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To cite this article: A A Plugin *et al* 2020 *IOP Conf. Ser.: Mater. Sci. Eng.* **1002** 012010

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Crack resistance of reinforced-concrete sleepers with elastic rail fastening systems without base-plate

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Abstract. The article presents the main results of complex experimental and theoretical research into the crack resistance and the limit state of reinforced-concrete sleepers with elastic rail fastening systems without base-plate. The objective of this study is to uncover reasons for the cracks and other breakages during operation, demonstrate their importance, and produce a set of recommendations for prevention of the most serious defects. The research also involved statistical analysis of the defect factor for sleepers, and determined the number of defects by type according to track layout, traffic density, tonnage transported, concrete grade and other characteristics based on the results of full-scale research of track sections and surveys from maintenance specialists. The full-scale research was made on rail sections under standard operational modes and on a test track section of straight and curved elements with sleepers of concrete grades C32/40, C35/45 and C40/50. The study was based on numerical methods, modelling of the stress-strain behaviour of the track, and estimation of the performance of sleepers with cracks. The method used incremental-iterative algorithms to consider the elastic plastic properties of materials, solve contact problems in operation of rail fastening systems, and also reveal the structural nonlinearity of joint action for track elements. The method was realized in LIRA-SAPR software on the basis of Building Information Modelling (BIM) and the Finite Element Method (FEM). The results were verified by experimental research into the sleepers under static and dynamic loads with estimation of crack development in terms of concrete grades, deformation modulus, rigidities of the ballast layer and the sub-grade, position of the reinforcement and other characteristics.

1. Introduction

The most popular type of reinforced-concrete sleepers on Ukrainian Railways is Sh1-type sleepers reinforced with high-tensile steel wire and pre-stressed with KB-type terminal-bolted rail fasteners [1]. This structure has a steel base-plate with a rubber pad between the rail base and rail seat of a sleeper, which redistributes the loads across a large concrete area. Since the 1990s Ukrainian Railways have introduced the SB3-type sleeper (figure 1) for elastic rail fasteners KPP-5 without base-plate; they are popular as they have a few details, low metal capacity and working intensity. A prototype of these fastening systems was the SB-3-type fastener (Poland). The SB3-type sleeper differs from the Sh1-type sleeper by the presence of embedded anchors instead of holes for the insert bolts, and by a higher rail seat.



The sleepers are made of concrete grade C32/40; they comply with the maximum loads 232kN/axle from the rolling stock [2], and undergo final inspection in accordance with [1]. However, in operation they suffer from crack development and other defects, which can be estimated through the tonnage carried [3]. Since the 2000s railways have witnessed new types of defects, e.g. a crack network emerging after 1-3 years of operation, which develops and results in damage. Track facility engineers have noticed that SB3-type sleepers are less reliable than Sh1-type sleepers, and their damage rate depends on the traffic intensity of the rail section. Therefore, Ukrainian Railways use elastic rail fasteners without base-plate only for sections with traffic capacity of less than 30 million gross tons per year. However, the authors did not manage to find any substantiated quantitative analysis proving this view.

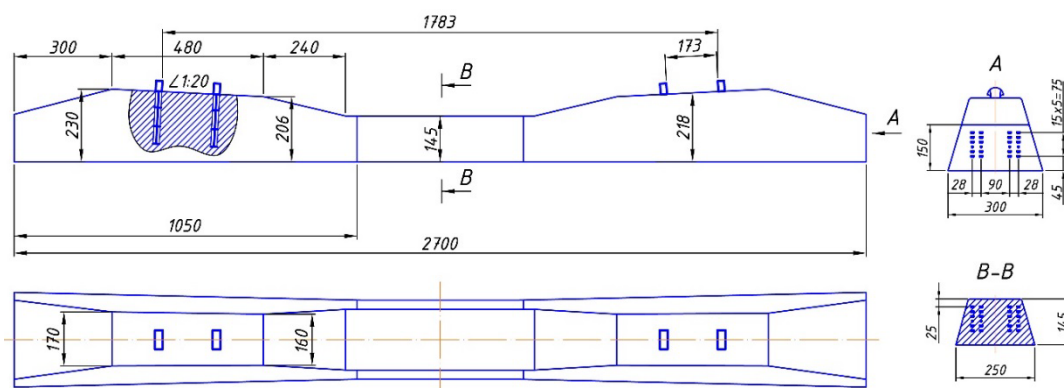


Figure 1. Structure of SB3-type sleeper.

2. Critical analysis of the results of earlier research

Practically, cracks in reinforced-concrete sleepers begin to develop when they are installed [4-7]. Study [4] substantiates the conditions under which force cracks do not open, and presents the most crack resistant sleeper structure; studies [5-7] propose an improved production technology aimed at greater crack resistance and durability of rail sleepers. Studies [8-12] explain the connection between crack network development and concrete corrosion due to the interaction of alkali in concrete with reactive aggregates [13-16]. However, the authors in [4-7] do not study sleepers with elastic fasteners without base-plate, and in [8-12] they consider only alkaline corrosion, irrespective of other factors of defects. The authors did not manage to find data on the dependencies between the damage factor of sleepers and the concrete grade, however, as known, many countries use higher concrete grades, unlike it is in Ukraine.

3. Statistical analysis of defects in sleepers

The full-scale research of track sections and statistical analysis of the results revealed typical defects in sleepers (table 1).

Table 1. Defects in sleepers with elastic rail fasteners without base-plate, percentage of sleepers with defects of all types.

№	Damage (defect)	%	Reason for defect, note
1	Abrasive wear of sleeper end by ballast (figure 2a)	41.4	Ballast settlement under sleeper ends and rail seats, vibrations of sleeper ends under vertical dynamic loads (development of transverse cracks near the anchors and in mid-span of sleeper)
2	Transverse cracks in mid-span of sleeper (figure 2b)	24.1	Ballast settlement under rail seats, deflections of sleepers under vertical loads (may result in fracture of sleeper)
3	Transverse cracks near anchors (figure 2c)	20.0	Crack development under horizontal loading component on anchor. Defect is intensified by ballast settlement under rail seats (results in complete damage of sleeper near anchor)
4	Longitudinal cracks at sleeper ends (figure 2d)	19.4	Irregular ballast settlement under rails, formation of shear stresses, cracks and spalls due to uneven stiffness of foundation (may result in spalls in sleeper)

5	Crack network on sleeper ends, sometimes along sleeper (figure 2e)	18.0	Crack network development due to corrosion of aggregates caused by the alkali of cement, alternate freezing and de-freezing (can lead to concrete degradation along cracks)
6	Transverse cracks under rail seats	4.5	Ballast settlement under rail seats, crack development under vertical loads
7	Longitudinal cracks across anchor	2.4	Crack development under horizontal load on the anchor (can result in splits of sleeper)
8	Longitudinal cracks in mid-span (figure 2f)	2.1	Corrosion of aggregates caused by the alkali of cement, crack development under initial tension of reinforcement due to lower concrete strength (results in splits in sleeper or complete concrete degradation)

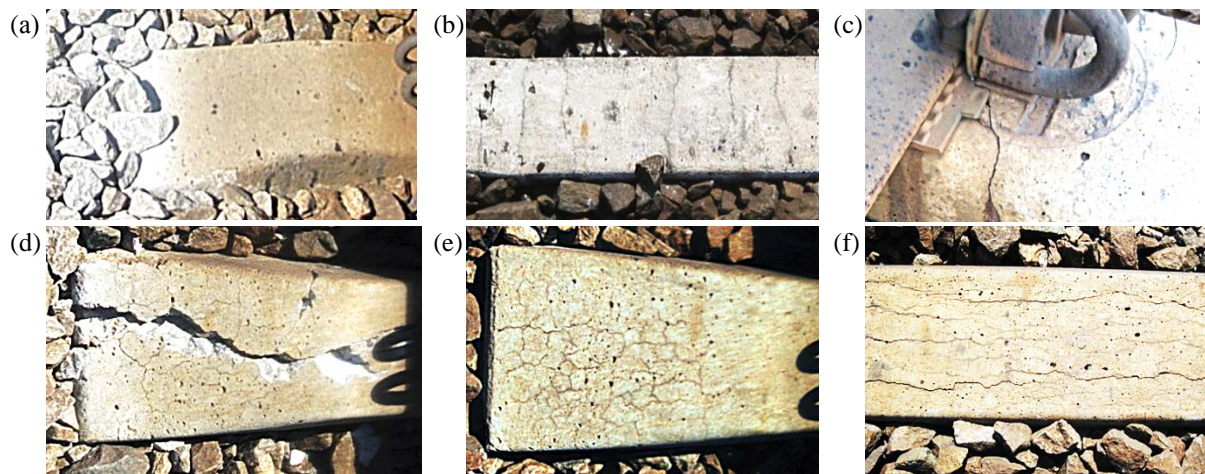


Figure 2. Defects in sleepers with elastic rail fasteners without base-plate.

Dependency of the defect rate of a sleeper on the tonnage carried is given in figures 3 and 4 (a) and on the traffic volume – in figure 4 (b). It demonstrates a slight correlation by Chaddock's scale (the squared correlation coefficient R^2 does not exceed 0.3) between the tonnage carried and the number of sleepers with defects, which to the utmost corresponds to the linear dependency. However, dependencies between sleepers with defects in pcs/km×million tons on the traffic density were not observed.

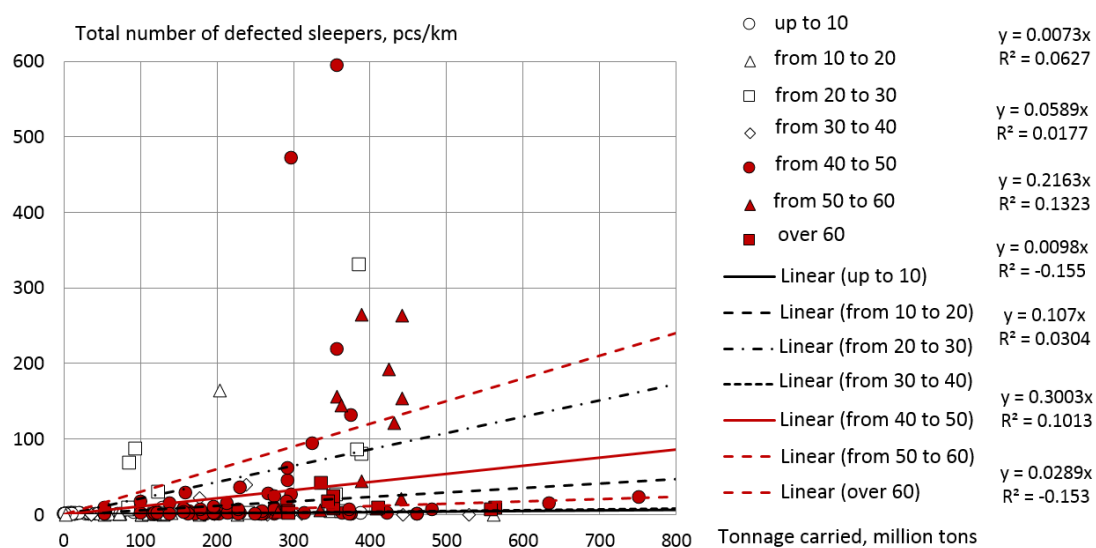


Figure 3. Dependency of the number of sleeper with defects (pcs/km) on tonnage carried (million gross tons) along sections with traffic density of up to 10, from 10 to 20, from 20 to 30, from 30 to 40, from 40 to 50, from 50 to 60, and over 60 million tons per year.

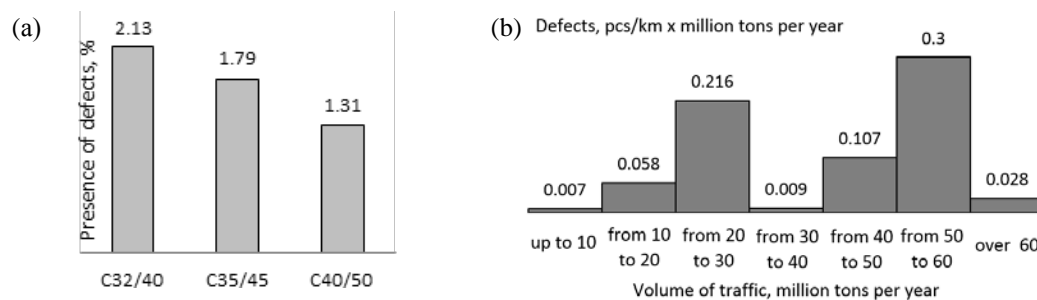


Figure 4. Dependency of the number of sleepers, with transverse cracks near anchors after 107 million gross tons transported, on concrete grade (a), dependency of defect rate on traffic density (b).

4. Analysis of stress-strain behaviour of sleepers by finite element method

4.1. Design diagram

Generally, the design engineering of today uses industrial software as the basic tool for computer modelling. An improved calculation of a track with rail fasteners without base-plate can be fully realized in LIRA-SAPR software [17] which earlier was proved to be an effective tool to study transport structures [18].

The following hypotheses were assumed in designing the finite element model (figure 5).

1. Steel elements, rail pads and inserts were designed with universal Solid finite elements of homogeneous isotropic linear elastic material in a three-dimension elasticity problem.

2. The strength and deformability of concrete sleepers were characterized by the parabolic rectangular deformation diagrams $\sigma_c - \varepsilon_c$ in accordance with EN 1992-1-1 (Eurocode 2), the pre-tension forces were set by decreasing the temperature of the axial finite elements installed in the axes of reinforcement of a sleeper. The research considered concrete grades C32/40, C35/45 and C40/50.

3. The models considered structural non-linearity of an assembly unit guaranteed by special bi-nodal finite elements of one-way connection (certain contacts were intended only for compression or compression with friction). These finite elements were inlaid between the adjacent nodes of the contacting elements and described the work of these contacts with the tensors of the axial rigidities. Generally, six contact problems were considered: rail pad – rail (S-R); anchor – insert (A-B); insert – rail (B-R); rail clip – insert (C-B); rail clip – anchor (C-A); anchor – sleeper.

4. A track fragment restricted by two sleepers was selected out of the track structure through the method of fragmentation. The boundary conditions of the fragment considered repeated the corresponding boundary conditions of a simplified full structure model. Thus, the fragment was calculated with a more detailed design diagram.

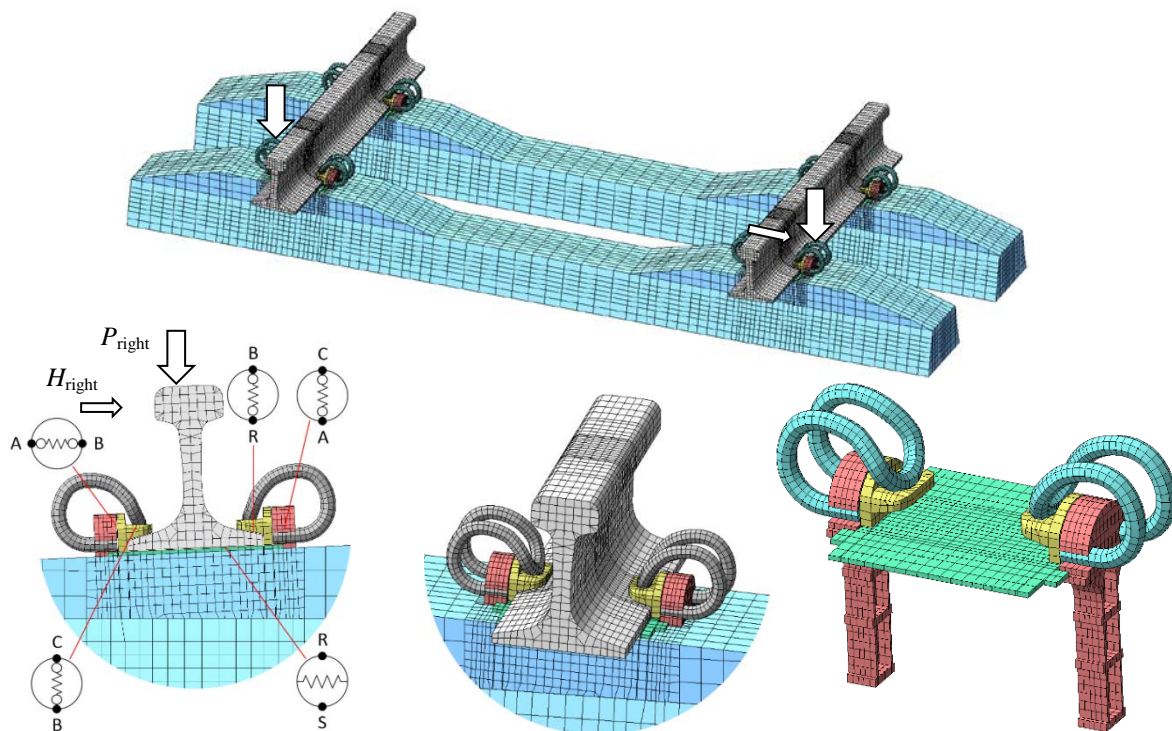
5. The rigidity of the sub-sleeper foundation was determined according to a three-dimensional model of the soil foundation and the ballast layer. According to this model the authors determined the moduli of sub-grade reaction C_1 , C_2 across the whole sleeper sole (these moduli depended on loads on the sleeper), and also the compressed depth and compaction. Therefore, the boundary conditions were set by the rigidity values of the rail seat and the loads in the rail sections on the boundaries of a fragment.

6. The load transfer from wheels to rail was performed through elliptical flanges of the finite element of the rail, the total area of which was 100mm².

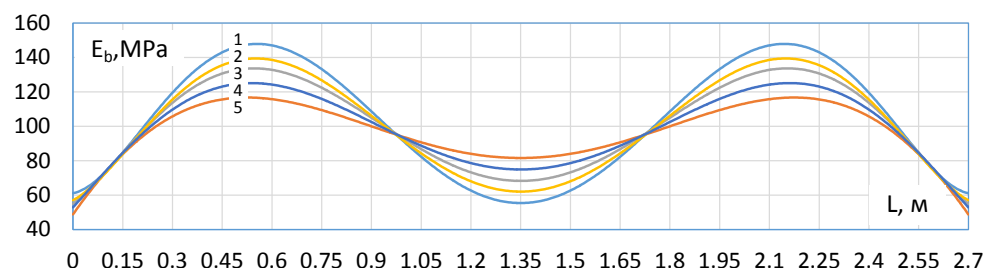
By applying series of loads such factors as dead weight impact, pre-tension of the reinforcement, and contemporary impacts were considered. The model assumed a possible loading on the rail with the axial load in any position within a span between the sleepers, which can be important for the analysis of other track elements. The analysis of the maximum loads in the sleepers was based on the position of the plate of loading, which laterally coincided with the sleeper axle and admitted displacement in the transverse section was conditioned by entering a curve. The operational loading was taken 232 kN/axle in accordance with [2]; it corresponded to the impact from rail passenger vehicles running at speed exceeding 160 km/h. The study considered loads for straight and curved track sections (table 2). For a curved line the horizontal loading was applied at 13mm lower than the rolling surface of the high rail.

Table 2. Temporary loads on rail.

Layout element	Forces, kN				
	Vertical		Horizontal		
	Left rail	Right rail			
	P_{left}	Eccentricity	P_{right}	Eccentricity	H_{right}
Straight	116	8 mm in the middle of track	116	8 mm in the middle of track	-
Curved	114	23 mm in the middle of track	118	7 mm high rails	120

**Figure 5.** Design diagram of track with elastic rail fasteners without base-plate.

Five technical track states were taken for the research: 1 – working (the deformation modulus of the ballast 120-145 MPa in the rail seat, 40-90 MPa in the mid-span); 2-5 – the deformation modulus decreases (figure 6). Changes in the deformation modulus did not influence the average rigidity for all epures; a decrease in the rigidity characteristics was determined by re-distribution of the deformation modulus values from the rail seat to the mid-span of a sleeper.

**Figure 6.** Changes in deformation modulus of ballast along sleeper according to the technical state of track.

A displacement of the pre-stressed reinforcement package of a sleeper from the design position was considered. The calculation was made for six levels of deviation in reinforcement: 1 – design position, 2-6 – geometric centers of reinforcement package displaced to sleeper bottom by 5–25 mm, respectively.

4.2. Analysis of stress-strain behaviour of sleepers

Stresses and deformations in a sleeper under the operational condition of a track are given in table 3. Figure 7 presents an example of stress fields for concrete grade C32/40 in a curved track section.

Table 3. Calculation results

Layout element	Concrete grade	Maximum stresses near anchor, MPa	Stresses in mid-span of sleeper, MPa	Vertical deformations, mm	Rail deflection, mm
Straight	C32/40	18.3	9.6	3.4	0.36
	C35/45	18.7	8.5	3.4	0.29
	C40/50	18.9	7.2	3.3	0.25
Curved	C32/40	30.3	11.2	4.28	0.72
	C35/45	31.4	10.4	4.28	0.65
	C40/50	32.2	8.7	4.23	0.51

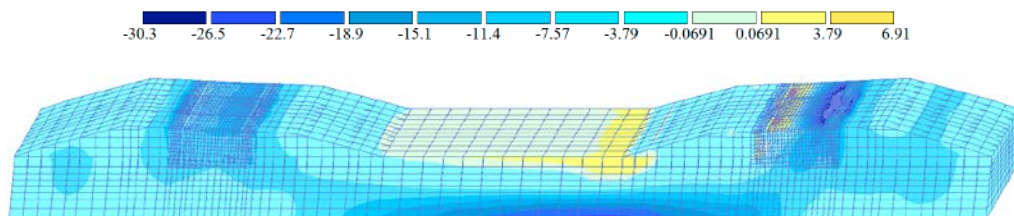


Figure 7. Main stresses in C32/40 sleeper for curved track section, MPa.

From the results of the calculation for different technical states of a track the research established changes in the stress-deformed state and the moment of crack development (the load corresponding to the emergence of the first crack) in the upper flange of a sleeper in the mid-span (figure 8). Deflections of the pre-stressed reinforcement package of a sleeper from the design position were illustrated in figure 9.

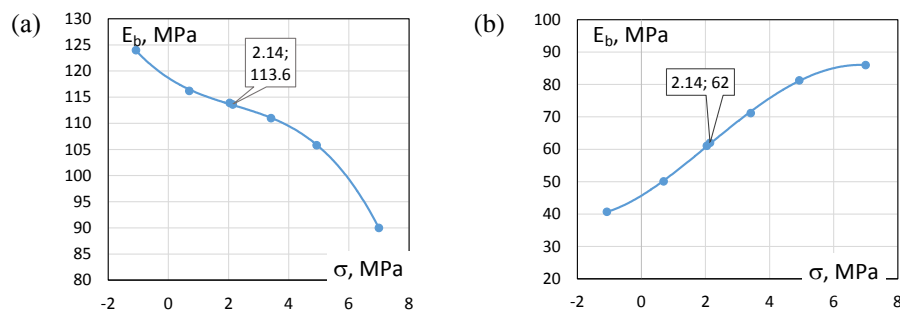


Figure 8. Stresses in upper flange of sleeper in mid-span according to deformation modulus of ballast in rail seat (a) and in mid-span (b).

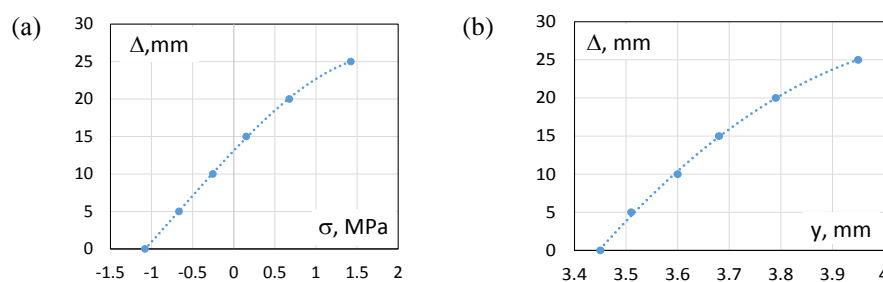


Figure 9. Changes in stresses σ in upper flange of sleeper in mid-span (a) and maximum vertical deformations y (b) according to deflections of reinforcement package from design position.

4.3. Main conclusions from the results of the calculation

Thus, the calculation by means of the finite element method established an effect of ballast settlement under rail seat, deflections of areinforcement package and concrete grade on the stress-strain behaviour.

Ballast settlement under the rail seats results in the development of transverse cracks in the middle of a sleeper. The moment of crack development is reached under settlement conditioned by a simultaneous decrease of the average deformation modulus of the ballast of up to 113.6MPa in the rail seat and an increase to 62MPa in the middle of a sleeper corresponding to the total rigidity decrease of the foundation by 22%.

Deflections of a reinforcement package from the design position in the sleeper production do not considerably affect crack development. A downshift of 25mm leads to a sign change of stresses in the middle of a sleeper reaching +1.4MPa, meanwhile the moment of crack development is not reached.

A change in the concrete grade from C32/40 to C40/50 results in:

- (for a straight line) an increase of the maximum loads in the anchor zone by 3%, a decrease of the loads in the midspan of the sleeper by 25%, a decrease in the vertical deformations by 3%, a decrease of the sleeper deflection by 31%;
- (for a curved line) an increase of the maximum loads in the anchor zone by 6%, a decrease of the loads in the midspan of a sleeper by 22%, a decrease in the vertical deformations by 2%, a decrease of the sleeper deflection by 29%.

Despite an increase of the maximum loads in the anchor zone by 3-6%, change of the concrete grade from C32/40 to C40/50, considering an increase in the compressive resistance of concrete by 25%, conditions a higher reserve of strength and rigidity of no less than 19%. These conclusions are proved by the coincidence with the results of the analysis of the on-site observation of the sections. Particularly, one of the most popular defects in sleepers is transverse cracks in the anchor zone (20%, table 7, table 3), and damage factor of sleepers by this type decreases with a higher concrete grade (figure 4a).

5. Experimental research

The study deals with static research into 17 sleepers specially manufactured with artificially formed deflectionsof a reinforcement package from the design position and lower depth of cross-sections. The sleepers were tested by static loading with a hydraulic press according tothe diagrams presented in figure 10.

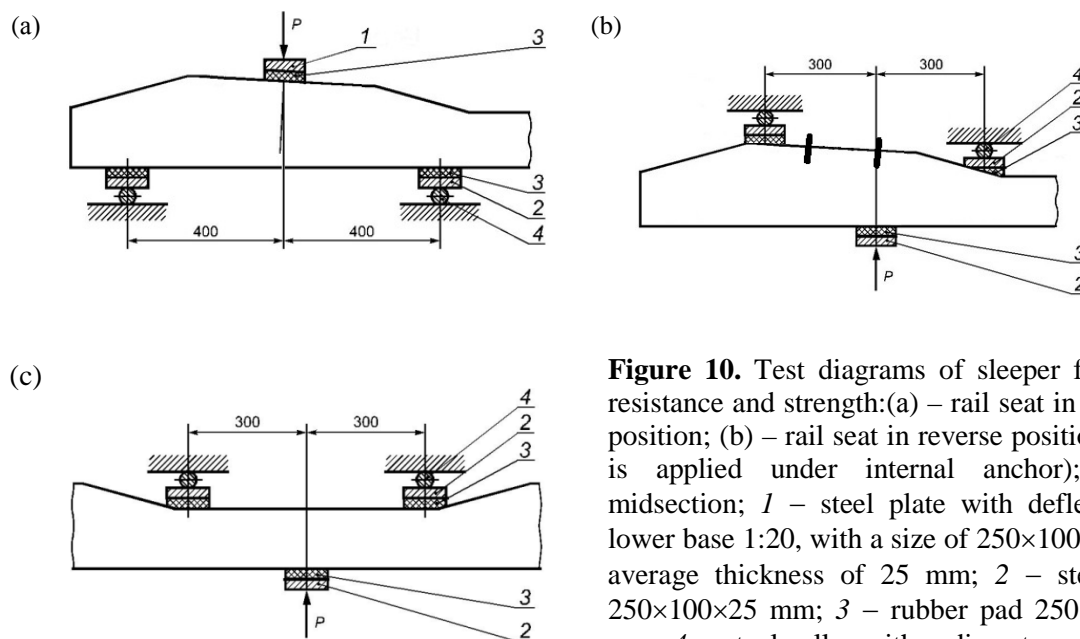


Figure 10. Test diagrams of sleeper for crack resistance and strength:(a) – rail seat in standard position; (b) – rail seat in reverse position (force is applied under internal anchor); (c) – midsection; 1 – steel plate with deflection of lower base 1:20, with a size of 250×100 mm and average thickness of 25 mm; 2 – steel plate 250×100×25 mm; 3 – rubber pad 250×100×10 mm; 4 – steel roller with a diameter of 40 mm and length of 250mm.

The results of the research into crack resistance and strength of the experimental sleepers under static loading are given in figure 11.

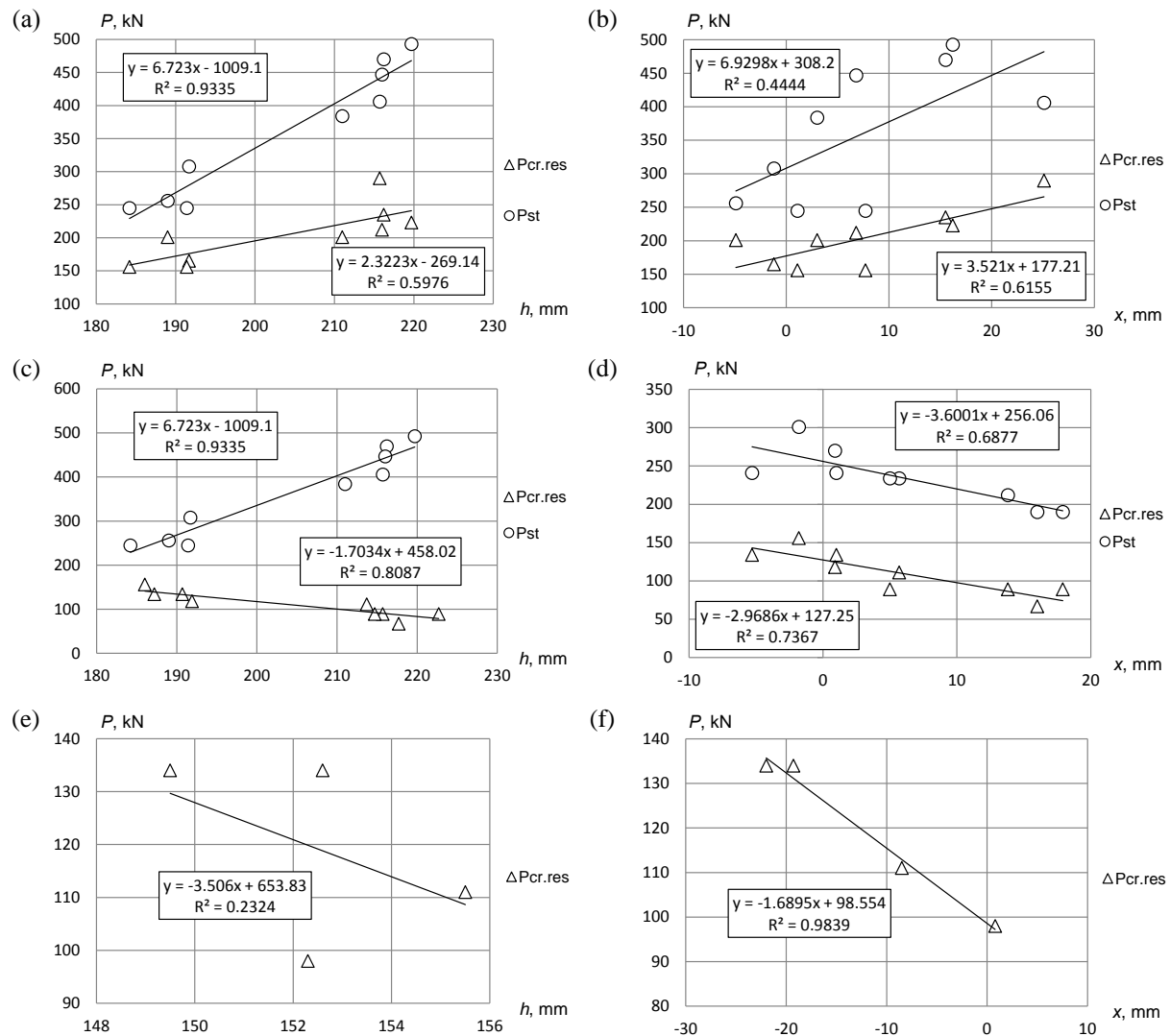


Figure11.Dependency of crack resistance boundary $P_{cr.res}$, kN and strength boundary P_{st} , kN of sleeper under loading:(a), (b) – rail seat section on top at height h (a) and deflection of reinforcement package x (b); (c), (d) – rail seat section at the bottom at height h (c) and deflection of reinforcement package x (d); (e), (f) – midsection at the bottom at height h (d) and deflection of reinforcement package x (f).

Therefore, the static tests established that due to the loading on the rail seat of sleepers from the top, which corresponded to the vertical loading component from the rolling stock, a decrease of the rail seat depth from 218 to 185 mm conditioned a fall of the crack resistance boundary by 33%, and the strength boundary – by 48%. Deflection of a reinforcement package upward by 5 mm conditioned a fall of the crack resistance boundary by 9%, and the strength boundary – by 13%. Deflection of a reinforcement package downward conditioned an increase of the crack strength boundary and the strength boundary.

When the sleeper section was loaded from the bottom under the internal anchor, which modeled an effect of the horizontal loading component from the rolling stock on the anchor, owing to the development of a similar moment in the cross section, a decrease in the rail seat depth from 218 to 185 mm conditioned an increase of the crack resistance boundary by 75%, and a decrease of the strength boundary – by 104%. An upward deflection of the reinforcement package conditioned an increase of the crack resistance boundary and

the strength boundary. A downward deflection of the reinforcement package by 25mm conditioned a decrease of the crack resistance boundary by 40%, and of the strength boundary – by 38%.

When the middle section of a sleeper was loaded from the bottom, which modeled ballast settlement under the rail seats, an increase of the middle section depth from 145mm to 155mm conditioned a decrease of the crack resistance boundary by 16%. An upward deflection of the reinforcement package conditioned an increase of the crack resistance boundary.

The authors tested sleepers of concrete grades C20/25, C32/40, C35/45, C40/50 with dynamic (impact) loading. The research was conducted with a shock testing machine by multiple drops of 10-kg weight from a height of 0.4 m (figure 12a). The tests used cubic models of 150-mm ribs with anchors installed in production. Some grooves were made in the concrete under the anchors (figure 12 b-f). The breaking knife impacted the anchor simulating the horizontal transverse force in the track. Three models were produced of each concrete grade. Each model was used to determine energy E spent for the development of the defect.

$$E = Nmgh/1000, \quad (1)$$

where N – number of impacts generating defect; m – falling-free weight, 0.1 kN; g – free fall acceleration, 9.81 m/s^2 ; h – drop height, 0.4 m; 1000 – J to kJ conversion factor.

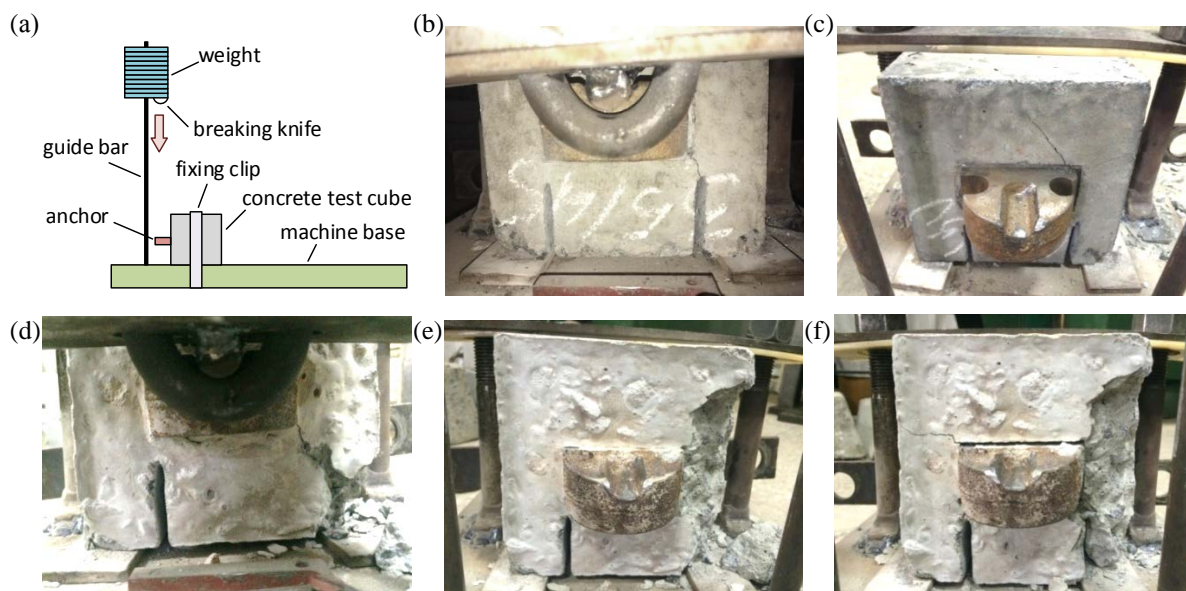


Figure 12. Tests on sleeper models through dynamic (impact) loading: (a) – model of shock testing machine; (b) – (f) – sleeper models with defects: initial cracks (b, c, concrete grades C35/45 and C40/50, respectively); initial spall, large palls, complete damage with separation of anchor from concrete (d, e, f, concrete grade C20/25, respectively).

The criterion, which characterizes a longer service life of sleepers due to higher concrete grade, is an increase in fracture energy in percentage to the fracture energy of the reference grade (C32/40):

$$\Delta P_{C35/45} = 100 \times (E_{C35/45} - E_{C32/40}) / E_{C32/40} \quad (2)$$

$$\Delta P_{C40/50} = 100 \times (E_{C40/50} - E_{C32/40}) / E_{C32/40} \quad (3)$$

The results of the research are given in figure 13. The dependencies were approximated: for initial defects (cracks and spalls) – by linear dependencies; for large spalls and complete damage – by exponential ones.

The analysis of the dependencies demonstrated that for initial defects the correlation between concrete strength and the number of impacts (energy) by Chaddock's scale was very slight, for large spalls ($R^2 = 0.57$; $R = 0.75$) it was noticeable, and for complete damage ($R^2 = 0.92$; $R = 0.96$) – very high.

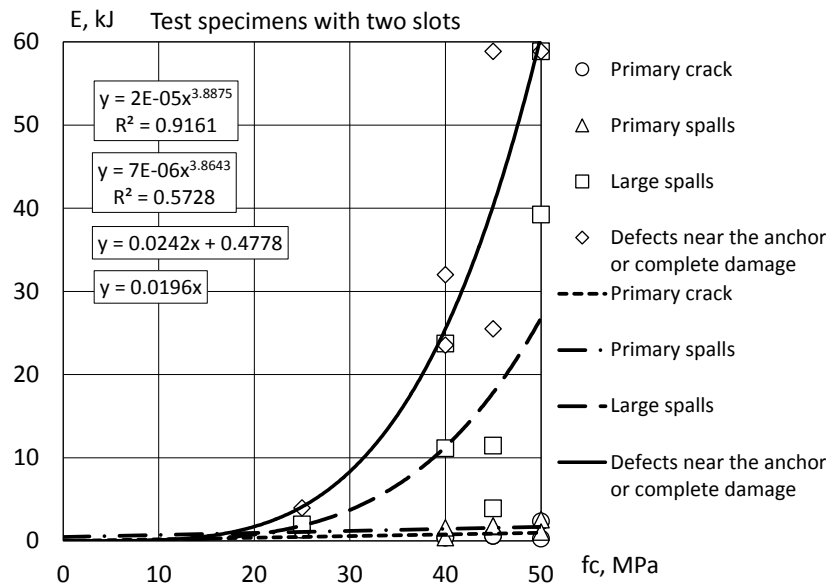


Figure 13. Dependency of energy E spent for development of defects (initial crack, initial spalls, large spalls, complete damage), on concrete compressive strength f_c .

The evaluation of a life gain is given in figure 14; the average sleeper life before development of defects due to higher concrete grade from C32/40 to C35/45 and C40/50 can increase by 33% and 187%, respectively.

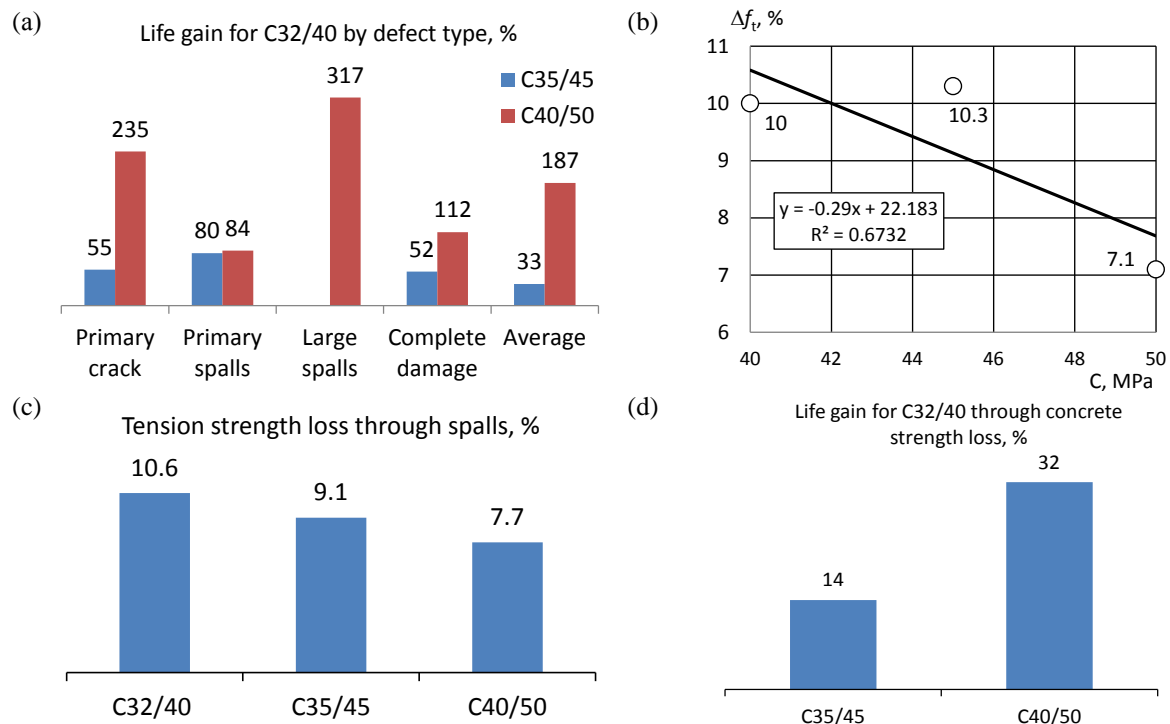


Figure 14. Results of tests on sleeper models by dynamic loading: (a) – by impact loading – better resistance to defects due to higher concrete grade from C32/40 to C35/45 and C40/50; (b) – (d) – by vibration loading: dependency between decrease in torsion strength at splitting Δf_t and concrete grade C (by strength factor of cubic samples, b, c); better resistance to spalls due to higher concrete grade from C32/40 to C35/45 and C40/50.

The tests were conducted on sleeper models from concrete grades C20/25, C32/40, C35/45, C40/50 with dynamic (vibration) loading. The models were half-sleepers with rail fragment and two assembled fasteners, in which a polymeric insert was replaced with a steel one; it provided a direct transfer of the horizontal loading component to the anchor and through it – to concrete (figure 15 a, b). The tests on half-sleepers with a rail and a pair of fasteners were made with the vertical force 22.5 ton-force and the load rate 9 Hz with the dynamic machine MYII-50, equipped with a base (figure 15a); it allowed for installation of the half-sleeper at an angle of 15° to the horizon and appropriate de-composition of the force relative to the sleeper into normal and transverse components (similar to vertical and horizontal forces in the track).

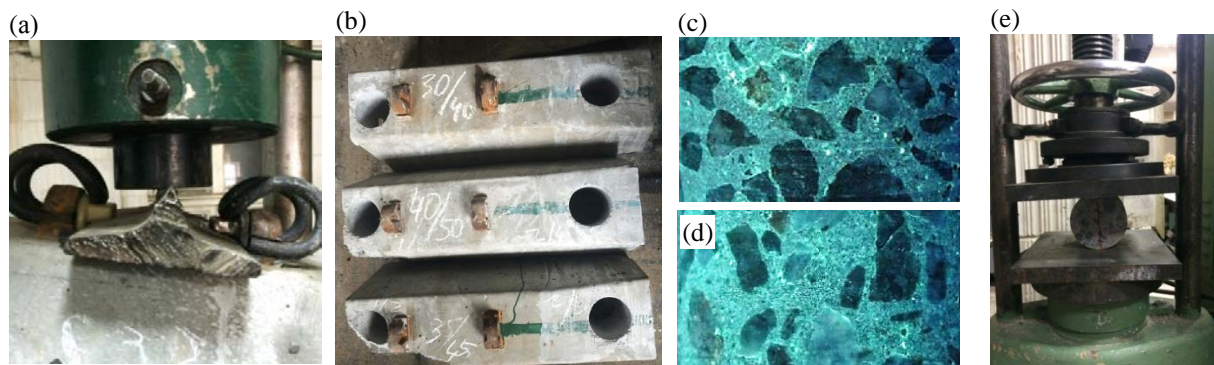


Figure 15. Dynamic tests on sleeper model with fastening assembly: (a) – model installed on MYII-50 at 15° (with right steel insert); (b) – models after selection of test samples; (c), (d) – test samples of concrete grades C32/40 (c) and C40/50 (d) treated with organic phosphor solution in Vaseline oil, in ultraviolet light; (e) – determination of concrete tensile strength under splitting according to [19].

After 1.5 million cycles of vibration impact, the 85-mm-diameter test samples were selected out of the models with circular bit: near the anchor where dynamic impact was maximum (left, figure 15c) and in the minimum dynamic impact zones (right, figure 15b). The test samples were studied with fluorescent non-destructive testing, they were used for manufacturing of sample-cylinders of 77–113mm in height; these cylinders were used to determine the characteristic which is most sensitive to micro-cracks, i.e. cylinder-splitting tensile strength (figure 15d). Besides, a decrease (in percentage) of this characteristic after vibration impact in the maximum impact zone in comparison with that of the minimum impact zone was also determined.

Using the results of the fluorescent non-destructive testing the authors established changes in the structure of concrete grade C32/40 near the anchor (in the left hand part of the photo, figure 14c) as a wavy crack network testifying the beginning of concrete segregation. Concrete grades C35/45, C40/50 did not demonstrate any structural change (figure 14d). A strength decrease in the maximum dynamic impact zone, obtained by the regression equation $\Delta f = -0.29C + 22.18$ (figure 13b), was 10.6% for concrete grade C32/40, 9.1% for concrete grade C35/45, and 7.7% for concrete grade C40/50. Consequently, a life gain of sleepers due to higher concrete grade can be estimated as 14% for C35/45 and 32% for C40/45.

6. Conclusions

1. The stresses in sleepers, which cause defects, do not depend on the traffic density of a section which indicates only intra-repair terms due to the tonnage carried. These stresses are determined by axle vertical loads, lateral horizontal loads (curve radii and traffic speeds), and dynamic impacts (maintenance conditions).
2. The stresses in the sleepers near the anchors are on the boundary of possible local concrete deterioration and crack development, thus, when concrete does not comply with the requirements for strength and homogeneity, such factors as track deterioration, additional influence of watering and continuous leakage currents cause defects and damage in sleepers.
3. The authors believe that better resource of sleepers with fasteners without base-plate for the sections of any traffic density can be reached with the following recommendations:
 - to use concrete grade C35/45 and higher for sleepers;

- for manufacturers of reinforced sleepers: to carefully follow requirements for quality of aggregates, particularly, reactive silica, and requirements for strength, freeze thaw and crack resistance by improving all types of control;
- not to apply fasteners without base-plate for sleepers in the track sections of epures less than 1840 sleepers/km; and
- to decrease tonnage norms for sections with fasteners without base-plate, and fill in ballast under the sleepers with worn-out ends.

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