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Static and Dynamic Analysis of Railway Track Sleeper

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Abstract— The increased speed and weight of modern trains puts the components of a railway track in a highly dynamic load situation. Irregularities of the wheels and rails induce substantial dynamic loads that have to be accounted for in the procedure of designing the railway track. The concrete sleeper is an essential part of the track structure and there is a growing demand for improved analytical tools for concrete sleepers under dynamic loading. A typical finite element model of the concrete sleeper is established that focuses on analyzing the behavior of a concrete sleeper during a train passage.

A finite element model of a pre-stressed concrete sleeper is established for static load conditions. The studies done with the sleeper model showed that the train load has great impact at the rail seat positions at the two ends of the sleeper maintained at broad gauge distance i.e. 1.76m. The natural frequencies obtained for a sleeper in free-free condition are lesser compared to the natural frequencies obtained for sleeper in-situ condition. The analysis also showed that the interaction between the sleeper and the underlying ballast is of great importance for the dynamic behavior of the sleeper.

Keywords— dynamic load, concrete sleeper, prestressed, finite element model, natural frequency, ballast, static load

INTRODUCTION

The railway track was originally developed in order to exceed the load-carrying capacity of the roads. In the development of the railway track a component acting and looking like the sleeper of today was invented. Bonnett (1996) specifies the functions that are required of a modern sleeper used in railway tracks today [4]:

- Spread wheel loads to ballast
- Hold rails to gauge and inclination
- Transmit lateral and longitudinal forces
- Insulate rails electrically
- Provide a base for rail seats and fastenings

The functions described above show that the sleeper has an important role in the track system. It is thereby obvious that the sleeper has to be analyzed in an accurate way.

Several physical phenomena occur when dynamic (impact) loads are applied to concrete sleepers that do not occur under static conditions. For instance, the dynamic loads introduce stress waves in the sleeper, the acceleration of the sleeper introduces inertial forces, and the high strain rate changes the material properties of the concrete. Furthermore, the ballast pressure supporting the sleeper in the track will change with time in a dynamic load situation [24].

Future railway traffic will certainly be even faster than the trains of today, and at the same time the demanded load capacity of the trains will probably increase. This implies that the demands on the concrete sleeper will increase and the need for detailed, reliable analytical tools will be of greater importance in the near future.

OBJECTIVE OF THE WORK

The objective of this work is to conduct detailed analysis on the concrete sleepers for both static and dynamic load situations. For dynamic load situations, the dynamic effects caused by the impact loads need to be considered. The analysis results should be well documented and available to the industry; hence, a commercial program is preferable.

A finite element model of a pre-stressed concrete sleeper should be established by use of existing element types and material models. The finite element model of the concrete sleeper should also be extended to involve the sleeper's surroundings. A comparison of the FE-analysis results with ballast and without ballast provides insight to the dynamic effects on the sleeper.

LITERATURE REVIEW

The combination of rails, fitted on sleepers with a suitable fastening system and resting on ballast and subgrade is called the railway track or permanent way [26]. Sometimes temporary tracks are also laid for conveyance of earth and materials during construction works[7]. The name permanent way is given to distinguish the final layout of track from these temporary tracks. Fig. 1 below shows a typical cross section of a permanent way on an embankment.

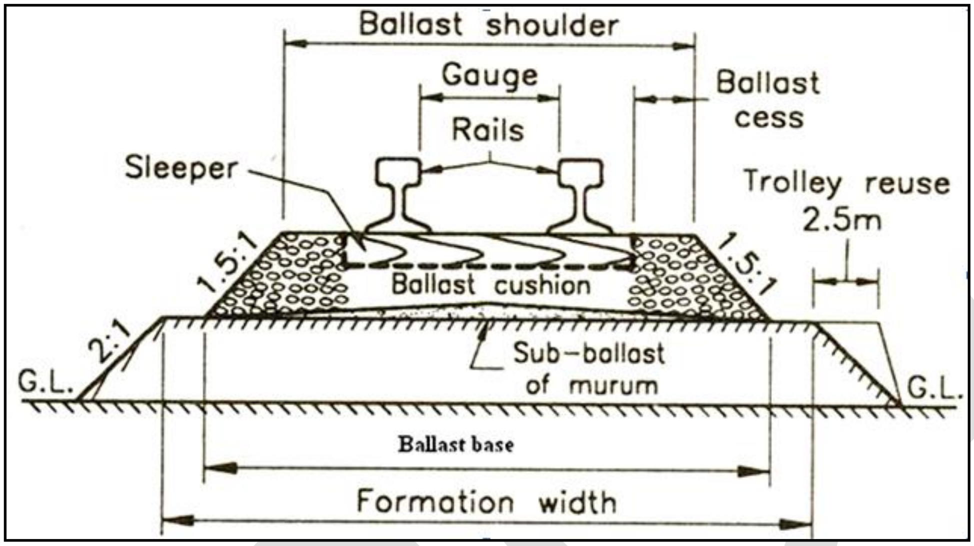


Fig.1. *Typical cross-section of a Permanent way on embankment*

In a permanent way the rails are joined in series by fish plates and bolts and then they are fixed to sleepers by different types of fastenings. The sleepers properly spaced, resting on the ballast are suitably packed with ballast. The layer of ballast rests on the prepared subgrade called the formation.

The rails act as girders to transmit the wheel load to the sleepers. The sleepers hold the rails in proper position with respect to proper tilt, gauge and level, and transmit the load from rails to the ballast. The ballast distributes the load over the formation and holds the sleepers in position. On curved tracks, super elevation is maintained by ballast and the formation is leveled. Minimum ballast cushion is maintained at the inner rail, while the outer rail gets kept more ballast cushion. Additional quantity of ballast is provided on the outer cess of each track for which the base width of the ballast is kept more than for a straight track [26].

Rails:

The rails on the track act as steel girders for the purpose of carrying axle loads. They are made of high carbon steel to withstand wear and tear. Flat-footed rails are mostly used in railway track. The functions of rails are as given below:

- Rails provide a hard, smooth and unchanging surface for passage of heavy moving loads with a minimum friction between the steel rails and steel wheels.
- Rails bear the stresses developed due to heavy vertical loads, lateral and braking forces and thermal stresses.
- The rail material used is such that it gives minimum wear to avoid replacement charges and failures of rails due to wear.
- Rails transmit the loads to sleepers and consequently reduce pressure on ballast and formation below.

The rails of larger length are preferred to smaller length of rails, because they give more strength and economy for a railway track. The weakest point of a track is the joint between two rails. Lesser the number of joints, lesser would be the number of fish plates and this would lead to lesser maintenance cost, smoother running of trains and more comfort to the passengers. Moreover the more number of joints increase wear and tear of the vehicle components, including wheels [26].

Rail Fasteners:

Probably one of the most spectacular developments that permanent ways went through since the beginning of the railways can be seen in the improvement of fastening systems. This development became more rapid in the last decades, especially in the last few years. It can be explained by the increasing demands of railway transport due to the competitive situation between transport means. The demands railways have to satisfy are the reduction of travel time, punctuality and comfort. These improvements are realized in practice by high-speed tracks and generally by continuously increasing speed. But these demands of railway traffic increase the severity of requirements a permanent way has to meet [11].

One of the most important aspects transportations are judged by is protection of the environment. Basically it can be stated that railway is an environment friendly means of transport. In spite of this fact the damaging influences that are mostly noise- and vibration nuisance have to be decreased [23]. These considerations also justify the development of special solutions of permanent way elements.

All the requirements mentioned above revive the need of development of new fastening systems that basically differ from the traditional types. The most important function of fastening systems is to provide strong and flexible connection between rail and its supporting structure that can be sleeper or slab. In addition to this main function fastenings have to meet other requirements that are in some cases contradictory [11].

Operations and maintenance requirements can be as important as the track strength considerations, because they address real issues of concern for maintenance personnel who have ultimate responsibility in using rail fastening components in the field. Among the intangible considerations are: fastener life, maintainability, and, where needed, electrical isolation [31, 30].

The final category of fastener characteristics is one that addresses the overall cost of the track system. It is a matter of particular importance to private freight railroads. Any criterion, then, developed for both tangible and intangible performance characteristic s must be evaluated in light of total system costs. Further, these must be life cycle costs taken within the railway operating environment as against simple first costs [23].

Sleepers:

Sleepers are members generally laid transverse to the rails on which the rails are supported and fixed, to transfer the loads from rails to the ballast and subgrade below [26]. Sleepers perform the following functions [26]:

i) To hold the rails to correct gauge (exact in straight and flat curves, loose in sharp curves and tight in diamond crossings).
ii) To hold the rails in proper level transverse tilt i.e., level in turnouts, crossovers, etc., and at 1 in 20 tilt in straight tracks, so as to provide a firm and even support to rails.
iii) To act as elastic medium in between the ballast and rails.
iv) To distribute the load from the rails to the index area of ballast underlying it or to the girders in case of bridges.
v) To support the rails at a proper level in straight tracks and at proper super elevation on curves.
vi) Sleepers also add to the longitudinal and lateral stability of the permanent track on the whole.
vii) They also provide means to rectify track geometry during service life.

For good performance of sleepers to fulfill the above functions or objectives an ideal sleeper should possess the following characteristics [26]:

i) The sleepers to be used should be economical, i.e., they should have minimum possible initial and maintenance costs.
ii) The fittings of the sleepers should be such that they can be easily adjusted during maintenance operations such as easy lifting, packing, removal and replacement.
iii) The weight of sleepers should not be too heavy or excessively light, i.e., they should have moderate weight, for ease of handling.
iv) The design of sleepers should be such that the gauge, alignment of track and levels of the rails can be easily adjusted and maintained.

v) The bearing area of sleepers below the rail seat and over the ballast should be enough to resist the crushing due to rail seat and crushing of the ballast underneath the sleeper.
vi) The sleeper design should be such as to facilitate easy removal and replacement of ballast.
vii) The sleepers should be capable of resisting shocks and vibrations due to passage of heavy loads of high-speed limits.
viii)The design of the sleepers should be such that they are not damaged during packing processes.

ix) The insulation of rails should be possible for track circuiting, if required, through sleepers.

Classifications of sleepers:

Sleepers can be classified according to the material used in their construction in the following way [26]:

1) Wooden sleepers
2) Metal sleepers
    a) Cast iron sleepers
    b) Steel sleepers
3) Concrete sleepers
    a) Reinforced concrete sleepers
    b) Prestressed concrete sleepers

A detailed note based on concrete sleepers is presented in the preceding sections.

Design Considerations for Concrete Sleepers:

As noted above, the railway was originally developed to have higher load-carrying capacities than the roads. One of the pioneers in the history of railways was G.Stephenson, who built his first steam locomotive in 1813. In the development of the railway a component acting and looking like the sleeper of today was invented quite soon. The demands on the sleepers have increased with the improvement of the railway [25]. In the early railways, the natural choice of material for the sleeper was often wood. One reason for starting to use reinforced concrete sleepers was to get a great reduction in the overall cost of track maintenance [1].

A reference body of experiments with reinforced concrete sleepers arose as far back as 1880, and reinforced concrete sleepers were used quite extensively in the 1920s and 1930s in countries such as Italy and India [5].The use of reinforced concrete sleepers increased the structural stiffness and developed unique problems that are not associated with wooden sleepers, such as flexural cracks which could lead to deterioration of the sleepers [19]. This fact, together with shortage of good-quality timber during World War II blockades, forced in the development and use of prestressed concrete sleepers. Since then, the use of prestressed concrete sleepers has increased and become standard in the railway tracks of several countries. The development of prestressed concrete sleepers solved the early problems associated with the ordinary reinforced concrete sleepers [27].

The study of loads on sleepers in tracks had low priority from the 1940s to the 1980s.Early work in the UK showed that very high loads occurred at rail joints, and also due to the balance weight on steam locomotive wheels. In the 1980s rail seat cracking of sleepers, i.e. cracks at the base of the sleeper in the position of the rail, was found in the Northeast Corridor, USA. This led to new studies of loads on sleepers [7].

The source of the overloading was found to be out-of-round wheels generating dynamic loads, and further research revealed additional factors involved in the dynamic load generation [30, 31]. Different influencing parameters regarding the generation and magnitude of the dynamic loads have been identified during the years, as per Ahlbeck (1980) [2], Grassie and Cox (1984) [12], Buekett *et al*. (1987) [6], Igwemezie and Saeed Mirza (1989) [17, 24], Dahlberg and Nielsen (1991) [8], Wakui and Okuda (1991) [28]. The reported parameters are vehicle speed, wheel imperfections, random differences of levels between rails, type and condition of the suspension system, rail joints, and corrugation of the railhead [14, 15, 16, 17]. A literature survey to describe the state of the art in research concerning out-of-round wheels has been written by Johansson and Nielsen (1998) [18].

According to Wakui and Okuda (1991) the largest dynamic load induced to the track may be one caused by irregularities of the wheel such as wheelflats. Wheelflats are caused by the wheels of a vehicle becoming locked during braking, and sliding along the track. The friction created by this grinds a flat spot on the wheel, see Newton and Clark (1979) [20]. The wheelflats causes impact loads, i.e. loads generated by a stroke with short duration. The duration of the impact load caused by wheelflats is in the range of 1-3 microseconds, according to Xiang *et al*. (1994) [29], and its magnitude can be several times larger then the static load caused by the weight of the train. Research carried out by Harrison and Moody (1982) [16] and Dean *et al*. (1982) showed that cracks found in the prestressed concrete sleepers were strongly connected with the presence of wheelflats.

Design considerations for prestressed concrete sleepers:

Results from many research projects show that the design philosophies used in different countries fail to capture all necessary considerations [5]. The traditional philosophy is to use a static design system, where the static nominal axle load, *FStat*, is increased by a dynamic factor, η_{Dyn}, as shown in Figure 2. Railway authorities often assume a uniform distribution of the ballast pressure, p, beneath the sleeper, or other simplified pressure distributions [9, 10]. However, this approach does not consider the dynamic effects in the sleeper, caused by the impact loads. The impact loads introduce stress waves and rebound reactions that are essential to account for, if the dynamic behavior of a sleeper is to be analyzed correctly [24].

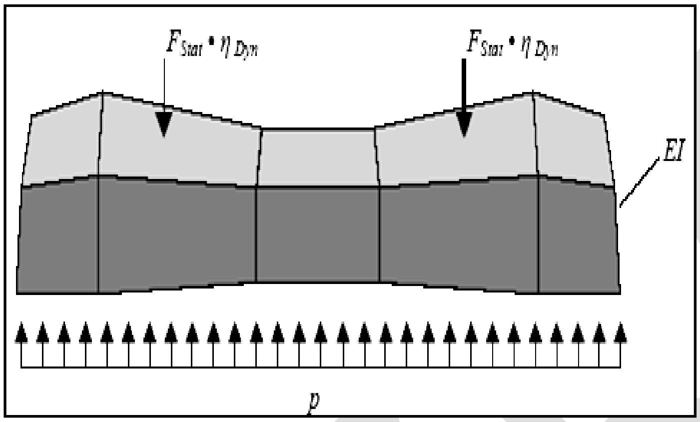


Fig.2. *Static design system of a sleeper*

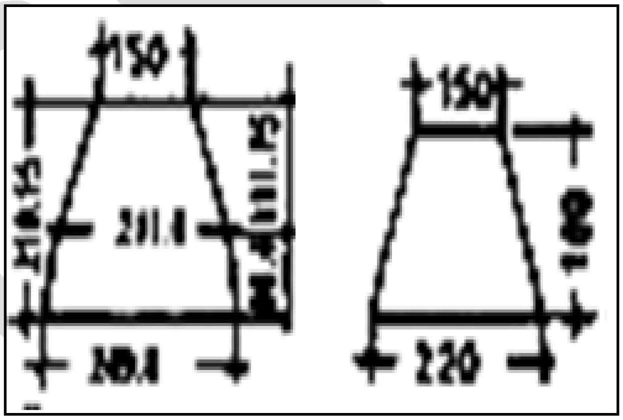


Fig.3.*Sleeper cross section as per RDSO/T-2496[32***]**

DESIGN AND MODELLING OF CONCRETE SLEEPERS

Sleeper Section:

The sleeper considered in the present work is of RDSO (Research Division and Standards Organization) T-2496 type pre-stressed concrete sleeper. The cross section of the sleeper varies in shape and size from the rail seat end to the centre of the sleeper [32]. The sleeper is symmetric in shape and size about its centre portion. The total length of the sleeper as per RDSO is 2600 mm. At the rail seat the top width of the sleeper end 150 mm where as the bottom width is 249.8 mm. The bottom width at the rail seat varies from 249.8 mm to 211.8 mm till a height of 98.4 mm from the seat bottom. At the centre of the sleeper the cross sectional width varies from 220 mm at bottom to 150 mm at the top with a height of 180 mm. The central distance between the rail seats, i.e. broad gauge distance between the two rails laterally is 1.761 m. The cross sectional area of sleeper as per RDSO specifications is shown in Figure 3.

Material Properties:

Prestressed concrete is basically concrete in which internal stresses of a suitable magnitude and distribution are introduced so that the stresses resulting from the external loads are counteracted to a desired degree. Prestress is defined as a method of applying pre-compression to control the stresses resulting due to external loads below the neutral axis of the beam tension developed due to external load which is more than the permissible limits of the plain concrete. The pre-compression applied (may be axial or eccentric) will induce the compressive stress below the neutral axis or as a whole of the beam c/s. Resulting either no tension or compression.

For the present work it is assumed that the prestressed concrete sleeper acts as an elastic beam member. As per IS1343:1980, Its density is taken as 2400 kg/mm^3, Young's modulus is taken as 30 GPa, Poissons ratio is taken as 0.3 and its ultimate strength is taken as 40 MPa.

Modeling of the concrete sleeper:

To model the sleeper, initially the geometric model of the sleeper is built in ANSYS12.1 and then the finite element model is built. In order to model the rather complicated geometry of the sleeper, key points are input in absolute coordinate form and these key points are created at one end, i.e. rail seat end of the concrete sleeper and also at the centre of the sleeper where the cross section varies. Further areas have been created by using key points at rails seat end cross section and also at the centre of the sleeper. Adjoining areas have also been created between the two cross sections. These areas have been glued using Boolean operations and then a volume is created using all the six areas. At this stage a half sleeper model is created. The half sleeper volumetric model is then reflected about the centre cross sectional plane to create the other half of the sleeper and both the volumes are added using Boolean operations. In this way, full sleeper volumetric model is built in ANSYS 12.1. The Line model describing the cross section areas and also the sleeper volumetric model built are shown in Fig.4. and Fig.5. respectively.

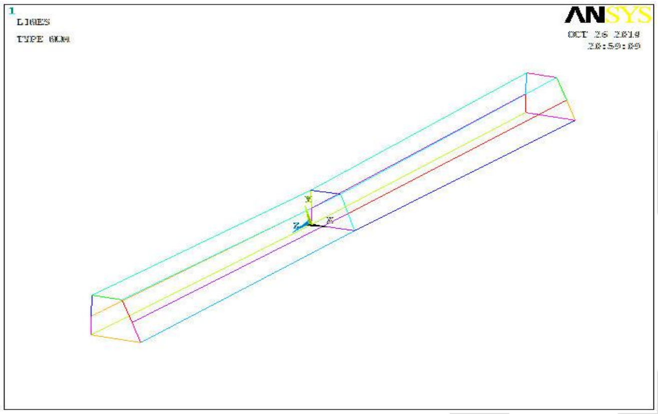


Fig.4. *Line Model of the Sleeper*

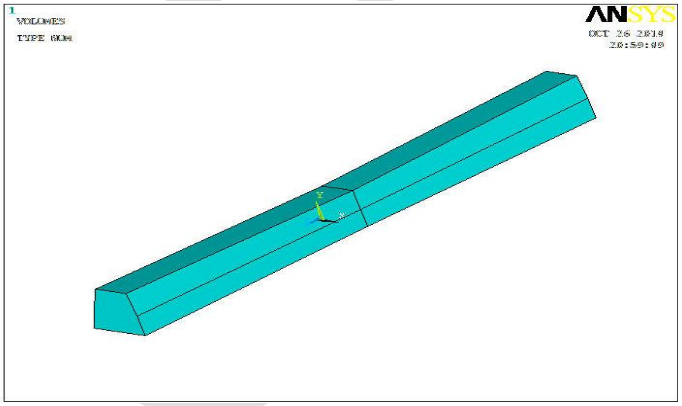


Fig.5. *Volumetric Model of the Sleeper*

FE Model of the Sleeper:

The volumetric model of the mono block sleeper built in ANSYS is then discretized with 20 node brick elements of SOLID 186 element type to build the Finite element model of the sleeper for further analysis. A total of 2940 elements and 1647 nodes have been used in the FE mesh of the sleeper model. The FE model has been utilized for studies of influential parameters and thereby a better knowledge concerning the structural behavior of a concrete sleeper is gained. The obtained FE meshed model of the sleeper is shown in Fig.6.

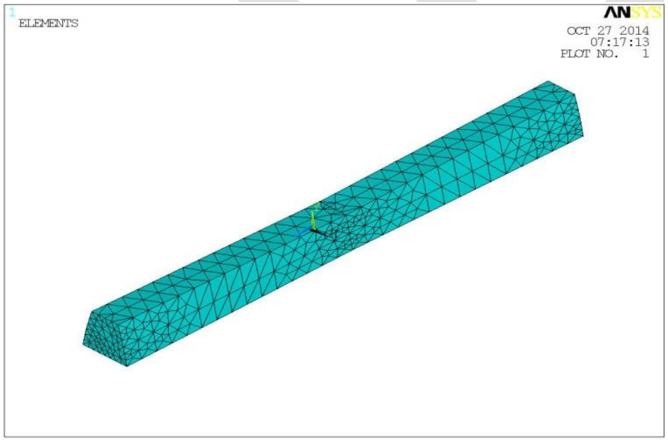


Fig.6. *FE Model of the Sleeper*

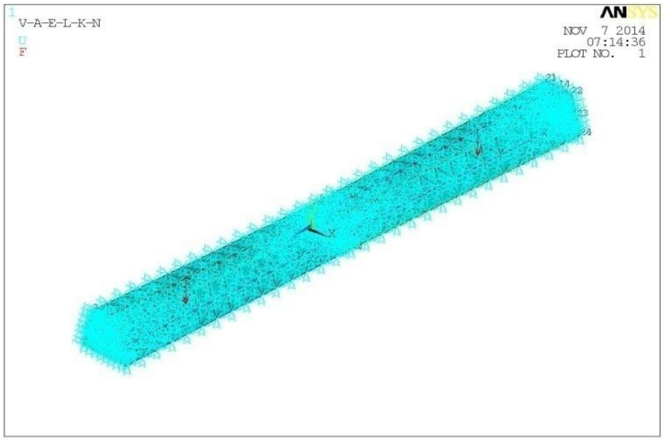


Fig.7. *Constrained Sleeper Model*

STATIC ANALYSIS OF CONCRETE SLEEPERS

Boundary conditions:

In general, the sleeper is supported by ballast which acts as elastic cushion for the sleeper between the rails and the embankment. Hence, for static stress analysis we consider that the sleeper is constrained at its bottom and also at its tapered cross section ends. The surfaces areas of the sleeper which are covered in and around by the ballast are hence constrained in the solution module of ANSYS.

Loading conditions:

The sleepers are rigidly fastened to the rails at a distance of 1.761 m which is called as broad gauge as per the RDSO specifications for the Indian Railways. The locations on the top surface of the sleeper where the I- sectioned rails are positioned are called as rail seats. As per RDSO specifications when the moving train travels, the operating conditions consider that a single sleeper takes a load of 15000 kg which is transferred by the rails on to the rail seat locations of the sleeper. Hence, considering a hypothetical load case of 15000 kg vertical load being transferred to a single sleeper, the identified nodes 823 and 824 which are the rail seat locations are given a load of 73575 kN each. The constrained FE Model of the sleeper along with the loads applied are shown in Fig.7.

Static Stress Analysis results:

On carrying out the static analysis, deflections and stresses are obtained for the sleeper model. It can be observed that the vertical displacement is maximum at the rail seat with a value of 21.165 mm. The maximum equivalent stress value is 4839 N/mm2 which can be observed at the rail seat. Since the elastomeric pad is linked between the rail and sleeper along with fasteners the behavior at rail seat is tolerable. The stress and displacement plots are shown from Fig.8 to Fig.11.

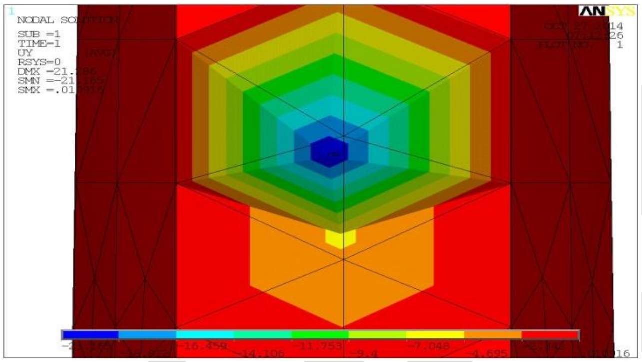


Fig.8. *Maximum Deflection at rail seat*

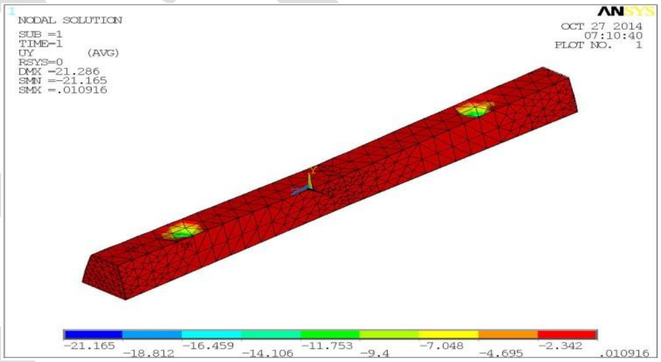


Fig.9. *Vertical Deflection of sleeper*

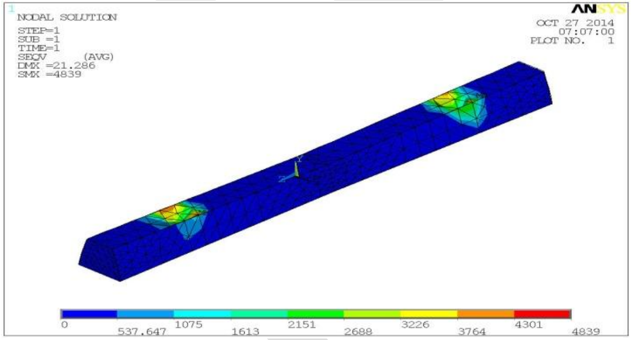


Fig.10. *Von-mises Stress*

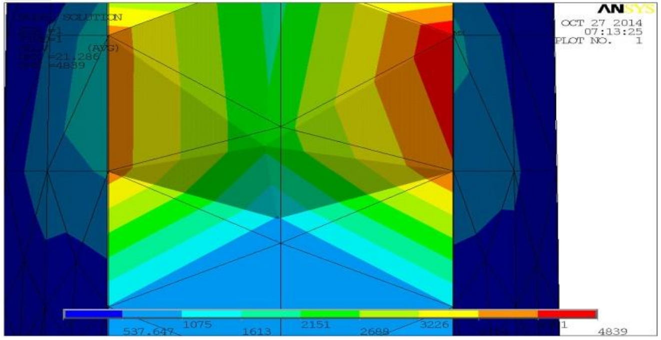


Fig.11. *Maximum Von-mises Stress*

DYNAMIC RESPONSE OF SLEEPER

For analyzing and understanding the dynamic response of the sleeper two different criteria are considered in the present work. In the first criteria, the sleeper's response under its self weight without considering any constraints is analyzed and its fundamental frequencies and mode shapes are obtained. This condition of sleeper is called free-free condition. In the second criteria, the condition of the ballast supporting the sleeper at its bottom surface and adjoining side surfaces at the rail seat end is considered similar to the boundary conditions considered in static analysis. This condition is called In-situ condition.

Modal Analysis of Sleeper in free-free condition:

Eigen frequency modal analysis is performed on the sleeper in a free-free condition without considering any constraints on the sleeper. In ANSYS, Block Lanczos method in the modal analysis is used for obtaining the first twenty natural frequencies and mode shapes of the sleeper model. Block Lanczos method successfully gives results for symmetric structures. The lowest fundamental frequency obtained in this condition is 3.3871 Hz with a maximum displacement of 0.122344 mm at the rail seat ends. The mode shapes obtained in free-free condition of the sleeper are shown in Fig.12and Fig.13.

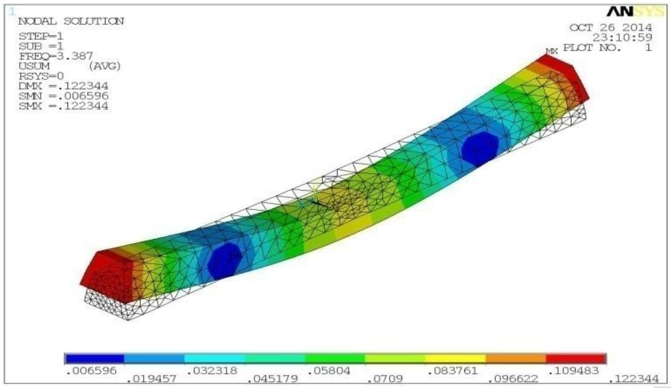


Fig.12.*Mode 1 of Sleeper in Free-Free criteria*

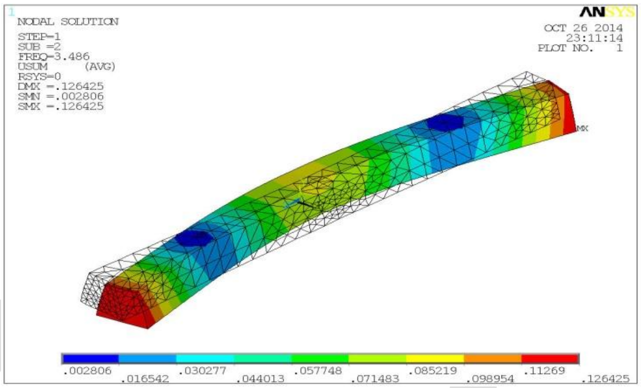
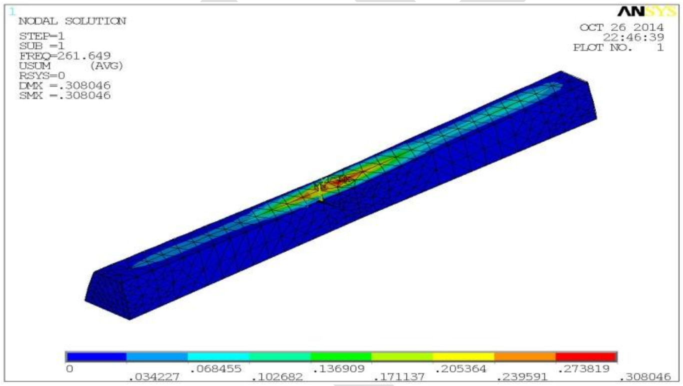


Fig.13.*Mode 2 of Sleeper in Free-Free criteria*

Modal Analysis of Sleeper in In-situ condition:

Eigen frequency modal analysis is performed on the sleeper in a In-situ condition by constraining the bottom surface and adjacent surfaces of the sleeper. In ANSYS, Block Lanczos method in the modal analysis is used for obtaining the first twenty natural frequencies and mode shapes. Block Lanczos method successfully gives results for symmetric structures. The lowest fundamental frequency obtained in this condition is 261.65 Hz with a maximum displacement of 0.308046 mm near the centre of gravity of the top surface of the sleeper. The mode shapes obtained in the In-situ condition of the sleeper are shown from Fig.14 to Fig.15.

The natural frequencies obtained for the sleeper model as in free-free and in-situ conditions are presented in the table 1. It can be observed that in the in-situ condition which is the practical condition for sleeper in the railway track, the frequencies are substantially higher and signifies that the ballast cushions the sleeper effectively.



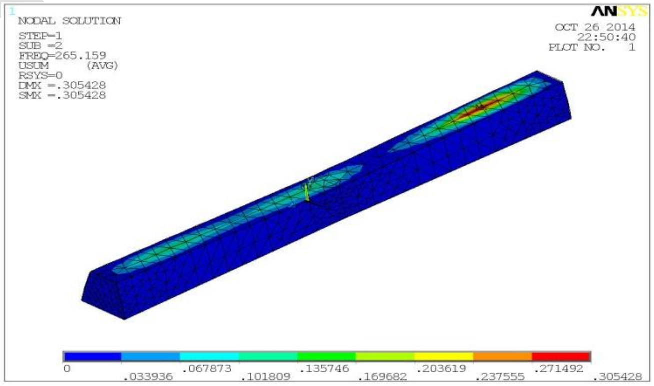


Fig.14. *Mode 1 of Sleeper in In-Situ criteria*

Fig.15. *Mode 2 of Sleeper in In-Situ criteria*

Table 1. *Natural frequencies of sleeper in Free- Free and In-Situ Conditions*

MODE No.	FREQUENCY(Hz) FREE- FREE	FREQUENCY(Hz) IN-SITU
1	3.3871	261.65
2	3.4861	265.16
3	10.011	266.90
4	10.092	278.34
5	14.753	283.68

6	18.676	288.44
7	18.827	288.65
8	20.418	290.10
9	29.070	299.36
10	29.554	299.80
11	34.631	309.17
12	41.046	310.37
13	41.402	311.96
14	43.078	314.70
15	48.503	322.85
16	54.384	328.35
17	54.923	330.52
18	64.194	335.80
19	65.819	344.71
20	68.121	346.83

CONCLUSIONS

Analytical results from the established finite element model of a concrete sleeper showed expected behavior static load conditions. The structural response up to the maximum load capacity of the sleeper, with yielding of the reinforcement, is well captured in the finite element analysis. This analysis showed that the finite element program was well suited for modeling concrete sleepers. The hypothetical load case considered in the present work shows that the rail seat end locations of the sleeper are affected. The finite element model of the sleeper and the constraints in the form of underlying ballast included showed fairly good agreement with the global track model for downward displacement of the rail from its original position. The sleeper model revealed a complex interaction between the sleeper and the underlying ballast, and showed that impacts occur between the sleeper and the underlying ballast as the wheel of the train passes the sleeper.

Vibration characteristics of railway concrete sleepers are crucial for the development of a realistic dynamic model of railway track as well as the concrete sleeper itself, which are capable of predicting its dynamic responses. The results of the simulated modal analysis for prestressed concrete sleepers under different boundary conditions are presented in this work. Two types of conditions are considered, and it is observed that in the free-free condition the natural frequencies are much lower to that of the in-situ condition which considers the ballast support condition. It is found that the resonant frequencies associated with the lower mode of vibration of prestressed concrete sleepers are considerably affected by the support boundary conditions. The dominant effect of the ballast support is placed on the modal damping in the ballast-sleeper interaction. In addition, the mode shapes, which can indicate the deteriorated state of concrete sleepers, were affected by the ballast conditions. In summary, the in-situ condition had a remarkable influence on the natural frequency, modal damping, and vibration mode shape of prestressed concrete sleepers, especially in the low frequency range and flexural deformation.

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