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Comparative Analysis of Ballastless Track System Design Using Analytical And Numerical Tools

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Abstract-Railways is becoming faster, with high speed running vehicles exerting wheel loads on tracks could become critical for track quality and the overall lifecycle. To cope with such high loads, state of the art ballastless track systems could be a long-term solution and to increase its acceptance under limited economic boundary conditions. Finite Element Modeling (FEM) is powerful tool that optimizes the design of the ballastless track. This study examines the reliability and verification of Finite element (FE) Models with analytical tools. Firstly, using analytical tools, the Zimmermann and the Westergaard methods, continuously reinforced concrete pavement (CRCP) slab with various cracking distances are designed followed by numerical design and analysis. Comparative design analysis is then carried out between analytical and numerical tool to evaluate the impact of input parameters on each of the tools. The finite element package SOFiSTiK is used to model ballastless track design. The verification of FE- model is also done based on calibrations, results and boundary conditions to check reliability, behavior and working. Lastly author gives some guidelines for the model verification.

Keywords-Ballastless Track System, Finite Element Modeling, Westergaard and Zimmerman Methods, Continuously Reinforced Concrete Pavement

I. INTRODUCTION

Railways have distinct advantages over other transport modes such as it's more efficient in terms of fuel costs and economy over longer distances, safety, reliability and speed, which is achieving new horizons. Railways is becoming faster and due to exponential increase in the number of people using railways, the need to maintain the quality of travel is believed to be more than ever before. The quality can only be improved by constant improvement in the technical design for both vehicles and tracks [i].

Countries around the world are strongly developing rail transportation, especially the development of high-speed rail. There are many forms of high-speedrailway, such as ballasted track, ballastless track, magnetic suspension railway, etc. High speeds and heavy loads of trains are usually accompanied with large vibrations in the train–track–ground system, especially when train speed reaches its critical value, leading to possible train derailment and track damages [ii]. Conventional ballasted railway tracks demand a lot of maintenance works due to uneven settlements of the ballast during operation. Existing experiences show this kind of maintenance work is significantly increased for high-speed lines [iii, iv]. As comfort safety and economy are primarily the most important, state of the art ballastless track constructions offer therefore an alternative solution due to the enormous reduction of maintenance work and the long service life with constant serviceability conditions [v]. The ballastless or slab track is a concrete or asphalt surface, replacing the standard ballasted track. In ballastless track system involving CRCP investment costs are higher and the maintenance costs are lower and the application of CRCP is limited to heavily loaded pavements Concrete is the prevailing material in slab track applications throughout the world. Asphalt has been used less as compared to concrete, as a material for slab track constructions due to its high construction demands. Continuously reinforced concrete pavement (CRCP) is the technology used for ballastless tracks. The absence of the transverse contraction joints and a well-defined pattern of transverse cracks are the major attributes that identify CRCP. [vi].

Taking care of economic boundary conditions and to increase the acceptance of ballastless track systems, Finite Element Models (FEM) is among the best solution to optimize the design of the ballastless track cross-section based on the selected parameters. This optimization can be done by a comparative analysis between analytical (Westergaard and Zimmerman) and numerical (FEM) approaches. Sofistik is Europe's leading software (FEM-based) for analysis, design and detailing of construction projects worldwide. For this paper SOFiSTiK is the main object of utilization and will be used throughout the work.

II. LI REVIEW

The ballastless or slab track is a concrete or asphalt surface, replacing the standard ballasted track. In Ballastless track rails and sleepers are embedded in concrete and can't be adjusted once laid. Therefore, it must be laid within a tolerance level limit of 0.005 m. As the structure is made of stiff and brittle materials, the required elasticity can be obtained by introducing elastic components below the rail or/and the sleeper [vii]. Typical ballastless track is shown in Fig. 1.

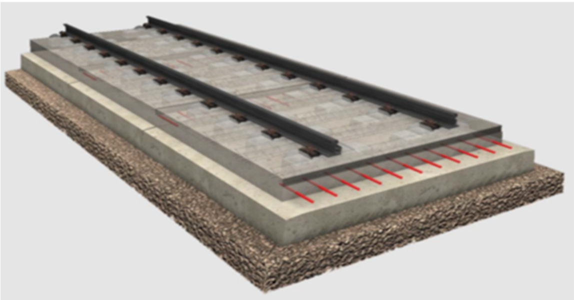

Fig. 1. Typical Ballastless track System

In slab track construction, ballast used in common railway is replaced by a more durable supportive material such as concrete or asphalt. To achieve the required level of track elasticity for wheel/rail systems – normally provided by ballast – slab track construction must use an elastic rail pad for the rail support points. Supportive forces are thus distributed to adjoining support points. The construction principle behind slab tracks is a layered structure with a gradual decrease in stiffness level from top to bottom: Rails with rail fastening to the supportive layer.[viii]. See Fig. 2

- Rails and Rail Fastening system
- Concrete supportive layer (CSL) or asphalt supportive layer (ASL)
- Hydraulically-bonded layer (HBL)
- Frost protection layer (FPL), Subgrade foundation..

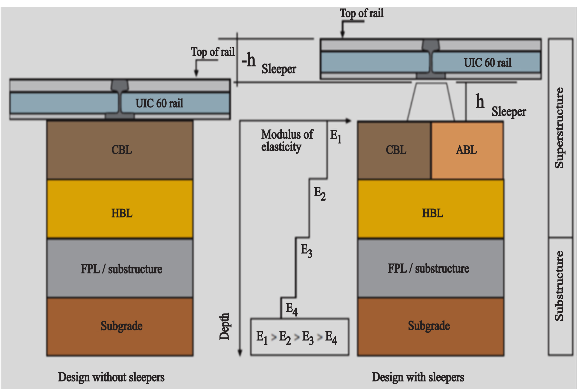

Fig. 2. Usual Construction Profile of Ballastless track system [Darr, 2000]

In practice the application of CRCP is limited to heavily loaded pavements. Continuously reinforced concrete pavements (CRCP) have a small amount of longitudinal reinforcement (around 0.6 to 0.7% by cross-sectional area) for controlling the crack pattern, i.e. the crack width and the crack spacing. The reinforcement is located (about) mid-depth within the concrete layer. A CRCP does not contain any transverse joint as shown in Fig. 3. In general, compared to JPCP, the CRCP investment costs are higher and the maintenance costs are lower. [ix].

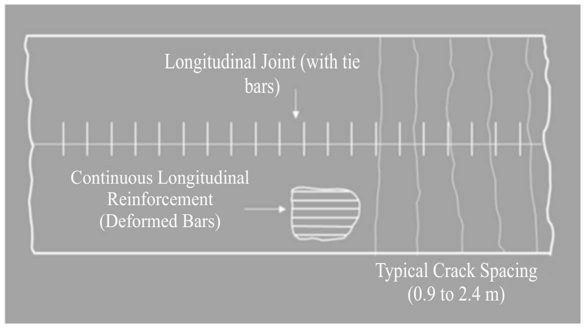

Fig. 3. Design characteristics of CRCP

Some of the main characteristics are:

- Reinforcement does not deal with stresses introduced by traffic loading
- Because of short crack spacing (<<5m) thermal stresses introduced by temperature differences Δt between surface and bottom of the concrete pavement due to heating and cooling (warping and curling) are smaller than for conventional JPCP (slab length 5m). Consequently, slab thickness can be reduced by about 10% to 20% compared with JPCP (Slab length 5m) for same traffic loading [x]
- Reinforcement controls transverse cracking due to shrinkage and temperature changes in such a way that crack width is not exceeding 0.5mm and crack distribution along the pavement is uniform. Crack distance shall be much shorter than 5m but not shorter than 0,5m

III. Analytical Design of Ballastless Track System

Ballastless track systems with continuously reinforced concrete pavements (CRCP) overlaid by the layer of Cement treated base (CTB) and unbound granular based layer are the case study. Ballastless track without sleepers but direct fixation (discrete rail seats) is considered using UIC (French: Union Internationale des Chemins de fer) 60E1 rail as shown in Fig. 4.

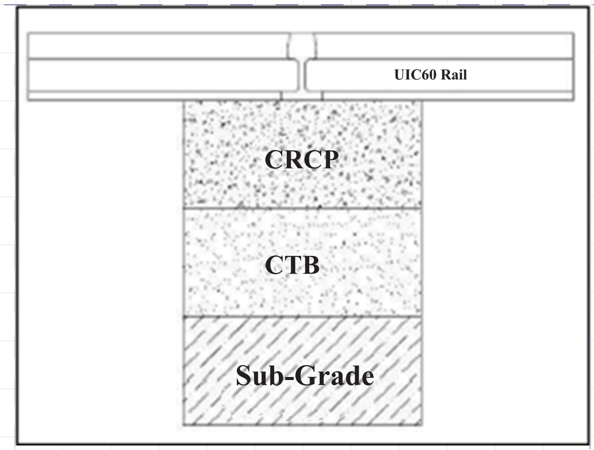

Fig. 4. Ballastless track without sleepers

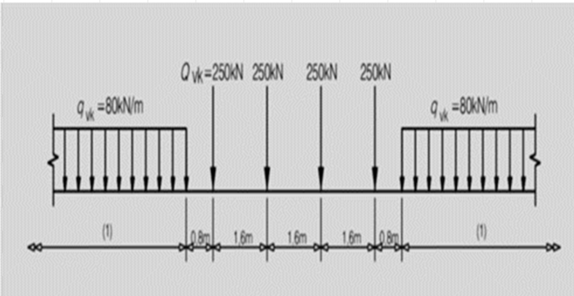

Fig. 5. Model UIC 71

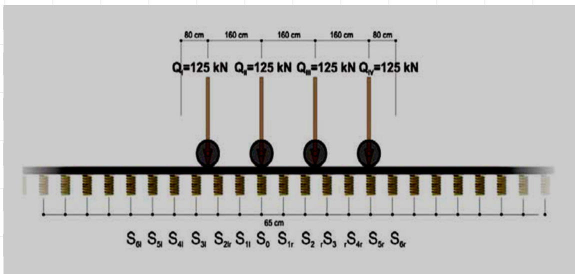

Fig. 6. Pattern of wheel load over the support points [Lehrstuhlfür Verkehrswegebau, 2014a]

For the calculations following parameters had been used:

- Rail 60E1
- Dynamic spring coefficient of Cdyn = 40 kN/mm
- Contact area 150x150mm
- Concrete slab with E1 = 34000 N/mm2
- Cement Treated Base with E2=5000N/mm2
- Unbound layer with Es=Ev= 120 N/mm2
- Spacing between rail pads = 650 mm
- Poisson's ratio of concrete slab µ1=.16
- I = 30550000 mm4 for Rail profile 60E1
- E = 210000 N/mm^2

Rail seat loads are calculated involves dimensioning of ballastless track system. Procedure includes distribution of rail loads into single loads which are further calculated as a rail seat loads.

Rail seat loads are calculated at 11 support points with load acting directly over support point So (Interior of slab)

Using input parameters, the elastic length of rail

$$L = \sqrt{\frac{4.E.I.a}{c}}$$

As seat load S = c.Y and deflection $Y = \frac{Q.a}{2.C.L} \times \eta$. Load, Q is increased by both dynamic and curvature (outside rail) by the factors of 1.5 and 1.2 respectively. While for inner side rails curvature factor of .8 is being used.

Maximum Seat load S_0 under load Q2 considering factors of 1.2 and 1.5 for curves and dynamic loading comes out to be S_0=101000 N using following wheel load pattern over the support points.All the support point forces and deflections due to adjacent loads at outside and inside rail are calculated.

See below Table I & Fig. 7

TABLE I
SUPPORT POINT FORCES AND DEFLECTIONS

Rail Seat Si Support Point on Outside rail	Deflection [mm] Outside rail	Rail Seat Load [kN] Outside rail	Rail Seat Si' Support Point on Inside rail	Deflection [mm] = Reduced by .8/1.2 (Inside rail)	Rail Seat Load [kN] = Reduced by .8/1.2 (Inside rail)
S4l	0.73	29.2	S4l'	0.49	19.6
S3l	1.90	76.0	S3l'	1.27	50.9
S2l	2.40	96.0	S2l'	1.61	64.3
S1l	2.24	89.6	S1l'	1.50	60.0
S0	**2.52**	**101**	**S0'**	**1.69**	**67.5**
S1r	2.16	86.4	S1r'	1.45	57.9
S2r	2.37	94.8	S2r'	1.59	63.5
S3r	2.38	95.2	S3r'	1.59	63.8
S4r	2.25	90.0	S4r'	1.51	60.3
S5r	2.34	93.6	S5r'	1.57	62.7
S6r	1.24	49.6	S6r'	0.83	33.2

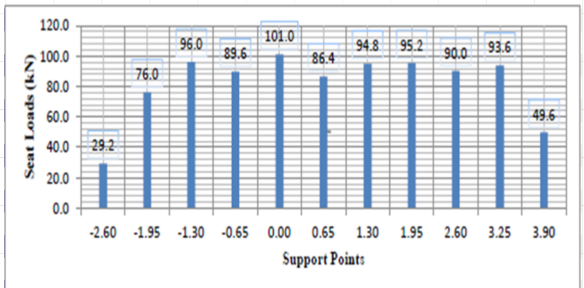

Fig. 7. Support point forces

IV. NUMERICAL DESIGN OF BALLASTLESS TRACK SYSTEM

The aim of this chapter is to understand the procedure to analyze the ballastless track system by developing 2D FE-Model of a slab using SOFISTIK Software.[xi] The model clarifies and verifies the theoretical/analytical analysis as discussed in previous section.

The 2D slab as per required slab length and width of slab track is drawn and the loads/seat loads are placed at their respective support points in Sofiplus as shown below in Fig. 8. After deciding the density of meshing, the model is imported to SSD. The Fig. 9 is showing the slab track model in SSD after getting imported from CAD tool and then linear analysis is taken place.

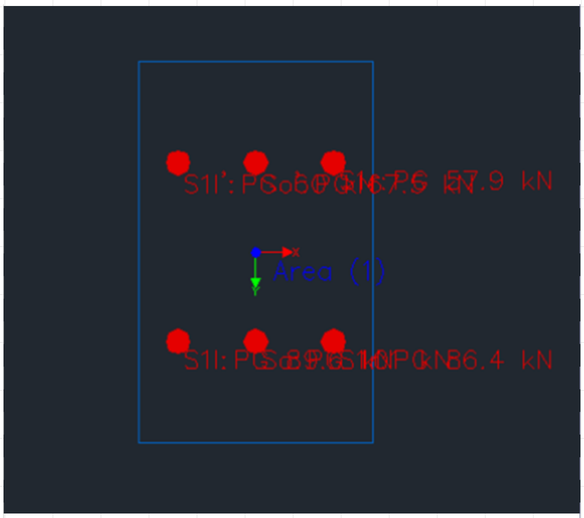

Fig. 8. 2D Slab/Pavement Model in Sofiplus

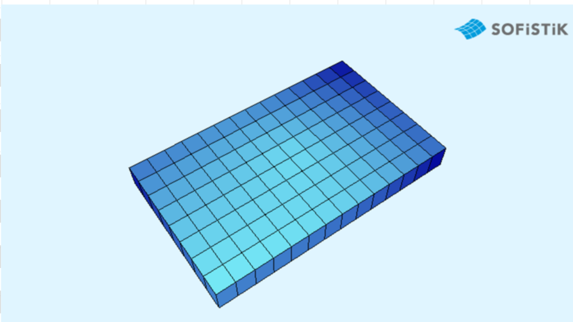

Fig. 9. Slab/Pavement Model in SSD

Different parameters were analyzed individually to see the behavior of model in SOFiSTiK including calibrating the slab model in SOFiSTiK with slab designed analytically. Different software parameters and their effect on the model were also studied. Actual bending tensile stress caused by single wheel acting in the centre of a slab was calculated with the Westergaard theory (Infinite slab size). The SOFiSTiK model was then calibrated by increasingthe slab size with load acting at the centre until it reached the analytical stress value as can be seen in Fig.10 and Fig. 11.

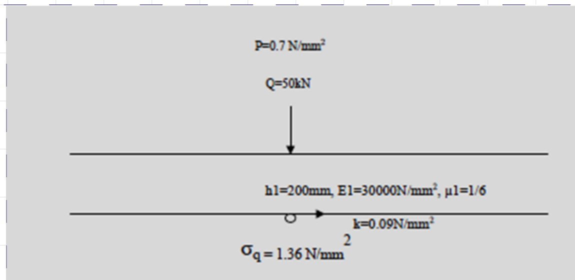

Fig. 10. Analytical Model – Westergaard

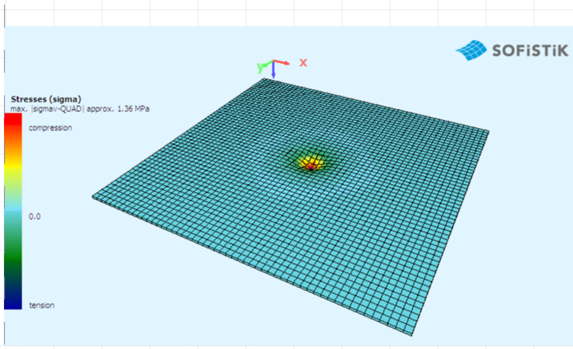

Fig. 11. Calibrated Model in Sofistik

Analysis of point and area loading with same input parameters showed little difference between the output results primarily due to relatively smaller contact area of 150 x 150 mm as shown in Fig. 12.

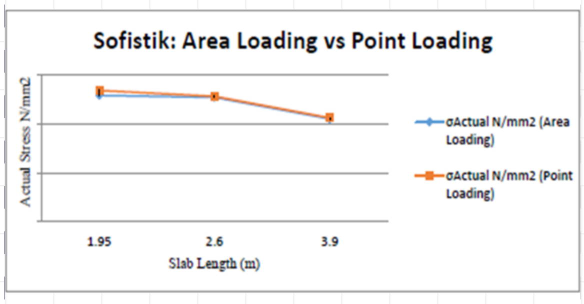

Fig.12. Area vs point load

Different meshing sizes/densities were analyzed to describe the effects on the output results. Analysis showed application of load changes with the change in density thus causes sharp decrease or increase in the output values.

A. Load At Intersection Of Elements

When changes in density of meshing caused load to act at node, a sudden increase in stresses were found thus a consistency of output results must be verified by analyzing meshing behavior. This loading position type was considered throughout in calculations as can be seen in Fig. 13.

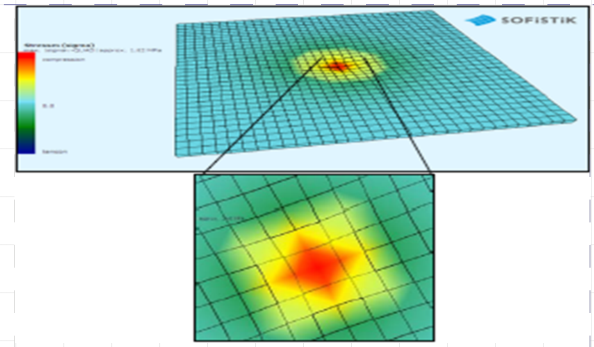

Fig. 13 Load acting at node

B. Load Acting At The Center Of Element

When changes in density of meshing caused load to act at centre of an element, a sudden decrease in stresses were found which can be seen in Fig. 14.

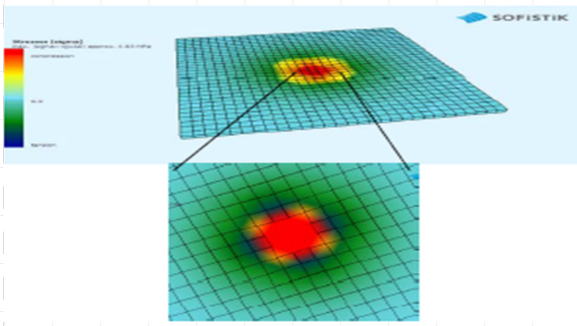

Fig. 14. Load acting at centre of element

Based on the study done in this chapter these are some of the important findings:

- Prior to confirmation results of stresses, suitable meshing density should be decided carefully to avoid sudden changes in the results due to changes in loading patterns. Here in this study load position at intersection of elements – nodes are considered for the calculations.
- Model needs adjustment to be comparable with theory; calibration does the role and shows how Sofistik model can be made compatible with theoretical results.
- Sofistik results shows with 150x150mm rail contact area, any loading type between rectangular and point can be considered for the design.
- Behavioural studies ensure consistent results.

V. Comparative Analysis of Results

Results from analytical and numerical studies are compiled together to understand their relation. Comparative analysis has been performed based on analysis of both analytical and numerical methods and the important conclusions from the study are discussed as follows.

A. Actual And Allowable Transversal/Longitudinal Stresses

Fig.15 and 16 are showing both, analytical and numerical designs are 'ok' and within the limits of allowable stresses for a slab length up till 4550mm thus exhibiting same trend. It is also clear from both figures that longitudinal stress is the decisive stress than the transversal stress. A difference in stress values can be seen between analytical and numerical actual stresses which are due to the fact that analytical design is based on infinite slab size and to make the differences less, calibration is needed.

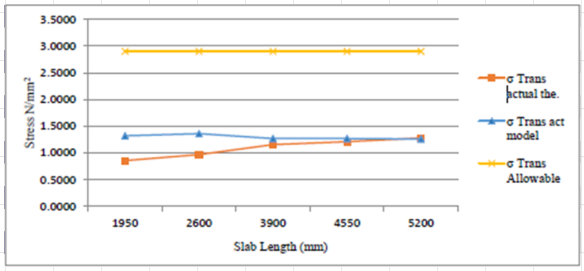

Fig. 15. Actual & Allowable transversal stresses

A. Vertical Stresses

Both actual analytical and numerical vertical stresses are below the allowable vertical stress at optimized thickness thus complimenting each other. The vertical stresses from numerical tool are constant in nature while analytical values increase with the increase in slab length, as shown in Fig. 16.

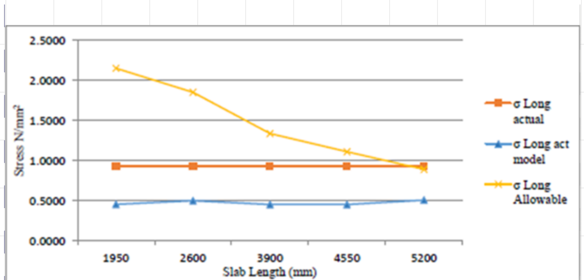

Fig. 16. Actual & Allowable longitudinal stresses

As the length increases the difference between numerical and analytical vertical stresses become lesser because of the UIC 71 loading pattern. Fig. 17 shows, in analytical design, relatively higher deflection trend in smaller lengths which gradually becomes lower with the increase in length because of the lower effect from the neighboring seat loads (as they are smaller in magnitude).

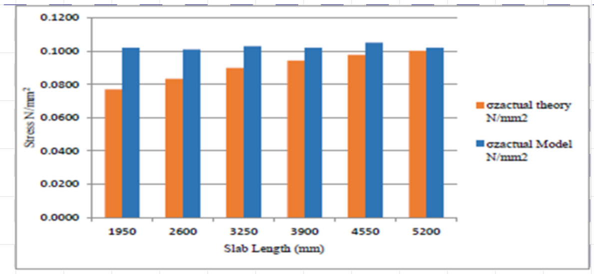

Fig. 17. Actual analytical and numerical vertical stresses

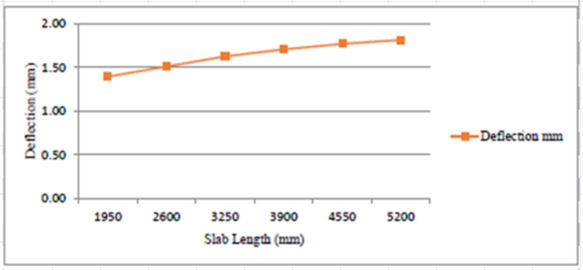

Fig. 18. Deflection-Analytical

VI. Verification of FE-Model

Verification of design based on FE-Models requires respective tools and procedures to ensure that models are properly working. Thus for accepting under study Sofistik model a realistic verification using analytical tools is carried out.

Comparisons between the stress results shows longitudinal stresses determined by FEM model are much lower than the stresses calculated by Westergaard/Zimmermann theories while transversal stresses calculated by numerical approach are higher than the analytical. Significant difference can be seen from Fig. 19 and 20.

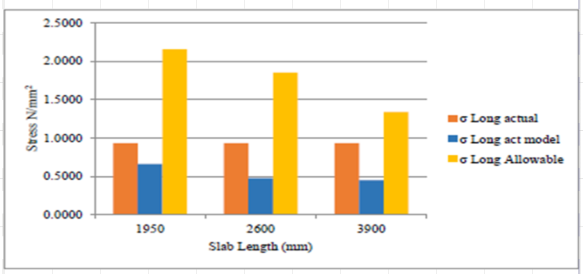

Fig. 19. Actual and Allowable stresses – Longitudinal

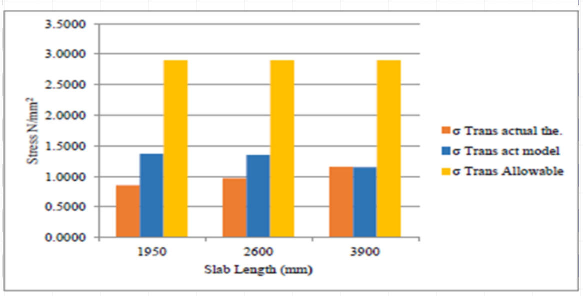

Fig. 20. Actual and Allowable stresses – Transversal

These differences between analytical and numerical could be understood from two theories. First theory refers to the geometry of a slab, Westergaard approach doesn't consider slab size rather size of a slab is considered infinite. Similarly, Zimmerman approach only considers width of slab. Second theory deals with the type of loading as mentioned in chapter 4, there are drastic changes in stress values with the change in load type e.g. load acting at a node.

So to verify the SOFiSTiK model with analytical results, the calibration is done based on both theories and the study being already discussed in chapter 5.

Comparative and closer results are found once model is adjusted and calibrated with analytical values as shown in tables below. As it is previously observed longitudinal stresses coming from models are lower than the theoretical values and transversal stresses have an opposite trend (Fig. 21&22). Lengths are adjusted to get the desired results by considering consistent loading type (meshing) for example in case of slab length 1950mm the adjusted slab lengths comes out to be 2600mm vs. 2750mm with load acting at the intersection of an element. It means longitudinal slab length is stretched by 325mm from each side of a slab and transversal slab length is curtailed by 225mm from each side. Similarly, with hit and trial method following results were found.

TABLE II
Calibrated Actual Transversal Stresses

Slab Length	σ Trans actual the.	σ Trans Call.	σ Trans Allowable
1950	0.8560	0.8880	2.9
2600	0.9690	0.9160	2.9
3900	1.1560	1.1900	2.9

TABLE III
Calibrated Actual Longitudinal Stresses

Slab Length	σ Long actual	σ Long Call.	σ Long Allowable
1950	0.9302	0.8670	2.15
2600	0.9302	0.9140	1.85
3900	0.9302	0.9970	1.34

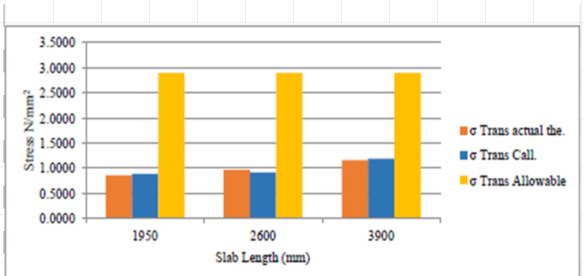

Fig. 21. Calibrated Actual transversal stresses vs. Allowable

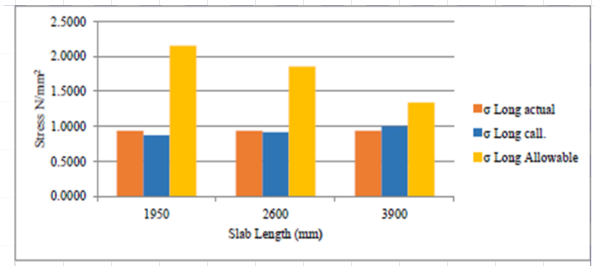

Fig. 22. Calibrated Actual Longitudinal stresses vs. Allowable stresses

Based on all the study being done so far some guidelines are developed showing the steps to be followed for the verification of FE-Models with respect to analytical results/model. Following are the developed guidelines:

- Analytical Design based on certain input parameters
- Numerical Design based on same consistent input parameters.
- Identification of the differences and similarities between numerical model and analytical using comparative analysis.
- Selection of a suitable meshing density/load position type to avoid sudden changes in the results due to changes in loading patterns.
- Calibrate an exemplary simple model with analytical result to get an idea of model behaviour e.g. effect of geometry change on bending stress.
- Calibration of a model process by considering both geometry of a slab in model and loading position types.

VII. Conclusions

There are different ballastless track systems available for coping with high speed running vehicles. This study comprises of a ballastless track system without sleepers but direct fixation (discrete rail seats) with special focus on continuously reinforced concrete pavements (CRCP).

For the design of ballastless track systems with CRCP, Westergaard and Zimmerman approaches are used to calculate stresses and deformations within the entire system. For optimizing design of ballastless track system it is necessary to verify FE model with analytical results. This task is performed by developing a FE model in Sofistik using the same input values as used for analytical.

The main aim of the work involves verification of FE model to ensure that model is working properly with reference to analytical results.

Based on the evaluation of different results and analysis a conclusive summary of whole thesis work can be provided as:

- Smaller rail pad areas can be taken place by point loads in SOFiSTiK without much difference in output results. Thus showing the flexibility of a FE Model as analytical calculations are based on converted circular rail pad area from a rectangular one.
- Geometry plays an important and decisive role in models as change in slab geometry causes considerable changes in bending stresses. Longitudinal length is needed to be stretched and transversal length is to be curtailed to get near the desired analytical bending stress values. However analytical calculations more and less doesn't depend on geometry.
- Load position type is one another vital input parameter to be considered very carefully while modelling in sofistik as nature of load position can change the results drastically. Loading position at intersection of an element – node is considered throughout for the calculations. Loading in analytical calculations are relatively straight forward either acting in the centre or at the corner/edges of a slab.

  Model showed accurate and realistic results under temperature loading; heating of a slab surface causes compression at upper surface and tension at lower surface of slab and vice versa.
- Model in SOFiSTiK was able to calculate actual bending stress using both traffic and temperature loading, however only linear temperature stress could be calculated due to the limitation of 2D FE modelling.
- More than two methods to calculate vertical stresses ensures accuracy in results, is an advantage over long analytical calculation
- Once input parameters are carefully handled, comparable results can be acquired from FE model with reference to analytical results (verification).
- Once the model is verified, the slab model can be analyzed up to different and numerous slab lengths at different thicknesses more conveniently thus ensuring better optimization of the design of ballastless track system.
- Thus verification of a model leads the system towards more economical system.

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