STRESS ANALYSIS OF BOLTED RAIL JOINT USING FINITE ELEMENT ANALYSIS

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Abstract

This study mainly focuses on identifying the stresses on the bolted rail joint under maximum vertical loading condition and comparision [1] of the result is done graphically in MATLAB. Analysis is done by equally distributing the total vertical load on each wheel and considering the loading conditions on one wheel. This study covers only the stress and failure caused by the loads. The analysis has been done for three possible locations of the rail joint which are – joint exactly between the two sleepers, joint between the sleepers but nearer to one of them, joint on the sleeper. Von mises stress, Normal stress, Shear stress values have been determined. 3D modelling of the track model and assembly has been done in SOLIDWORKS 2015. Once the assembly was completed then the model was imported to ANSYS^{R16} to analyse the stresses. Tetrahedral mesh was applied to the model with suitable refinement of mesh sizes in required regions. Standard dimensions[2][3][4] of track, wheel, fishplate, sleeper geometry were used.

Keywords: *Bolted Rail Joint, Stress, Sleeper, Von Mises Stress, Mesh, Fishplate*

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1. INTRODUCTION

Rail joint is a critical component of rail infrastructure component of rail infrastructure. Rail joints are widely used in the rail network. It consists of two joint bars. The bolts, nuts and washers are used to tightly fastening the assembly[12] .The increasing rate of travel on railways also applies increasing stresses to the rails and this requires improvement in the strength of the rail joints. The design and mode of attachment of the fish plates are factors of decisive importance as far as the strength of the rail joint is concerned. Attempts have been made to avoid gaps between the butting ends of the rails by Welding the rails either together or to the fish plates, and to enhance the mechanical strength of the weld by reinforcement with the aid of straps welded to the foot and web of the rail. However, the weld seams connecting the straps to the rail tend in their turn to weaken the Joint as a whole, since the rail is damaged along the weld seam producing a weakening of the rail which is similar to that which would result from a grooving of the rail along the line of the weld seam. A primary condition for a good rail joint is that the means of attaching the fishplates shall have the greatest resistance or be subjected to the least specific stress. The attaching of the fish plates by means of rivets would appear to be best suited for the purpose, since rivets fit snugly against the walls of the holes in the parts to be connected together and in consequence are only subjected to shearing stress [10].

2. MODELING

The 3D CAD model was designed in SOLIDWORKS 2015 with all the standard dimensions [2][3][4].

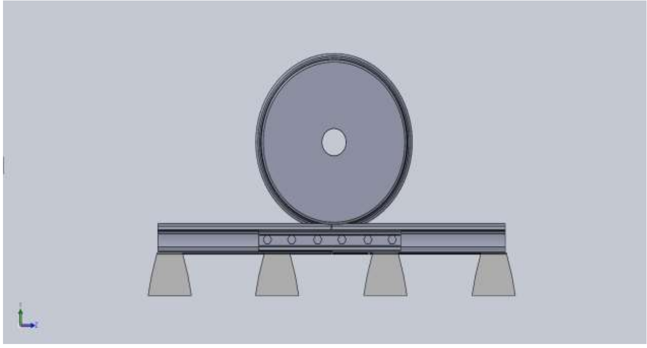


Fig2.1. Assembly of the rail joint model

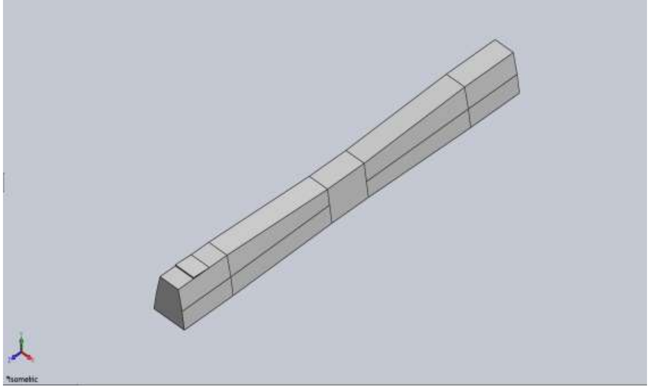


Fig2.2. 3D model of Sleeper

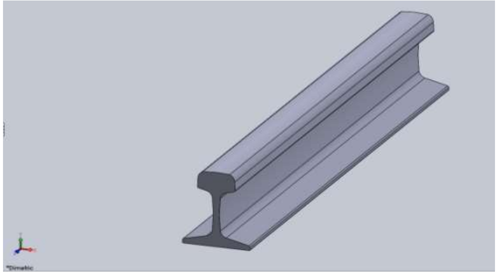


Fig 2.3. Rail Track model

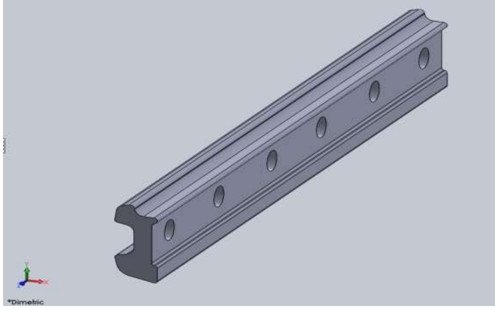


Fig 2.4. Fishplate model

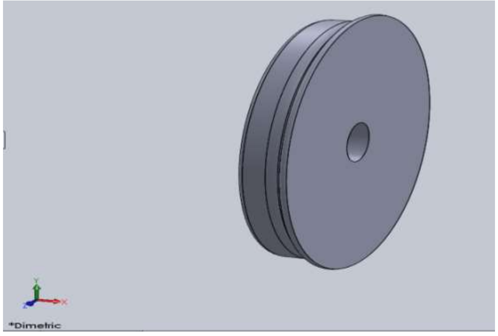


Fig 2.5. Rail wheel model

Meshing

In the figure below, completed meshed model of the rail joint assembly is shown.

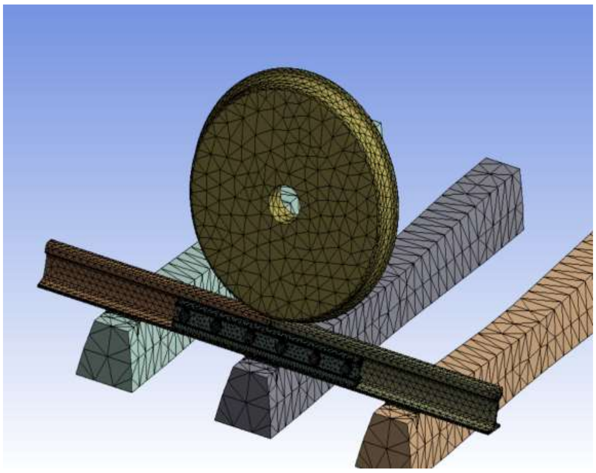
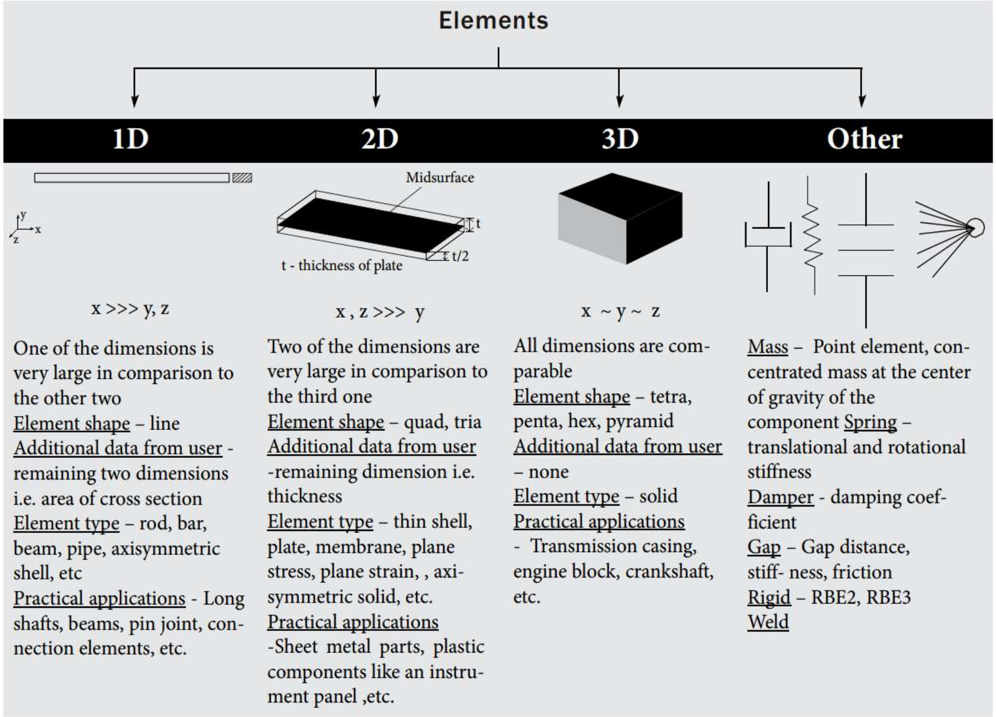


Fig2.6. Meshed model of rail joint assembly

Amongst many available types of elements for meshing, tetrahedral mesh was used because in this study every part model is a 3D model with their lengths in x,y,z axes comparable[9] and in such situations, tetrahedral mesh generates accurate results. For further assurance, relevance was set to 100 (maximum) and proper mesh refinement was done in the regions of importance. Minimum edge length of the tetrahedral mesh was 0.81 mm. Patch conforming option was enabled for smoother size transition. Finally 193494 nodes and 109024 elements were obtained.



1D	2D	3D	Other
x >>> y, z	x , z >>> y	x ~ y ~ z	
One of the dimensions is very large in comparison to the other two Element shape – line Additional data from user - remaining two dimensions i.e. area of cross section Element type – rod, bar, beam, pipe, axisymmetric shell, etc Practical applications - Long shafts, beams, pin joint, connection elements, etc.	Two of the dimensions are very large in comparison to the third one Element shape – quad, tria Additional data from user -remaining dimension i.e. thickness Element type – thin shell, plate, membrane, plane stress, plane strain, , axi-symmetric solid, etc. Practical applications -Sheet metal parts, plastic components like an instrument panel ,etc.	All dimensions are comparable Element shape – tetra, penta, hex, pyramid Additional data from user – none Element type – solid Practical applications - Transmission casing, engine block, crankshaft, etc.	Mass – Point element, concentrated mass at the center of gravity of the component Spring – translational and rotational stiffness Damper - damping coefficient Gap – Gap distance, stiff- ness, friction Rigid – RBE2, RBE3 Weld

Fig2.7. Comparision of various mesh elements[8]

Below is a figure which shows (with the help of legend) the element quality in all the regions of the model. All the important regions (near the joint) were having an element quality greater than or equal to 0.70.

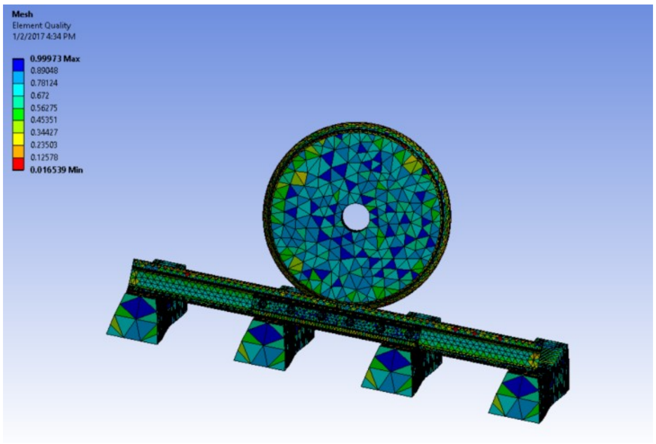


Fig2.8. Element quality of the model

The **Element Quality** option provides a composite quality metric that ranges between 0 and 1. This metric is based on the ratio of the volume to the sum of the square of the edge lengths for 2D quad/tri elements, or the square root of the cube of the sum of the square of the edge lengths for 3D elements. A value of 1 indicates a perfect cube or square while a value of 0 indicates that the element has a zero or negative volume.

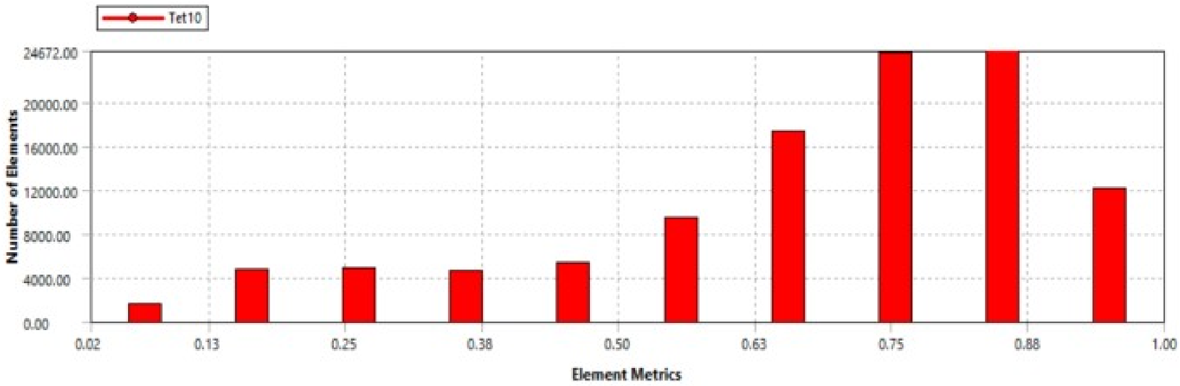


Fig 2.9. Element quality graph

Element quality in the range of 0.15-.20 is said to be acceptable and above 0.20 is considered to be Good element quality[9] and most of the elements lie in the Good quality region.

2.1 Dimensions and Specifications

Item No	Description	Dimension
1	Type of rails for main lines and depot	50 kg/m
2	Track gauge:	1435 mm
3	Wheel diameter (new wheel)	≤660 mm
4	Plate length	820 mm
5	Plate thickness	19 mm
6	Sleeper space	625 mm
7	End gap	5 mm
8	Joint bar bolt and nut	M28(AT109)

2.2. Material Selection

2.2.1 Rail Material Selection

Item No	Mechanical property	value
1	Poison's Ratio	0.3
2	Young's Modulus (GPa)	207 GPa
3	Ultimate tensile strength (MPa)	780 MPa
4	Yield strength	640 MPa
5	Density	7800 kg/m
6	Elongation	12 %

2.2.2 Chemical Composition of Rail

Item No.	1	2	3	4	5	6
Chemical element	C	Mn	Si	S	P	Cr
Composition	0.80	1	0.8	0.05	0.04	----

2.2.3 Material Selection of Joint Plate, Mechanical Property of Joint Washer, Bolt and Nut

Item No	Mechanical property	value
1	Poison'sRatio	0.3
2	Young's Modulus (GPa)	207 GPa
3	Ultimate tensile strength (MPa)	780 MPa
4	Yield strength	640 MPa
5	Density	7800 kg/m
6	Elongation	12 %

3. LOADS AND SUPPORTS

All data of load and supports are based on [1] with necessary changes and improvements in their values.

Seating capacity of vehicle

Item No	Number of passengers (persons)	Seated	Standing	Total
1	Seats (AW1)	65	0	65
2	Seating capacity (AW2) (standing: 6 persons/m2)	65	189	254
3	Overload capacity (AW3)(standing: 8 persons/m2)	65	252	317

Vehicle weight

Item No	Loads	Carbody weight	Passenger weight	Total weight
1	Empty vehicle (t)	44	0	44
2	Seating capacity (t)	44	15.24	59.24
3	Overload capacity (t)	44	19.02	63.02
4	Axle load	≤11（1+3%） t		
5	Axles	6		

Note: Take 60kg as average weight of each passenger.

Operating speed of tram

Item No	Parameter	Speed
1	Maximum operation speed	70 km/h
2	Average travelling speed	≥20km/h

The total vertical load is calculated as follows:
a. Tram car weight = 44 ton

- The load apply on each axle = 7.334 ton =7334Kg
- The load apply on each wheel = 3.667 ton = **3667Kg**

b. Carrying Capacity = 60kg/person *317 person = 19020Kg
Therefore load on each wheel = 19020/12 = **1585 Kg**
c. Maximum Axle load = 11,000 kg

The total vertical load = maximum Axle load+3% maximum Axle load = 11,000+330 = 11,330 Kg
Therefore load on each wheel = 11,330/2 = **5665Kg**
Thus, total weight on each wheel = 5665 * 9.81 = **55573.65 N**
d. Maximum operating speed = 70 Kmph or 19.445m/s
Therefore rotational velocity, ω = v/r = 19.445/0.33 = **58.92 rad/s**

The values of loads obtained from above calculations were then used to solve the rail joint problem in ANSYS. The loading conditions were setup and applied to the rail joint model and following results were obtained.

4. STATIC ANALYSIS

The analysis is performed by using finite element method with tetrahedral mesh element and relevance set to 100. Proper mesh refinement was done wherever needed and impact of wheel load on rail joint was studied. Different support locations were used to perform finite element analyses, although the geometry and load application are the same for all support locations.

A static structural analysis is setup to determine the stresses caused by loads that do not induces significant inertia and damping effects. The load and the structure responses are assumed to vary slowly with respect to time that means steady loading and response condition are assumed. The types of loading that were applied in static analysis included:

- Vertical wheel load (force)
- Rotational velocity
- Displacement

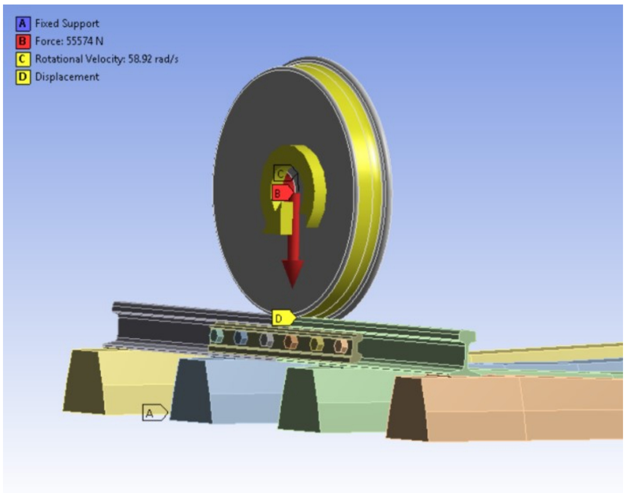


Fig 4.1. Loading and boundary conditions

First of all let's solve this given problem by assuming a hypothetical case where there is no joint between the tracks but the fishplates are attached to the sides (as shown in figure below), so that we can solve the problem by Strength of Material's approach [11] and check our results which we got from ANSYS, which will help us to verify all our boundary conditions, applied loads and geometry.

We would first solve this hypothetical case numerically and then match our results with the software's results.

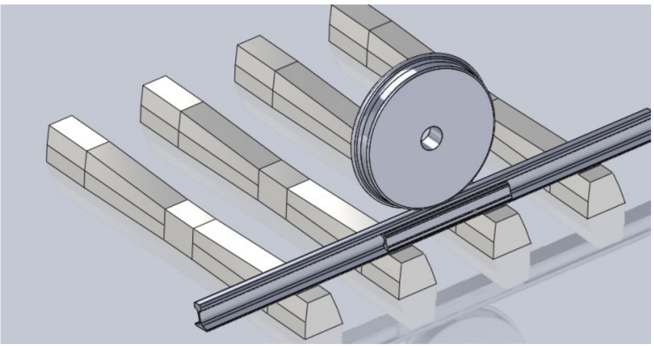
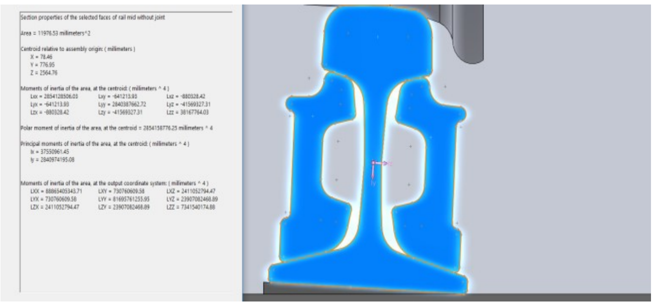


Fig 4.2. Hypothetical case with no joint gap



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Section properties of the selected faces of rail mid without joint

Area = 11976.53 millimeters^2

Centroid relative to assembly origin: ( millimeters )
    X = 78.46
    Y = 776.95
    Z = 2564.76

Moments of inertia of the area, at the centroid: ( millimeters ^ 4 )
    Lxx = 2854128506.03       Lxy = -641213.93          Lxz = -880328.42
    Lyx = -641213.93          Lyy = 2840387662.72       Lyz = -41569327.31
    Lzx = -880328.42          Lzy = -41569327.31        Lzz = 38167764.03

Polar moment of inertia of the area, at the centroid = 2854158776.25 millimeters ^ 4

Principal moments of inertia of the area, at the centroid: ( millimeters ^ 4 )
    Ix = 37550961.45
    Iy = 2840974195.08


Moments of inertia of the area, at the output coordinate system: ( millimeters ^ 4 )
    LXX = 88865405343.71      LXY = 730760609.58        LXZ = 2411052794.47
    LYX = 730760609.58        LYY = 81695761255.95      LYZ = 23907082468.89
    LZX = 2411052794.47       LZY = 23907082468.89      LZZ = 7341540174.88
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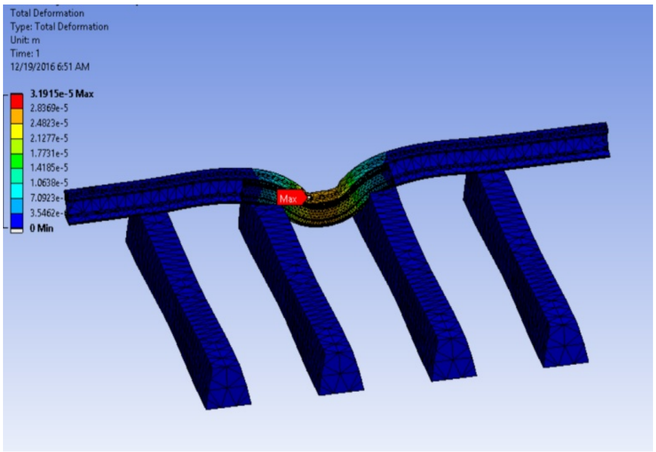
Fig 4.3. Moment of inertia about the Neutral axis

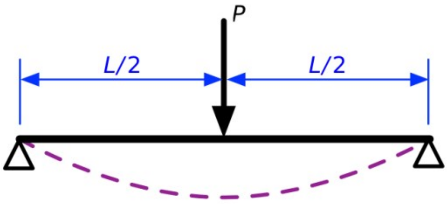
4.1 Case-A : Wheel Load Acts between Two Sleepers



Total Deformation
Type: Total Deformation
Unit: m
Time: 1
12/19/2016 6:51 AM

From the software we get the maximum deflection $=3.1915*10^{-5}$m.

Now, solving the problem as depicted by the case-



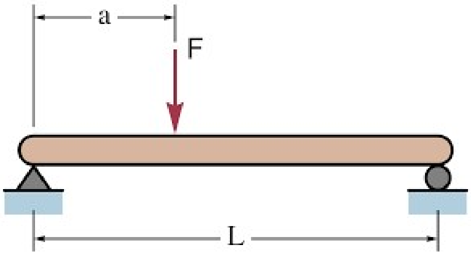
Where, P = 55573.65 N
L = 0.625 m

Now, equation for maximum deflection = $Y_{max} = PL^3/48EI = 55573.65*(0.625)^3/48\ EI = 3.7*10^{-5}$ m

Where, E = Young's Modulus = $2*10^{11}$ Pa
I = Area moment of inertia = $3816.776*10^{-8}$ m^4

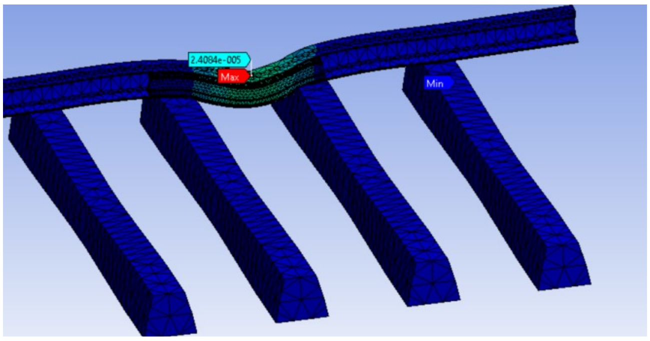
Therefore, Percentage error = |experimental value – theoretical value|/theoretical value *100
= |3.2 – 3.7|/3.7*100
= 13.5 %

4.2 Case-B : When Load Acts Near to One Sleeper



Where, P = 72446.85 N
L = 0.625 m, a =0.150 m

Now, equation for maximum deflection = $Y_{max} = Pa(L^2-a^2)^{3/2}/9\sqrt{3}EIL = 55573.65*0.15((0.625)^2-(0.15)^2)^{3/2}/9\sqrt{3}EIL = 2.5*10^{-5}$m
Where, E = Young's Modulus = $2*10^{11}$ Pa
I = Area moment of inertia =$3816.776*10^{-8}$ m^4



From the software we get the maximum deflection $=2.408*10^{-5}$m.

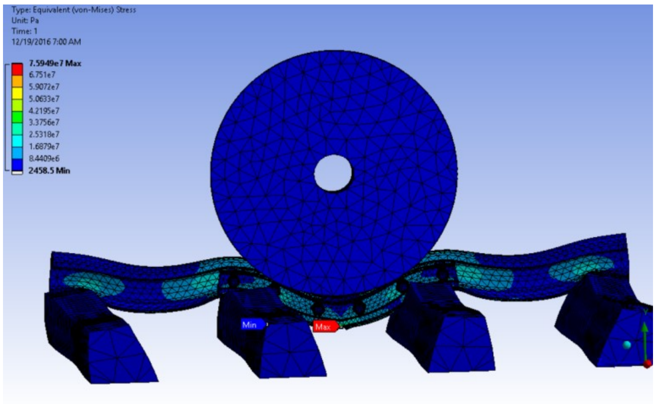
Therefore, Percentage error = |experimental value – theoretical value|/theoretical value *100
= |2.408 – 2.5|/2.5*100
= 3.6 %

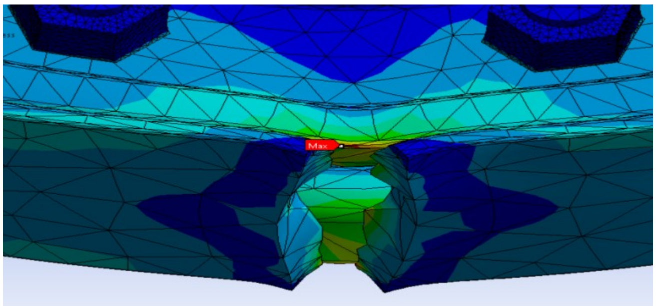
Now, since the results we get from ANSYS and numerical calculations are conforming to each other, within permissible error, we can conclude that all the loading conditions and geometry used for analysis are correct. Hence we can now extend our analysis to the real problem of Rail joints.

4.2.1 Case-1 : Joint Between Two Sleepers

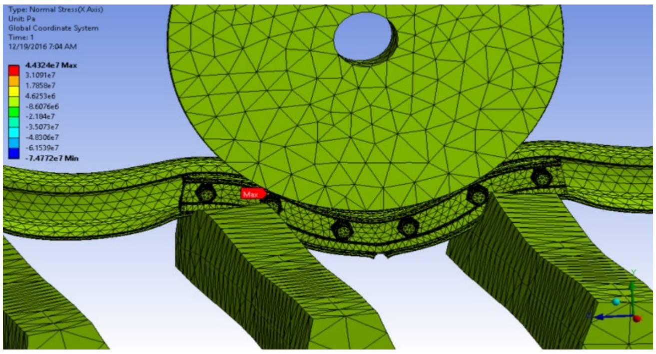
- **VON MISES STRESS (Pa)**
  As shown in the figure below, the maximum von-Mises stress is 75.94 MPa and the minimum von –mises stress is 2458.5 Pa.

  Factor of Safety (FOS) = yield stress/actual stress = 640/75.94= **8.42**

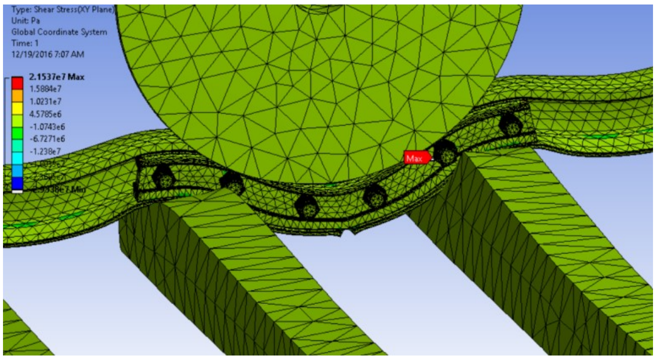




- **NORMAL STRESS (Pa)**
  As shown in the figure below, the maximum normal stress is 44.32 MPa and the minimum normal stress is -74.77 MPa

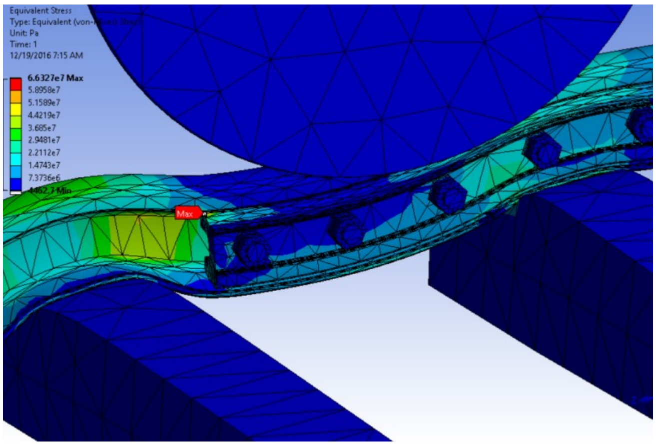


- **SHEAR STRESS (Pa)**
  As shown in the figure below, the maximum shear stress is 21.53 MPa and the minimum shear stress is -29.33 MPa.

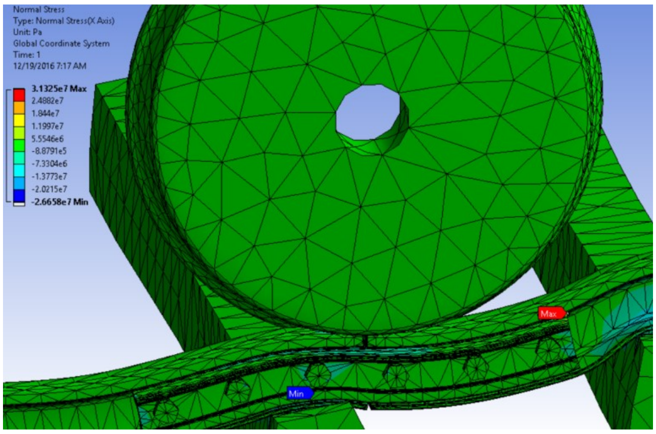


4.2.2 Case-2 : Joint Near One Sleeper

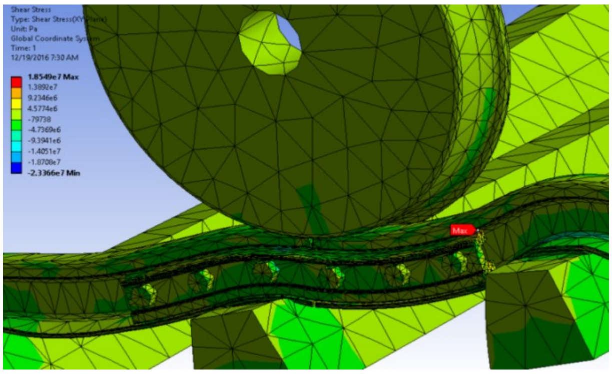
- **VON MISES STRESS (Pa)**
  As shown in the figure below, the maximum von-Mises stress is 66.32 MPa and the minimum von –mises stress is 4462.7 Pa.
  Factor of Safety (FOS) = yield stress/actual stress =640/66.32 = **9.65**



- **NORMAL STRESS (Pa)**
  As shown in the figure below, the maximum normal stress is 31.32 MPa and the minimum normal stress is -26.65 MPa.



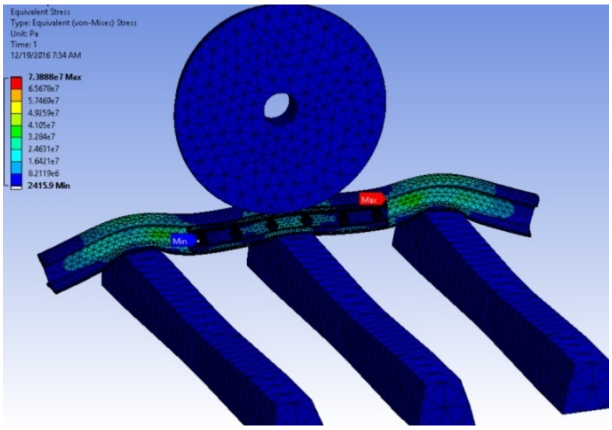
- **SHEAR STRESS (Pa)**
  As shown in the figure below, the maximum shear stress is 18.54 MPa and the minimum shear stress is -23.366 MPa.



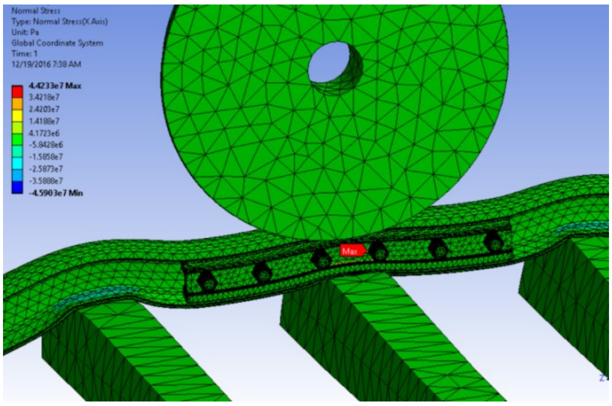
4.2.3 Case-3 : Joint on the Sleeper

- **VON MISES STRESS (Pa)**
  As shown in the figure below, the maximum von-Mises stress is 73.88 MPa and the minimum von –mises stress is 2415.9 Pa.

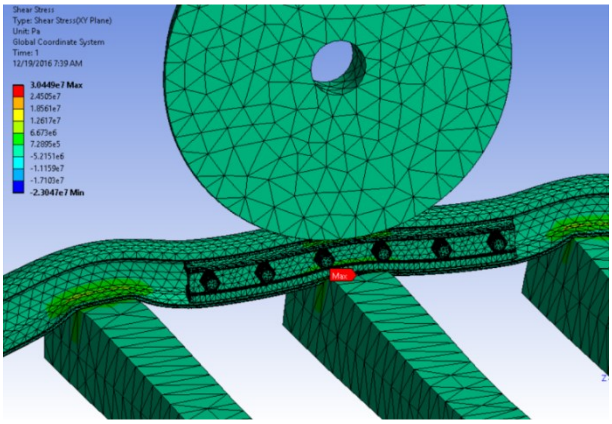
  Factor of Safety (FOS) = yield stress/actual stress = 640/73.88 =**8.662**

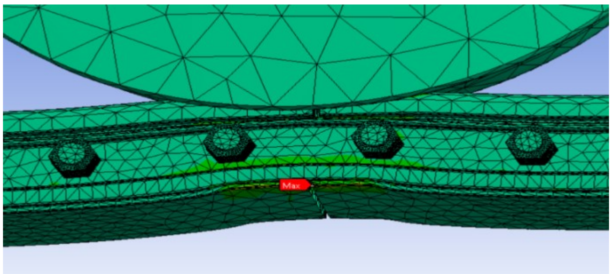


- **NORMAL STRESS (Pa)**
  As shown in the figure below, the maximum normal stress is 44.233 MPa and the minimum normal stress is -45.9 MPa.



- **SHEAR STRESS (Pa)**
  As shown in the figure below, the maximum shear stress is 30.44 MPa and the minimum shear stress is -23.04 MPa.





5. DISCUSSION

Graphs between the results obtained from the current loading conditions and previous loading conditions are plotted.
Case1- When rail joint is between the sleepers.
Case2- When rail joint is nearer to one sleeper as compared to the other sleeper.
Case3- When rail joint is on the sleeper.

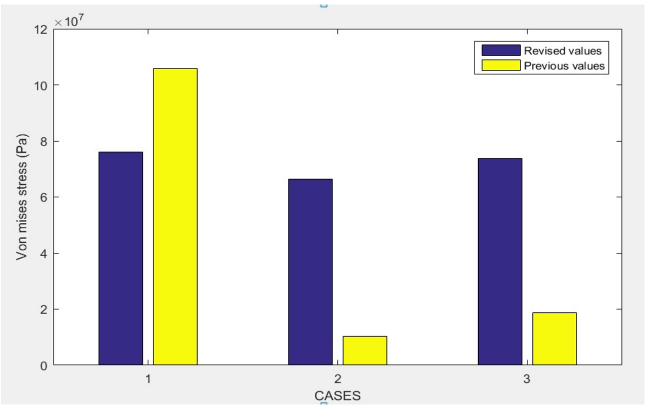


Fig5.1- Variation of Von mises stress for different positions of rail joint

The value of Von mises stress is observed to be maximum for CASE-I and minimum for CASE-II. The region of maximum stress in CASE-I is found to be on the lower part of the joint, however in CASE-II & III the region of maximum stress is not near the joint but on the edges of fishplates.

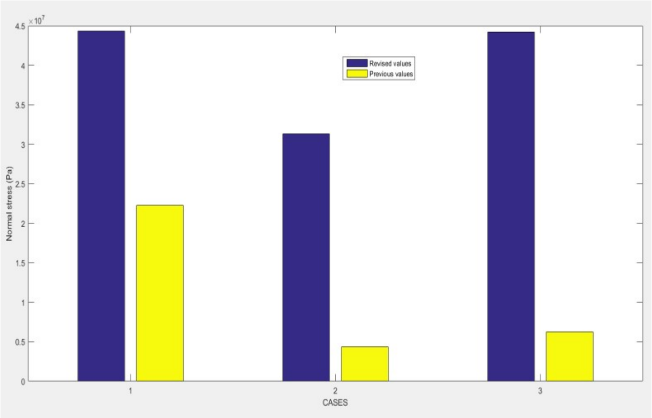


Fig5.2- Variation of Normal stress for different positions of rail joint

The value of Normal stress is observed to be maximum for CASE-I and minimum for CASE-II. The region of maximum stress in CASE-I is found to be near the bolts of the bolted joint, however in CASE-II & III the region of maximum stress is on the edges of fishplates.

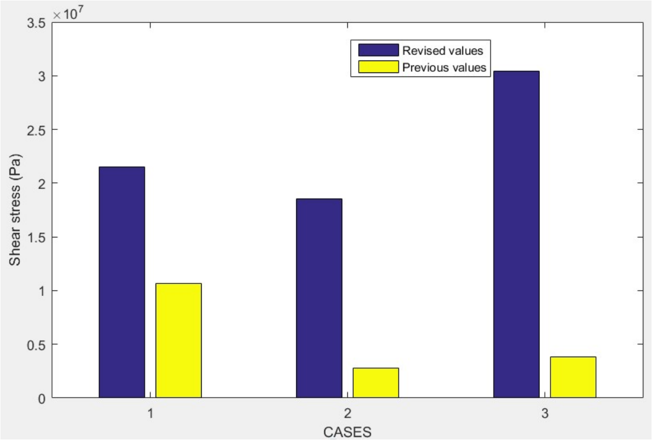


Fig 5.3- Variation of Shear stress for different positions of rail joint

The value of Shear stress is observed to be maximum for CASE-III and minimum for CASE-II. The region of maximum stress in CASE-III is found to be on the lower part of the joint which is sandwiched between the wheel and the sleeper. In CASE-I the region of maximum stress is found to be the area near the bolt and in CASE-II its is the edge of the fishplates where maximum stress occurs.

Therefore, **joint between the sleepers but nearer to one of them**, proves to be the best way of placing the joint. In all other cases the stress value is high either around the joint bottom or near the fishplate edges.

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APPENDIX

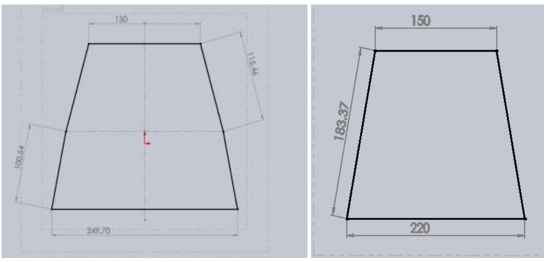

Fig1. Cross sectional view of Sleeper (with dimensions)

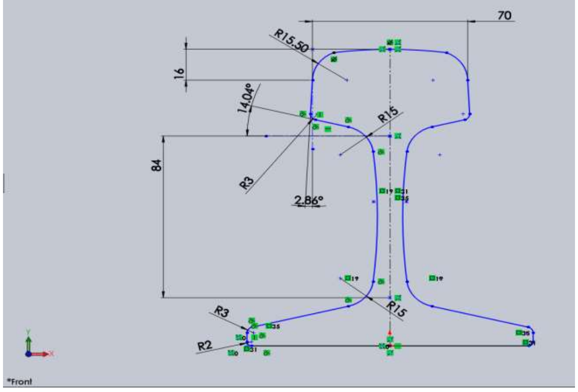

Fig2. Rail Track cross section

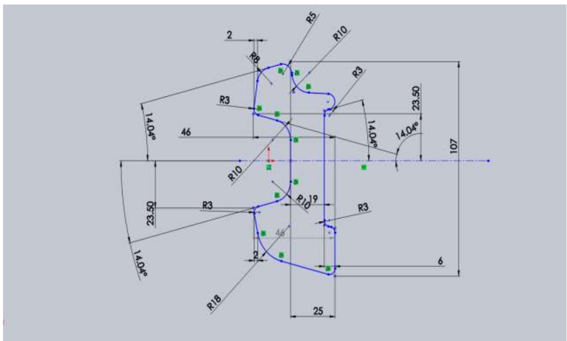

Fig3. Fishplate cross section

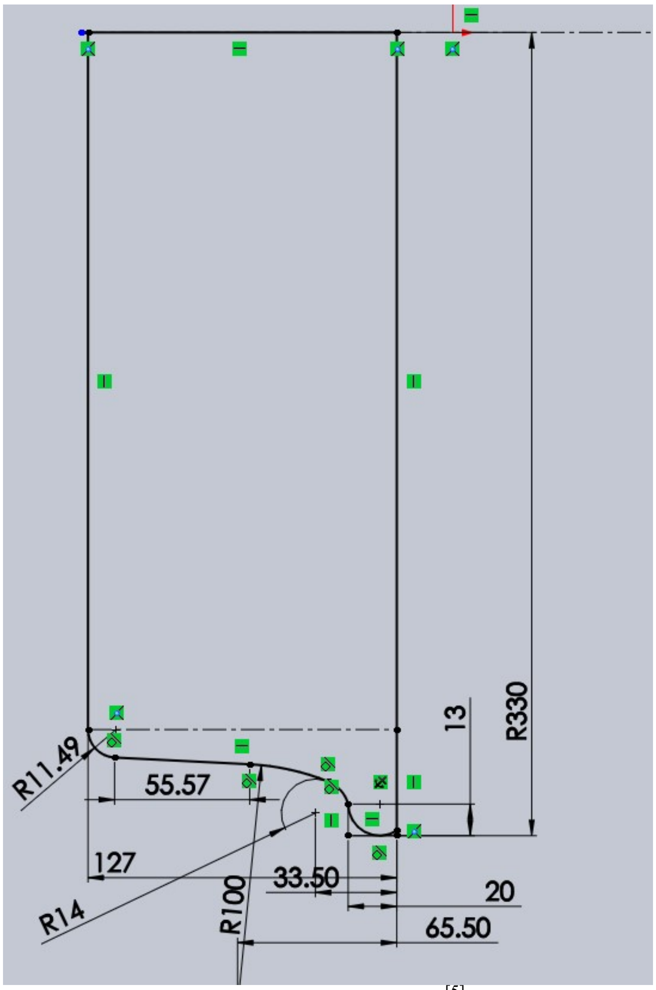

Fig 4. Rail wheel profile[5]