EVALUATION OF THE TRACK SUPERSTRUCTURE OF LITHUNIAN RAILWAY LINES CALCULATING CHARACTERISTICS OF STRENGTH

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Abstract. Railway track is affected by rolling stock wheels, climatic factors, mostly temperature and fall, and inner tension, which originates in the elements, mostly rails, of the track superstructure, during manufacture, installation and maintenance. Railway track construction must assure resistance to these factors. Calculating railway track superstructure strength, minimal necessary construction strength is estimated, assuring that the rail will not break under the stress of temperature and loads of trains. Calculation of strength of railway track, considering type of the track superstructure, train load and train speed, estimates tension in the rails, tension under the fish plate, when sleepers are wooden (tension in the fish plate and concrete when sleepers are made of reinforced concrete), tension in the ballast under the sleepers and tension in the main platform of the track formation.

The main purpose of the article is to apply the strength calculation method in Lithuanian railway lines for existing constructions, considering their technical and running conditions, and estimate how technical and running conditions of the construction influence strength of the track. Also, recommendations about what should be taken into account while calculating and maintaining the track superstructure are presented.

To execute the purpose, technical and running conditions of Lithuanian railway lines are briefly presented. The matter of calculation methodology, assumptions and formulas for calculation are presented as well. After calculation experiment obtained results and their analysis are described and discussed.

Keywords: railway track, rail, sleeper, ballast, strength, stress, loads.

1. Introduction

The financial impact of railway track related decisions are felt mainly in train operating performance (transit time, arrival time reliability and axle loading); and in on-going track maintenance costs required to keep track quality to a specified service level. There are strong linkages between track design standards, allowable train operating performance and track maintenance need [1].

Railway track is affected by rolling stock wheels, climatic factors, mostly temperature and fall, and inner stress, which originates in the components, mostly rails, of the track superstructure, during manufacture, building and maintenance.

Railway track construction must assure resistance to these factors. Loads are divided into static and dynamic, considering rolling stock wheel adding, and into vertical, lateral longitudinal and torsional, considering working direction.

When vertical and lateral forces act, complicated deformations and stresses appear in the railway track. Forces acting on rail bend it in vertical and lateral planes, push in respect of sleepers, torque in respect of longitudinal axis and press.

Elastic deformations disappear after removing the load (when train passes through the track). Rail will bend under the wheels of the train but it will return to its initial state after the train passes through. Another part of deformations called as permanent do not fully disappear even when the load is not acting anymore. For example, compression of the rail ends does not disappear, on the contrary – it increases. Rail wearing increases as well. Therefore, permanent deformations of the railway track superstructure gradually accumulate. The main factor determining accumulation of permanent deformations is intensity.

Permanent deformations of the track, appearing every time a train passes through, are very small in comparison to elastic deformations. However, as they gradually accumulate fair importance is obtained. For example, rails bow elastically. The same loadings that influence bending of rails, influence appearance of permanent deformations as well. For example, rail wearing and head compression. Sleepers slope to the ballast and bend. Their surface under the sealing is compressed gradually. Ballast under the sleepers is toughly pressed as well. At the same time, due to movement and
crumbling of the ballast particles, permanent deformations take place in the ballast as well.

They differ under different sleepers. This causes unevenness of track, such as: deformity, settling and washout under the sleepers. It is true to say that the main reason of all track deformations is permanent deformations. Accumulation of these deformations is influenced by vibratory nature of load.

Considering that the railway track is affected by many complicated factors, researches performed in this sphere often are not thorough, but concentrated on a particular point.

Track system Model (TSM) was created in England. The work takes a systems approach and involves the development and application of a suite of numerical models used to investigate the in-service conditions of track components with particular emphasis on Rolling contact Fatigue (RCF). The suite of models, called the Track System Model (TSM), comprises of vehicle dynamics models, a Global Track Model and a rail-wheel Contact model and provides results that can be fed from one model to another. At the centre of the TSM are the track measurements conducted at additional monitoring sites that are being used to validate the models. The practical assessment of RCF sites used in conjunction with the track system modeling will aid the development of analytical based fatigue life prediction models that supports the track engineer to adopt an effective rail grading and rail placement strategy [2].

There are several spheres of the research: interaction wheel/rail [3, 4, 5]; degradation model of track superstructure [6, 1]; research and development of the separate components of railway track superstructure: structure improvement of rail fastenings, improvement of steel quality of rails, decrease of wear intensity of rails and wheels et cetera [7-10]. All of the research spheres have their advantages and disadvantages, because while performing the research of the system as a complex it is necessary to know very well all input data and what has to be obtained in the output. Therefore sometimes individual researches are very useful. However, perhaps the main attention is paid to the research of wheel/rail interaction. Therefore, it may be stated that investigations of wheel/rail interface has been subject of investigation since the creation of the railway system.

Railway track deteriorates over the time due to dynamic loading of passing rolling stock. To ensure safe passing of trains, the track has to be properly designed and maintained. This article will focus on the methodology on how to calculate stresses in track components. Calculations are done for the constructions used in Lithuanian railway lines. Proposals on possibilities to increase life time of the track construction are presented.

2. Methods of strength calculation of railway track

2.1. Point, purpose and assumptions of the methodology

Construction of railway track can be analyzed in four aspects, evaluating four features of the construction: strength, stability, durability and economy.

Strength is the feature of a construction not to crack when mechanical factors (loads) act on it. When railway track construction is analyzed, strength is treated as a feature of railway track construction not to crack under the loadings of trains and temperature.

Component of any construction is treated as not strong anymore and unable to sustain mechanical impacts, when its stress becomes too large, i.e. when stress exceeds permissible one. It is not enough to warrant that the stresses, appearing in the components of the construction, do not exceed the permissible limit. Resources of strength have to be sufficient as well.

Calculation of strength of railway track superstructure estimates minimal necessary strength of railway track construction, assuring that the rail won’t break under the influence of loadings of trains and temperature.

Several tools are currently available to describe railway track mathematically, each has its own advantages and disadvantages: finite element modeling (FEM), dynamic modeling, analytical methods and any combination of these. Finite element modeling is a method that can be used to model discrete track components and determine the interaction between them, as well as stresses, under both static and dynamic conditions. FEM is not limited to static analyses. However, dynamic analyses are computationally expensive. Another disadvantage of finite element analyses is that one model can represent only one chosen track layout and cannot easily be adapted to model a track with different geometry. This means that a new model should be created for each new layout. As with finite element modeling, dynamic models cannot be changed quickly to represent different track layouts or different loading conditions and can only present results for the specific vehicle and track under consideration. When designing track in general, or evaluating a railway line under changing operating conditions, analytical model is the most economical to use. Analytical models make it possible to quickly evaluate different layouts and loading conditions without the necessity to build detailed models for each scenario [11].

When analytical model is used strength of the track is estimated determining stresses in components of the track superstructure.

Calculation of strength of railway track superstructure, considering its type and load and speed of the train, allows estimate the following:

- Stresses in rails. Stresses in rails are directly related to the life of the rail and susceptibility of the rail to fatigue damage. If the stress is external the rail will wear of fracture. If the stress is internal, such as residual or thermal stresses, it can accelerate the growth of fatigue defects, again causing fracture [7].
- Stresses under the fish plates, when the sleepers are wooden (when the sleepers are made of reinforced concrete – stresses in the fish plate and concrete);
- Under the sleepers.

Comparing the obtained results with the permissible values condition of stresses and deformation of track, reserve of its strength and traffic safety are evaluated.

The main assumptions of the calculations are: it is assumed that the rail is a beam of infinite length with constant cross section, laid on continuous smooth elastic
basement. The vertical forces are set symmetrically to the rail in respect of cross section, i.e. tilt of the rail is not evaluated. It is assumed that when wheels pass the rail, they do not pull away from the rail, i.e. – movement without impact forces takes place. Characteristics of track are assumed as determinate values, i.e. non- incidental, non-variable values. Only normal bending stresses are set for the rail (not including local and contact ones). The calculation is done considering permissible stresses. Permissible stresses, i.e. stresses, that originate without exceeding yield limit of rail steel. Longitudinal temperature forces are not directly evaluated in the calculation scheme. Influence of climatic factors is evaluated only considering that the rails are affected by temperature changes and that stiffness of track varies when sleepers and ballast freezes. Non-elastic resistance is not evaluated.

In spite of the fact, that a lot of assumptions are considered, calculation results are precise enough, because they match experimental researches.

2.2. Formulas for calculation

Strength of the track is assured when system of conditions is assured [12]:

\[
\begin{align*}
\sigma_p &= \frac{M}{W_p} \cdot 10^{-6} = \frac{10^{-6}}{4kW_p} (F_{sk, \text{ din.}} + \Sigma F_{vid.} \cdot \mu) \leq [\sigma_p] \\
\sigma_{pab. \text{ med.}} &= \sigma_{pab. \text{ gb.}} = \frac{k \cdot l_{pab} \cdot 10^{-6}}{2\Omega} (F_{sk, \text{ din.}} + \Sigma F_{vid.} \cdot \eta) \leq [\sigma_{pab. \text{ med.}}, [\sigma_{pab. \text{ gb.}]}] \\
\sigma_h &= \frac{k \cdot l_{pab} \cdot 10^{-6}}{2\Omega} (F_{sk, \text{ din.}} + \Sigma F_{vid.} \cdot \eta) \leq [\sigma_h] \\
\end{align*}
\]

(1)

Where: \(\sigma_p\) – bending stresses of vertical load in the rail flange; \(M\) – bending moment; \(W_p\) – strength moment of rail cross section in respect of flange, m³; \(k\) - coefficient of rail and rail flange relative stiffness, calculated according to formula, m³; \(f\) – coefficient, evaluating eccentricity of acting forces; \(F_{sk, \text{ din.}}\) - vertical dynamic load on rail from rated wheel, N; \(F_{vid.}\) – Mean vertical load on rail from wheel, N; \(\mu = f_1(kx), \eta = f_2(kx)\) – coefficients, evaluating influence of contiguous (not rated) axes (bending moment is proportional to the influence line \(\mu\) and load to sleeper; elastic deflection will influence line \(\eta\)); \(\sigma_{pab. \text{ med.}}, \sigma_{pab. \text{ gb.}]}\) – Mean compression stresses under the fish plates, when the sleepers are wooden and in the sealing, in case of reinforced concrete sleepers, MPa; \(\omega\) – fish plate area, m²; \(l_{pab}\) – distance between axes of sleepers, m; \(\Omega\) – area of supporting half-sleeper, m²; \(\sigma_{pab. \text{ med.}}, \sigma_{pab. \text{ gb.}]}\) – permissible stresses in ballast under each sleeper, MPa; \([\sigma_p]\), \([\sigma_{pab. \text{ med.}}, [\sigma_{pab. \text{ gb.}]}]\) permissible values of corresponding stresses. Permissible values differ in various sources [12-14]. In this project permissible values of stresses are estimated considering steel quality of rails, type of ballast, traffic intensity and type of rolling stock.

Sometimes permissible stresses in the rail flange are estimated considering type of the rails, type of the track (i.e. – jointless or section way) and whether the rails are new or not. However permissible stresses in ballast are as one uniform value [13]. On the other hand it is stated that permissible stresses in the rail flange do not depend on any technical, running or other characteristics. However, permissible stresses under the fish plates (in the sleepers) depend on type of the sleepers (reinforced concrete or wood and even quality of wood) [14].

The purpose of track is to transfer train loads to the formation. Load transfer works on the principle of stress reduction, which means layer by layer, as depicted schematically in figure 1. The greatest stress occurs between wheel and rail and is in order 300 Pa. Between rail and sleeper the stress is two orders smaller and diminishes between sleeper and ballast bed down to about 3 MPa. Finally the stress on the formation is only about 0,5 MPa.

![Scheme of load transfer](image)

Fig 1. Scheme of load transfer [13]

3. Technical and maintenance condition of Lithuanian railway lines

Running length of Lithuanian railway lines is 1782.5 km: when gauge width is 1520 mm – 1760.7 km and gauge width 1435 mm - 21.8 km. Single track district – 1375.9 km, double track district – 382 km, triple track district - 2.1 km. Two international corridors cross Lithuanian territory: Crete Transportation Corridor IX (B, D) and I. They are exclusively important to the whole European transport system. They are renovated according to the requirements of European Union standards. Particular attention is paid to major repairs of the main tracks. Financial sources for the infrastructure modernization are: credits from the international finance institutions, government budget and company asset and EU financial support.

At the moment the following is used in Lithuanian railway lines: rails R75, R50, R65 and E1; wooden and
reinforced concrete (S1 and ATRAK) sleepers (wooden sleepers make 30 % and reinforced concrete – about 70%); epures of sleepers: 2000 units/km (about 15 % of total amount), 1840 units/km (75 % of total amount), 1640 units/km (10 % of total amount); fastenings KB, E-Clip, F-Clip and Vossloh and break-stone, sand and gravel ballast. At the moment permissible axial load is 225 kN. Train speed is: 60, 80, 90, 100 and 120 km/h.

As the calculation methodology comprises of many formulas and strength of the track depends on many factors (type of locomotive and its constructive speed, maximum permissible speed, minimum curve radius of a track section, type of rails, type of sleepers, epure of sleepers, parameters of ballast prism, etc.) there may be many ways to perform calculations. Further you will find calculation examples for the most popular railway track superstructure constructions used in Lithuanian railway lines and locomotives used here as well.

Technical condition of rails in Lithuanian railway lines is presented in Table 1. Data presented in the table varies due to unceasing repairs and reconstruction of the railway track. From the table you may see that mostly: for the rail type R75 – wear is 7-9 mm; for the rail type R65 – wear is 0-6 mm; for the rail type UIC60 – wear is 0-6 mm and for the rail type R50 – wear is 7-9 mm.

**Table 1. Technical condition of rails**

<table>
<thead>
<tr>
<th>Rail type</th>
<th>Recalculated wear value of rail head, mm</th>
<th>0-6 mm, % of total amount</th>
<th>7-9 mm, % of total amount</th>
<th>10-12 mm, % of total amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>R75</td>
<td>-</td>
<td>80</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>R65</td>
<td>80</td>
<td>18</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>E1</td>
<td>100</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>R50</td>
<td>26</td>
<td>60</td>
<td>14</td>
<td></td>
</tr>
</tbody>
</table>

* - Recalculated wear of rail head is sum of vertical wear and half of the side wear.

Technical condition of sleepers may be described as follows: there are 30 % of unusable wooden sleepers and only 1 % of reinforced concrete sleepers. 85 % of the tracks of Lithuanian railway lines are built on break stone ballast, 11 % on sand ballast and 0.4 % on gravel ballast. Sand and gravel ballast impurity is more than 20 %. Thickness of gravel ballast is 25-34 cm and sand ballast – more than 35 cm. Thickness of break-stone ballast in Lithuanian railway lines is the following: 35 cm and more – 45%, 25-35 cm – 40 %, less than 25 cm – 15%. Length of the track built on the break-stone ballast with impurity more than 20 %, comprises about 27 % of all the tracks built on the break-stone ballast.

The following locomotives are used in Lithuania: freight diesel locomotives – M62 and 2M62, switching locomotives TEM-2 and ČME-3, passenger – TEP60 and TEP70.

Load intensity in Lithuanian railway lines changes continually and varies in different lines from 2 to 50 million t km/year (for example in the section Radviliskis-Obelai - State’s border load intensity is 3 million t km/year, Kužiai-Mažeikiai- State’s border – 20 million t km/year, N.Vilnia-Kena- State’s border – 15 million t km/year, and in line Vilnius-Klaipeda – 10-50 million t km/year).

As it was mentioned before, one of the main purposes of the article is to employ strength calculation methodology to the existing constructions of Lithuanian railway lines, considering technical and maintenance characteristics of the constructions and estimate how much track strength is influenced by technical and maintenance condition of the construction. Reaching the goal, most common constructions of the railway track are estimated and technical condition of Lithuanian railway lines is evaluated. It has been estimated, that the following cases should be analyzed:

1. Rail type R65 (non-tempered, recalculated rail wear is 6 mm, 9 mm and 12mm), reinforced concrete sleepers (epure of sleepers is 1840 units/km in the straight line and curves with radius less than 1200 m; 2000 units/km in the curves with Rdius less than 1200 m), breakstone ballast prism having ballast prism layer of 35 cm. Passenger locomotive TEP 60, freight locomotive M62, tetra axle freight wagons with axial load of 225 kN. Passenger train speed in straight line: 120, 100 and 80 km/h and in curve: 100, 80 and 60 km/h. Freight train speed in straight line – 90 and 70 km/h, in curve – 80 and 50 km/h. Minimal curve radius is 600 m. Train traffic intensity in the section is 40 million tons km/year.

2. Rail type E1 (non-tempered, recalculated rail wear is 6 mm, 9 mm and 12 mm), reinforced concrete sleepers (epure of sleepers 1640 units/km in straight line and curves with radius less than 2000 m; 1840 units/km in curves with radius less than 2000 m), breakstone ballast prism having ballast prism layer of 30 cm. Passenger locomotive TEP 70, freight locomotive M62, tetra-axial freight wagons with axial load of 225 kN. Passenger train speed in straight line 120, 100 and 80 km/h and in curve 100, 80 and 60 km/h. Freight train speed in straight line – 90 and 70 km/h, and in curve – 80, 50 km/h. Minimal curve radius is 500 m. Train traffic intensity in the section is 20 million tons km/year.

Analyzing the first case it has been estimated that: the largest stresses in rail flange are caused by wagon when it passes curve at 80 km/h. However, neither stresses caused by calculating locomotives, neither the ones caused by wagons exceed permissible stresses even in case recalculated wear reaches 12 mm (when recalculated rail wear is equal to 12 mm, stresses in rail flange are equal to $\sigma_{fl}=0.5 [\sigma_{fl}]$). As you may see from Fig. 2, maximum stresses in rail flange are caused by wagon when train passes curve at 80 km/h.

The largest stresses in the sleepers of the calculating construction are caused by wagon when it passes straight section at maximum 90 km/h (see Fig. 3). However, stresses in sleepers do not exceed permissible ones even when recalculated rail head wear is 12 mm. Therefore it
may be concluded that the reserve of strength in this component of the construction is sufficient similarly as in the rail flange.

The largest stresses in the ballast of the calculating construction are caused by wagon when it passes straight track section at 90 km/h (Fig. 4). However when recalculated rail wear is 12 mm, stresses in the ballast are close to permissible ones, i.e. \( \sigma_b=0.24 \) MPa and permissible stresses - \( [\sigma_b]=0.3 \) MPa. Supposing traffic intensity increases and exceeds 50 million tons km/km per year, permissible stresses in the ballast would be \( [\sigma_b]=0.26 \) MPa. In such case stresses caused by locomotive when it passes straight track section at 90 km/h would be almost equal to permissible ones. Therefore it may be concluded that permissible speeds, traffic intensity and axial loads in such construction must not be increased.

![Fig 2. Dependence of stresses in rail flange (\( \sigma_p \), MPa) on recalculated rail wear (R65 rails)](image)

**Permissible stresses in rail flange:**
- locomotives – \( [\sigma_p]=200 \) MPa,
- wagons – \( [\sigma_p]=160 \) MPa

![Fig 3. Dependence of stresses in sleepers (\( \sigma_{pab} \), MPa) on recalculated rail wear (R65 rails)](image)

**Permissible stresses in sleepers:**
- locomotives and wagons – \( [\sigma_{pab}]=3 \) MPa
Permissible stresses in ballast: locomotives – $[\sigma_b]= 0.42$ MPa, wagons – $[\sigma_b]= 0.3$ MPa

Permissible stresses in rail flange: locomotives – $[\sigma_p]= 240$ MPa, wagons – $[\sigma_p]= 200$ MPa

Permissible stresses in sleepers: locomotives and wagons – $[\sigma_{pab}]= 3$ MPa

Fig 4. Dependence of stresses in ballast ($\sigma_b$, MPa) on recalculated rail wear (R65 rails)

Fig 5. Dependence of stresses in rail flange ($\sigma_p$, MPa) on recalculated rail wear (UIC60 rails)

Fig 6. Dependence of stresses in sleepers ($\sigma_{pab}$, MPa) on recalculated rail wear (UIC60 rails)
Analyzing the second case it has been estimated that: the largest stresses in the rail flange are caused by locomotive when it passes curve at 100 km/h. Yet, same as in the first case stresses in the rail flange caused by calculating locomotives or wagons do not exceed permissible ones even if recalculated wear reaches 12 mm (see Fig. 5).

The largest stresses in the sleepers of the calculating construction are caused by wagon when it passes straight section at maximum 90 km/h (see Fig. 6). Stresses in sleepers caused by locomotive and wagon wheels do not exceed permissible ones.

The largest stresses in the ballast of the calculating construction are caused by wagon when it passes straight track section at 90 km/h (see Fig. 7). When recalculated rail wear is 12 mm, stresses in ballast do not exceed permissible ones. In such case, stresses caused by locomotive when it passes straight track section at 90 km/h would exceed permissible stresses. On purpose to increase speed of trains, especially freight ones, in case of such construction, it would be necessary to recalculate strength of construction and see if it is sufficient.

4. Conclusions

1. To ensure safe train traffic, track has to be properly designed and maintained. This article is focused on the methodology how to calculate stresses in track components.

2. Several tools are currently available to describe railway track mathematically, each has its own advantages and disadvantages: finite element modeling (FEM), dynamic modeling, analytical methods and any combination of these. Advantages and disadvantages of these models are described in the article. It this article analytical method is used to determine strength of the track estimating stresses in the components of track superstructure.

3. Technical and maintenance condition of Lithuanian railway lines is reviewed in this article. Strength calculation methodology has been employed for the constructions of Lithuanian railway lines. Their technical and maintenance characteristics have been considered. Influence of construction technical and maintenance condition on track strength has been estimated.

4. Tracks of the following structure have been calculated: 1) Rails R65 (non-tempered, recalculated rail wear equal to 6 mm, 9 mm and 12 mm), reinforced concrete sleepers (epure of sleepers 1840 units/km in straight section and curve with radius less than 1200 m; 2000 units/km in curves with radius less than 1200 m), breakstone ballast prism having ballast prism layer of 35 cm. Passenger locomotive TEP 60, freight locomotive M62, tetra axle freight wagons with axial load of 225 kN. Passenger train speed in straight line: 120, 100 and 80 km/h and in curve: 100, 80 and 60 km/h. Freight train speed in straight line – 90 and 70 km/h, in curve – 80 and 50 km/h. Minimal curve radius is 600 m. Train traffic intensity in the section is 40 million tons km/year. 2) Rail type E1 (non-tempered, recalculated rail wear is 6 mm, 9 mm and 12 mm), reinforced concrete sleepers (epure of sleepers 1640 units/km in straight line and curves with radius less than 2000 m; 1840 units/km in curves with radius less than 2000 m), breakstone ballast prism having ballast prism layer of 30 cm. Passenger locomotive TEP 70, freight locomotive M62, tetra-axial freight wagons with axial load of 225 kN. Passenger train speed in straight line: 120, 100 and 80 km/h and in curve: 100, 80 and 60 km/h. Freight train speed in straight line – 90 and 70 km/h, in curve – 80 and 50 km/h. Minimal curve radius is 500 m. Train traffic intensity in the section is 20 million tons km/year.

4. It has been estimated that strength of rail track superstructures maintained in Lithuanian railway lines is
sufficient, considering their technical and maintenance conditions. However, in order to increase load intensity, train speed or axial loads it would be necessary to estimate if strength of newly designed construction will be sufficient.

5. Purpose of further researches and calculating analyses could allow improvement of rules regulating maintenance and building of rail track. How track strength is influenced by increased axial loads should be analyzed as well.

References


