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Effect of easement geometry on rail end fillet stress at bolted rail joints for transit track

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Abstract

Continuously welded rail (CWR) has become more popular than bolted joints because of the advantages of continuous geometry and stiffness and the resulting maintenance savings. Due to a variety of reasons, a considerable number of bolted joints are still in service in rail transit systems. With the high frequency of impact loads, rail at bolted joints are vulnerable to defects, such as cracking and head-web separation that could lead to more drastic failures and consequences (i.e. derailments, etc.). To prolong the service life of joint bars and rails, rail-end easements in the center of the bar were proposed and became standard in some freight rail companies. However, the effectiveness of a joint bar easement largely depends on the geometry of the easement. Therefore, the easement designed for freight track may not be effective for rail transit infrastructure. Further, the effect of easement geometry has not been thoroughly investigated and documented. Therefore, this study investigates the stress distribution at the rail end bolt-hole and upper fillet areas for joint bars with different easement geometries through a parametric analysis performed with Finite Element (FE) modeling. The FE model used in this study was developed specifically to study rail joints and was validated through full-scale laboratory testing. Results from this study show that a deeper easement yields lower contact stresses, while a longer easement does not necessarily reduce the contact stresses with the studied combination of rails and bolted joints for transit track. An easement may reduce the service life of the joint if the geometry of the easement is not properly engineered.

Keywords

Rail transit track, bolted rail joints, bolt-hole stress, fillet stress, easement, laboratory testing, finite element analysis

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Introduction

Before the widespread use of continuously welded rail (CWR), rails were connected with rail joints through the use of joint bars. Other than compromise joints, which connect rails with different sizes, most bolted rail joints use joint bars having a uniform geometry throughout the length of the bar. There is a gap between the two connected rails to facilitate thermal expansion or contraction to reduce the temperature-induced stress in the joints. However, the gap introduces discontinuity of geometry and stiffness which causes high impact loads at the top center of the joint bars and rail ends where the majority of joint bar and rail failures occur for jointed rails. As such, rail joints have been a challenge for railroad maintenance for more than a century. Many approaches were introduced in history, attempting to prolong the service life of rail joints, including but not limited to cold expansion,[1] saddled joints,[2] and joint bar easements.[3]

Joint bar easements refer to removing a certain portion of material from the center portion of the joint bar to recess the top-center of the joint bar, thus eliminating the contact between the rail end and joint bar when loaded. Any loads, including impact loads, would be supported by the outer sections of the joint bars that are designed to be in good contact with the rails. Intuitively, a joint bar easement

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would eliminate the high-stress concentration by removing the sharp edge contact between the rail-end and joint bar and also appears to be an economical solution given no extra material or components are required during installation and operation.

Previous research has confirmed the effectiveness of the easement through numerical modeling with the finite element method (FEM).[4] The American Railway Engineering and Maintenance-of-Way Association (AREMA) Manual on Railway Engineering (MRE) of the American Railway Engineering and Maintenance-of-Way Association (AREMA)[3] recommends an easement with a minimum length of 5/4 in. (3.175 cm) and a maximum length of 2 in. (5.08 cm). The AREMA MRE also recommends the minimum recessed depth of 1/32 in. (0.08 cm) for rails smaller than 119 RE rail and 3/64 in. (0.12 cm) for rails larger than 119 RE rail. Unfortunately, these recommended values are based on freight infrastructure and loading conditions and is based on studies conducted as much as seven decades ago. Further, the AREMA recommended easement parameters are still vague and can be interpreted in different ways. Finally, there is limited documentation providing justification for these minimum recommendations, thus creating the need for additional study. One possible reason that AREMA has not paid much attention to joint bar easement design is the increasing popularity of CWR. The remaining rail joints that are proceed for use in freight track are mainly for secondary routes, short lines, or yards. CWR has also become the dominant choice for rail transits recently. However, there are still a large number of rail joints in transit infrastructure, especially in legacy systems, such as New York City Transit Authority (NYCTA), where millions of passengers are relying on the integrity of the track every day.

Due to the small number of rail joints and relatively high research cost, joint bars used for rail transit are adapted from the designs for the freight track. Recently, there have been some high profile derailment that can be traced to joint bar or rail joint failures which cost unaccountable financial loss and negative societal impact, including a Metro-North Railroad passenger train derailed in May 2013,[5] a passenger train derailed and collided with a station platform at Bretigny-sur-Orge, France, on July 2013,[6] and a derailment on NYCTA at 65th street, Queens Line, on May 2nd, 2014.[7] It is necessary to thoroughly examine the joint bars used in the transit track and optimize the joint bar design to improve the track safety and quality of life. Recent research performed by the Rail Transportation and Engineering Center (RailTEC) at the University of Illinois at Urbana-Champaign (UIUC) and the University of South Carolina has been focused on investigating the stress distribution around the rail end bolt-hole and upper fillet areas to better understand crack initiation and propagation and possibly solutions to prolong the service life of rail joints. This paper will present preliminary results from both numerical simulations and laboratory testing of bolted joints under static transit loading conditions with different joint bar easement geometries.

Objective and scope

This paper investigates the stress distribution near the rail joint, specifically at the rail bolt-hole and upper fillet areas, through the use of finite element modeling. Easements having four different lengths of including 0-inch (0-cm), 1-inch (2.54-cm), 2-inch (5.08-cm), and 3-inch (7.62-cm), and four different depths including 0-inch (0-cm), 1/32-inch (0.079-cm), 1/10-inch (0.254-cm), and 3/16-inch (0.476-cm), respectively, were investigated with a typical rail transit track setup. The findings are interpreted to quantify the effects of the joint bar easement for transit infrastructure, and subsequently provide recommendations for alternative joint bar easement designs.

Numerical simulation setup

A commercially available software (Abaqus/CAE) was selected to perform the simulations in this study. A model designed specifically to study rail joints was previously developed by the research team to investigate the joint bar bolt condition, bar length, contact profile, and wheel speed.[8–10] The same model was utilized and tailored to investigate the effect easement profile in this study. 100-8 rail and AREMA standard joint bars (SB)[9] were selected to represent typical jointed track used in rail transit systems in the United States while the prototype joint bars (PB) provided another baseline. Figure 1(a) and (b) highlights both joint bars used in this study. Figure 1(c) provides an overview of the FE model. Details of the prototype joint bar were introduced in an earlier publication.[9] The crosstie spacing was 22.5 in. (57.2 cm), the joint gap was 11.5 in. (29.2 cm) to one crosstie, and 11.0 in. (27.9 cm) to the other. The ends of the rails were set to free as described in detail in earlier publications.[8–10] The total length of each rail was 216 in. (548.6 cm), based on the sensitivity analysis of rail length published in an earlier publication,[8] the length of each rail modeled with 3-D deformable solid elements set to 36 in. (91.4 cm), and the remaining 180 in. (457.2 cm) of each rail was simplified by assigning rail section properties to linear beam elements. Each rail was meshed with 47,916 linear hexahedron elements. Each joint bar was meshed with 105,430 linear elements, mainly with tetrahedron elements. For the areas with complex geometry, such as the easement, hexahedron elements were used. Table 1 summarizes important modeling parameters and

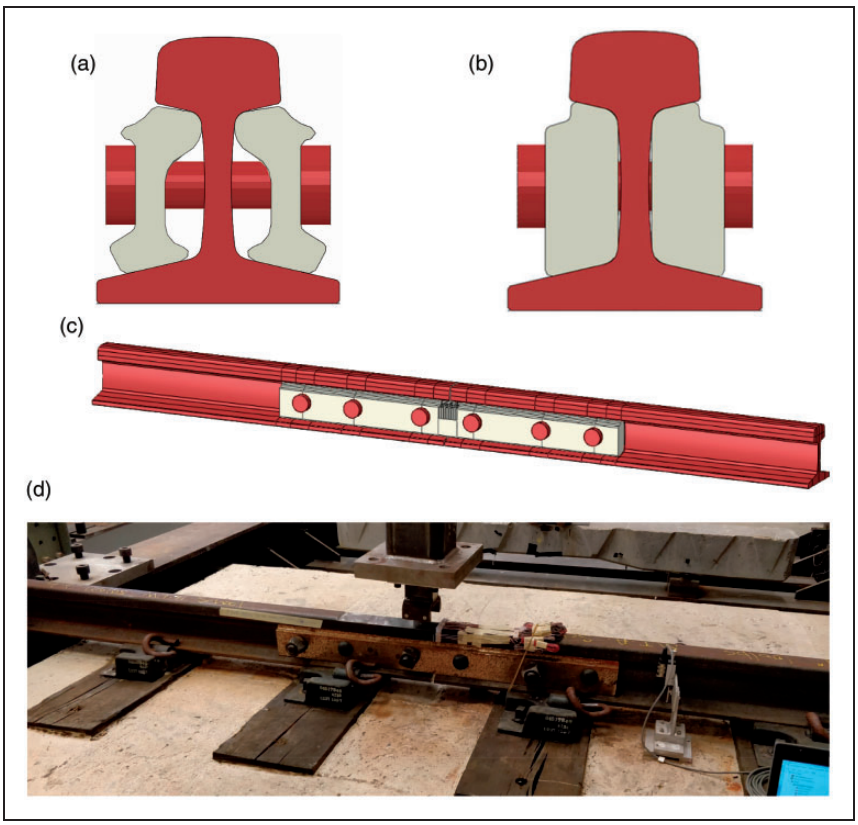

Figure 1. Overview of the numerical model and laboratory setup. (a) Standard joint bar; (b) Prototype joint bar; (c) Overview of part of the FE model; (d) Overview of the test track at LSTF.

Table 1. Constants, variables, and outputs for parametric study.

Constants	
Rail section	100–8
Track foundation	
Track stiffness	4,000 psi (27.6 MPa)
Tie spacing	22.5 in. (57.2 cm)
Equiv. spring stiffness	90,000 lb/in (157.6 kN/cm)
Joint support type	Suspended
Wheel load	
Static wheel load	16,500 lb (73.4 kN)
Testing loads	49.5, 20, 10 kips (220.2, 88.96, 44.48 kN)
Loading position	1.5 inches (3.8 cm) from rail end
Variables	
Easement profile	
Length	0, 1, 2, and 3 in.
Depth	0, 1/32, 1/10, and 3/16 in.
Joint bar	
Standard	
AREMA	
Outputs	
Largest vertical displacement at rail end	
Largest Von Mises stress at rail fillet	

1 in. = 2.54 cm.

other details regarding the FE model, and the material properties can be found elsewhere.[8–10]

Laboratory experiment setup

The laboratory experimentation was performed at the Research and Innovation Laboratory (RAIL) managed by the Rail Transportation and Engineering Center (RailTEC) UIUC. A servo-hydraulic loading system with 55-kip (244.67 kN) actuator capacity was used to apply static or cyclic loading (Figure 1(d)).

The test track used in this study was constructed according to the track design specifications of a heavy rail transit property in the United States. Four standard wood blocks are embedded in a 13.5-in. (34.29 cm) thick concrete bed (Figure 1(d)). The distance from the top of each block to the top of the concrete surface is 0.5 in. (1.27 cm), thus the distance from the top of each block to the bottom of the concrete bed is 14 in. (35.56 cm), which satisfied the requirement that the minimum distance between the bottom of the rail and the bottom of the concrete bed is no less than 14 in. (35.56 cm) in depth per the specifications of the transit agency. The compressive strength of the concrete used to construct the test track exceeds 4,000 psi (27.58 MPa) at 28 days, as

required. Note the test results for four compressive strength test specimens are 6,516 psi (44.93 MPa), 6,496 psi (44.79 MPa), 6,343 psi (43.73 MPa), and 6,482 psi (44.69 MPa), respectively. The four blocks are equally spaced with a distance of 22.5 in. (57.15 cm) from center to center and the joint is 11.5 in. (29.21 cm) away from the center of one block and 11 in. (27.94 cm) away from the center of the other adjacent block, which follows the configuration of the "Suspended Joint" case described in an earlier study.[9] The rails used in this project were 100-8 with a length of 4 ft. and 9 in. (144.78 cm). Rails are fastened into the plates with the e-clips and modified e-clips (The two blocks close to the joint use the modified e-clips to facilitate installation of the joint bars due to limited clearance). Blocks, plates, joint bars, e-clips, modified e-clips, and rails were all supplied by the transit agency. Note that other than the limited length, the laboratory test setup was the same as the numerical model and the field track configurations. Due to the limited space in the laboratory, it is not practical nor necessary to build a laboratory setup the same as the numerical model to every detail. Furthermore, the sensitivity analysis in earlier publication[8–10] showed the results from the setup with four blocks are comparable with the much longer numerical model. The ends of the rails were set to free in the laboratory setup, which were the same as the numerical simulation. No longitudinal loading was applied for both laboratory testing and the numerical simulation.

Strain gauges were used to measure the strains of the rail under loading and calculate the stresses. Because the test material is homogeneous in composition and is isotropic in its mechanical properties (i.e., the properties are the same in every direction), the stress-strain relationship is linear. With stress proportional to strain, the biaxial form of Hooke's law can be used to convert the principal strains into principal stresses at the rail end fillet area. The C2A-06-062WW-120 stacked rosette with matrix length of 0.262 inches (7.16 mm) and matrix width of 0.323 inches (8.20 mm), produced by Micro-Measurements were selected to fit the limited area at the rail end fillet. For each test, four stacked rosettes were placed at the rail end, as shown in Figure 2(a). The location of the maximum rail strain is found near the rail end upper fillet area according to the numerical simulation results from previous studies.[8–10] An example of the calculated stress distribution near the upper fillet from the numerical simulation is shown in Figure 2(b). The instrumented rail end fillet is shown in Figure 2(c), and a side view of the test setup after the instrumentation is provided in Figure 2(d).

Results and discussions

The Von Mises stress at the rail end upper fillet area was calculated and compared to show the performance of joint bars with different easement geometries. Figure 3 presents an example of the results for the joints with the standard joint bar (SB) with an easement and the prototype joint bar (PB) without an easement under various magnitudes of wheel loads applied on top of the rail end. The easement on the standard joint bar had a length of 2 in. (5.08 cm) and a depth of 1/10 in. (0.254 cm). Both numerical simulation results and laboratory test

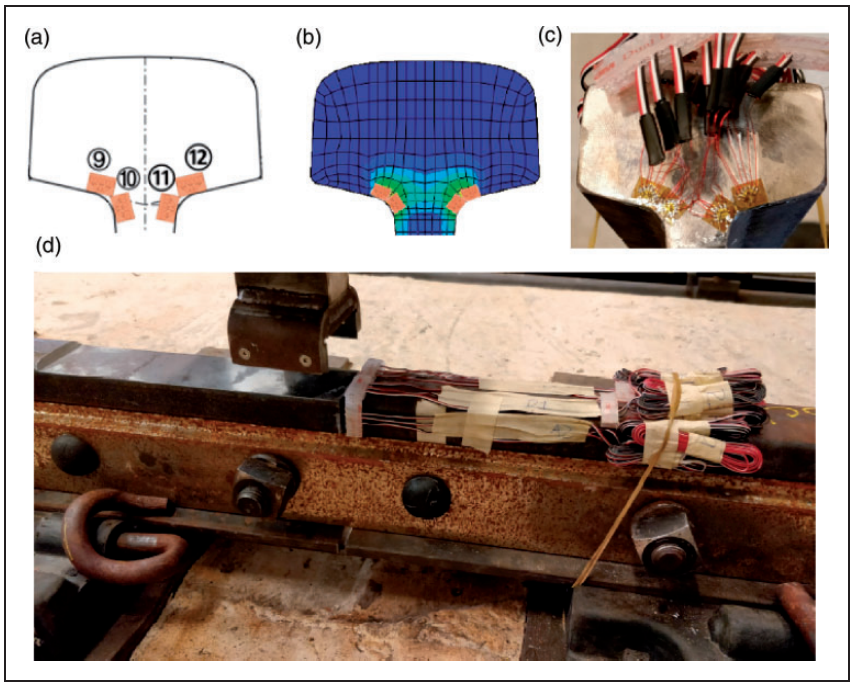

Figure 2. Strain gauge configuration at rail end upper fillet area. (a) Instrumentation Plan; (b) FE Model; (c) Actual Application; (d) Overview of the Instrumentation.

results are shown in Figure 3 to validate the FE model. It can be observed that the stress increased as the loading magnitude increased, and the numerical simulation predictions are close to the laboratory measurements, especially for the case of the PB configuration. When the wheel loading was up to 49.5 kips (220.2 kN), the rail end stress predicted by the FE model for the SB with an easement was 4.4 ksi (30.2 MPa) while the measurement from the laboratory testing was 7.2 ksi (49.9 MPa). For the PB without an easement, the values were 38.4 ksi (264.4 MPa) and 36.1 ksi (248.7 MPa), respectively. All predicted and measured values under different loadings for both SB and PB are summarized in Table 2. In all instances, the PB without the easement predictions were in closer agreement with the laboratory results than the SB. The authors believe that the discrepancy between the predicted and measured SB are minimal in magnitude and can be explained by the fact that the easement on the bar was not centered, thus making it off-set toward one of the rails. Because of this, and since the contact location is so critical, the stress values measured were higher than what was predicted. This was confirmed when looking at contact locations which were documented after the test.

An earlier study mentioned that an easement could be an effective solution to reduce the contact stress between the rail and the joint bars,[4] which is also apparent in the results presented in Figure 3. However, when analyzing the rail stresses on other areas within the joint bar, no significant reduction of the maximum contact stress was observed. Further, it was seen that the location of maximum stress moves from the end of the rail to the inside of the element.

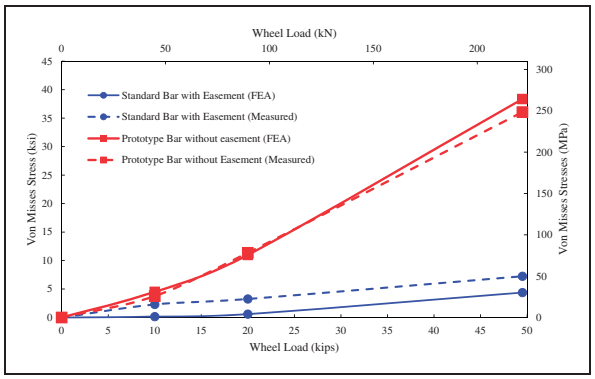

Figure 3. Example of comparison between FE model prediction and lab testing measurement.

The distribution of the contact stress at the rail end fillet area obtained from the FE model for both SB and PB, with and without an easement are presented in Figure 4. The easement does reduce the contact stress at the rail end fillet (compare cross-section A-A and C-C for SB or cross-section D-D and F-F for PB in Figure 4). The maximum stress at the rail end fillet reduced from 172.2 ksi (1,187 MPa) to 6.02 ksi (41.50 MPa) for SB, which is equal to a 96% reduction. For the PB, the maximum stress at the rail end fillet reduced from 184.2 ksi (1,270 MPa) to 3.36 ksi (23.15 MPa) for PB, which is a 98% reduction. Judging by the maximum stress at the rail end, the easement indeed reduced the maximum stress at this location as was concluded earlier.[4]

As stated previously, the stresses at the end of the rail are only part of the problem as the easement does not eliminate the stress concentration but only shifts it inward away from the rail end gap. When comparing the maximum stresses along the rail, it is found that the critical cross-section is located approximately 1.25" (3.18 cm) from the rail end, just at the location that the joint bar makes contact with the rail fillet. This can be observed in cross-section B-B for SB or E-E for PB in Figure 4. As stated before, without an easement, the maximum stress for SB was 172.2 ksi, while in the case of an easement, it was 164.1 ksi, a 4.7% reduction. The maximum stress along the rail for PB without an easement was 184.2 (1270 MPa). When adding the easement, the value reduced to 104.1 ksi (717.8 MPa) which corresponds to a 43.4% reduction. It is also noted that the prototype joint bar has the lower global maximum stresses of all the configurations analyzed, supporting the findings of an earlier study.[9]

While the easement reduces and changes the location of maximum stresses on the rail, the question of how this reduction is affected by the easement geometry remains unclear. The previous observations may be an artifact of the specific easement geometry modeled for both bars, in particular, the easement length and depth. Thus, a parametric analysis to further

Table 2. Summary of maximum stress at the rail end from FE model and laboratory testing.

SB with an easement			PB without an easement		
Load	FE Model	Lab Testing	Load	FE Model	Lab Testing
10 kips (44.98 kN)	0.2 ksi (1.03 MPa)	2.3 ksi (15.8 MPa)	10 kips (44.98 kN)	4.5 ksi (31.0 MPa)	3.8 ksi (25.9 MPa)
20 kips (88.96 kN)	0.6 ksi (4.14 MPa)	3.3 ksi (22.5 MPa)	20 kips (88.96 kN)	11.0 ksi (75.7 MPa)	11.4 ksi (78.3 MPa)
49.5 kips (220.2 kN)	4.4 ksi (30.2 MPa)	7.2 ksi (49.9 MPa)	49.5 kips (220.2 kN)	38.4 ksi (264.4 MPa)	36.1 ksi (248.7 MPa)

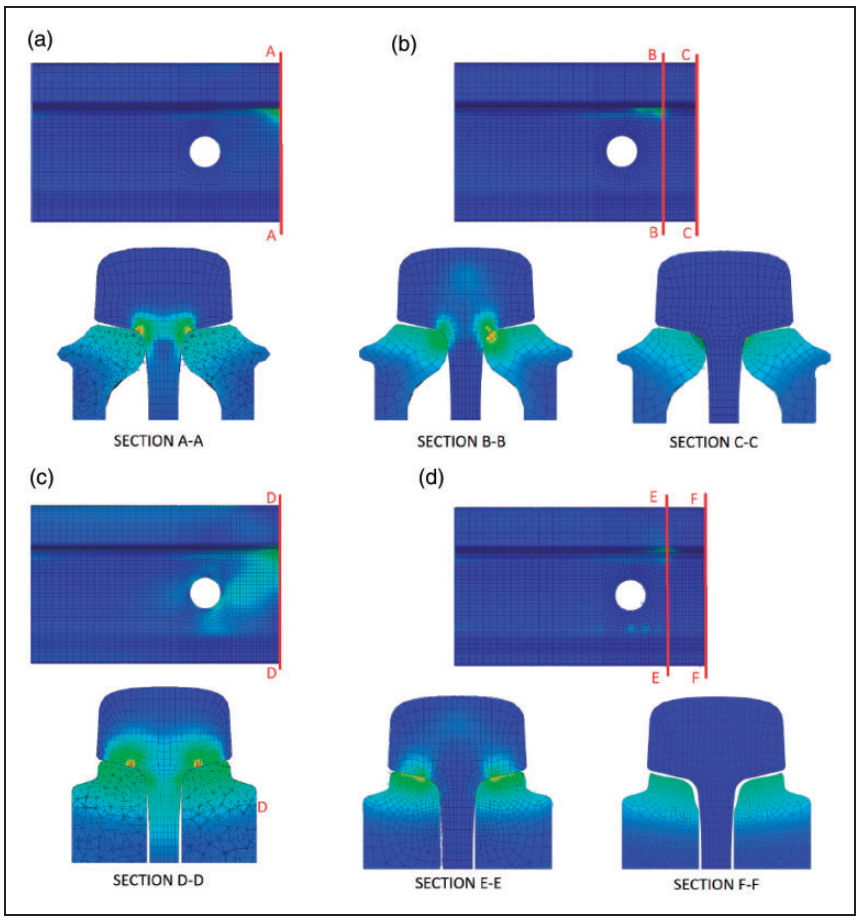

Figure 4. Comparison of stress distribution with and without an easement. (a) Instrumentation Plan; (b) FE Model; (c) Actual Application; (d) Overview of the Instrumentation.

investigate the effect of the easement geometry is necessary. The validated FE model was run with the prototype joint bar having different easement profiles for the parametric analysis. Firstly, the effect of the easement length was investigated. Other than the joint bar without an easement, three easement lengths were simulated, including 1 in. (2.54 cm), 2 in. (5.08 cm), and 3 in. (7.62 cm), respectively, while the easement depth was held constant at 1/10 in. (0.254 cm). Secondly, the effect of the easement depth was investigated. Other than the joint bar without an easement, three easement depths were simulated, including 1/32 in. (0.079 cm), 1/10 in. (0.254 cm), and 3/16 in. (0.476 cm), respectively, while the easement length was held constant at 2 in. (5.08 cm). As mentioned earlier in this paper, the minimum depth of 1/32 in. (0.079 cm) and a maximum length of 2 in. (5.08 cm) are recommended by AREMA[3] for 100-8 rail, and therefore the easement geometries used in this study covered the range recommended by AREMA. Figure 5 provides the joint bar schematics for the profiles used in the parametric analysis.

Other than the easement geometry, all the other parameters were held constant during the parametric analysis and the maximum loading applied to the rail was 49.5 kips (220.2 kN). Figure 6(a) presents the contact stress obtained from joint bars that have the same depth but different length. With loading applied at the rail end, the maximum stresses for easement length of 1 in. (2.54 cm), 2 in. (5.08 cm), and 3 in. (7.62 cm) were 76.5 ksi (527.3 MPa), 81.1 ksi (558.9 MPa), and 97.9 ksi (675.1 MPa), respectively, as shown in Figure 6(a). It is interesting to note that the maximum stress along the rail did not decrease but increase. Compared with the maximum stress in the case without an easement, 189.8 ksi (1308.4 MPa), there were 60%, 57%, and 48%, respectively, increase of the maximum stress due to the introduction of the easement. These results further confirmed the observation from Figure 4 that easement does not guarantee the reduction of the maximum stress along the rail but only help to reduce the maximum stress at the rail end.

Figure 6(a) also indicates the positions where the maximum stresses located for easements with different lengths. For easement lengths of 1 in. (2.54 cm), 2 in. (5.08 cm), and 3 in. (7.62 cm), the position of the maximum stress was 0.4 in. (1.02 cm), 0.7 in. (1.78 cm), and 1.1 in. (2.79 cm) away from the rail end, respectively. Consider the maximum stress located at the rail end, and the positions of the maximum stresses for other cases, a linear correlation can be observed. Figure 6(b) provides a comparison between

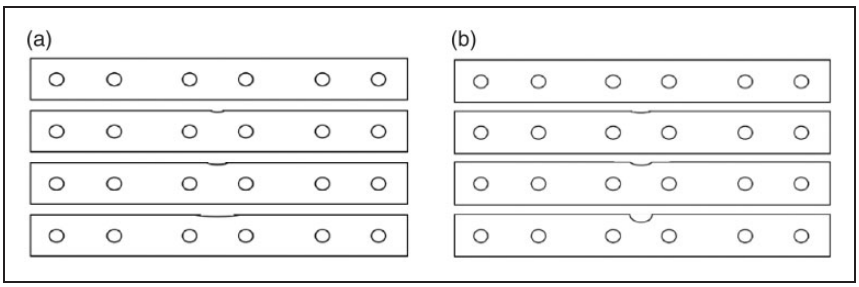

Figure 5. Different joint bar profiles employed in the parametric analysis. (a) Same depth, different lengths; (b) Same length, different depths.

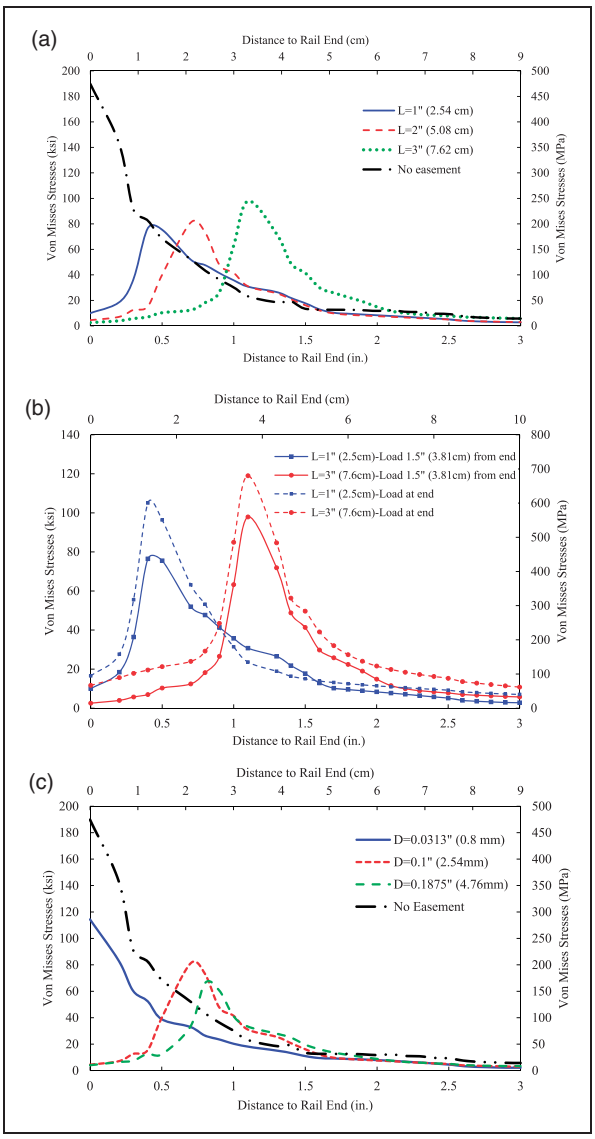

Figure 6. Comparison of (a) easement with the same depth but different length, (b) different load application locations, and (c) easement with the same length but different depth.

loading at the rail end and loading at 1.5 in. (3.81 cm) away from the rail end. The maximum stress positions stayed the same when the loading was shifted away from the rail end, while the maximum stress magnitude increased from 76.5 ksi (527.3 MPa) to 105.1 ksi (724.7 MPa) for the easement with a length of 1 in. (2.54 cm), and from 97.9 ksi (675.1 MPa) to 118.9 ksi (819.8 MPa) for the easement with a length of 3 in. (7.62 cm), respectively.

The reason that the maximum stress positions stayed the same may likely be attributed to the contact profile remaining the same, which is dictated by the geometries of the rail and the joint bar. By changing the loading position only, the joint bars and the rails were the same, so the positions of the maximum stress stayed the same. The reason that the maximum stress magnitude increased can likely be attributed to the loading getting closer to the end of the easement. This observation agrees with a previous publication that reported the maximum stress was at the rail end when the loading was applied at the rail end without easement.[9] For the cases with different easement depths, the loading was applied at the rail end only because the maximum contact stress position would stay the same.

Figure 6(c) gives the contact stress obtained from joint bars that have the same length but different depths. From Figure 6(a) that the maximum stress along the rail followed a linear relationship with the easement length, similarly, results from Figure 6(c) indicate the maximum stress magnitude along the rail was negatively related with the easement depth. With loading applied at the rail end, the maximum stresses for easement depth of 1/32 in. (0.079 cm), 1/10 in. (0.254 cm), and 3/16 in. (0.476 cm) were 114.3 ksi (788.3 MPa), 81.1 ksi (558.9 MPa), and 66.0 ksi (455.2 MPa), respectively. Compare with the value obtained from the case without an easement, 189.8 ksi (1308.4 MPa), a reduction of 40%, 57%, and 65% can be calculated, respectively. For the easement depth of 1/32 in. (0.079 cm) which was recommended by AREMA for rail that was smaller than 119RE rail, the maximum contact stress was still observed at the rail end, which means the easement was still in contact with the rail fillet and suggests the easement depth might not be sufficient. Note the rail used in this study was 100-8 rail, a section that is commonly used by one of the major legacy heavy rail transit operators. This indicates the AREMA recommended values which were based on studies performed decades ago may need to be updated to consider the current track structure and loading environment, at least for transit applications.

Conclusions

This paper presents results from both laboratory testing and numerical simulations of the stress distribution around the rail end with and without easement on the joint bars with loading applied at a single location. The validated FE model was utilized to perform a parametric analysis of the effect of easement geometry on rail stress distribution. Other than no easement case, three different easement lengths, and three easement depths were simulated and compared. The following conclusions can be drawn from the results of this study:

1. Holding rail section constant,
   a. A longer easement did not guarantee a reduction in the maximum stress along the length of the rail.
   b. While a longer easement reduced the maximum stress at the rail end, it shifted the maximum stress away from the rail end with an increase of the magnitude.
   c. A linear correlation was observed between the easement length and the maximum stress along the rail.
2. Holding rail section constant,
   a. An easement with increased depth did reduce the maximum stress along the rail.
   b. A negative linear correlation was observed between the easement depth and the maximum stress along the rail.
   c. However, if the easement depth was below a certain threshold, the easement may not be effective.
3. It is recommended that joint bar easement recommendations in the AREMA MRE be revisited in light of recent findings in this and other reports.

Further studies are needed to investigate the optimal easement design to accommodate the modern track structure and loading environment, especially for rail transit applications.

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Authors' contribution

The authors confirm contribution to the paper as follows: study conception and design: Yu Qian, Marcus Dersch, Ricardo Quiros-Orozco and Riley Edwards; data collection: Yu Qian, Marcus Dersch, Ricardo Quiros-Orozco and Riley Edwards; analysis and interpretation of results: Yu Qian, Marcus Dersch, Ricardo Quiros-Orozco and Riley Edwards; draft manuscript preparation: Yu Qian, Marcus Dersch, Ricardo Quiros-Orozco and Riley Edwards. All authors reviewed the results and approved the final version of the manuscript.

Declaration of Conflicting Interests

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References

1. Duncheva GV and Maximov JT. A new approach to enhancement of fatigue life of rail-end-bolt holes. *Eng Fail Anal* 2013; 29: 167–179.
2. Igwemezie J and Nguyen AT. Anatomy of joint bar failures III. *Railway Track and Structure* 2010; Feburary: 31–36.
3. American Railway Engineering and Maintenance-of-Way Association (AREMA). Rail. In: *Manual for railway engineering*. Lanham, MD: AREMA, 2010.
4. Carolan ME, Jeong DY and Perlman AB. Engineering studies on joint bar integrity, part II: finite element analysis. In: *Proceedings of the 2014 joint rail conference*, Colorado Springs, CO, 2–4 April 2014, JRC 2014-3708.
5. National Transportation Safety Board Railroad Accident Brief 1409: *derailment and subsequent collision of two metro-north passenger trains*.
6. Schlesinger D. 2016. *Sources of transportation accident information*. In: *Proceedings of the 2016 joint rail conference*, Columbia, SC, 12–15 April 2016, JRC 2016-5836.
7. New York City Transit. 2014. Office of system safety derailment report: 65th street, queens line, https://drive.google.com/file/d/0B2Yk9q8Exf2hV2FGcGZhcndaWGU0MS1xSFh3MnhnQlI5Tzg0/view (accessed 15 July 2019).
8. Zhu K, Edwards JR, Qian Y, et al. Finite element analysis of the effects of bolt condition on bolted rail joints stresses. *Transport Res Record* 2016; 2545: 36–45.
9. Zhu K, Qian Y, Edwards JR, et al. Finite element analysis of rail end Bolt-Hole and fillet stress on bolted rail joints. *Transport Res Record* 2017; 2607: 33–42.
10. Yin H, Qian Y, Edwards JR, et al. Investigation of relationship between train speed and bolted rail joint fatigue life using finite element analysis. *Transport Res Record* 2018; 2672: 85–95.