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Modern Railway Infrastructure: Resilient Fastenings improve Track's Life-Cycle

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Abstract

During the study for the dimensioning as well as the selection of the individual materials constituting a railway track, the ballast and the substructure present residual deformations, directly related to the deterioration of the geometry of the track. The slighter the residual deformations and the slower their alteration over time is, the better the quality of the track. The actions acting on the track panel are almost proportionally dependent on the total track stiffness that is also influenced seriously by the fastening's and total track's stiffness. This implies that the average stress on ballast underneath the sleepers' seating surface is also influenced by the stiffness. It is imperative to reduce as much as possible the average stresses at the sleepers' seating surface, by increasing track's stiffness. In the Greek network since the late 1980's up to 2000 an extended research program was performed due to cracks on twin-block concrete sleepers (over 60% on the total number laid on track). In the frame of this investigation, a new approach for the actions on sleepers and the ballast has been developed, by taking into account the real conditions of the line (maintenance etc.) which led to the increase of the demands in the specifications for the use of very resilient fastenings.

Keywords: railway track; sleepers/ties; dynamic loads; ***rigid*** *fastenings; resilient fastenings; loads; actions/reactions; stiffness.*

1. Introduction

Construction of a new line is expensive (10 - 25 Mio €/km) and in general can only be justified if the available capacity on the existing line has been exhausted and/or journey times are far from satisfactory.

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Competition from the road and air modes should also be taken into account. Where for quantitative and qualitative reasons a new line is not required, ways are often sought to bring about improvements at a low cost. The permissible speed and as a result the journey time of a train is contingent on: the vehicle design type, the type and length of train, the braking conditions, the line conditions, the operating conditions. When it comes to line conditions, the curves and gradients as well as the constitutive elements of track are of decisive importance. A good track alignment should allow shorter journey times to be achieved and, with energy consumption and braking efficiency in mind, should keep breaks in speed to the strict minimum. In curves, the speed is determined in particular by: running conditions, lateral forces exerted on the track, stability of goods, comfort thresholds for passengers. The centrifugal force in the curves can be partially or wholly compensated by track cant. The profile of the track in principle does not require, or hardly requires, any special conditions to be satisfied other than the basic conditions to be fulfilled for conventional trains operation. The actions acting on the track panel are almost proportionally dependent on the total track stiffness and consequently the average stress on ballast underneath the sleepers' seating surface. The ballast and the substructure are the elements of the track that develop residual deformations directly connected to the deterioration of the geometry of the track due to the average stress. The smaller the residual deformations and their increase over time, the better the quality of the track.

The AASHTO testing for road construction equation for maintenance costs is also applicable for a railway track (Giannakos, 2004, 2011):

(Decrease in track geometry quality) = (increase in stress on the ballast bed)^m

where m = 3 to 4.

The decrease in track geometry quality affects proportionally the maintenance costs -10% higher stress, 51% greater annual maintenance cost- and it is related to the stresses on the ballast-bed and the degree of fouling of the ballast-bed. The latter influences the preservation of the track geometry. Since stress is equal to the ratio of the actions on the sleeper (reaction per "point") to the seating surface of the sleeper, and the seating surface of each sleeper type is standard, the estimation of the actions on the track mainly dependent on the total track stiffness affected by the fastening's stiffness is decisive for the deterioration of track's geometry.

In this paper an investigation is presented, using the four methods cited in international literature, on the improvement of track's life-cycle by the use of very resilient fastenings.

2. Stiffness as a characteristic parameter for the magnitude of the Actions on Track

2.1. Stiffness

In Figure 1 left a cross section of a classic ballasted track is depicted with the terminology of layers as determined by U.I.C. (UIC, code719, 1994). A railway track structure can be modelled by a multilayered structure of ν layers simulated by a combination of springs (with coefficient ρ_i [kN/mm]) and dampers (with coefficients c_i). For the total track structure the following equation applies:

$$\frac{1}{\rho_{total}} = \sum_{i=1}^{\nu} \frac{1}{\rho_i} = \frac{1}{\rho_{rail}} + \frac{1}{\rho_{pad}} + \frac{1}{\rho_{sleeper}} + \frac{1}{\rho_{ballast}} + \frac{1}{\rho_{substructure}} \quad (1)$$

where ρ_i is the coefficient of "Rail Support Modulus" [c in German literature and k in American] of each layer. This implies that ρ_{total} is a coefficient of quasi elasticity (stiffness) of the track, the equivalent of the "spring constant" in Hooke's law. It is defined as the "reaction coefficient of the tie", and ρ_i is the "spring constant" of each layer. In figure 1 right a simulation of the multilayered structure "track" is depicted with the more characteristic values of ρ_i for the five main layers of the track. It is underlined that the pad's stiffness –from very stiff to very resilient fastening varies from 600 – 45 kN/mm. Three out of the five layers, namely the rail, the tie, and the ballast, contribute only 6 to 10% to the total track stiffness ρ_{total}. The total track stiffness is mainly affected by the static stiffness coefficients of the pad, $\rho_{pad,}$ and of the substructure, $\rho_{substructure}$.

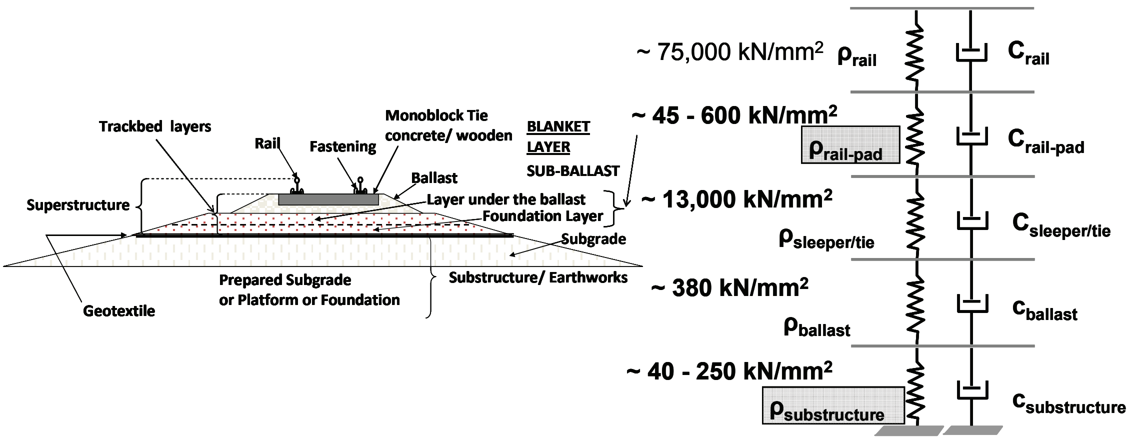

FIGURE 1 Cross section of a classic ballasted track (left) and schematic representation of the track as a combination of springs and dashpots (right).

2.2. Actions on track according to international literature

The theoretical analysis is based mainly in Winkler's theory (Winkler, 1867) of an infinite beam on elastic foundation. In international literature four methods are –mainly- cited.

Method in the American literature

In the American literature this analysis is described in Hay (1982, (1), p. 247-273), in AREMA (2005, (10), p. 16-10-26 to 16-10-32 and Chapter 30), in Selig & Waters (1994/2000, (11), p.5.1-5.4 etc.). The most adverse reaction/action on each support point (sleeper) is given by (see Giannakos, 2011):

$$R_{\max} = \overline{A}_{stat} \cdot \left(1 + \frac{D_{33} \cdot V}{D_{wheel} \cdot 100}\right) \cdot Q_{wheel} \qquad (2)$$

where: D_{33} in inches the diameter of a wheel of 33 inches, D_{wheel} in inches the wheel's diameter of the vehicle examined, V the speed in miles/hour, and $\overline{A}_{stat}$ is the same as in equations of the European literature below and it is given by:

$$\overline{A}_{stat} = \frac{1}{2\sqrt{2}} \cdot \sqrt[4]{\frac{\ell^3 \cdot \rho_{total}}{E \cdot J}} \qquad (3)$$

where: ρ_{total} the "rail support modulus" or "total track stiffness (static)" in kN/mm, ℓ the distance between the sleepers, E, J the modulus of elasticity and the moment of inertia of the rail.

Method in German literature

In German literature the most adverse reaction R_{max} per sleeper is dependent upon the probability of occurrence and for 99.7% probability is given by (Fastenrath, 1981, Eisenmann, 2004):

$$R_{\max} = Q_{wheel}\left(1+0.9\cdot\left(1+\frac{V-60}{140}\right)\right)\cdot\overline{A}_{stat} \tag{4}$$

for V ≥ 60 km/h, if V < 60km/h then $R_{max}=1.9\cdot Q_{wheel}\cdot\overline{A}_{stat}$ (4a)

Method in French literature

There is also the method cited in French literature (Alias, 1984 and Prud' homme A., & Erieau, 1976) covering a probability of occurrence 95.5% and distributing the total acting load with reaction per tie $1.35\cdot\overline{A}_{stat}\cdot Q_{total}$ as follows:

$$R_{\max} = \overline{A}_{stat}\cdot 1.35\cdot\left[Q_{wheel}\cdot\left(1+\frac{Q_{\alpha}}{Q_{wheel}}\right)+2\cdot\sqrt{\sigma\left(\Delta Q_{NSM}\right)^2+\sigma\left(\Delta Q_{SM}\right)^2}\right] \tag{5}$$

where Q_{wheel} = the static wheel load, Q_{α} = the load due to cant deficiency, 2 coefficient of dynamic load for a 95.5 % probability of occurrence, $\sigma(\Delta R_{NSM})$ = the standard deviation of the dynamic load due to non suspended masses, $\sigma(\Delta R_{SM})$ = the standard deviation of the dynamic load due to suspended masses.

Giannakos (2004) method

After an -over 10 years- investigation program, in the Greek network, due to the appearance of extensive cracks in concrete ties laid on track, in a percentage over 60%, the author developed a method that is able to predict the observed conditions on track (Giannakos, 2004, Giannakos & Loizos, 2009). The actions on track panel are calculated through the following equation covering a probability of occurrence 99.7%:

$$R_{\max} = \left(Q_{wheel}+Q_{\alpha}\right)\cdot\overline{A}_{dyn}+3\cdot\sqrt{\sigma\left(\Delta R_{NSM}\right)^2+\sigma\left(\Delta R_{SM}\right)^2} \tag{6}$$

where Q_{wheel} = the static wheel load, Q_{α} = the load due to cant deficiency, $\overline{A}_{dyn}$ = dynamic coefficient of sleeper's reaction, 3 coefficient of dynamic load for a 99.7 % probability of occurrence, $\sigma(\Delta R_{NSM})$ = the standard deviation of the dynamic load due to non suspended masses of the vehicle, $\sigma(\Delta R_{SM})$ = the standard deviation of the dynamic load due to suspended masses of the vehicle (for details the interested reader should read Giannakos & Loizos, 2009) and :

$$\overline{A}_{dynam} = \frac{1}{2\sqrt{2}}\cdot\sqrt[4]{\frac{\ell^3\cdot h_{TR}}{E\cdot J}} \tag{7}$$

where h_{TR} the total dynamic stiffness of the track given by:

$$h_{TR} = \frac{1}{2\cdot\sqrt{2}}\cdot\sqrt[4]{E\cdot J\cdot\frac{\rho_{total}}{\ell}} \tag{8}$$

In the motion of the Non Suspended Masses (NSM) of the vehicle a section of track is also participating. For an accurate calculation of this track mass m_{TRACK} -participating in the motion of the m_{NSM}- a detailed theoretical analysis compared to data from measurements is cited in Giannakos (2010b).

In all the theoretical methods above the total static stiffness of track plays a key role: the more elastic the track is, the less the ties are stressed. It is therefore evident that resilient fastenings play a key role in the distribution of loads on track, and eventually in the life-cycle of the track.

3. Application for rigid and resilient fastenings in the Greek network

3.1. Evaluation of the methods in a case study of the Greek network

The results of Giannakos (2004) method are in agreement with observations on tracks under operation (a detailed description in Giannakos & Loizos, 2009 and Giannakos, 2010a). After an over ten-years research program -under the guidance of the author- in the Greek Railway network (with the participation of the research department "Voie" = track of the French Railways, of the subsidiary of Belgian Railways -Transurb Consult- and Universities of Greece -NTUA, AUTh- Austria -Graz- etc) to investigate the causes of the appearance of extensive cracking in concrete sleepers of French technology U2/U3 type (over 60% of the total number laid on track) the Giannakos method was developed. The laboratory tests showed –beyond any doubt- that the cracked sleepers in Greek network, were produced in full compliance with the existed prescriptions and technical specifications of the time. Moreover the sleepers' samples –chosen randomly from the track- presented strength values in laboratory tests higher than the prescribed in the specifications. The cracking was not a result of defective manufacture of the original ties or of no compliance with the specifications. The values of actions derived when applying the formulas cited in the American, German and French literature, under the most adverse conditions, are lower than the limits of the regulations, fact justifying sporadic appearance of cracks (in the order of 1-2%) but not at all their systematic appearance at 60% of the sleepers (and even more) for a characteristic stiffness $\rho_{substructure}$=100kN/mm, in the Greek railway network at the 1980-2000s. The results in summary are depicted in Fig. 2 (for a detailed description see Giannakos & Loizos, 2009 and Giannakos, 2004).

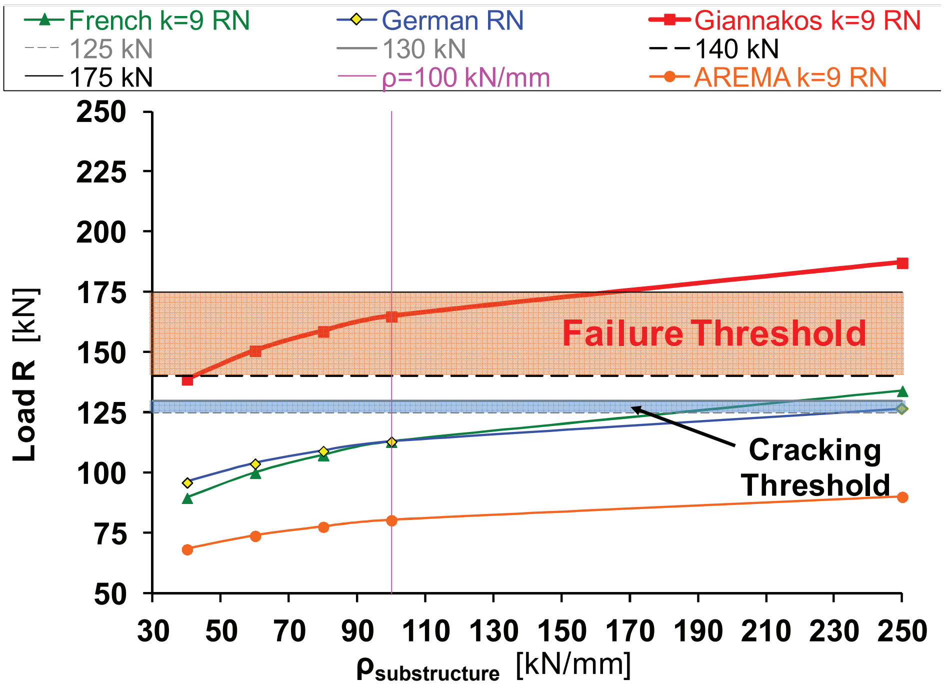

FIGURE 2 Calculation of actions on U2/U3 twin-block sleepers with RN fastenings (4.5 mm pad) with the method: (a) cited in French literature (Eqn 5), (b) cited in German literature (Eqn 4), (c) cited in American literature (Eqn 2) and (d) Giannakos -2004- (Eqn 6).

3.2. Estimation of the Actions for different combinations of sleepers and rigid or resilient fastenings

In the Greek network three types of sleepers are used with different types of fastenings (rigid or resilient) and different types of pads.

1.- Wooden sleepers with K fastening, scheduled in Germany on 1925 (see Schramm, 1961) and at this era with plywood pads and now with EVA pads of approximately 450-600 kN/mm stiffness. In Greece in the 1970s -after the adoption of RN fastening in concrete sleepers (twin-block U2, U3) with 4.5 mm pads, these pads were laid with K fastening also. The research program led to the conclusion that it was not an appropriate combination due to the very low toe-load (see Giannakos, 2004). In the 1990s the EVA pad was adopted either in K original fastening or with Skl-12 (Giannakos, 2004). In this paper these two combinations are used.

2.- Steel sleepers with (in the same logic) 4.5 mm pad in the beginning and then with EVA pads in the original rigid clips or afterwards with Skl-ET (Giannakos, 2004). In this paper these two combinations are used.

3.- Concrete sleepers: (a) twin-block concrete sleepers U2, U3 with RN fastening and 4.5 mm pad (of medium stiffness), (b) twin-block concrete sleepers U31 with Nabla fastening (resilient) and (c) Monoblock sleepers of prestressed concrete B70 with W14 fastening (resilient) either with Zw700 pad of Wirtwein or Zw700 pad of Saargummi, with two different stiffness coefficients. In this paper these three combinations are used plus one more -not existing in Greece- the concrete sleeper with EVA pad (and Skl-1) that was investigated at the past.

The calculations of the actions/reactions per sleeper have been performed by the four aforementioned methods. In Figure 3 the results of the method cited in German literature are depicted.

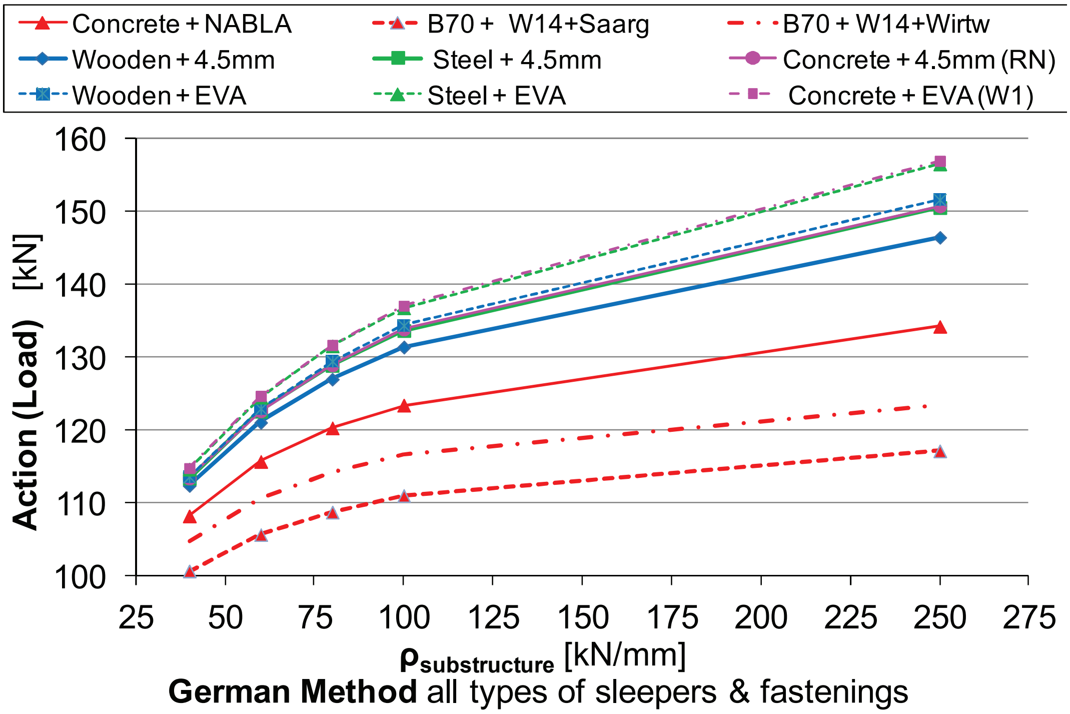

FIGURE 3 Actions on sleepers according to the method cited in German literature (Eqn4)

In Figure 4 the results of the method cited in French literature are depicted and in Figure 5 the results of the method cited in American literature are depicted.

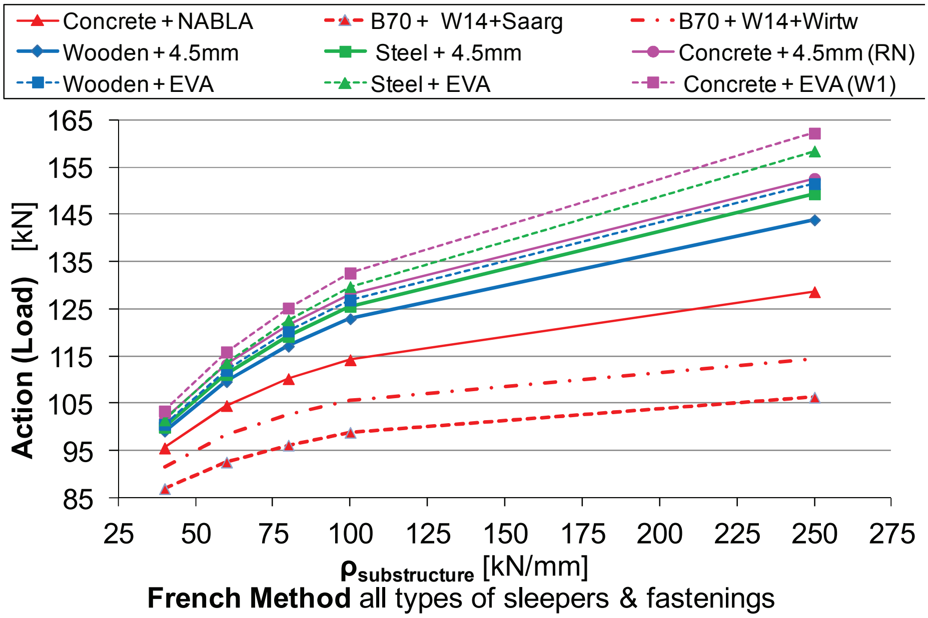

FIGURE 4 Actions on sleepers according to the method cited in French literature (Eqn5)

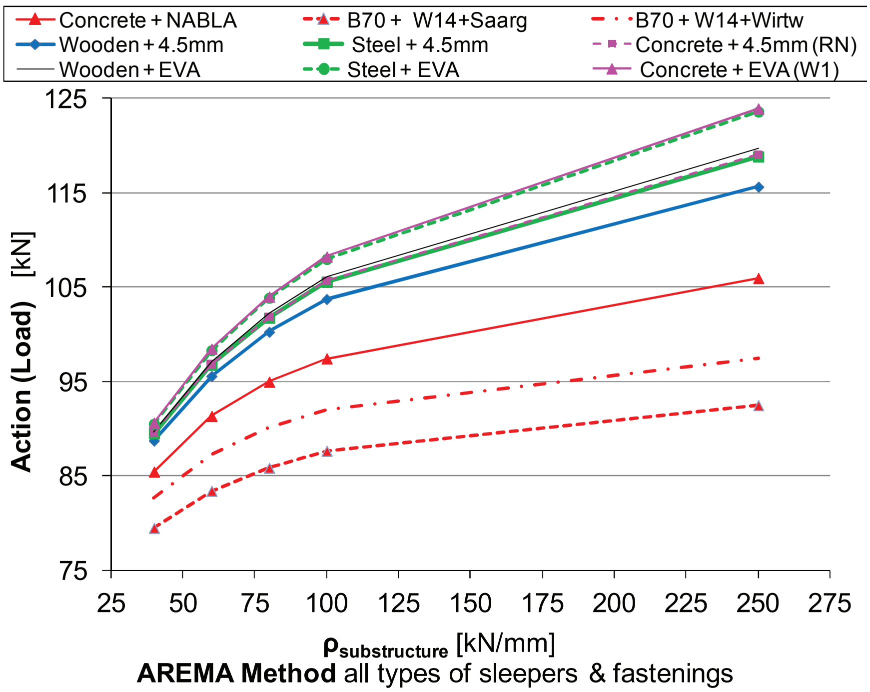

FIGURE 5 Actions on sleepers according to the method cited in American literature (Eqn2)

In Figure 6 the results of the Giannakos (2004) method are depicted.

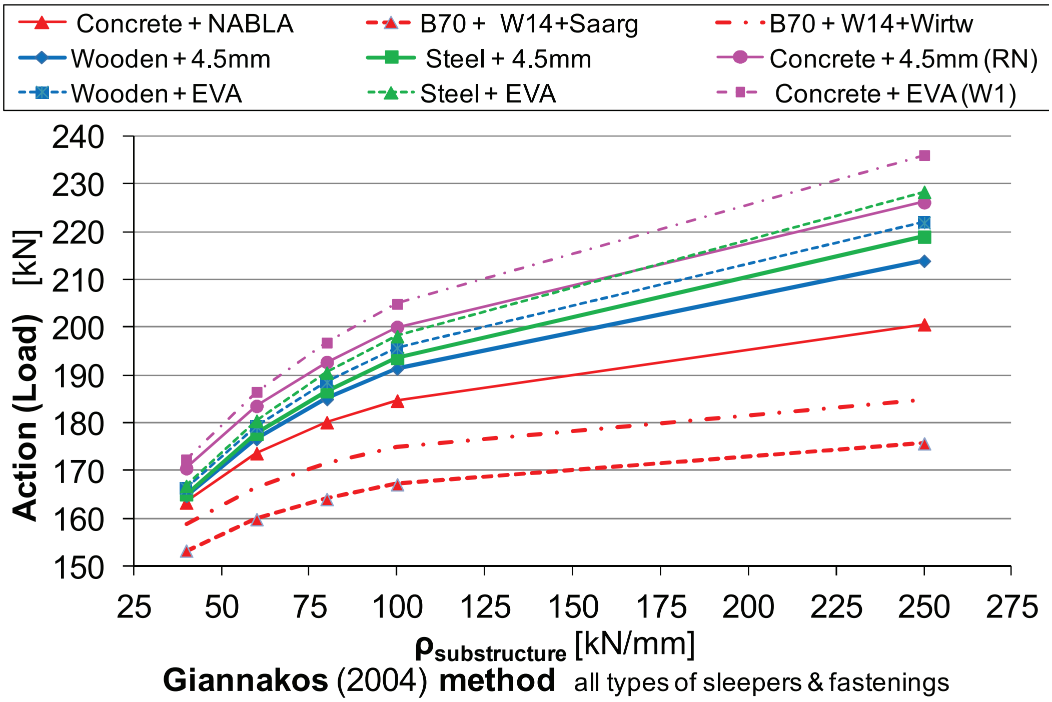

FIGURE 6 Actions on sleepers according to the Giannakos (2004) method (Eqn6)

In the above cases the calculations have been performed for V=200km/h, axle load 22.5 t, rail UIC60, ℓ=60cm, cant deficiency 160mm, height of the vehicle's centre of gravity from rail running surface 1.5m, Non-Suspended Masses 1.5t, average condition of rail running table (k=9) and D_{wheel}= 33.86inch. In this study the steel sleeper, the wooden sleeper with 4.5mm pad as well as the concrete sleeper with RN fastening were evaluated even if it is almost prohibitive to be used in lines with V_{max}=200 km/h.

4. Mean Stress on Ballast-bed and Life-Cycle of track

Regarding the issue of ballast fatigue, the existing literature assumes a uniform distribution of stresses under the sleeper and without further details uses the mean value of pressure. *Based on research performed by the International Union of Railways(U.I.C.) –with the participation of principal European Railway Networks- the maximum moment measured actually on track results from parabolic stress distribution* (ORE D71, Rp9). But in reality, the seating of the sleepers is supported on discrete points, the points of contact with the grains of the ballast (Eisenmann & Kaess, 1980), and the resulting necessity to calculate the stress per grain of ballast cannot give results that are comparable with the existing literature. So it is possible to use the mean value of pressure not as an absolute quantity, but comparatively, *as an evaluation criterion,* and in combination with the possibility it covers (Giannakos, 2010a). The mean stress is estimated by dividing the action by the seating surface of the semi-sleeper. For the same seating surface -as in the case of each sleeper- the action on each sleeper is the decisive factor. Finally it is not the sleeper's material but the total stiffness of the track ρ_{total} -modulated mainly by the fastening and substructure in a percentage of 84-90%- that plays the key role for the magnitude of the actions on track panel and, consequently, for the magnitude of the mean stress on the ballast-bed. Experiments performed by ORE (ORE D117, Rp2, Rp4) showed that sleepers made of different materials (wood, concrete) exhibit almost identical values of track settlement. ORE/UIC was the main international railway research body for decades performing the experiments in many European Railway Networks such as the French, the German, the Polish, the British etc, with the participation of these networks. From Figures 3 through 6 the lower magnituge actions occur for B70+W14+Zw700 Saargummi pad and the higher magnitude for wooden sleeper+EVA pad or steel sleeper+EVA pad. More analytically, for the most characteristic value of $\rho_{substructure}$=100kN/mm the difference from the higher to the lower actions is as follows:

1.- for the German method the steel sleeper+EVA pad gives 23.2% higher and the wooden+EVA 21% (the same percentage for concrete+EVA also)
2.- for the French method the steel sleeper+EVA pad gives 31.2% higher, the wooden 28.4% and the concrete+EVA 34.1%.
3.- for the American method the steel sleeper+EVA pad gives 23.5% higher (the same percentage for concrete+EVA also) and the wooden+EVA 21 %, and
4.- for the Giannakos (2004) method the concrete+EVA pad gives 22.6% higher, the concrete+RN 19.7%, the steel sleeper+EVA pad gives 18.6% and the wooden+EVA 17.1 %.

The seating surface of B70 is considered to be 100%, the seating surface for the wooden sleeper is 96.5% (smaller), the steel sleeper 97.1%, the twin-block U31 69.2%, and the U2/U3 is 65.2%, meaning that the stress is higher. It has to be underlined that even the same combination of sleeper type (monoblock B70 of prestressed concrete) with fastening type (W14) but with different pads (Zw700 Wirtwein or Zw700 Saargummi) gives different values of actions on track panel (and mean stresses on ballast-bed) fluctuating (a) from 4.1-5.4% for the German method, (b) from 5.3-6.3% for the French method, (c) from 4.1-5.4% for the AREMA method and (d) from 3.5-5.2% for the Giannakos (2004) method for a relevant variation of ρsubstructure between 40kN/mm for pebbly substructure to 250 kN/mm for rocky bottom in tunnels with small depth of ballast. This difference is sufficiently high to secure more adverse performance in tracks with relatively more "rigid" pad according to the AASHTO testing for road construction equation for maintenance costs (Giannakos, 2004, 2010a, 2011):

(Decrease in track geometry quality) = (increase in stress on the ballast bed)^{m}

where m = 3 to 4, *implying that a 10% higher stress on ballast-bed provokes 33.1-46.4% higher annual maintenance cost for the track.*

For 20% to 30% as above the increase in maintenance cost could even reach 285%. The Life-Cycle of the track -dependent upon the fatigue of the repetitive loading- is highly influenced by the action and stress reduction.

5. Conclusions

In modern railway infrastructure fastenings of high-resilience significantly reduce the actions on the concrete ties and track superstructure, as well as the mean stress on ballast-bed compared to the stiffer fastenings. Therefore their use should be of utmost importance in the modern railway tracks since they eliminate the problems created by the loading of the track superstructure and substructure. The fastening and substructure stiffness contributes over 85% to the total static stiffness coefficient and the final values of actions/reactions. The increase of the actions on the track ballast-bed (and consequently to the stresses) -due to the use of stiff or rigid fastenings in comparison to the very resilient ones- varies from 19% to 34 % depending on the calculation method and affects significantly the annual maintenance cost according to the AASHO road test that can almost triple in some cases. Moreover the Life-Cycle of the track is dependent upon the fatigue of the repetitive loading is highly influenced by the action and stress reduction.

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