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# Investigation and Comparision of Modeling and Numerical Soloution of the Dynamic Ballasted Railway Tracks with Unsupported Sleepers

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**A B S T R A C T**

The phenomenon of unsupported sleepers is considered one of the most critical factors affecting the dynamic performance of ballasted railway tracks. Disrupting the contact between the sleeper and the ballast leads to increased deflection, stress concentration, and reduced track stability. This study aims to numerically analyze and simulate the dynamic effects of unsupported sleepers, focusing on their numbers and layout patterns in the ballasted railway tracks. For this purpose, a three-layer mechanical model consisting of rail, sleeper, and ballast was developed in MATLAB, and its results were compared with an equivalent finite element model created in ABAQUS. The MATLAB model employs mass, stiffness, and damping matrices along with a time-dependent moving load to evaluate the system's response under various unsupported sleeper conditions. In the ABAQUS model, sleepers and ballast were modeled as concentrated masses, with their interactions represented via equivalent spring-damper systems; loading was applied incrementally along the train path. The results indicate that increasing the number of unsupported sleepers—particularly in sequential arrangements—significantly amplifies rail deflection and mid-span stress, with the most critical response observed in the case of three-consecutive-unsupported-sleepers. These findings indicate the necessity of continuous monitoring and preventive maintenance of unsupported zones to ensure track safety and extend structural service life.

## 1. Introduction

Railways, as critical transportation infrastructure, play a vital role in freight movement, economic growth, and sustainable development. Due to their reliability, safety, and high energy efficiency, rail systems have attracted significant attention from nations worldwide. With heavy capital investments and long lifecycles, railways represent key assets where even minor improvements in efficiency or reductions in maintenance costs can yield substantial economic impacts. In some countries, railway development forms part of industrial strategies to establish economic corridors and reduce logistical costs, driving sustainable economic transformation [1-4].

However, railway construction and maintenance present significant technical challenges. Moreover, rail systems are naturally exposed to vulnerabilities from heavy loading, harsh environmental conditions, and gradual degradation of track components. Under such

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conditions, timely defect detection and optimal maintenance decisions play a fundamental role in enhancing productivity, improving safety, and reducing long-term costs [5].

Ballasted railway tracks, as essential components of rail infrastructure, consist of two main parts: the superstructure and substructure. The superstructure includes components such as rails, sleepers, fasteners, and ballast layers, which are crucial for transferring dynamic loads from train traffic and maintaining track stability. Sleepers, as key superstructure elements, serve to support the rails and distribute loads to the ballast [6].

In ballasted tracks - still the most common track form worldwide - non-uniform ballast settlement represents one of the primary causes of progressive track deterioration. These settlements, particularly prevalent in transition zones such as bridge approaches, rail joints, switches, and underground facilities, lead to void formation at sleeper-ballast interfaces. This condition, known as unsupported sleeper, has been identified in numerous studies as one of the most frequent localized track defects [7-10]. When part of a sleeper loses effective contact with the ballast, the connected rail section becomes partially suspended, causing significant fluctuations in stress distribution, wheel-rail contact forces, and dynamic track behavior. Based on the extent of void formation beneath sleepers, this phenomenon can be classified into two types: partially supported and fully hanging sleepers. Additionally, the void location (center or edges of the sleeper) provides another classification criterion for analyzing its dynamic effects [7-10].

Field evidence and experimental data show that unsupported sleepers occur in over half of all track segments, particularly in sections that have lacked proper maintenance for extended periods [11]. This phenomenon significantly reduces operational efficiency, making a detailed investigation of dynamic behavior and cumulative settlements caused by unsupported sleepers essential for railway maintenance practices.

## 2. Technical Literature Review

Unsupported sleepers are considered among the main factors reducing track stability and increasing maintenance costs due to creating uneven settlements, increased vibrations, and dynamic stresses. Detection of this defect is performed using various methods that fall into three main categories: traditional methods, data processing technologies, and intelligent sensor systems.

In traditional methods, visual inspection, manual equipment, and track geometry measurement machines are used. However, the limitations in accuracy and repeatability of these methods have highlighted the need for more advanced technologies. For this purpose, the combination of surface and subsurface data using laser and GPR[1], analysis of accelerometer data, and dynamic track modeling have been employed to detect areas with voids.

Additionally, machine learning algorithms such as SVM[2], CNN[3], RNN[4], and FCN[5] have shown accurate performance in classifying the severity of unsupported sleeper defects. These models are trained on data extracted from finite element simulations, with some like CNN and FCN achieving over 92% accuracy. Furthermore, the use of self-sensing sleepers with carbon nanotubes presents a novel approach for real-time monitoring of sleeper support conditions through electrical resistance measurements that can detect load variations and ballast movements [12-17].

Unsupported sleepers, by creating voids between the sleeper and ballast, are recognized as one of the factors reducing track stiffness, increasing track displacement, and intensifying dynamic forces in the surrounding area. Figure (1) shows a schematic of this phenomenon. Numerical studies using finite element modeling have demonstrated that even small voids of 0.4 mm can increase adjacent sleeper displacement by over 40% and significantly amplify sleeper-ballast contact forces. When the void size increases to 1 mm, the contact between the unsupported sleeper and ballast is completely lost, transferring the load to adjacent sleepers and increasing their effective stress from 4 to 8 MPa.

[1] Ground Penetrating Radar
[2] Support Vector Machine
[3] Convolutional Neural Network
[4] Recurrent Neural Network
[5] Fully Convolutional Network

Moreover, increasing train speed and void size leads to severe impacts, excitation of resonant frequencies, and higher transient rail stresses. Particularly at high speeds, the collision of unsupported sleepers with ballast generates sudden impacts and severe vibrations. Frequency analysis revealed that increasing void size shifts the dominant frequencies from 15 and 35 Hz to the 55-90 Hz range. Studies on sleeper spacing have also shown that increasing the distance between sleepers or having multiple consecutive unsupported sleepers can increase rail displacement by over 70%. These results emphasize that unsupported sleepers not only cause significant changes in the track's dynamic response but also seriously threaten track stability and the service life of its components [18-20].

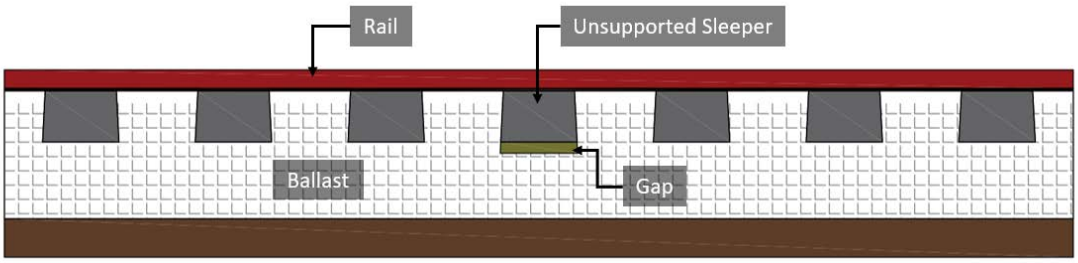


Figure 1. Unsupported Sleeper Phenomenon [21]

Unsupported sleepers directly reduce the lateral resistance of railway tracks and weaken track stability by creating discontinuities in the sleeper-ballast contact. Laboratory tests and simulations have shown that voids between sleeper and ballast lead to increased load transfer to adjacent sleepers and intensified slippage in the contact area. As the number of unsupported sleepers in a panel increases, the overall lateral resistance of the track decreases exponentially, while the track stiffness at adjacent supported sleepers becomes unevenly distributed.

Although the size of the void doesn't directly affect the resistance loss, dynamic excitation and acceleration changes are significantly greater when unsupported sleepers are present. In terms of dynamic stability, test results show that under cyclic loading, unsupported sleepers can temporarily increase the surface lateral resistance of ballast, but simultaneously exacerbate stiffness differences between adjacent sleepers, leading to stress concentration and reduced load distribution uniformity in the track foundation.

From the perspective of wheel flange derailment risk, nonlinear wheel-rail dynamic simulations on transition curves have demonstrated that unsupported sleepers can increase derailment probability by creating deep depressions in the rail, particularly on sharp curves (e.g., 150m radius). The key factor in derailment is the vertical rail deviation depth, which has different critical thresholds depending on train speed (e.g., 30mm at 39 m/s). These results also indicate that vehicle type, loading condition, or depression location (inside/outside of curve) don't decisively affect derailment occurrence; rather, the local deviation depth and dynamic excitation from unsupported sleepers play the key role. [22-24]

The presence of unsupported sleepers significantly affects the vibrational characteristics of both the track and surrounding environment. Numerical and experimental studies have shown that compared to tracks with fully supported sleepers, tracks with unsupported sleepers exhibit higher environmental vibration velocity and amplitude. Dynamic train-track interaction analysis using finite element models confirms that unsupported sleepers reduce the ballast's damping effect and increase vibrational response due to reduced effective contact with ballast.

Tests with different void heights (0, 30, 60 and 90 mm) revealed that as void height increases, sleeper vibration amplitude grows substantially because fewer ballast particles participate in vibration absorption. At 90 mm void height, sleeper acceleration reached 0.29g, showing significant increase compared to no-void conditions. Frequency domain analysis showed that increasing void height under

sleepers decreases fundamental natural frequencies while increasing excitation in high frequency ranges (450-1000 Hz) - frequencies that aren't well damped by the ballast layer, leading to resonant vibration amplification and accelerated degradation. These findings highlight how unsupported sleepers transfer vibrations to the surrounding environment, degrade track performance quality, and increase long-term damage potential. [23, 25]

A destructive two-way relationship exists between ballast settlement and unsupported sleepers. In initial stages, ballast settlement from poor materials, inadequate drainage or repeated loading creates voids under sleepers, putting them in partially supported conditions. This leads to dynamic stress concentration and reduced effective contact. Gradually, these sleepers become fully unsupported, transferring more load to adjacent sleepers and exacerbating settlement along the entire track.

MATLAB simulation results show that increasing unsupported sleepers can increase vertical rail displacement by 74%, with even small voids (0.8 mm) causing significant displacement increases. Void depth and length directly affect settlement severity - sleepers near void edges endure highest stresses and are most prone to ballast breakdown. Loading type also plays a determining role: impact loads increase settlement linearly/parabolically, while cyclic loads show nonlinear cumulative behavior. Vibration acceleration fluctuations and static settlement, especially during intermediate loading cycles, are key factors in void development.

Design studies show sleeper geometry affects settlement patterns - wide sleepers reduce longitudinal settlement but may create transverse irregularities that threaten long-term geometric stability. These findings emphasize the need for predictive tools like GPR[6] and neural networks combined with smart sensors and preventive maintenance programs to break the destructive settlement-unsupported sleeper cycle, thereby extending track life and reducing maintenance costs. [9, 10, 20, 26, 27]

The quantity and arrangement pattern of unsupported sleepers significantly influence track dynamic response and stability. Numerical studies show that sleepers located between unsupported sleepers endure the highest dynamic and impact forces. In cases with 2-3 consecutive unsupported sleepers, sleeper-ballast contact force and rail seat bending moment increase by 66%, potentially causing structural damage and fatigue life reduction.

Increasing unsupported sleepers, especially in consecutive arrangements, leads to substantially higher vibration amplitude, ballast settlement and stress concentration. However, simulations show this effect saturates after 5-6 consecutive unsupported sleepers as track stiffness drops drastically and the track enters a flexible regime. The distribution pattern also matters - intermittently spaced unsupported sleepers create different vibration behavior compared to clustered ones. Larger voids and higher vehicle speeds increase loading oscillation amplitude and wavelength, reducing damping effectiveness and accelerating ballast deterioration. These results demonstrate that both quantity and geometric arrangement of unsupported sleepers must be carefully considered in track stability analysis and maintenance planning. [11, 18, 19]

One major consequence of unsupported sleepers is vertical level loss, indicating the deviation of running surface from mean track position. Defined in BS-EN 1348-1, this typically occurs in two phases: initial ballast compaction after construction/repair, followed by gradual settlement under repeated loading. In tracks with unsupported sleepers, the second phase occurs more intensely, with rate following a logarithmic function of cumulative traffic load. [8].

## 3.Methodology

In studies related to dynamic analysis of railway tracks, numerical modeling is of great importance, and various methods have been developed to accurately represent the interaction between track and vehicle. For railway track modeling, the beam on continuous elastic foundation model, which was first developed based on Euler-Bernoulli beam theory and later modified with Timoshenko corrections, is considered one of the most fundamental and widely used models. In this model, beam bending is considered and the foundation is

[6] Gaussian Process Regression

modeled as continuous springs. Other models such as:

- Beam on discrete supports (where sleepers are defined as discrete springs under the rail)
- Double continuous beam for simultaneous representation of rail and concrete slab or ballast
- Multi-layer models (2 to 7 layers) considering mass and stiffness of various track components including sleepers and ballast

have also been developed. At more advanced levels, 3D finite element models with high accuracy are used to investigate detailed track behavior in various domains, especially under nonlinear conditions

For vehicle modeling, depending on required accuracy level, models range from simple moving load or mass to more advanced models including:

- Two-axle bogies
- 2D vehicles with limited degrees of freedom
- Complete 3D models with 17 degrees of freedom

In more accurate models, primary and secondary suspension systems, vertical, rotational and lateral movements of bogies and vehicles, and rolling/vibration effects are also considered. This variety in models requires selection of appropriate model type based on study objectives, desired accuracy and computational cost. In the current research, considering the goal of analyzing effects of unsupported sleepers on railway track behavior, a three-layer numerical model has been used, implemented and compared in both MATLAB and ABAQUS environments.

## 4. Numerical Method in MATLAB

To analyze dynamic response of railway track in presence of unsupported sleepers, a three-layer mechanical model including rail, sleeper and ballast was developed in MATLAB. In this model:

- Rail is considered as Bernoulli beam with continuous supports (representing pads)
- Sleepers are considered as concentrated masses connected to rail and ballast
- Ballast is considered as distributed mass connected to ground foundation

For dynamic interaction simulation, mass (M), stiffness (K) and damping (C) matrices for the entire system were assembled in block form [28].

The total stiffness matrix K includes three main parts and two coupling matrices:

$$Ktotal = \begin{bmatrix} K_r & K_{rs} & K_0 \\ K_{sr} & K_s & K_{sb} \\ K_0 & K_{bs} & K_b \end{bmatrix} \quad (1)$$

Where:

- $K_r$: Rail bending stiffness from Bernoulli beam elements (with parameters E, I, and element length)
- $K_s = k_p + k_b$ : Total sleeper stiffness including pad and connection to ballast
- $K_b = k_b + k_f$ : Ballast stiffness including ballast itself and contact with ground
- $K_{rs}$ and $K_{sr}$ : Coupling matrices between rail-sleeper and sleeper-ballast

The total mass matrix is also assembled diagonally as:

$$Mtotal = \begin{bmatrix} M_r & M_0 & K_0 \\ M_0 & M_s & M_0 \\ M_0 & M_0 & M_b \end{bmatrix} \quad (2)$$

Where:

- $M_r$ : Linear rail mass (as 4×4 for each element) calculated using classical beam method
- $M_s$ : Sleeper masses as diagonal matrix with constant values
- $M_b$ : Ballast mass under sleepers
- The total damping matrix has similar structure:

$$Ctotal = \begin{bmatrix} C_r & C_{rs} & C_0 \\ C_{sr} & C_s & C_{sb} \\ C_0 & C_{bs} & C_b \end{bmatrix} \quad (3)$$

Where:

- $C_r = \alpha M_r + \beta K_r$ : Rail damping using Rayleigh method
- $K_s = K_p + K_b$ : Total sleeper stiffness including pad and connection to ballast
- $K_b = K_b + K_f$ : Ballast stiffness including ballast itself and contact with ground

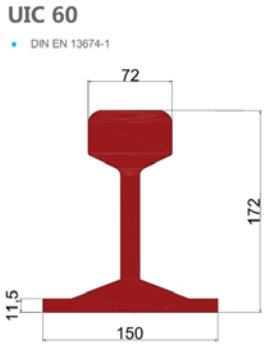


Figure 2. Cross-sectional profile of UIC60 rail [30].

For train passage simulation, a moving axle load was defined as function of time and train speed. Load position at each moment was calculated based on speed and concentrated force was distributed using Hermite functions over rail element nodes. System time analysis was performed using Wilson-theta numerical integration method (θ=60) [29].

Finally, vertical displacements at:

1. Mid-span rail
2. Central sleeper
3. Ballast under sleeper

were extracted for unsupported sleeper conditions and results were compared with similar model in ABAQUS for validation. Effects of unsupported sleeper quantity and arrangement patterns were also investigated in various cases.

## 5. Modeling in ABAQUS

In this part of study, for precise analysis of railway track dynamic behavior with unsupported sleepers, finite element simulation was used in ABAQUS software. Modeling was performed considering standard UIC60 rail profile shown in Figure (2). To simplify geometry while maintaining inertia moment accuracy, rail cross-section was modeled as rectangle with:

- Height: 172 mm (based on actual UIC60 specifications)
- Equivalent width calculated from $I = (bh^3)/12$ relation

to achieve similar moment of inertia.

After defining the mechanical properties of the rail, the system assembly process was started. In this stage, the sleepers and ballast were defined as concentrated mass points and the foundation (ground support) as fixed, with regular spacing of 60 cm from each other along the track path, and the stiffness and damping between them were modeled using spring-damper elements in the vertical direction. According to Figure (3), the K+C spring-dampers represent the stiffness-damping between rail, sleeper, ballast and ground.

The boundary conditions were defined such that both ends of the rail were fixed in horizontal and vertical directions and only allowed rotation about the z-axis. The nodes corresponding to

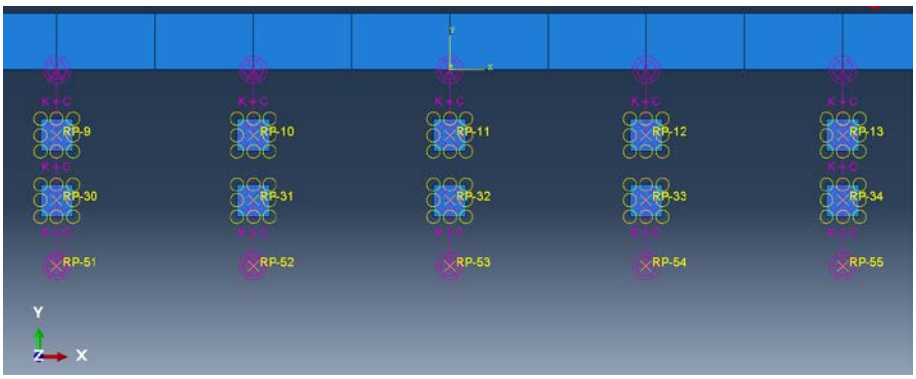


Figure 3. Representative schematic of the ABAQUS model's spring configuration

sleepers and ballast had only vertical movement capability, while the nodes corresponding to ground were completely fixed. Then, a moving concentrated load at 100 km/h was applied on the rail from -6 to +6 meters. To apply the load precisely and continuously, the loading was performed in time intervals corresponding to 0.3 meter mechanical steps; thus, the load was distributed on the rail both at sleeper locations and between them. This loading covered the entire 12-meter path in 0.45 seconds and was transferred to the corresponding node at each time step.

In the next step, to investigate the effects of unsupported sleepers, vertical springs were selectively removed at some points to simulate unsupported conditions. These cases included four main cases: (1) only the middle sleeper as unsupported, (2) two unsupported sleepers alternately, (3) two consecutive unsupported sleepers, and (4) three consecutive unsupported sleepers. In each case, the vertical displacement results of rail, sleeper and ballast reaction were extracted and analyzed. The obtained outputs were also used for further comparison with the numerical model results in Matlab environment. This comprehensive simulation made it possible to precisely examine the geometric and structural effects of unsupported sleepers on stability and dynamic performance of railway track.

In Table (1), the specifications of the ballasted railway track used in both models are presented.

Table 1. Specifications of the modeled railway track in both software packages [31]

| Track Parameters | value |
|---|---|
| **E(N/m)** | 210e9 |
| **I($m^4$)** | 0.0000322 |
| **$M_r$ (kg/m)** | 60 |
| **$K_P$ (KN/m)** | 240000 |
| **$C_P$ (KN.S/m)** | 248 |
| **$M_S$ (kg/m)** | 320 |
| **$K_B$ (KN/m)** | 70000 |
| **$C_B$ (KN.S/m)** | 180000 |
| **$M_B$ (kg/m)** | 1400 |
| **$K_F$ (KN/m)** | 130000 |
| **$C_F$ (KN.S/m)** | 62.3 |
| **L(m)** | 12 |

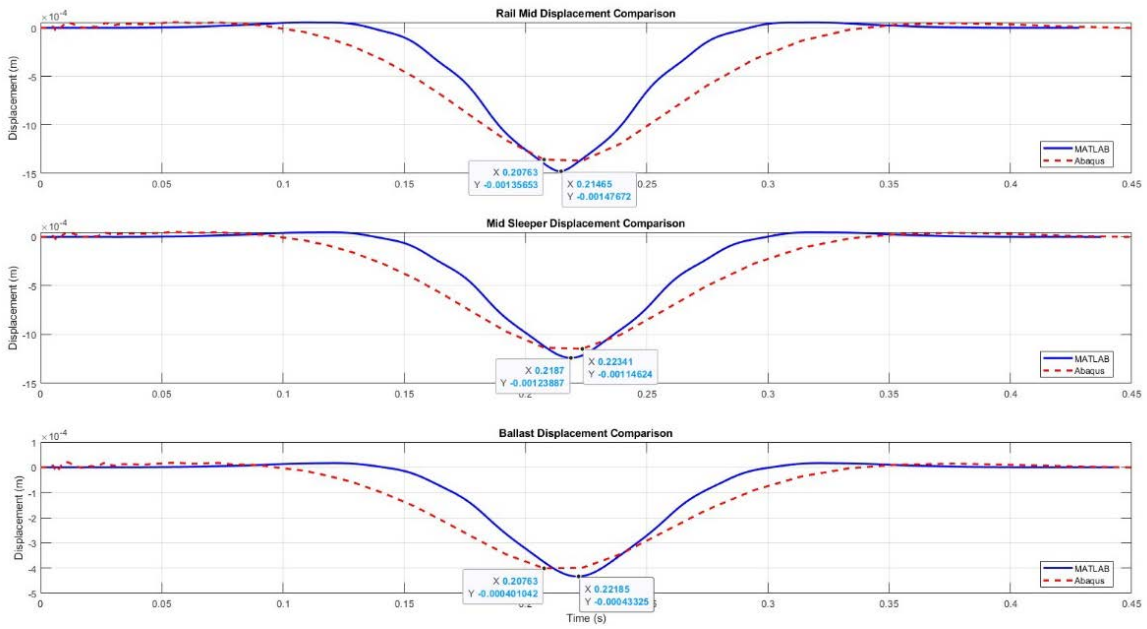


Figure 4. Comparison of displacement results for rail, sleeper, and ballast

## 6. Results and Interpretation

In this section, the results obtained from numerical modeling in different sleeper support conditions are examined. The analysis focuses on comparing displacement and stress distribution in conditions without unsupported sleepers and with one, two, and three unsupported sleepers to determine the effect of this phenomenon on the dynamic behavior of the track.

In Figure (4), the results from modeling in both MATLAB and ABAQUS software for the case without unsupported sleepers are compared. In the first part of the graph which shows mid-span rail displacement, the maximum negative deflection occurs at approximately 0.21 seconds in both models. The maximum displacement value in ABAQUS is about 1.35 mm, while in MATLAB it is slightly higher at 1.47 mm. This small difference can be attributed to differences in modeling track continuity, boundary conditions, as well as differences in mesh type or formulation of the governing equations of the models.

In the second part, which shows mid-sleeper displacement, the displacement pattern is similar to the rail case but with slightly reduced amplitude. Here, the maximum displacement in ABAQUS is 1.14 mm and in MATLAB it is 1.23 mm. The difference in this value may be due to the more nonlinear effect of energy dissipating elements in MATLAB's model.

Finally, the third graph examines displacement in the ballast layer. As expected, the displacement values in this area are significantly lower than those of the rail and sleeper. The maximum displacement in ABAQUS is about 0.43 mm and in MATLAB it is close to 0.40 mm. The very close agreement of these results indicates that the mass-spring-damper model has successfully reproduced the dynamic behavior of the underlying track layers in the numerical analysis. These initial results confirm the validity of the three-layer numerical model under basic defect-free conditions.

In Figure (5), the effect of having only one unsupported sleeper at the middle of the rail path on the system displacement at two key points - mid-rail and mid-sleeper - has been investigated, and the results of MATLAB and ABAQUS models have been compared with each other. Similar to the case without unsupported sleeper, both displacement graphs show negative displacement in the time range of about 0.21 to 0.23 seconds, which matches the time when the wheel passes over the center of the unsupported sleeper.

In the first part of the graph, the mid-rail displacement in ABAQUS model is about 1.73 mm and in MATLAB it is 1.82 mm. This increase compared to the baseline case (without

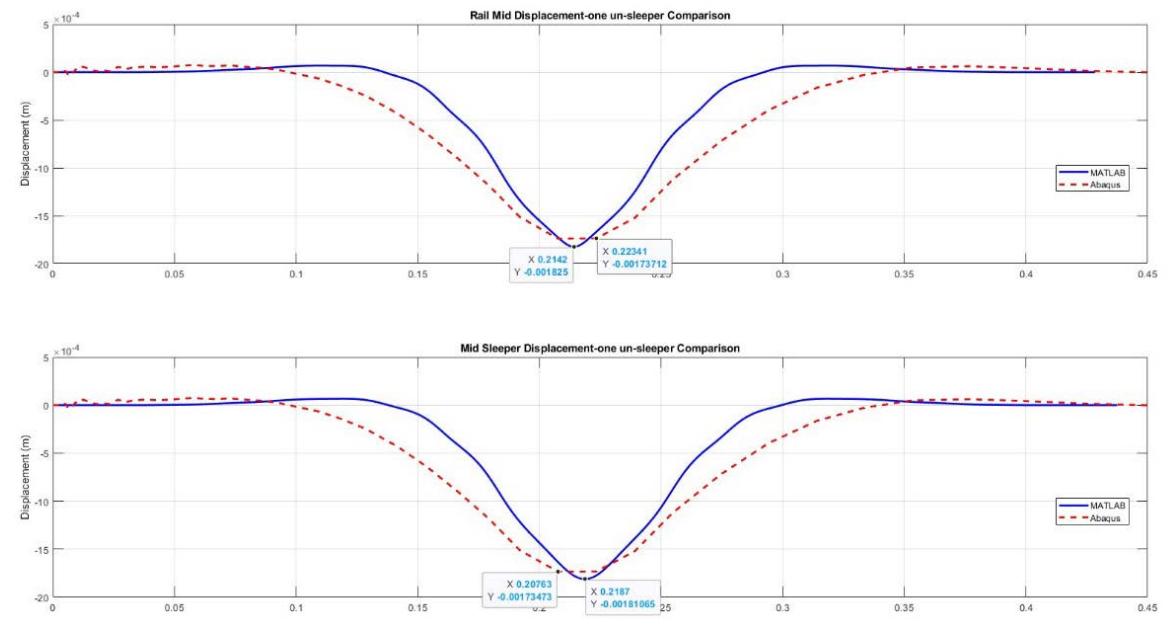


Figure 5. Comparison of rail and unsupported sleeper displacements obtained from both analyses (with one unsupported sleeper)

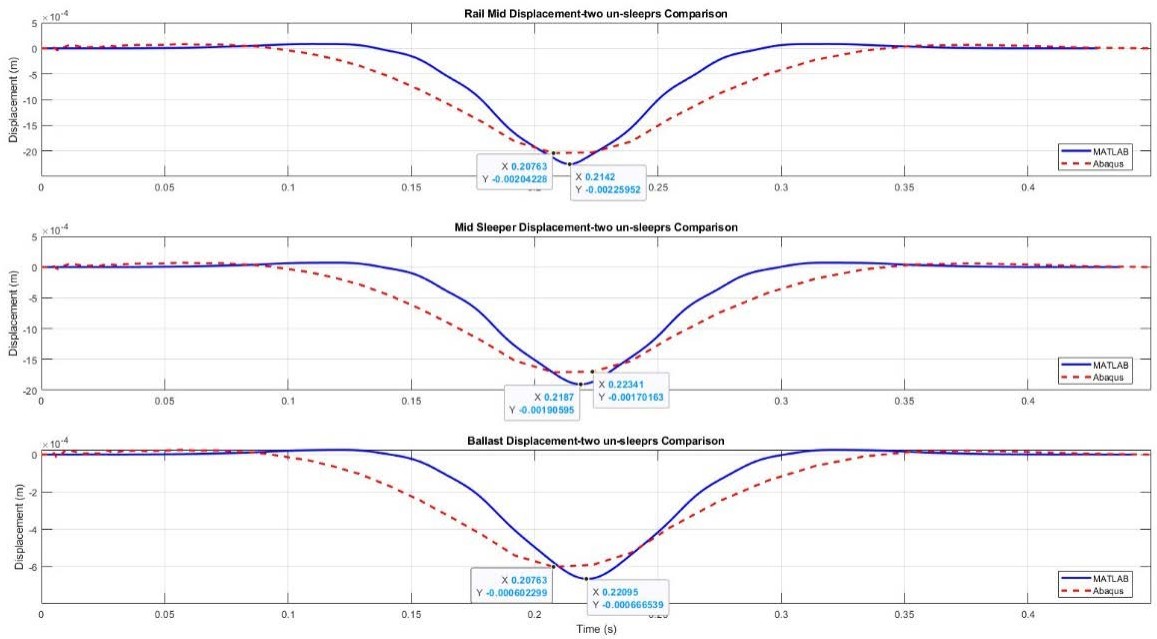


Figure 6. Comparison of rail and sleeper displacements obtained from both analyses (with two alternately unsupported sleepers)

unsupported sleeper) confirms the negative effect of creating empty space under the sleeper on the dynamic performance of the track.

In the second part, the sleeper displacement in both models has increased compared to the case without unsupported sleeper, as expected, because removing the effective contact with ballast at the location of unsupported sleeper causes force concentration and reduces the effective stiffness of the system. The maximum displacement in MATLAB is 1.81 mm and in ABAQUS it is 1.73 mm. It is noteworthy that despite the small difference between the two models, the overall pattern and timing of the displacement peaks are completely aligned and reliable.

Overall, the results clearly show that even the presence of only one unsupported sleeper can intensify the dynamic responses of the track, especially in the area where concentrated loading occurs. This emphasizes the importance of timely detection and repair of such discontinuities in railway track maintenance systems.

In Figure (6), the effect of having two unsupported sleepers in alternating arrangement on the dynamic behavior of the system is examined. The analyzed point is the middle sleeper which itself is not unsupported but is located between two unsupported sleepers. This configuration clearly shows the secondary effects of unsupported sleepers on adjacent sleepers.

In the first part of the graph (mid-rail displacement), a significant increase in displacement amplitude is observed compared to the case without unsupported sleepers. The displacement value in MATLAB reaches about 2.25 mm and in ABAQUS 2.04 mm, showing about 50% increase compared to previous cases. This indicates that sleepers adjacent to unsupported sleepers undergo greater deformation due to increased force transfer.

In the second graph (mid-sleeper displacement of the supported sleeper), the displacement amplitude remains high and considerable. The displacement value in MATLAB is about 1.90 mm and in ABAQUS about 1.70 mm. This phenomenon occurs because the middle sleeper bears more load due to longer loading duration (in absence of effective resistance from two adjacent sleepers) and consequently shows stronger dynamic response.

In the third part, it is observed that the ballast layer displacement has also increased significantly. The maximum displacement in MATLAB is about 0.66 mm and in ABAQUS about 0.60 mm. These differences indicate stress concentration in areas beneath sleepers adjacent to unsupported sleepers, where more load is

transferred to ballast in absence of uniform support. Overall, this case shows that the negative effect of unsupported sleepers is not limited to their own locations, but can also intensify stress and displacement in adjacent sleepers, even when they have full contact with ballast.

In Figure (7), the first graph compares rail deflection in three different arrangements of unsupported sleepers. The red curve, which relates to the point above the middle sleeper in the arrangement with three consecutive unsupported sleepers, shows the maximum displacement and reaches about 3 mm. This situation, due to severe reduction in local stiffness, leads to stress concentration and maximum displacement in the rail.

The blue curve shows rail deflection above an unsupported sleeper in the case with two consecutive unsupported sleepers. In this case, the rail has more lateral supports and experiences less deflection.

The green curve, which refers to the position between two unsupported sleepers in the dual unsupported sleeper case, shows that this point - located between two unsupported areas - has slightly higher deflection than the blue curve but less than the red curve, due to the overlapping effect of unsupported areas.

Overall, the results indicate that the maximum deflection occurs in the case with three consecutive unsupported sleepers.

In Figure (8), the effective stresses in the rail are shown when none of the sleepers are unsupported and all support points have complete stiffness and damping. As evident from the stress distribution in this model, the maximum stress concentration is observed in the central area of the rail where the dynamic loading reaches its peak. The maximum stress value in this condition is about $2.71\times10^{7}$ Pa, which is concentrated in the area of direct contact between the rail and moving load, and spreads as a symmetrical two-sided pattern along the length of the rail.

In this case, the stress distribution is relatively uniform and no heterogeneous concentration or severe discontinuity in force transfer is observed, indicating proper structural stability of the rail and sleepers in this condition. Furthermore, the pattern of stress distribution clearly shows the

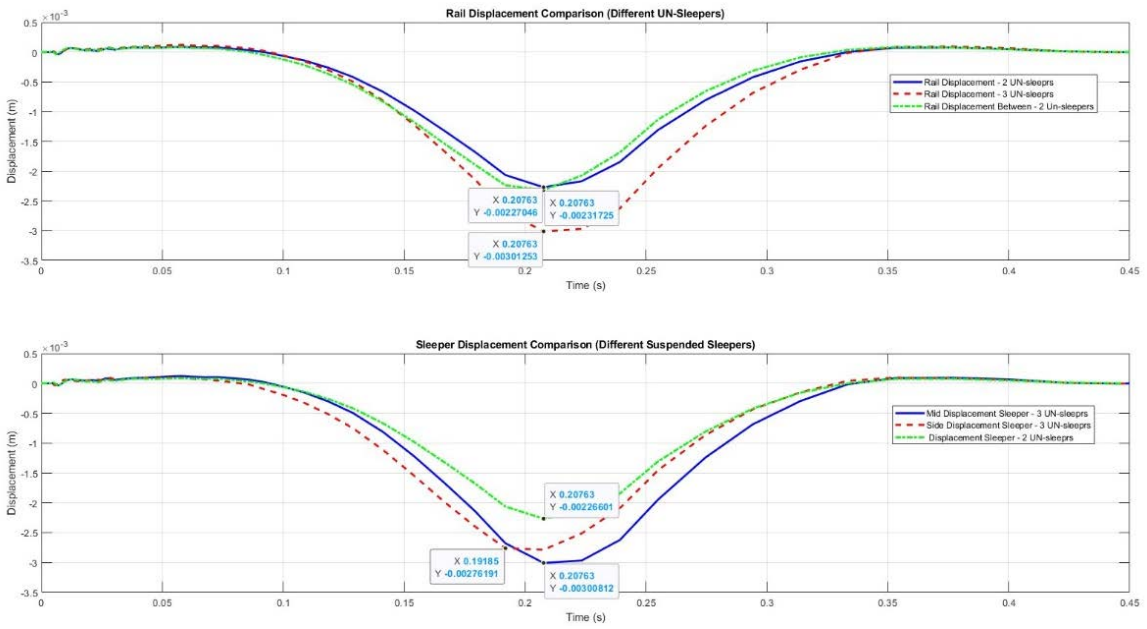


Figure 7. Displacement diagrams of rail and sleeper from ABAQUS model analysis in three conditions

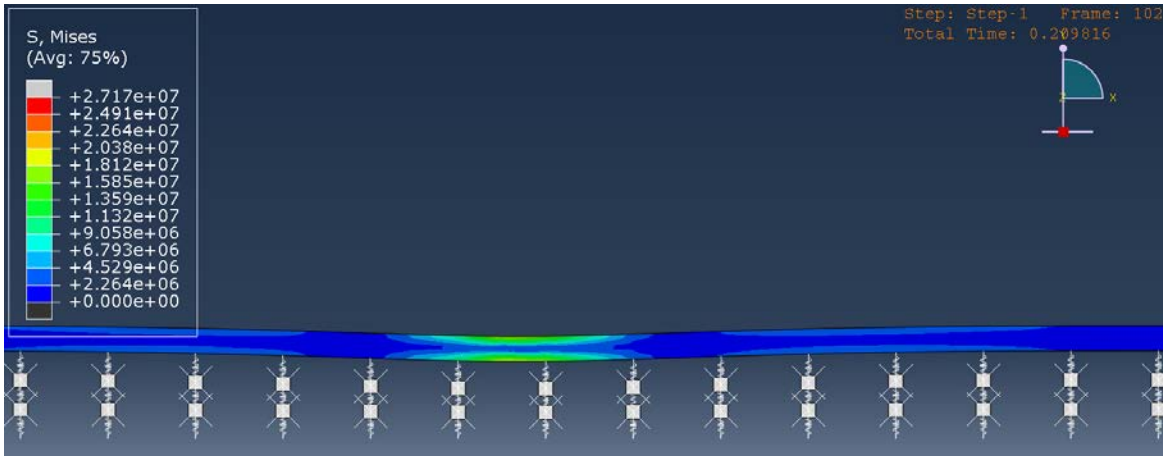


Figure 8. Stress distribution contours in a section of rail without unsupported sleepers

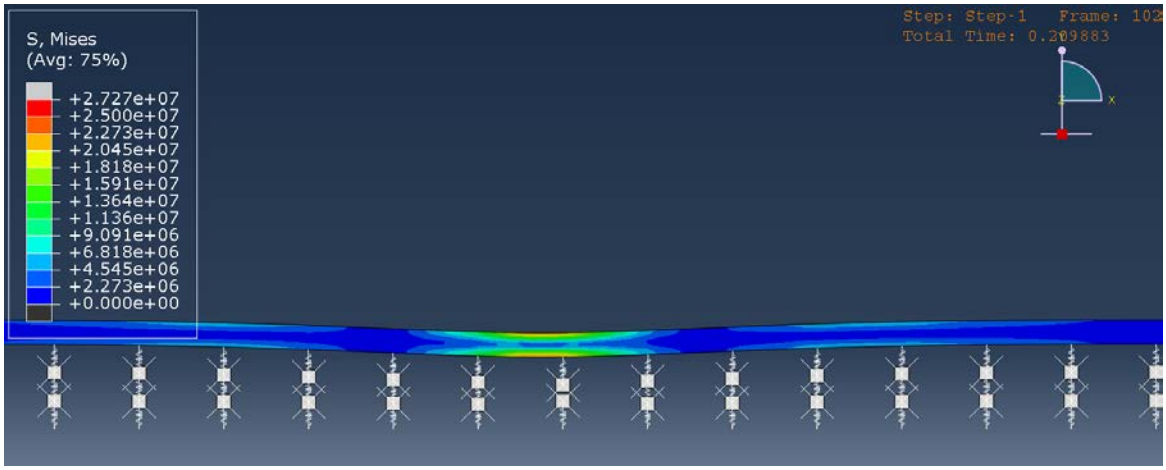


Figure 9. Stress distribution contours in the rail section with one unsupported sleeper

effective performance of ballast and sleepers in load distribution to the substructure.

In Figure (9), the effective stress state is shown when one middle sleeper is considered as unsupported. Comparing this image with the baseline case (without unsupported sleeper) shows that by removing the support under the sleeper, the stress distribution pattern has undergone changes. Specifically, the stress concentration in the central area of the rail has increased and the affected region has expanded further.

The dominant color in the central area has shifted toward yellow, indicating increased stress in the range of $2.04\times10^7$ Pa to $2.72\times10^7$ Pa, whereas in the model without unsupported sleeper, peak stresses were concentrated in a more limited area. Also in this case, the boundary between medium and high stress areas has extended toward adjacent sleepers, which itself indicates transfer of part of the load to neighboring points and increased stress in the area around the unsupported sleeper.

In Figure (10), the effective stress distribution is displayed for the case with two unsupported sleepers in alternating arrangement, where the middle sleeper (under analysis) maintains ballast support. In this configuration, the rail at the examined point is positioned directly above a supported sleeper, while the adjacent sleepers lack contact with ballast.

In this condition, unlike the single unsupported sleeper case, the maximum stress in the central area remains concentrated but shows noticeable reduction compared to previous cases. The yellow zone (corresponding to stress range of 2.04 to 2.72 MPa) has become narrower, and compared to the previous image with one unsupported sleeper, the stress concentration intensity is lower. The predominant color around

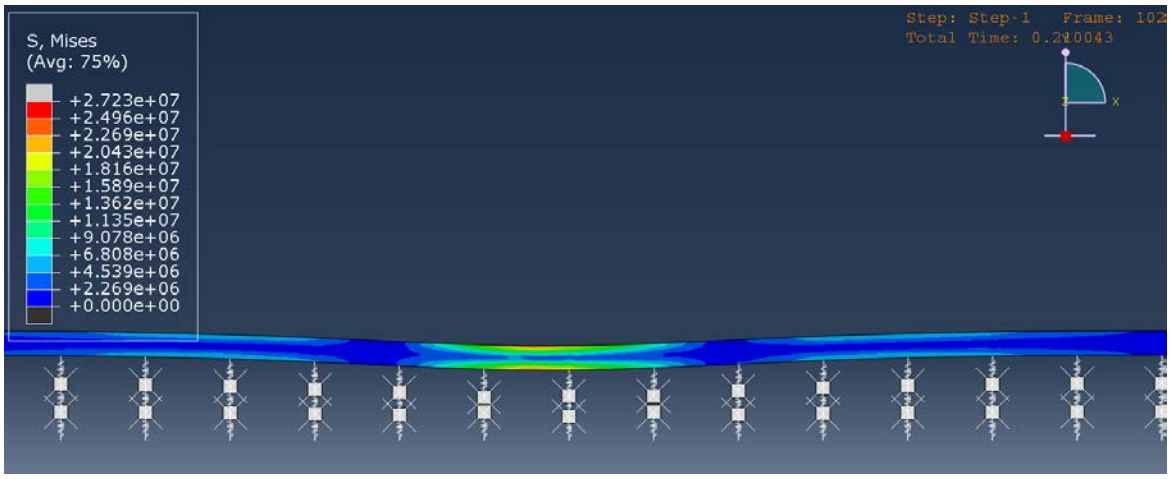


Figure 10. Stress distribution contours in rail section with two alternately unsupported sleepers

the middle sleeper falls mostly in blue-greenish ranges, indicating significant stress reduction in this area.

This pattern confirms that when the examined sleeper is located between two unsupported sleepers but maintains effective contact with ballast, it leads to relative increase in local stiffness and consequently reduces the stress magnitude in the rail and underlying foundation. In other words, although the influence of adjacent unsupported sleepers is observable, the preserved support at the central point enables more balanced force distribution along the path, preventing severe stress concentration.

In Figure (11), the effective stress in the area of middle sleeper is examined for the case where two unsupported sleepers are placed consecutively along the track. This condition represents the most critical case among all analyzed cases, because the middle sleeper not only lacks support, but is also located between two completely unsupported ballast areas.

According to the color spectrum observed:

- The maximum stress in this case exceeds 30 MPa
- A more concentrated and expanded red zone appears under the rail
- The high stress areas extend to both sides, showing stress distribution along the track and increased dynamic reflection effects from adjacent areas
- Comparison with previous images indicates that in this case:
- Stress concentration in central area is clearly more severe
- Structural stability is noticeably reduced

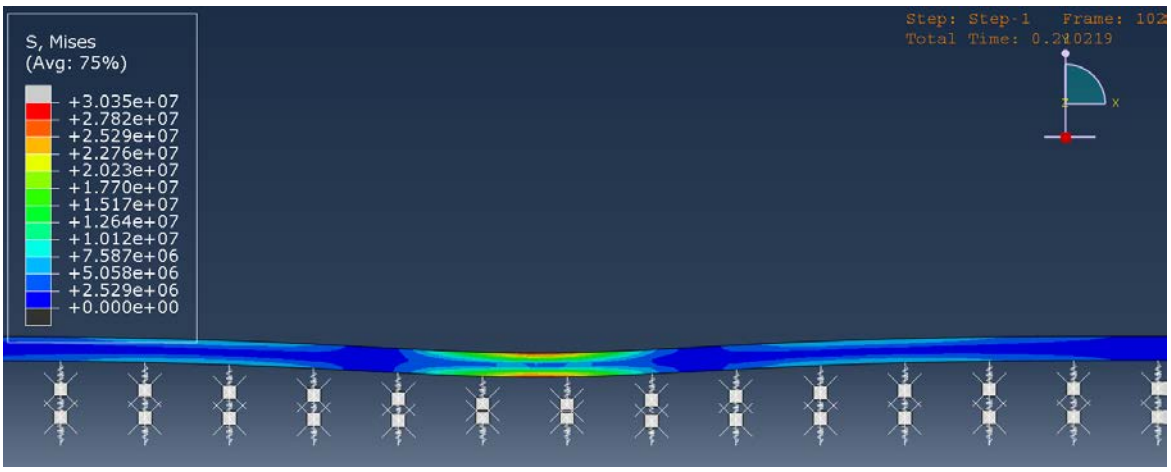


Figure 11. Stress distribution contours in the rail section with two consecutive unsupported sleepers

- This stress increase:
  - Raises cracking risk in rail/sleeper cross-sections
  - Due to intensified dynamic behavior, reduces fatigue life of track components

In summary, the condition with two consecutive unsupported sleepers is identifiable as the most critical case mechanically and requires immediate maintenance measures or geometric corrections.

In Figure (12), the effective stress distribution is shown in the area under the rail when three unsupported sleepers are placed consecutively along the track. This case represents the most critical condition in terms of failure progression, as a significant portion of the track remains simultaneously unsupported and the vertical stiffness of the system is severely reduced.

In comparison to previous cases, the maximum stress has reached about 32 MPa, which is higher than all other conditions. This is clearly visible in the intense red and orange color zones that show significant expansion along both the length and width of the area under the rail. The critical area has not only become more extended but has also penetrated deeper layers, significantly increasing stress concentration in the sleeper bed and ballast.

These results indicate that longitudinal expansion of the unsupported area, especially with consecutive unsupported sleepers, causes:

1.Severe intensification of dynamic behavior

2.Increased displacement

3.Stress concentration in mid-track regions

This condition not only leads to:

- Reduced sleeper durability
- Surface cracking

but also increases:

- Early ballast bed deterioration
- Loss of lateral track stability

Therefore, it can be concluded that consecutive unsupported sleepers represent the most dangerous operational case in ballasted tracks compared to isolated or scattered unsupported sleeper cases.

## 7. Conclusions

Unsupported sleepers—defined as sleepers with partial or complete loss of ballast support—represent a critical defect in ballasted railway tracks, often leading to localized stiffness degradation, increased sleeper displacement, ballast settlement, and stress concentration. This study employed a combined numerical approach using MATLAB and ABAQUS to simulate various unsupported sleeper configurations and evaluate their effects on rail deflection, sleeper displacement, ballast settlement, stress distribution, and overall dynamic track behavior.

The examination of numerical solution and modelling according to the MATLAB and ABAQUS software respectively demonstrates that the displacement patterns and stress distributions in the ballasted railway tracks are strongly influenced by the arrangement of unsupported sleepers.

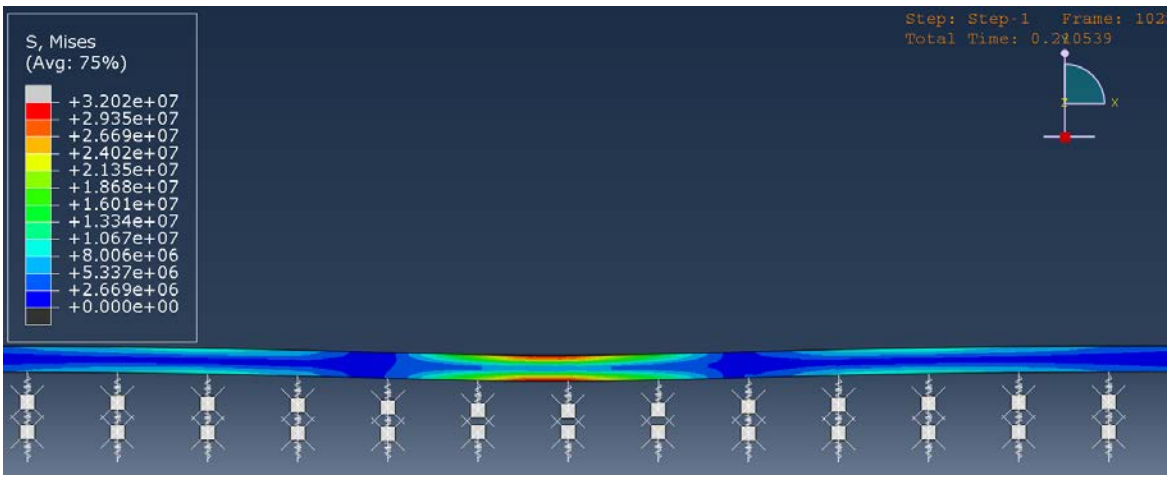


Figure 12. Stress distribution contours in rail section with three consecutive unsupported sleepers

In the case of no unsupported sleepers, both displacement and stress remain within the normal range, showing good agreement between the two models. By considering one unsupported sleeper, both displacement amplitude and stress value increase, particularly at the unsupported point, indicating a reduction in local stiffness.

In the case of two non-consecutive unsupported sleepers, although the system response intensifies compared to the base case, load distribution remains more balanced, preventing excessive stress concentration in a single area. In contrast, the critical scenario involving three consecutive unsupported sleepers yields the highest deflection and peak stress values, revealing a sharp reduction in stiffness and an increase in dynamic vulnerability.

However, the results indicate that increasing the number of unsupported sleepers, particularly in consecutive arrangements, not only leads to increased displacement and stress in the track but also substantially reduces the mechanical stability of the track system. Therefore, identification and remediation of areas with unsupported sleepers, especially through preventive maintenance measures, play a crucial role in maintaining the ballasted railway track performance and safety.

Results indicate that the model with no unsupported sleepers showed more uniform stress distribution along the middle sleeper, with a maximum equivalent stress of approximately 27.1 MPa.

By considering one unsupported sleeper, the stress concentration area expanded around the center, with stress increasing to about 27.2 MPa and showing wider distribution. In the case of two consecutive unsupported sleepers, stress at the center of the middle sleeper showed a noticeable increase, reaching about 30.4 MPa, indicating local stiffness reduction and increased track flexibility.

The highest stress value was observed in the three consecutive unsupported sleepers case, reaching 32.02 MPa. This case also showed that the stress concentration and range extended to the under rail, demonstrating the critical nature of this arrangement.

In summary, progressive removal of sleeper support leads to increased stress and displacement in the ballasted railway tracks. The results demonstrate that even a single damaged sleeper can lead to performance degradation and increased risk of structural failure in the track system. Therefore, the continuous monitoring and timely rehabilitation of sleepers play a vital role in maintaining and safety of ballasted railway tracks.

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