading 16, 32, 64, and 128 nodes around the rail-end bolt hole (Figure 6). The difference between the 64- and 128-node plots is difficult to distinguish, and the maximum Von Mises stress increases from 25,770 to 26,310 psi (177.7 to 181.4 MPa)—only 2.1%. Therefore, to optimize computational accuracy and expense, a mesh density of 64 nodes was selected for the parametric study.

Wire elements were used to simplify the rail at both sides away from the rail section simulated with 3-D solid elements. To avoid a boundary effect and ensure that simulations were accurate and efficient, optimal lengths of 3-D rail section and wire rail extension were determined via a process of trial and error. For this study, the optimal length was 36 in. (91.4 cm) for 3-D rail sections at each side or 72 in. (182.9 cm) total length for the entire 3-D rail in the model, in agreement with the value in the literature (3, 5).

DISCUSSION OF RESULTS

To compare the performance of the four joint bar designs, the three critical outputs of the 100-8 and 115RE rail joint models (vertical displacement at rail end, tensile stress around rail-end bolt hole, and Von Mises stress at rail-end upper fillet) were calculated and plotted with the five crosstie support configurations (Cases A through E). Figure 7 presents an example setup and results for joints with an SB or D, and those with Case B configuration exhibit greater deflection than those with Case A configuration because of a longer span. The longer bar designs LB-8 and LB-6 (48 in. (1.21 cm) and the standard joint bar SB perform similarly. The LB-6 has more deflection than the SB. However, vertical deflection always is less with the TB than with the SB. In the model with the Case E configuration and the TB, for example, vertical deflection is approximately 12.7% less for 100-8 rail [from 0.43 to 0.37 in. (from 1.09 to 0.95 cm)] and by 6.5% for 115RE rail [from 0.29 to 0.27 in. (from 0.74 to 0.69 cm)].

Vertical Deflection at Rail End

Maximum deflections at rail end are presented in Figure 8 for 100-8 and 115RE rail with four joint bar designs and five crosstie support configurations. The wheel load was applied on top of the rail end with an impact factor of 3.0, which could lead to larger deflections at the rail end (15). Track modulus was set as 4,000 psi (27.6 MPa), corresponding to the use of resilient plate referenced earlier. Sketches of the five crosstie support configurations appear along the x-axis. Trends for the effects of different support configurations differ drastically with a broken plate. The models with a suspended joint configuration (Case E) have the smallest deflections because joint stiffness is higher. The models with a supported joint configuration (Case A or B) have deflections larger than those with Case C or D, and those with Case E configuration exhibit greater deflection than those with Case A configuration because of a longer span.

Tensile Stress Around Rail-End Bolt Hole

Maximum tensile stresses around rail-end bolt hole are presented in Figure 9 for 100-8 and 115RE rail with four joint bar designs and five crosstie support configurations. The wheel load was applied on top of rail-end bolt hole with an impact factor of 3.0, which could lead to larger stresses on the bolt hole (15). The red dashed line shows the material fatigue limit of 61.5 ksi (424.0 MPa), which was estimated as 35% of ultimate tensile strength (18).

The maximum rail-end bolt hole tensile stresses of 115RE rail generally are smaller than those of 100-8 rail, probably because of greater stiffness and smaller deflections at a 115RE rail joint (Figure 9). Results for both 100-8 and 115RE rail are well below the material fatigue limit of 61.5 ksi (424.0 MPa).

Trends for the effects of different support configurations differ for 100-8 rail and 115RE rail. For 100-8 rail, tensile stresses around rail-end bolt hole stress value reaches its maximum when the wheel is directly above it and that the rail-end upper fillet stress reaches its maximum when the wheel is at the rail end (15). Track modulus was set as 4,000 psi (27.6 MPa), corresponding to the use of resilient plate referenced earlier. Sketches of the five crosstie support configurations appear along the x-axis. Trends for the effects of different support configurations differ drastically with a broken plate. The models with a suspended joint configuration (Case E) have the smallest deflections because joint stiffness is higher. The models with a supported joint configuration (Case A or B) have deflections larger than those with Case C or D, and those with Case E configuration exhibit greater deflection than those with Case A configuration because of a longer span. The longer bar designs LB-8 and LB-6 (48 in. (1.21 cm) and the standard joint bar SB perform similarly. The LB-6 has more deflection than the SB. However, vertical deflection always is less with the TB than with the SB. In the model with the Case E configuration and the TB, for example, vertical deflection is approximately 12.7% less for 100-8 rail [from 0.43 to 0.37 in. (from 1.09 to 0.95 cm)] and by 6.5% for 115RE rail [from 0.29 to 0.27 in. (from 0.74 to 0.69 cm)].
FIGURE 7  Examples for SB joints with Case B crosstie support: (a) loading condition and support configuration, (b) 100-8 rail model results, and (c) 115RE rail model results \( U, U_2 \) = vertical deflection; \( S, \text{max. principal (abs)} \) = absolute value of maximum principal stress; deformation scale factor = 50; 1 in. = 2.54 cm; 1 psi = 6.89 kPa).
rail-end bolt hole are similar in models with suspended joint configurations (Cases A and B) and in models with supported joint configurations (Cases C and D). For 115RE rail, models with a Case A or B configuration have larger tensile stresses than models with a Case C or D configuration. For both rail types, tensile stresses always are largest in models with a Case E configuration.

Joint bar designs perform differently for 100-8 and 115RE rails. The tensile stress of the LB-8 generally is similar to that of the SB for 100-8 rail but higher than that of the SB for 115RE rail. The tensile stress of the LB-6 generally was higher than that of the SB for 100-8 rail, except in models with the Case E configuration; however, tensile stress of LB-6 was lower than that of SB for 115RE rail in models with a Case A, B, or E configuration. With all support configurations, tensile stress in the end bolt hole was considerably higher in models with the TB than in models with the SB for 100-8 rail and similar in models with the TB or the SB for 115RE rail.
The maximum Von Mises stresses at the rail-end upper fillet are presented in Figure 10 for 100-8 and 115RE rail with four joint bar designs and five crosstie support configurations. The wheel load was applied on top of the rail end with an impact factor of 3.0, which could lead to larger stresses in the upper fillet. The red dashed line shows the material fatigue limit of 61.5 ksi (424.0 MPa).

Maximum Von Mises stresses in the rail-end upper fillet generally are smaller in 115RE rail than in 100-8 rail, probably because of a greater stiffness and smaller deflections at the 115RE rail joint. More important, the results of both 100-8 and 115RE rail exceed the material fatigue limit of 61.5 ksi (424.0 MPa).

Overall trends for the support configurations are similar for 100-8 and 115RE rail. The models with a suspended joint configuration (Case A or B) have greater Von Mises stresses in the rail-end upper fillet than models with a supported joint configuration (Case C or D). The Von Mises stresses at the rail-end upper fillet always are largest in models with the broken plate configuration (Case E).

In general, Von Mises stresses in the rail-end upper fillet with LB-6 and LB-8 were similar to or higher than those with the SB. However, Von Mises stresses were lower in the rail-end upper fillet with the TB than with the SB. In the model with the broken plate configuration (Case E), for example, adopting the TB can reduce maximum stress in the rail-end upper fillet by approximately 51% for 100-8 rail [from 328.5 to 161.1 ksi (2,265 to 1,111 MPa)] and by 41% for 115RE rail [from 175.3 to 102.9 ksi (1,209 to 710 MPa)].

**CONCLUSIONS**

The results of detailed numerical simulations of the stress distribution around the rail-end bolt hole and rail-end upper fillet areas are presented for 100-8 and 115RE rail. Four joint bar designs were simulated and compared: a standard joint bar, a longer joint bar with eight holes, a longer joint bar with six holes, and a thicker joint bar.

The following conclusions can be drawn from the results of this study:

1. For stress distribution in rail-end bolt hole and upper fillet areas, the LB-6 and LB-8 generally performed the same as the SB in the same rail section. In other words, longer joint bars did not noticeably improve performance.

2. Stress in the rail upper fillet with Case E was up to 51% lower in 100-8 rail and 41% lower in 115RE rail with the TB than with the SB. Thus, the TB may be used to reduce or prevent rail fillet cracks.

3. When evaluating joint bar designs, the rail and joint bar must be considered together, as a system, because the performance of one joint bar design might change with different rail sections. For 100-8 rail, the TB can reduce stress in the rail upper fillet but will increase stress in the rail-end bolt hole; for 115RE rail, the TB can reduce stress in the rail upper fillet without increasing stress in the rail-end bolt hole.

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