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Case study

Pre-stressed concrete railway sleepers type B70W-60: requirements, technology of production, numerical modelling and calculations of immediate technological shortening

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Abstract: A railway sleeper is one of the basic elements of track that directly impacts traffic safety. Therefore is essential a high quality requirements for the sleepers. This thesis shortly demonstrate requirements for pre-stressed concrete railway sleeper and present production technology and the method of prestressing of sleeper B70W-60. Goal of this paper covers the numerical modelling of the sleeper and determination of immediate strain and shortening directly after prestress activation. Longitudinal shortening the sleeper immediately after releasing tension bolts, manifest itself in separating concrete from mould walls. Measuring the width of this separation is a useful indicator value – if it is too high, it may mean that there are technological process errors or an internal defect of an individual sleeper. Therefore, the numerical estimation of the separation width is a part of design process.

Keywords: concrete sleepers, pre-stressed sleepers, railway sleepers

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1. Introduction

A railway sleeper is one of the basic elements of track that directly impacts traffic safety. Railway sleepers are laid on the ballast and their purpose is to take the loads from the rails loaded with the rolling stock and to ensure the required width of the track and provide resistance to potential the vertical and horizontal shifts of the railway track system. Therefore, for safety reasons, it is essential to set out very high quality requirements for pre-stressed concrete sleepers. It is necessary for the entire construction project, the quality of material used, the technologies of production and treatment of concrete mix, and the infallible method of sleeper prestressing. Especially, the Young modulus is most important parameter determining of displacement of a sleeper laid on the ballast [15].

This thesis shortly demonstrate technological and material requirements for pre-stressed concrete railway sleeper and present production technology and the method of prestressing of sleeper B70W-60 – Fig. 1 (the sleeper is designed for Vignole 60E1 rail profile [16]). Main goal of this paper covers the numerical modelling of the sleeper and determination of immediate strain and shortening directly after prestress activation. Shortening the sleeper immediately after releasing tension bolts, manifest itself in separating concrete from mould walls. Measuring the width of this separation is a useful indicator value – if it is too high, it may mean that there are technological process errors or an internal defect of an individual sleeper. Therefore, during the production process, the manufacturer performs control measurements of the immediate shortening of random sleepers to ensure high product quality. The numerical estimation of the separation width is a part of design process.

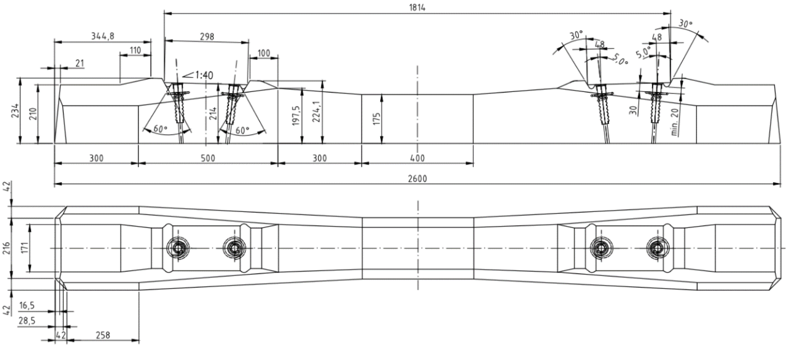

Fig. 1. Shape and dimensions of the B70W-60 sleeper [16]

Due to the dual symmetry, one quarter of the sleeper volume together with prestress was modelled using appropriate support conditions corresponding to the aforementioned symmetry. The spatial FEM model, fully based on volume elements, makes it possible to analyze local phenomena. In addition, the modelling of the geometry production moulds as non-deformable surfaces having mechanical contact with concrete form is an integral part of this paper.

The analysis presented in this paper was carried out using MSC.MARC software [11]. The software used in this paper is designed for contact phenomenon analysis.

2. Selected standard requirements for pre-stressed sleepers

Basic requirements for pre-stressed sleepers are included in a series of European standards [6]. The requirements and the methods of testing prefabricated components are described there. However, the standard mentioned refers also to individual requirements of infrastructure managers in different countries, where individual parameters have been specified, for example in Poland [8], in Germany [16], in Netherlands [14], in Czech Republic [12]). The standard [6] specifies the usage of materials compliant with the European Standards, if such exist, or with the relevant national standards. When selecting materials, special attention should be paid to ensuring a long-term durability of concrete, taking into account the requirements for frost, porosity and abrasion resistance. It is therefore necessary to use CEM I Portland cements, class 42.5 or higher. Depending on customer's demands, concretes C45/55 or C50/60 shall be used. It is necessary to provide a minimum of 300 kg/m^3 cement content and the water-cement ratio below 0.45. To protect concrete against chemical corrosion, the standard [6] obliges the producers to adopt special protective measures when using aggregates containing silicas vulnerable to Na_2O and K_2 alkalis originating from concrete or other sources when cement is exposed to moisture. As typical protective measures, the standard recommends, among other things, use of low-alkali cement with an equivalent total content of alkalis lower or equal to 0.6%, use of chemically inactive aggregates, or the reduction of the total mass of alkalis to 3.5 kg/m^3, or even lowering of that content in accordance with national recommendations [9]. Excessive alkali content in cement leads to chemical reactions with the aggregate, which result in creating alkali-silica gel with swelling properties. The gel is susceptible to absorbing water, which results in increasing its volume and degrading the concrete over time [1, 17].

The next dangerous phenomenon is internal corrosion caused by the formation of ettringite, which can be formed for example in structures subjected to heat treatment, i.e. in the prefabricate form [10]. Ettringite is a crystalline phase, which forms quickly in a cement slurry (after approx. 4 minutes). Then, the content of ettringite remains at a constant level for about 6 hours, after which it increases and after 24 hours it reaches the maximum value. In the next stage, the ettringite content decreases although it never drops to zero. The objective of technological procedures is to ensure that ettringite forms in the plastic stage of concrete, because during it the stresses resulting from the crystallisation of ettringite are naturally compensated by the concrete mix that is still plastic. The ettringite formation in concrete that has already hardened causes scratches and damage to it.

For prestressing tie rods, the manufacturer is obliged to use the high- strength steel compliant with the standard [5]. It should be noted, however, that the German railways, based on years of experience, banned the usage of prestressing steel strands in sleepers [16]. This is due to the formation of the so-called water-permeable cannulas as filling up the group of strands with a cement slurry is incomplete and allows water to penetrate.

3. Concrete sleeper prestressing systems

Due to high quality requirements for pre-stressed sleeper manufacturing the effective methods are vital for preventing the formation of cracks in pre- stressed sleepers – both during their manufacturing and their use together with the railway track. Despite the relatively simple structure of pre- stressed sleepers, the fact that they are subjected to large cyclic loading, in addition to weather conditions, makes it important to design them in such a way that the fatigue load can be transferred.

The adequate selection of the sleeper cross-section in the middle part and in the zone under the rail is necessary, with the method of anchoring the prestressing reinforcement being particularly important. The prestressing force can be transferred from prestressing wires to the cross-section of concrete in two ways: 1° by adhesion between steel and concrete along the entire transfer length; or 2° by pressure on the concrete of anchor blocks, in which prestressing wires are fixed. The study [4, 7] shows that better mechanical performance of sleepers is achieved when block anchoring is used instead of adhesion one.

One of the known systems is the BBRV anchoring method. It consists of making an anchoring head cold-formed by its swelling at each end of the prestressing rod. The resulting plastic deformation within the head is a prerequisite for the transfer of forces between the head and the anchoring element without any jams [13].

Prestressing is carried out by the use of straining bolts, screwed into the anchor plates [3,13]. Fig. 2 shows a photograph of the anchor block together with the swelling of the wire in the form of heads – see also [3].

Fig. 2. Anchor block with prestressing rods with heads shaped using the BBRV method. Photo: authors' own elaboration

4. Production technology

B70W-60 railway sleepers are concrete elements made of special C50/60 concrete maturing in controlled temperature and humidity conditions [3]. After reaching the appropriate durability, this element is prestressed with eight smooth rods, 7 mm in diameter each, anchored in a block using the BBRV anchoring method; the rods are made of prestressing steel having the durability of $R_m = 1670$ MPa. The average total prestressing force is $F_0 = 325$ kN, so the initial stress in each wire is $\sigma_0 = 1055.62$ MPa, which is 63.2% of R_m. The rods has been anchored by four retaining plates placed inside the concrete volume at the ends of the sleeper. The total weight of the sleeper is approx. 300 kg.

The basic elements required for the production of a single sleeper are [16]:

- Four steel anchoring plates. Each anchoring plate consists of two wider parts, which constitute direct pressure fields acting on concrete when stress is released, and of the neck connecting these two parts (Fig. 2). The wider parts each have two (smooth) holes, through which the prestressing rods are pulled and each have one M16 tapped hole for active straining bolts. The bolts go through the external mould walls and are screwed into the anchoring plates.
- Steel mould in which the sleepers are cast – Fig. 3. Each mould resembles a chest which is technologically separate, i.e. it requires to be operated separately on the technological line. In turn, each mould is divided into 4 cells enabling simultaneous casting of four separate concrete sleepers (the geometry of the mold is the negative of the geometry of the sleeper).

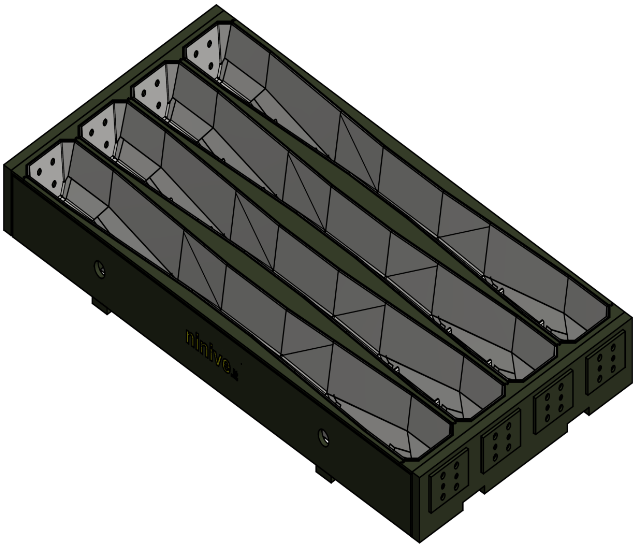

Fig. 3. General view of the production mould for B70W-60 sleepers

Sleeper production consists of several stages [8, 16]:

1. The first step is to prepare all steel elements of the sleeper outside the main technological line. The prestressing system assembled is then put into the mould – Fig. 3. However, after moistening the inner surface of the mould with a sprayed anti-adhesion agent first, the anti-adhesion fluid causes a radical decrease of static friction coefficient μ between the surface of the already set concrete and the surface of the mould, simultaneously allowing the concrete to be separated from the mould easily.
2. In the next stage, prestressing rods are tensioned. To do so, four bolts at one side of the mould in the anchoring plates are screwed for each sleeper – they are passive tension bolts.
3. The previously prepared mould with tensioned rods is cast with an appropriate concrete mix having the composition required by relevant standards and additional industry regulations. Next the mould is mechanically vibrated – the concrete is made denser and any air gaps are removed.

4. The mould prepared is transported to the thermal chamber (approx. 85°C) for approx. 24 hours, in which concrete sets and matures in controlled thermal and humidity conditions. The precise control over maturing conditions aims to increase the immediate strength of concrete appropriately fast, while minimising of the shortening [1,4].
5. The next stage, after removed from chamber, is the release of the straining bolts. The entire process of releasing all bolts takes about 1 minute. It is in this moment that the concrete of the sleeper is prestressed because the pre-tensioned rods are characterised by shortening. Anchoring blocks push the retaining surface and directly add compression into the volume of the concrete. The process of releasing tension causes an immediate shortening of the sleeper that can be observed as the separation of the sleeper from the mould walls.

Next stages of production are: removal of sleepers from the mould, screwing in the dowels, closing technological holes left by straining bolts in the sleeper, allowing the sleeper to cool, and further maturing.

5. Numerical model of B70W-60 sleeper

First of all, the geometry of the sleeper was precisely reconstructed in the FEM model. An important consequence of the reconstruction of the model double symmetry is also an introduction of interaction symmetry, in particular tension release. So, the final simulated shortening of the numerical model and the calculated width of a slit between the mould and the sleeper wall should be doubled so it could be compared to the actual width. Such an approach is primarily explained by an observation that both the simulation and *in situ* testing results do not indicate that the sleeper jams in the mould.

Subsequent Fig. 4, Fig. 5, Fig. 6 show the FEM mesh and the selected details of the sleeper FEM model. Fig. 6 shows the FEM mesh of anchor blocks from the side of prestressing rod endings.

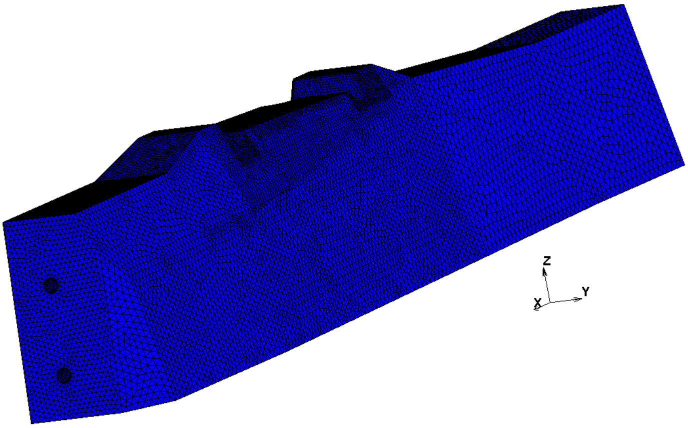

Fig. 4. View of the sleeper geometry and FEM mesh

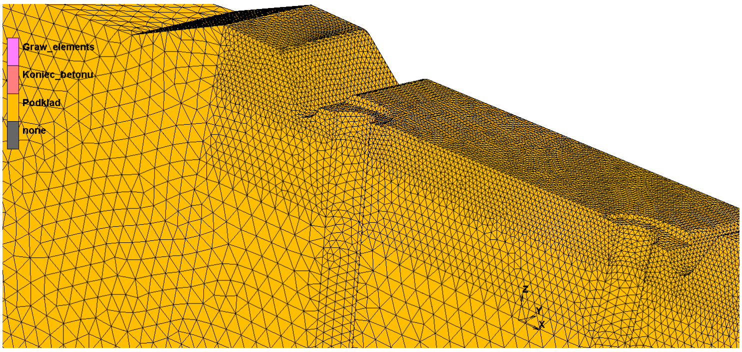

Fig. 5. Zoom of the sleeper geometry and FEM mesh

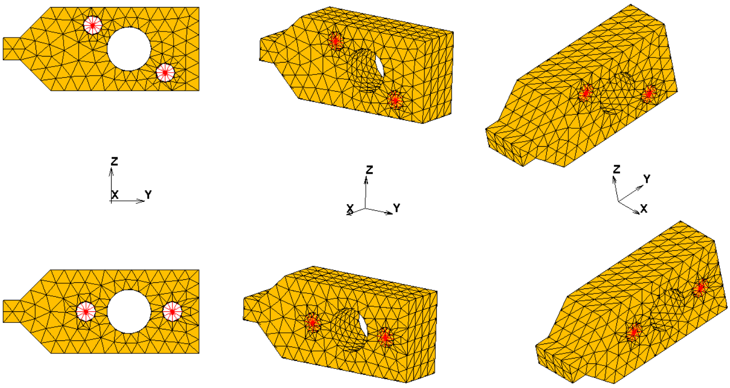

Fig. 6. Anchor blocks and FEM mesh – different views and visualization of RBE2 rigid bonds connecting the axes of prestressing rods with the edges of anchor blocks

Thermal effects were not taken into account in the analysis because straining bolts are released immediately after leaving the thermal chamber and it takes approx. 1 min. – thus it can be assumed that thermal conditions are constant.

In the FEM model, the following finite elements were used [11]: 1° Volume of sleeper consists solely of *tetrahedral* elements with sizes from 0.5 mm to 12 mm. Anchoring blocks consist solely of tetrahedral elements with the average size of the block is approx. 5 mm; 2° Steel prestressing rods are modelled as spatial rods with initial stress on prestressing. The rods in the model do not have contact with concrete and they freely penetrate the sleeper volume; 3° The mould was modelled by triangular elements of the shell – these elements were made as a rigid body.

In the analysis, the following material parameters were assumed: 1° C50/60 concrete: elastic modulus $E_b = 27$ GPa, Poisson's ratio $\nu_b = 1/6$, specific density $p_b = 2400$ kg/m^3; 2° Steel: elastic modulus $E_s = 210$ GPa, Poisson's ratio $\nu_s = 0.3$, density $\rho_s = 7850$ kg/m^3.

Kinematic boundary conditions include bilateral (fixings) and unilateral bonds that enable contact between bodies in practice. The essence of the task is the contact phenomenon. The basis for defining these types of tasks is to distinguish the objects that potentially make contact with each other and define the mechanical parameters of their interaction [2, 11]. In this task, the following bodies have been distinguished: 1° Concrete sleeper as a susceptible body that makes contact with two anchoring blocks and with a mould; 2° Upper and lower anchoring blocks as susceptible bodies, which make contact only with concrete; 3° Mould, as a rigid body, which makes contact with a concrete sleeper only. Due to the fact that before concreting the walls of the mould were covered with an anti-adhesive agent, the friction coefficient between surfaces that make contract, equal to $\mu = 0.1$, was assumed, and simultaneously the possibility of free separation for surfaces with zero average forces was adopted.

Figure 6 shows how to sew the wind-bracing elements of prestressing rods together with the edge of the anchoring blocks. RBE2 rigid elements (red color) were used to do so – they ensure the compatibility of displacements of all block edge constraints with a constraint placed at the end of the rod.

Two types of loads were considered in this case: a gravitational load and a load resulting from prestressing rods. The gravitational load $g_z = 9.81$ m/s^2. As the calculations show, the inclusion of dead weight has an important role only in the beginning of the analysis because it enables the sleeper to make contact with the mould on each wall. After prestressing is initiated, the stresses related to that state are predominant although vertical weight forces still cause local contact with the mould to be made.

Initial prestressing of rods was introduced as an initial axial tensile stress and in each wind-bracing element it was equal to σ_0. Needless to say, the process of tension release is carried out when gravitational loads act.

Due to the non-linear nature of the contact phenomenon, geometrically nonlinear analysis has been applied. However, the linear elastic models of materials were maintained. In the solution, the Newton–Raphson method has been applied to iterate balance [2, 11]. The Coulomb friction model with approximation of the arctangent type was also adopted.

6. Calculation results

The first analyzed stage is filling the mould with a concrete mix matures in a thermal chamber. The full contact between concrete and metal elements is achieved in this case. Simultaneously, it is a stage with zero stresses in concrete, possible internal stresses of concrete that occur in this process are negligible in relation to the stresses after prestressing activation. After prestressing activation sleeper concrete separates fully from the mould, the sleeper presses against the mould by gravitational forces only.

The next all figures shows results after prestressing activation. Fig. 7 shows the longitudinal displacement U_X of the sleeper. The calculated separations, amounting to a maximum $U_X = 0.37$ mm, occur at the mould end wall. The localization of maximum separation is the same as observed *in situ*. Due to the assumed symmetry of the model, the calculated U_X should be doubled to compare it to the actual shortening of the sleeper. Therefore, total shortening resulting from the calculations is approx. $\widetilde{U}_X = 0.73$ mm.

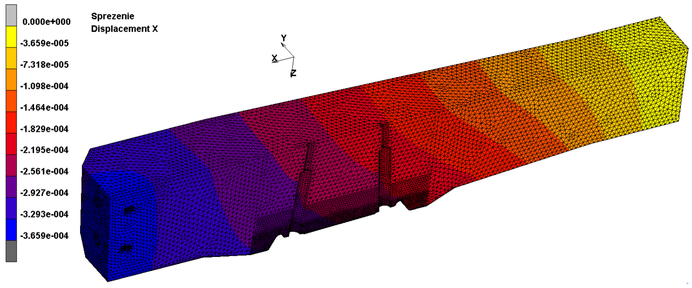

Fig. 7. U_X horizontal displacements in the concrete sleeper after prestressing activation

Fig. 8 shows the final configuration of the sleeper and U_Z vertical displacements. This figure reveals that the middle of the sleeper, because of prestressing, bends upward.

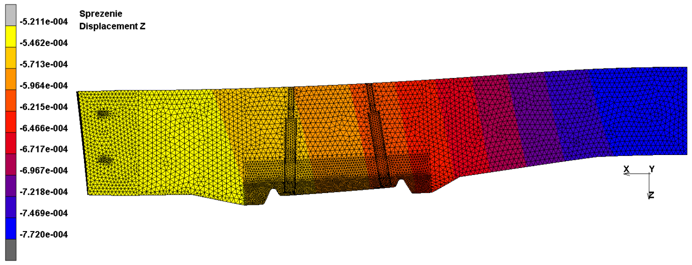

Fig. 8. U_Z vertical displacement in the concrete sleeper – side view

The stresses occurring after prestressing activation were also determined in the calculations. Values of stresses are caused by specific loads. Subsequent Fig. 9 show the σ_{XX} stresses. In general, it can be stated that the stresses along the sleeper cause its compression in the entire volume. The distribution of σ_{XX} longitudinal stresses is consistent with the sleeper displacement shown in Fig. 8. After prestressing activation, the top of the sleeper (in the operating position) is more compressed (about –15 MPa) than the bottom of the sleeper (about –7.2 MPa). Thus the displacement shown in Fig. 8 and the distribution of σ_{XX} stresses in Fig. 9 proves that the eccentrics of prestressing forces were designed properly.

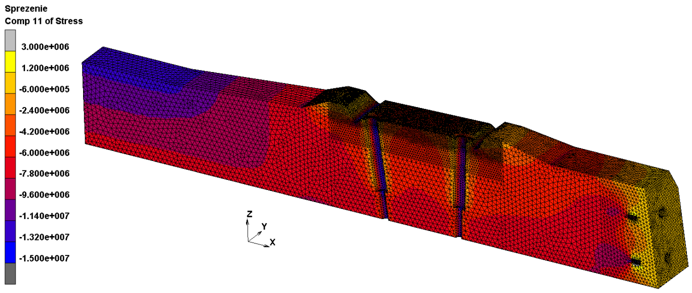

Fig. 9. σ_{XX} stresses in the concrete sleeper

7. Conclusions

Numerical analysis was based on the volume model of the sleeper and anchoring blocks. The analysis assumes the linear elasticity of materials and nonlinear geometrical equations due to the phenomenon of contact. This model is sufficient to analyze the immediate shortening of the sleeper after prestressing activation. The simulation of prestressing force activation was carried out with contact between the mould, sleeper, and anchoring blocks taken into account.

The numerical simulation demonstrates that the separation of concrete from the mould can be explained physically and technologically. The total immediate longitudinal shortening of the sleeper after prestressing activation equals approx. 0.73 mm and is visible at the point of contact between the mould and end walls of the sleeper. In situ measurements, made with a feeler gauge for good quality sleepers, show that the actual value of the total shortening is in the range of 0.59–1.05 mm. The width is a useful indicator value – if it is too high, it may mean that there are technological process errors or an internal defect of an individual sleeper. A longitudinal shortening more than 1.3 mm indicates a defect into the sleeper, so it should be discarded and not be used anymore. Therefore, during the production process, the manufacturer performs control measurements of the immediate shortening of random sleepers to ensure high product quality.

The stress and the displacement pattern caused by prestressing are beneficial for the target application since the ballast resistance on the middle part of the sleeper is opposite when its ends are subjected to the load of rolling stock wheels.

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References

[1] K. Cieszyński, “Technological quality assurance in the production of prestressed concrete sleepers”, *Infrastruktura Transportu*, vol. 2010, no. 5, pp. 44–45, 2010 (in Polish).

[2] M.A. Crisfield, *Non-linear Finite Element Analysis of Solids and Structures*, vol. 1 & 2. John Wiley & Sons, 1997.

[3] W. Czyczuła, W. Derkowski, and Ł. Chudyba, “Analysis of the main factors influencing the durability of railway sleepers”*, Rynek Kolejowy,* vol. 2015, no. 10, pp. 114–119, 2015 (in Polish).

[4] W. Derkowski, B. Słyś, and M. Szmit, “Effect of standards anchorage system in railway sleepers on behavior of its rail seat zone”, *Architecture Civil Engineering Environment*, vol. 2015, no. 1, pp. 61–68, 2015.

[5] EN 10138 – Prestressing steels.

[6] EN 13230-1 Railway applications – Track – Concrete sleepers and bearers - Part 1: General requirements.

[7] D. Hoffmann, W. Mohr, and S. Freudenstein, „Untersuchungen an Spannbetonweichenschwellen zur Eingrenzung der Laengsrissproblematik”, *ZEVrail*, vol. 142, no. 11–12, 2018.

[8] WTWiO – ILK3a-5187/01/05 Technical Conditions for the Production and Acceptance of Sleepers and Prestressed Concrete Turnouts. PKP PLK S.A., 2020 (in Polish).

[9] J. Kisilowski and W. Kurdowski, “Robustness as an element of system safety”, *Rynek Kolejowy*, vol. 2014, no. 5, pp. 1–8, 2014 (in Polish).

[10] W. Kurdowski and H. Szeląg, „Concrete corrosion caused by delayed ettringite formation”, in *Konferencja Naukowo-Techniczna Awarie Budowlane 2011, Międzyzdroje*. Szczecin: Zachodniopomorski Uniwersytet Techniczny, 2011, pp. 1119–1126 (in Polish).

[11] MSC.Marc/Mentat Manuals, v.2022. MSC Software Corporation, 2022.

[12] 14503/07-OP Obecne Technickie Podminky. Betonove Prazce Pro Zeleznicni Drahy. Správa železnic dopravní cesty, 2007.

[13] S. Plica and P. Plica, “Vermeidung von Schwellenrissen durch Änderungen bei der Herstellung“. München. Dr. Plica Ingenieure Partnerschaft für Bauwesen, 2011.

[14] Productspecificatie. Dwarsligger NS90. SPC00021. V007.06.2021.

[15] M.M. Shokrieh and M. Rahmat, “Effect of Young’s modulus on response of railway sleeper”, *Applied Mathematical Modelling*, vol. 31, no. 4, pp. 700–711, 2007, doi: 10.1016/j.apm.2005.12.004.

[16] Technische Lieferbedingungen 889.0143 Gleis- und Weichensch-wellen aus Beton für Schotteroberbau und Feste Fahrbahn. Deutsche Bahn, 2021.

[17] A. Titze, “The damage caused by the alkali in the concrete. Risk, which can be avoided”, *Infrastruktura Transportu*, vol. 2011, no. 2, pp. 56–58, 2011 (in Polish).

Strunobetonowe podkłady kolejowe B70W-60: wymagania, technologia produkcji, modelowanie numeryczne i obliczenia natychmiastowego skurczu technologicznego

Słowa kluczowe: podkłady betonowe, podkłady kolejowe, podkłady strunobetonowe

Streszczenie:

Podkład kolejowy jest podstawowym elementem toru mającym bezpośredni wpływ na bezpieczeństwo ruchu. Dlatego istotne są wysokie wymagania jakościowe tych elementów. W niniejszej pracy krótko przedstawiono wymagania stawiane podkładowi kolejowemu z betonu sprężonego oraz przedstawiono technologię produkcji i sposób sprężania podkładu B70W-60. Celem artykułu jest prezentacja modelu numerycznego tego podkładu oraz określenie natychmiastowych odkształceń i skróceń bezpośrednio po aktywacji sprężenia. Skrócenie podkładu po odkręceniu śrub naprężających objawia się oddzieleniem betonu od ścian formy. Pomiar szerokości powstałej szczeliny jest przydatną wartością wskaźnikową – jeśli jest zbyt duża, może to oznaczać błędy procesu technologicznego lub wadę wewnętrzną pojedynczego podkładu. Dlatego numeryczne oszacowanie szerokości separacji jest częścią procesu projektowania.

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