Technical Requirements for Transition Closure Rails on Tangent Track Using Finite Element

Thulani Sitimela[1], Thato Mahlatji[2], Siboniso Vilakazi[3]
Transnet Freight Rail, Johannesburg, South Africa

ABSTRACT: The aim of this paper is to develop a methodology to conduct a case study to determine the root cause of failure on thermite junction welds. Transnet Freight Rail, like other similar rail operators, is characterized by continued efforts to run and operate an efficient and uninterrupted railway service. The high prevalence of internal rail defects on thermite junction welds spells susceptibility to catastrophic failures and derailments. Junction welds are conducted using specially designed moulds when joining two rails of different profiles. The moulds are designed with a groove on the bottom weld collar to reduce stress concentration on the rails due to the height difference between the two rails being joined. The rail stress results are used to determine a design criterion for a prefabricated transition closure rail that will be used to join two rails of different profiles by means of a single forged closure rail. The new design is reviewed by using Finite Element Analysis (FEA) conducted using a non-linear commercial software Marc/Mentat. The results show that the contact stress on the transition rails are less than the yield limit, therefore the plastic deformation stage is not reached. Multi-body dynamic simulations were done to determine the wheel rail interaction points and distortion due to rolling contact. The purpose of this study is to provide a theoretical basis for the rational design of profiles to optimize transition rails.

1 INTRODUCTION

The effective transportation of heavy goods or commodities has been made possible through the railway system. The system consists of the railway infrastructure, in particular the rails to achieve this goal. Freight operators often propose enhanced operations such as increased longer trains, axle loads, and more frequent operations, but these are commonly not understood due to infrastructure limitations. A systemic approach to the design and maintenance of wheel and rail interface can result in the minimization of rail gauge and wheel flange wear, avoidance of detrimental wheel and rail defects, stable vehicle performance, and minimization of noise generation [1].

Modern rail steel members are welded together to form the so called continuously welded rail (CWR) after discontinuation of mechanical joints. CWR is defined as long members of rail joined together with standard rail lengths. There are two common welding processes adopted to develop a CWR track. These are flash butt and aluminothermic welding.

Flash butt is a welding method often done in stationery plants. It utilizes electrical induction as a heating method for rails and hydraulic forging of the heated rails to form a high performance joint. Aluminothermic welding is an on-field welding process used to permanently join two rails using a silica sand mould. The process utilizes the exothermic (Goldshmidt) reaction where active iron oxides are chemically reduced by highly reactive aluminium to produce molten metal. Ultimately, it is a combination of casting and joining. The process is used to join longer rail segments previously welded using the flash butt method to be installed on track.

Both welding processes are used for joining modern rails. However, railway authorities use thermite welding more extensively for rail joining and removal of rail flaws during maintenance. The process is simple, flexible, economic and efficient for both short term and long term maintenance interventions.

Besides its practical benefit, the aluminothermic process is associated with formation of defects and high stress concentration on the so-called thermite junction welds (single rail joint consisting of two different rail profiles). These challenges lead to increased frequency of maintenance, line occupation times and inherently loss of revenue.

The purpose of this paper is to introduce the use of transition closure rail for joining rails of two different profile on tangent track. Additionally, to develop the technical requirements using Finite Element Analysis (FEA), installation requirements and compare the overall cost benefit. This is aimed at reducing the concern on welding related junction rail breaks.

2 CASE STUDY

2.1 *Aluminothermic Welding*

The principle of the thermic reaction is represented by the exothermic reaction:

$$Fe_2O_3 + 2Al \quad 2Al_2O_3 + 2Fe \quad \Delta H=-850kJ, T=2960^{\circ}C$$

The welding process is quick and much easier to execute. The critical steps required in welding:

- Track preparation (loosening of sleeper)
- Alignment and cleaning of joint
- Insertion of mould, shoes and sealant
- Preheating
- Ignition and casting of joint
- Removal of clamps and Shearing
- Grinding
- Quality Control (NDT)

Thermite welds are prone to formation of detrimental defects after solidification. Welding defects on track are detected using non-destructive radiographic examination techniques. The most common defects detected in thermite welds are shrinkage cavities, lack of fusion, inclusions and porosity. Railway companies are plagued by high number of defected welds and also welding related rail breaks. This results in excessive degradation of the track integrity and disruption of train operations whilst doing maintenance.

Literature indicates that the formation of defects in thermite welding is due to the welding parameters (e.g. gap size) and thermal conditions during welding. During welding the so called heat affected zone (HAZ) develops. This is the region in the vicinity of the weld fusion line (on the parent rails) affected by latent heat of welding and has its microstructure properties changed. Aluminothermic welds compared to other track welding processes have longer widths of HAZ because of the high amount of superheat generated by the exothermic process [2]. Figure 1 illustrates the heat affected zone on a thermite weld joint.

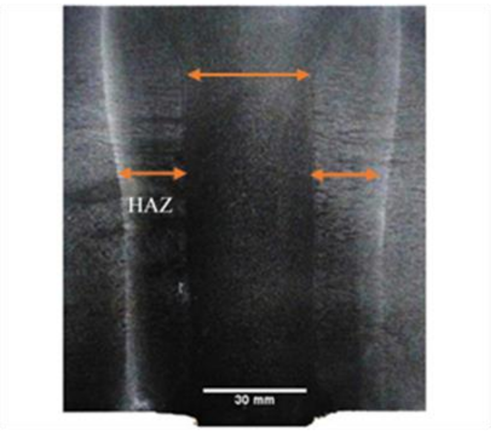

Figure 1: HAZ

A thermite weld is a discontinuity in the rail due to [3]:

- Varying microstructures (weld, HAZ, rail)
- Introduction of residual stresses
- Geometrical shape and dimension difference due to the presence of the weld collar

The thermite welding process of rails introduces residual stresses. Furthermore, these contribute to the total stress levels experienced by the welds. Welding of rails is done at neutral temperature whereby the rail is neither in compression nor tension. During welding, thermal stresses which are higher than the neutral temperature become concentrated on the weld joint. When the ambient temperature is above the neutral temperature, buckling of the rail occurs due to compressive stresses. Temperatures below the neutral temperature are associated with development of tensile thermal stresses which add on to total static load applied on the track by the trains.

Residual stresses are introduced into the rails by welding and heat treatment during the manufacturing process of rail. A study revealed that the middle of the rail foot and the crown have a distribution of high compressive stresses. The remaining counter tensile residual stresses are found in the web of the rail. Figure 2 illustrates the residual stresses in the rail after welding.

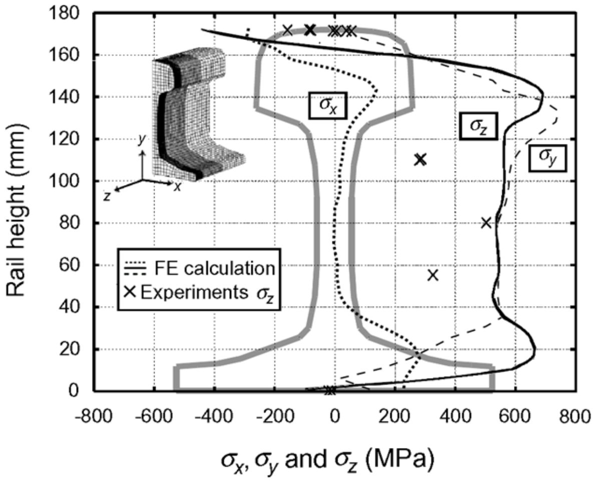

Figure 2: Residual stresses

2.2 *Rail Breaks on Junction Welds*

Welding defects can be reduced by effective improvement of welder skills, equipment used and strict quality control. However, rails breaks are plague experienced by most railway authorities These rail breaks are transverse rail fractures mostly adjacent to the aluminothermic weld. They occur as a result of crack propagation due to high stress concentration exerted by the dynamic load traffic tonnages. Initially, the crack length is subcritical, but with subsequent load cycles, the crack grows to acquire length close to the critical length.

A case study into welding related rail breaks was done in Transnet Freight Rail, South Africa. It was revealed that over 75% of the total recorded rail breaks did not occur due to the presence of defects. Theses rails were recorded to have failed adjacent to the fusion line of the joint or in the HAZ. Over 50 % of the total rail breaks were experienced amongst the so called junction welded joints. A junction welded joint is a welded connection of two rails with dissimilar profiles as shown in figure below. Figure 3 illustrated a junction thermite rail joint.

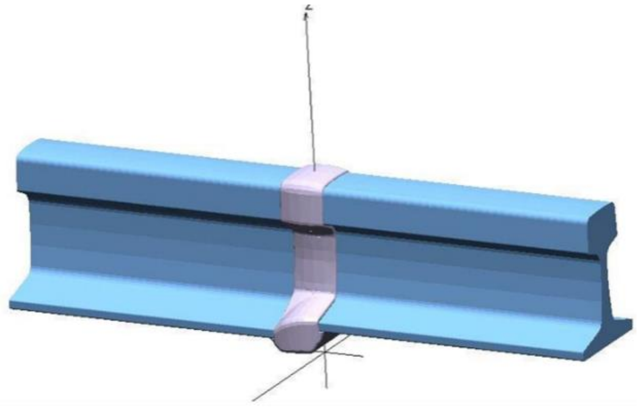

Figure 3: CAD Representation of a thermite weld junction

The MINI-PROF portable instrument was applied at the test sites, as show in Figure 4. This instrument is widely used on track to measure rail profiles. Not only are the recorded rail profiles used to generated the CAD model, they are also used as inputs to the multi-body dynamic simulation.

Figure 4: Thermite junction rail profile measurements

Figure 5 shows the number of recorded rail breaks from year 2013 to 2018 in Transnet Freight Rail. H1 represents rail break on a flash butt weld and H4 through an arc butt weld. H2 and H3 are rail breaks recorded for straight thermite joints transverse and adjacent to the weld respectively. H6 and H7 are rail breaks recorded for junction thermite joints transverse and adjacent to the weld respectively. H5 represents cracks longitudinal to thermite welds.

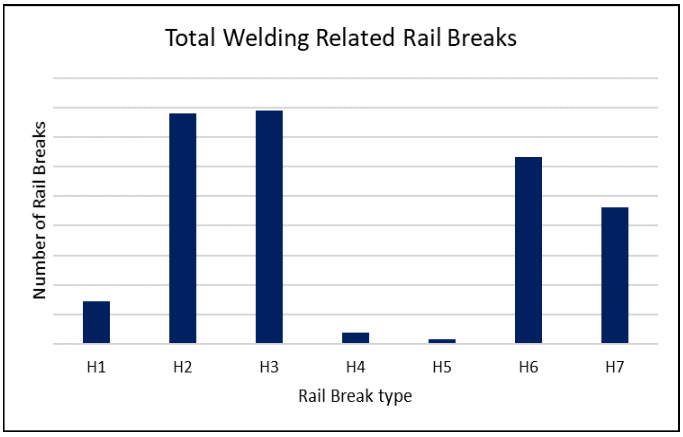

Figure 5: Total welding related rail breaks

The joint is welded using the thermite welding process and a wide range of rail profiles can be joined in this nature. In South Africa, the SAR 48, SAR57 and UIC 60 or 60E1 rail profiles are commonly used. These can be welded interchangeable or joined together (junction welds) when upgrading rails to a newer profile. Junction welds are also applied during installation of turnout crossings with bigger rail profiles than that of the tangent rail.

A root cause investigation into the failure of thermite welded junctions was done internally using macrofractography. Two common failure modes were discovered:

- Fatigue failure due to fatigue cracks on the foot of the rail
- Clean brittle fracture in the HAZ adjacent to the weld

The fatigue crack on the rail foot initiated from the weld collar mainly on the side of the rail with the smallest profile. This side of the rail experiences high stress concentration when the effect of the profile cross sectional area is taken into consideration. This is expected because literature also states that the centre of the rail foot experiences high compressive residual stresses after thermite welding. Figure 6 shows an image of a failed junction

Figure 6:Typical failure on junction weld (picture taken by Lutendo Ndou TFR RTDC)

Furthermore, this issue revealed a welding process problem. The specific stepped type mould designed for this purpose cannot effectively encompass the complex change in height between the two rails. Other factors arise during the installation such as excessive rail wear difference between the already dissimilar rails. This leads to excessive height difference which increases the stress concentration at the joint interface and on the HAZ. Additionally, such joints are required to be supported by the sleeper particularly on the rail with the smallest profile. This is to prevent excessive bending moments experienced in the vicinity of the weld joint which increases stress concentration. The higher the stress concentration the higher the chances of fatigue crack nucleation, growth and failure especially in the weak HAZ.

Fatigue loads are fluctuating loads often causing failure in structural components. Fatigue loads can cause the growth of subcritical cracks to their critical length, followed by the rapid crack growth and eventual failure of the component. During the design phase of a mechanical component, service conditions should be identified and an appropriate analysis carried out to avoid its premature failure.

2.3 *The Track Structure*

The railway infrastructure consists of the track structure which is commonly known as the permanent way. The installed components of the track are the rails, sleepers, fasteners, ballast and formation. These components are sub systems combined to form a complex system that is effective for handling and transportation of high traffic and volumes on the railway line. The complex system is a modelled engineering system that ensures coherency and interlinkage within serving a dynamic purpose continuously as illustrated in Figure 7.

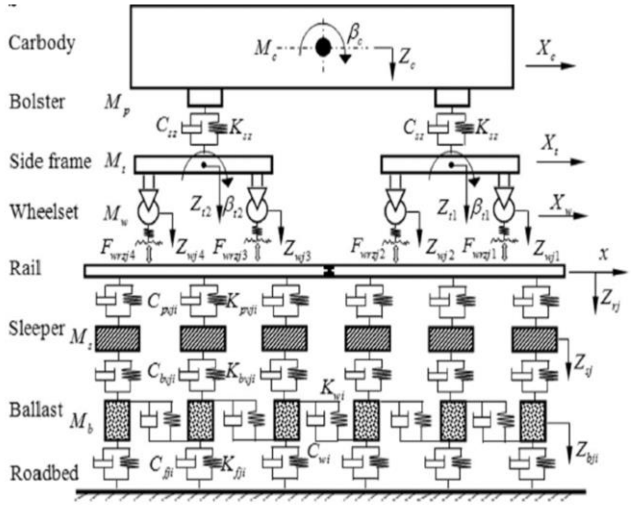

Figure 7: Vehicle/Track coupled model [15]

The primary function of rails is to provide a suitable wheel-rail contact and interaction to guide the rolling stock. Rails transfer the concentrated wheel loads to the sleeper system without excessive deflection. The highest stresses are at the contact point between the wheel and the rail. U. Zerbst et al, 2009, highlighted that these contact stresses can reach up to 1500MPa for axle loading of up to 25 tons per axle. In South Africa, the heavy haul lines are designed to carry significant load of up to 30 tons per axle on the ore line.

2.4 *Transition Rails*

Rail components may require geometrical transitions within the track to accommodate specific requirements. A classic example is amongst turnout crossing components where transitions are required to accommodate complex profile change. The switch blades of turnout crossings are made up of transition rails which are geometrical transition from a bigger tangent rail profile to a complex profile that allows for switching.

Pre-rolled transition rails for joining two rails of different profiles using aluminothermic rails have been in existence. However, the technology has not been extensively utilized practically on tangent track and its long term economic benefit has not been expressed railway asset managers.

3 NUMERICAL MODEL

3.1 *Material Properties and Assumptions*

The material properties to be used for the model are similar to that of the rail as per BS EN 13674 specification. Table 1 illustrates material properties of the rail to be used in the Finite Element Model (FEM).

Table 1: Material properties of the rail

Property	Rail[1]
Young’s Modulus	205e9
Poisson Ratio	0.3
Type or Grade	350LHT
Profile	60E1

A proposed finite element computational methodology was proposed by Liu et al. [4] to calculate the complex 3D stress histories of the wheel/rail contact interaction. It includes both material and geometric non-linearity, i.e. elasto-plastic material behaviour and contact stress analysis. The model represents realistic wheel and rail profiles and gives accurate stress response under rolling contact condition.

---

[1] BS EN 1346 (rail spec)

A vehicle dynamics simulation is used to import contact forces resulting from the multi-body dynamic behaviour at the wheel-rail interface. The multi-body dynamic software package used is Vi-Rail which can accurately portray the dynamic behaviour of the wheel-rail contact. These force are used as inputs to the finite element methods contact and fracture models which offer more reliable estimations of the stress intensity factors [5]. Figure 8 illustrates a graph of vertical force exerted on the rail against the wheel displacement.

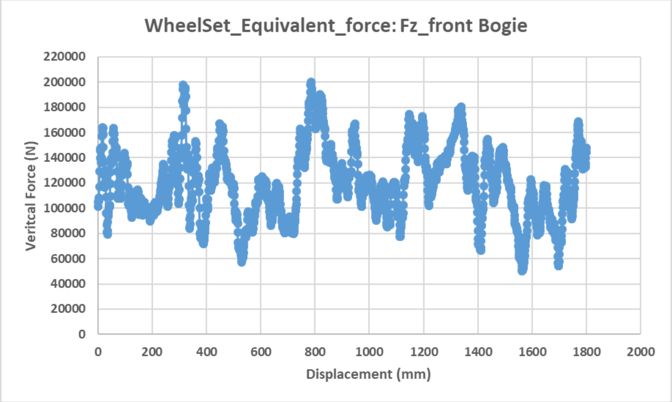

Figure 8: Equivalent vertical forces exerted on the rail

Geometric and material properties for the wheel and the rail were automatically incorporated into a three-dimensional crack growth model. Since the contact between the wheel and rail is highly nonlinear in its nature and the model proposed by Arslan and Kayabasi [6] can be is used to obtain the contact conditions and stresses at the wheel rail interface. The stress values at the wheel rail interface for the investigation were observed as 600 MPa and 696 MPa on the rail and wheel, respectively. The equivalent strain value is maximum over a small region almost the size of a 5cents coin over the contact area due to rolling contact at the wheel rail interface.

3.2 *CAD Generation*

The geometric design of the wheel and rail was developed using Siemens NX (version 11). The track geometry parameters were applied to set up a model for a dynamic load simulation using MSC software Marc/Mentat software. Figure 9 illustrates a three-dimensional CAD model of a transition closure rail.

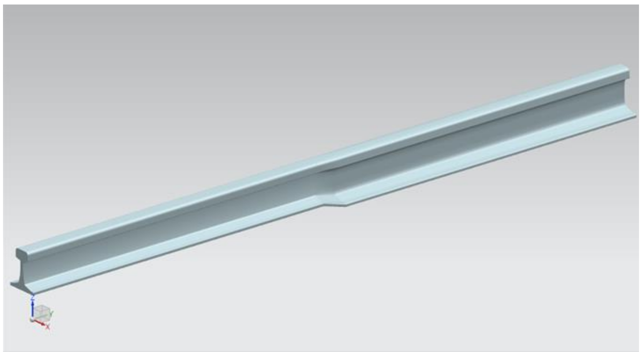

Figure 9: The three dimensional transition closure rail

3.3 *Finite Element Model*

A combination of the variations in the rail profile geometry and the large lateral wheelset displacements lead to multipoint contact conditions and/or flange contact on the outer rail. The semi-Hertzian method can deal with both multipoint contact and non-elliptic contact situations [7]. Figure 10 shows a representation of the semi-Hertzian method that is applied to determine the contact patch shape and the distribution of normal stress.

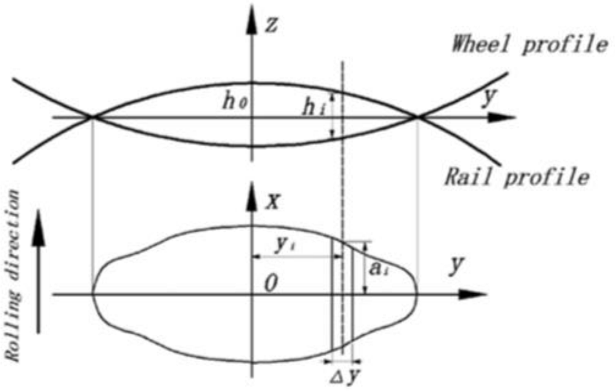

Figure 10: Schematic of the semi-Hertzian method [31]

Due to the non-linearity of this contact analysis, the contact surfaces need a fine mesh averaging an element length of approximately 3 mm for an accurate stress analysis near wheel tread surface and rail head surface [8]. Figure 11 illustrates the track structure modelled in the FEA. The model consists of the sleepers, fastening system, the rail and wheel profile. The rail length equals the length between two sleepers. Fixed boundary conditions are applied to the two ends of the rail.

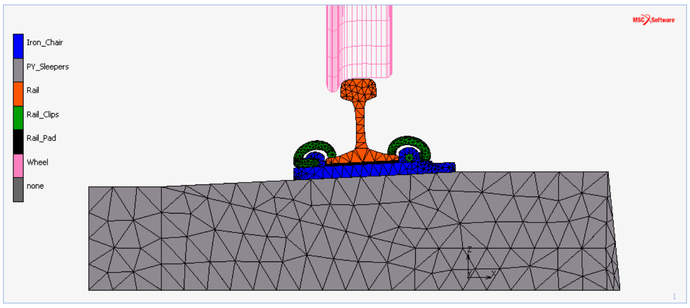

Figure 11: Track Structure

The commercial Finite element software package Marc/Mentat is used to simulate the stress contact patch in the rail under wheel-rail rolling contact [9]. The FE model is only concerned with half of the symmetric tangent track, which significantly reduces the computational cost and hardware requirements. The computational cost imposed by the discrete element method [10] to define the tract substructure (ballast, sub-ballast, and subgrade) is high and the focus of this study is not on the behaviour of the track substructure, therefore it was simplified as a single supporting block.

3.4 *Maintenance Cost Calculator*

Basic life cycle costing will be done to assess the long term economic benefit of using pre-rolled transition closure rails on track. The cost of using a pre-rolled transition rail shall be compared to that of a conventional thermite welded junction. The thermite welded junctions are associated with high maintenance interventions (lead to recurring costs) due to predominant failure.

The life cycle cost (LCC model) equations shall be used with the following parameters considered.

- Service life
- Period of analysis
- Cost variables

Service life includes the life cycle of the rails on track assessed over a 25 to 50-year period. Cost variables such as acquisition costs, maintenance, operational and management costs shall be considered. The current inflation rate, taxes, utility costs, discount rate and residual value of the asset will be used as part of the cost model. Cost of train delays due to maintenance were not considered for this LCC calculation.

3.5 *Installation Requirements*

The transition closure rail is designed such that it does not impact the existing maintenance processes. The rail can be used interchangeable with conventional closure rails used to replace defected aluminothermic welds. The transition closure rail ends will be joined to the track with the thermite welding process (straight joint). The two ends of the track shall be consisting of two different rail profiles. The transition closure rails will be installed as pairs (left hand side and right hand side). The major requirements for installation are:

- Tools (cutting, tamping, welding and grinding)
- Skills (welding team and infrastructure team)

Other factors to consider during installation are adherence to safety, ensure electrical continuity is done for electrified lines and assessment of the stress state of the rail before welding (neutral temperature).

3.6 *Operational Requirements*

Before installation is done, appropriate planning and resource management must be done. The transition closure rail pairs must be available for installation. Excluding preparation of track before welding (taming loosening of sleepers etc.), the insertion of a single transition closure rail takes up to three (3) hours. Execution of two aluminothermic welds can be done in between moving trains or during total line occupation.

4 RESULTS & DISCUSSIONS

4.1 *Life Cycle Cost (LCC) benefit*

The LCC cost was calculated using the present value method. The cost of producing a transition rail is relatively high because of the additional forging required compared to that of a conventional rail. The initial investment cost is higher for transition rails.

The cost of labour and other consumables remain the same as that of installing a thermite welded junctions. Figure 12 illustrates the LCC of thermite vs. pre-rolled junction. It indicates that the using thermite welded junction, assuming that they are permanently installed is more expensive over a long period of time. This is because thermite welded junction have high frequency of failure due to stress concentration. This leads to additional costs of consumables, labour and closure rails incurred over the years.

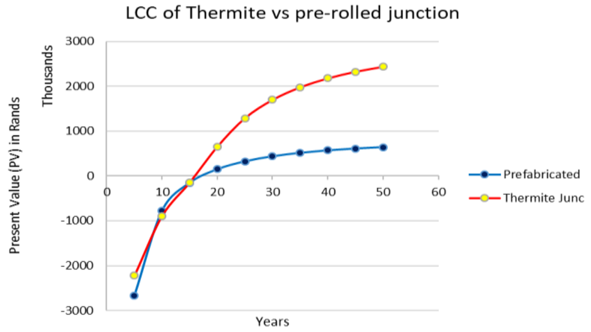

Figure 12: LCC of Thermite vs. Pre-rolled junction

When one of the thermite welds is defective, a straight closure rail can be used to repair the affected section without interfering with the forged area. When upgrading the railway line, the closure rails which are still within the rail wear limits can be used as second hand rails on the track. They can be applied to new areas with junction joints or be used on general freight bulk lines (GFB).

4.2 *Finite Element Analysis*

The maximum value of 447 MPa was recorded on the transition rail, as illustrated in Figure 13. This is less than the yield strength of the rail and no plastic deformation exists. The stresses in other fields are smaller than the stress in the contact area.

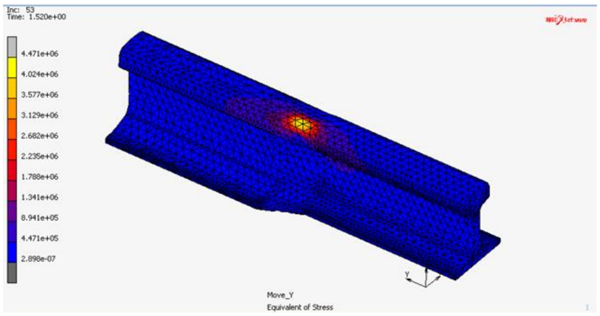

Figure 13: Equivalent stress on the rail

5 CONCLUSIONS

Transition rails consists of a high performance joint compared to that of a thermite welded junction rails. The maximum equivalent stress recorded on the rail in the transition area does not exceed the yield limit, therefore the plastic deformation stage is not reached as the train well passes through the transition. This should significantly reduce the number of rail breaks at welded junctions. The transition closure rail is also designed such that it does not impact the existing maintenance processes, and this is attractive for maintenance.

Future work will be done using strain gauges and linear variable differential transformers (LVDTs) to determine on-site measurements of equivalent stresses and rail deflections on the welds heat affected zone of the junction thermite welds. The measurements will be used to validate FEA simulations to determine the life cycles for a transition rail in comparison with thermite welded junctions.

6 RECOMMENDATIONS

It is recommended that Transnet Freight Rail depots replace thermite junctions after they fail with newly manufactured transitions rails. This will assist in reducing the number of adjacent rail breaks which lead to the closure of lines and train delays.

7 ACKNOWLEDGMENTS

The Authors will like to acknowledge the support of Transnet Freight rail and Rail Network depots.

8 REFERENCES

[1] “"Wheel and Rail interface issues" in Guidelines to best practices for heavy haul operations,” in *International Heavy Haul Association*, Virginia, May 2001.

[2] F. Zhang, “Flash butt welding steel crossing and carbon steel rail,” *Materials Science Engineering A,* Vols. 454-455, pp. 288-292, 2007.

[3] A. K. ,. P. M. Iman Salehi, “Multi-axial fatigue analysis of aluminothermic rail welds under high axle load conditions,” *International Journal of Fatigue,* vol. 33, pp. 1324-1336, 2011.

[4] Y. Lui, B. Stratman and S. Mahandevan, “Fatigue crack initiation life prediction of railroad wheels,” *International Journal for Fatigue,* vol. 28, no. 7, pp. 747 - 756, 2006.

[5] B. Sambo, A. Bevan and C. Pislaru, “A novel application of image processing for the detection of rail surfcace RCF damage and incorporation in a crack growth model,” in *Institude of Railway research*, University of Huddersfield.

[6] M. A. Arslan and O. Kayabasi, “3-D Rail-Wheel contact analysis using FEA,” *Advances in Engineering Software,* vol. 45, pp. 325 - 331, 2012.

[7] P. Wang, J. Xu, K. Xie and R. Chen, “Numerical simulation of rail profiles evolution in the switch pane of a railway turnout,” *Wear,* Vols. 366 - 367, pp. 106 - 115, 2016.

[8] M. Sankaran, L. Liu and Y. Liu, “Analysis of subsurface crack propagation under rolling contact loading in railroad wheels using FEM,” *Engineering Fracture Mechanics,* vol. 74, pp. 2659 - 2674, 2007.

[9] D. Corp, “ABAQUS Analysis User's Manual, Version 6.13,” 2013.

[10] H. Huang and E. Tutumluer, “Discrete Element Modeling for Fouled Railroad Ballast,” *Construction and Building Materials,* pp. 3306 - 3312, 2011.

[11] L.C Schroeder, “Improving the structure and Properties of Thermite weld Metal,” *Material Science and Engineering,* vol. 63, pp. 23-33, 1984.

[12] E. C, Modern Railway track 2nd Edition, Zaltbommel, Netherlands: MTR Productions, 2001.

[13] Naveron Rooskrans & Leonard Msibi, “Determining the stress state of rails after Aluminothermic welding using a thermal-stress analysis.,” in *International Heavy Haul Association*, Cape Town, 2017.

[14] T.M. Sitimela & L.L. Msibi, “Applicability of the Niyama criterion to predict the volume fraction shrinkage porosity in aluminothermic welds,” in *International heavy Haul Conference*, Cape Town, 2017.

[15] L. Xin, V. L. Markine and I. Y. Shevtsov, “Numerical procedure for fatigue life prediction for railway turnout crossing using explicit finite element approach,” *Wear,* no. 366 - 367, pp. 167 - 179, 2016.