UDC 691.328:625.142
DOI: 10.15587/1729-4061.2025.341427

# ESTABLISHING PATTERNS IN THE STRESSED-STRAINED STATE OF CONCRETE SLEEPERS WITH PRESTRESSED COMPOSITE REINFORCEMENT AND THEIR MODELS

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***This study investigates the finite-element and physical models of railroad sleepers made of concrete with steel and composite prestressed reinforcement.***

***Reinforced concrete sleepers withstand mechanical loads well but have low electrical resistance, which contributes to traction current losses, leakage currents and electrocorrosion of linear structures on electrified railroads, as well as disruption of auto-lock. Since low electrical resistance is due to the electrical conductivity of steel reinforcement, its replacement with composite makes it possible to solve a number of problems in railroad operation. However, its use for sleepers is complicated by the difference from steel reinforcement in elasticity and remains insufficiently studied.***

***Sleeper models and a scheme for their testing have been devised, which corresponds to the standard sleeper test. Calculation and full-scale experiments with loading the models have been performed. It has been established that as the models are loaded and the deformation moment increases, it evolves in three stages: crack formation; their development to the formation of a plastic hinge; failure with reinforcement slipping. In the model with composite reinforcement, compared to steel reinforcement, the moments corresponding to these stages are smaller by values that correlate with lower tension forces and the modulus of elasticity of the reinforcement. The type of reinforcement affects all moments characterizing the strength and crack resistance of the models less than the pre-tensioning forces.***

***The results from the calculated and full-scale experiments have been compared. Correction factors were proposed for calculating the moments of crack formation in sleepers. The results make it possible to design sleepers with composite reinforcement of the required crack resistance. Such sleepers could be implemented provided that a positive result is obtained from their experimental operation on an electrified section of the railroad***

***Keywords: railroad sleeper, concrete, steel reinforcement, composite reinforcement, prestress, crack***

*Received 22.07.2025*
*Received in revised form 24.09.2025*
*Accepted 03.10.2025*
*Published 31.10.2025*

***How to Cite:*** *Plugin, A., Murygin, M., Plugin, D., Najafov, E., Musiienko, S., Lobiak, O. (2025). Establishing patterns in the stressed-strained state of concrete sleepers with prestressed composite reinforcement and their models. Eastern-European Journal of Enterprise Technologies, 5 (7 (137)), 6–16. https://doi.org/10.15587/1729-4061.2025.341427*

## 1. Introduction

The sub-rail foundations of railroads are mainly sleepers. On the world's railroads, 60–65% of sleepers are reinforced concrete. Due to significant dynamic loads, high requirements are imposed on them for strength and crack resistance, so they are made of high-strength concrete with steel rod or wire prestressed reinforcement. They resist mechanical loads well, including dynamic loads, but have low electrical resistance, which contributes to traction current losses, the formation of leakage currents and stray currents on electrified sections, and disruption of auto-blocking systems. Leakage currents and stray currents, in turn, have a powerful electro-corrosive effect on linear and other structures of railroad infrastructure.

At Ukrainian enterprises, for the manufacture of sleepers, reinforcement made of high-strength carbon steel wire 44∅3 mm is conventionally used, the tension of which with a force of 358 kN is carried out on the form and transferred to the concrete after it reaches a transfer strength of at least 32 MPa. At the ends of the sleepers, the reinforcement protrusions allowed by current standards remain, which leads to the participation of the reinforcement in leakage current circuits and, accordingly, to an increase in traction current losses, creating conditions for electrocorrosion.

In the most modern technologies, smooth bar reinforcement is used, and its prestress is transferred to the concrete not along its entire length due to the periodic profile of the reinforcement but through anchor plates embedded in the concrete at the ends of the sleeper. Prestressing can be carried out not only on the form but also on concrete that has acquired a certain initial strength. For this purpose, smooth reinforcement is used in 4 or 8 bars per sleeper. The tension of the reinforcement is carried out by wrenches using nuts and threads cut at the ends of the bars and is transferred to the concrete through anchor plates, loops at the opposite end of the sleeper, etc. Since all these elements are located in the recesses formed by void formers in the ends of the sleepers, the ends of the reinforcement are protected with a cement-sand mortar several tens of mm thick. This minimizes the participation of the reinforcement in the leakage current circuits on electrified railroads, minimizing in turn the loss of traction currents and electrocorrosion processes.

Since the low electrical resistance is mainly due to the electrical conductivity of steel reinforcement, its replacement with non-conductive composite reinforcement would solve a number of problems in the operation of railroads. The use of composite reinforcement for railroad sleepers made of concrete is complicated by its significant difference from steel reinforcement in elastic properties and remains insufficiently studied. Therefore, such studies remain relevant.

## 2. Literature review and problem statement

In [1], the results of studies on the influence of concrete properties on the properties of reinforced concrete sleepers are reported. It is shown that increasing the strength of concrete, for example, by using alkali-activated cements, ensures an increase in the durability of sleepers. Such concrete will certainly have lower electrical conductivity. However, the issues of reducing the electrical conductivity of sleepers as a whole remain unresolved. The likely reason is that the authors did not question the need to use steel reinforcement because it ensures their crack resistance.

An option for overcoming such difficulties is to use sleepers made of a completely non-conductive material. This is the approach used in [2], in which composite sleepers made of secondary polymers were studied. However, the authors themselves established that such sleepers have too high deformability due to the creep of the polymer, which could also degrade from insolation. Therefore, the use of such sleepers would have a number of limitations, especially on main railroad lines.

Another option may be the dispersed reinforcement of sleepers with non-conductive synthetic fibers. This approach was used in work [3], in which sleepers reinforced with polypropylene macrofiber were studied. However, the issues of ensuring the durability of sleepers remain unresolved. The reason for this may be the lack of prestressing of concrete and therefore the inability to provide the required crack resistance and, consequently, insufficient durability and high operating costs for replacing damaged sleepers.

In [4], it is noted that structures made of concrete with composite reinforcement have greater plasticity than similar reinforced concrete structures. To enable work in the elastic stage, this requires a lower level of structural loading, and, consequently, the use of more powerful sections and reinforcement, so the authors propose and study combined reinforcement with steel reinforcement. But for complex work of structures, for example, on a solid elastic base, such as sleepers, such a combination of reinforcement with very different elastic moduli has remained unexplored and does not seem acceptable.

In [5], it is shown that the stiffness and crack resistance indicators of concrete structures with composite fiberglass reinforcement are lower than those of similar reinforced concrete structures. In the studied samples with composite reinforcement, the deflection exceeded the deflection of samples with steel reinforcement by 43.3%, the crack opening width by 28.8%, the crack formation moment was 16% smaller, and the fracture moment by 18.1%. Therefore, the authors concluded that the use of composite reinforcement for bending beam structures is inappropriate, and composite reinforcement is recommended for structures on a solid elastic base. However, the prestressing of composite reinforcement, as in sleepers, remained unstudied.

In work [6], the lower stiffness and crack resistance of concrete structures with composite reinforcement compared to reinforced concrete structures, as well as the brittle nature of the fracture of composite reinforcement and structures with it, are also noted. To increase crack resistance, an increase in the strength of concrete is proposed and investigated. Since sleepers, especially for unlined rail ties, are made of high-grade concrete, it can be assumed that the use of composite reinforcement is more suitable for sleepers than for most building structures.

A number of works investigate the possibility of prestressing the external reinforcement of structures with composite rods [7], strips [8]. External reinforcement does not seem acceptable for sleepers, but those papers show that compared to steel, it is more difficult to provide anchoring for composite reinforcement. Those studies also investigate mechanical anchoring of reinforcement and do not pay attention to adhesive connections of reinforcement with anchor devices.

In work [9], a structural and technological solution for sleepers with composite epoxy-basalt reinforcement 8∅8 mm instead of steel 44∅3 mm is proposed. Using the finite element method and the LIRA-SAPR software package, an analysis of the stress-strain state of prestressed sleepers with steel wire and composite epoxy-basalt reinforcement was performed. It is shown that sleepers with composite reinforcement meet the strength requirements. The stress-strain state of the sleeper is influenced to a greater extent by the prestressing value of the reinforcement package, to a lesser extent by the type of reinforcement. At a package tension of 358 kN, the maximum compressive stresses in the concrete of the specified sleepers are the same – 26 MPa. However, with composite reinforcement, the crack resistance of the sleeper deteriorates – the maximum tensile stress in its average cross-section of 1.1 MPa is an order of magnitude higher than the stress in the sleeper with steel reinforcement of 0.12 MPa, although it does not cause the formation of cracks. Halving the tension of the composite reinforcement package causes an increase in the maximum tensile stress to 7.1 MPa, which exceeds the tensile strength of concrete and causes the formation of cracks in the stretched zone of the average cross-section. Therefore, a decrease in the prestressing of the composite reinforcement will not lead to the destruction of concrete in compressed zones but will cause the sleepers to operate with cracks. Since cracks in concrete, unlike steel reinforcement, do not cause corrosion of composite reinforcement, it was assumed that the prestressing level of composite reinforcement for sleepers could be reduced.

However, the finite element model of the sleeper is quite complex and has not been tested for composite reinforcement. Therefore, the calculations of the strength, stiffness, and crack resistance of sleepers with composite reinforcement performed by the finite element method require verification. Thus, the deformability and crack resistance of such sleepers have remained insufficiently studied. The likely reason was the difficulties associated with the inability to conduct experimental studies on full-size sleepers in sufficient volume. All this allows us to state that it is advisable to conduct experimental studies on the strength, stiffness, and crack resistance of sleepers on models.

## 3. The aim and objectives of the study

The purpose of our research is to establish features in the stressed-strained state of concrete sleepers with prestressed composite reinforcement using models. This will make it possible to design sleepers with composite reinforcement of the required crack resistance.

To achieve the goal, the following tasks were set:

– to perform an experimental comparative study of the physical and mechanical properties of steel and composite reinforcement;

– to perform computational and full-scale experiments on loading models of concrete sleepers with steel and composite reinforcement and compare their results.

## 4. The study materials and methods

The object of our study is the finite-element and physical models of railroad sleepers with steel and composite prestressed reinforcement.

The principal hypothesis of the study assumes that the stressed-strained state of the physical model of a sleeper in the form of a concrete reinforced beam with prestressed reinforcement in the compressed and tension zones corresponds to the stressed-strained state of the sleeper during a standard test.

The assumptions and simplifications adopted in the study: a concrete beam with prestressed reinforcement in the compressed and tension zones, loaded with a central concentrated force, simulates the operation of the sleeper in the under-rail and middle section during a standard test.

The structure of a concrete sleeper reinforced with prestressed steel wire (44∅3 mm) and composite (epoxy-basalt, 8∅8 mm) reinforcement is shown in Fig. 1. According to DSTU B.V.2.6-209 (Ukrainian analog of EN 13230-2), sleepers are tested for crack resistance without bringing to failure according to the scheme shown in Fig. 2. Control loads *P*, at which the length of the cracks should not exceed 30 mm, and the opening of 0.05 mm, for the under-rail section is 130 kN, for the middle section – 98 kN. These values correspond to bending moments of 52 kN and 29.4 kN.

Considering the complex structure of the sleeper for manufacturing and testing under laboratory conditions, for research and verification of the results of calculations of strength, stiffness, and crack resistance of sleepers with composite reinforcement, a study on simplified models is proposed. These models are concrete beams measuring 560 × 100 × 50 mm, reinforced with two bundles of steel wire or two composite rods, one located in the tension zone, the other in the compression zone (Fig. 3). Prestressing, as in the sleeper (Fig. 1), is carried out on the entire reinforcement. The loading scheme is selected in accordance with standard sleeper tests (Fig. 2) – a beam supported at two ends by a concentrated central load.

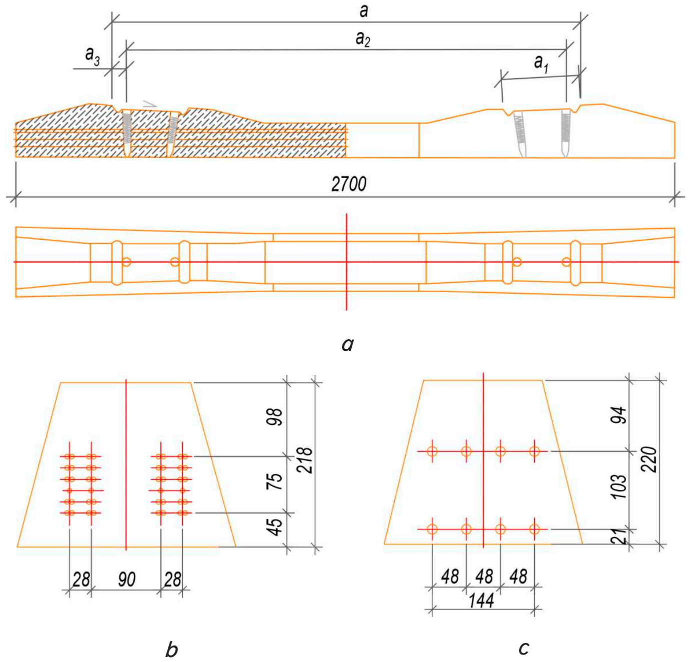



Fig. 1. Concrete sleepers with pre-stressed reinforcement: *a* — sleeper design for screw-dowel intermediate rail fastening (Vossloh System W30, etc.); *b* — under-rail cross-section of sleepers with steel wire reinforcement; *c* — under-rail cross-section of sleepers with composite reinforcement

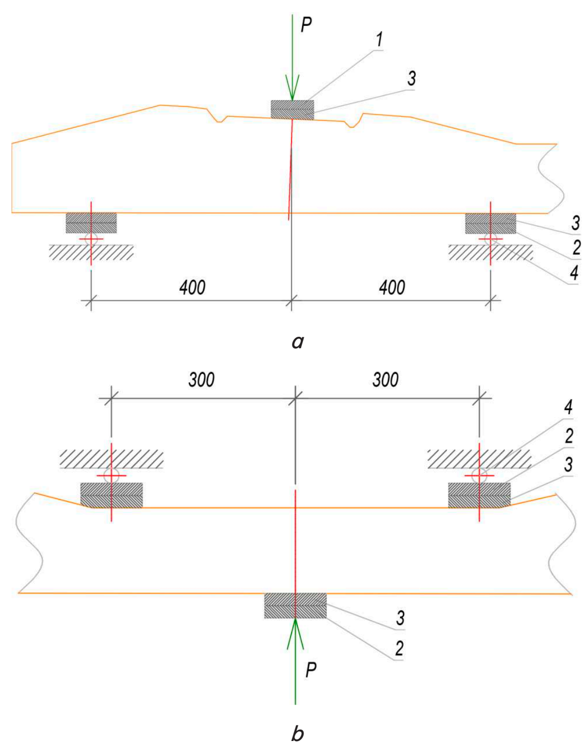
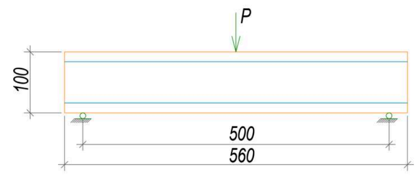



Fig. 2. Scheme of sleeper crack resistance tests: *a* — under-rail section; *b* — middle section; 1, 2 — steel plates; 3 — rubber gasket; 4 — steel roller

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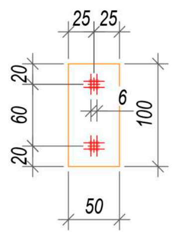


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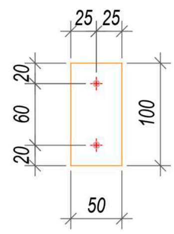



*c*

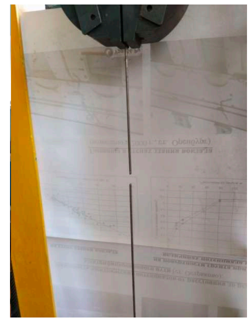
*d*

Fig. 3. Testing models with loads: *a* — diagram of the model and its load; *b* — cross-section of the model with steel wire reinforcement; *c* — the same with composite reinforcement; *d* — testing the model on the MUP-50 testing machine with deflection measurement by a clock-type indicator

Before manufacturing the models, tensile testing of the reinforcement was carried out using a tensile testing machine (Fig. 4) with the construction of relative deformation-stress diagrams.

The models were made in molds equipped with a device for pre-stressing the reinforcement (Fig. 5, *a*). The reinforcement was anchored using glued cylindrical thrust washers (Fig. 5, *b*). Before tensioning, the rods or bundles of reinforcement were pushed through the holes in the end walls of the mold, thrust washers with plugs were put on their ends (Fig. 5, *b*) and the gap between the reinforcement and the washer was filled with epoxy composition by injection through the holes in the washers. Tensioning was carried out after one day of hardening of the epoxy composition using tension bolts and a socket wrench (Fig. 5, *c*). The magnitude of the tension force was controlled by the elongation of the reinforcement by measuring the increase in the distance between the tension plate and the mold wall at four points.

*a*



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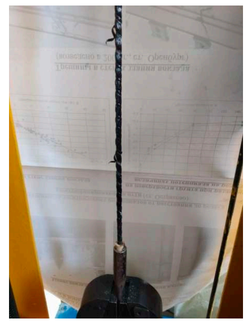
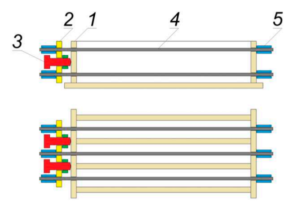


*c*

Fig. 4. Tensile testing of reinforcement: *a* — R-50 tensile testing machine with a sample of reinforcement; *b* — a destroyed sample of steel wire reinforcement; *c* — the same of composite reinforcement

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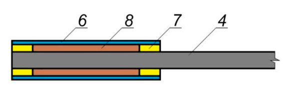



*b*

*c*

Fig. 5. Fabrication of pre-stressed models: *a* — mold diagram; *b* — thrust washer; *c* — pre-stress of reinforcement with a wrench; 1 — prefabricated mold; 2 — tension plate; 3 — tension high-strength bolt with nut; 4 — reinforcing bars (wire bundles); 5 — thrust washers; 6 — steel tube with holes; 7 — plug — reinforcement position lock; 8 — epoxy composition

The tension of the reinforcement package in the models $N_{mod}$ was taken for reasons of comparability of the stresses in the reinforcement of the models with the stresses in the reinforcement of the sleepers from the design tension in the sleeper $N_{sl} = 358$ kN. For this purpose, the tension of the package should be proportional to the number of rods: $N_{mod} = N_{sl} \cdot 8 / 44 = 65.1$ kN, where 8 and 44 are the number of steel wires in the model and sleeper, respectively. The tension of the reinforcement package of the model with composite reinforcement should have been the same. However, the tension of the reinforcement in the models was limited by the available means (Fig. 5). The tension control was carried out by the elongation of the reinforcement. The results of the tension control and its actual values are given in Table 1.

The models were molded from concrete of the following composition (with dry aggregates), kg/m$^3$: granite crushed stone fraction 2–5 mm – 1220; quartz sand with an average grain size of 0.23 mm – 451; Portland cement CEM II/A-S-500 – 403; tap water – 232. Water-cement ratio W/C = 0.58. Properties of concrete on the 28$^{th}$ day of natural hardening: compressive strength – 33.4 MPa, average density – 2355 kg/m$^3$.

During molding, steel electrodes were installed in the model to measure their electrical resistance. Control cubes with an edge size of 100 mm were molded together with the models. The concrete mixture was compacted on a laboratory vibrating platform with a frequency of 50 Hz, an amplitude of 0.25 mm. The models and control cubes were cured at a temperature of 20±2°C and a relative humidity of 100% for 28 days. To ensure a relative humidity of 100% during the curing period, the models were covered with polyethylene film.

Table 1

Prestressing of reinforcement in models

| Models with reinforcement | Sample No. | Base $l$, mm | Elongation | | Elastic modulus $E$, MPa | Tension $\sigma = E\varepsilon$, MPa | Reinforcement area in the model $A_s$, mm$^2$ | Package tension | |
|---|---|---|---|---|---|---|---|---|---|
| | | | Absolute $\Delta l$, mm | Relative $\varepsilon = \Delta l/l$ | | | | $N_{mod} = \sigma A_s$, kN | % of projected |
| Steel | S1, S2, S3 | 640.5 | 4.1 | 0.0064 | 81301 | 517 | 56.55 | 29.3 | 45 |
| Composite | C2 | 62.6 | 0 | 0 | 14981 | 0 | 100.53 | 0 | 0 |
| | C1, C3 | 646.25 | 9.7 | 0.0150 | | 225 | | 22.7 | 35 |

The models were tested with a load at an age of at least 28 days on a MUP-50 testing machine (Fig. 3, *d*) with failure. As the load was applied, the deflection arrow $\Delta$ was measured with a clock-type indicator ICH-1, the formation of cracks was recorded, and the electrical resistance of the model $R$ was also measured on alternating current. According to the test results, the diagrams "deflection arrow" – "load" were constructed.

For the models and their loading scheme (Fig. 3), a calculation experiment was conducted using the finite element method and the LIRA-SAPR software package with step-by-step loading to failure, analysis of the stressed-strained state at each loading stage, and construction of the "deflection arrow $\Delta$"-"load $P$" diagrams. The calculation was performed in a nonlinear statement. To build the model, by analogy with [10], the following hypotheses were adopted:

1) concrete was modeled by physically nonlinear three-dimensional finite elements, reinforcement – by physically nonlinear rod finite elements;

2) the strength and deformability of concrete were characterized by parabolic-linear deformation diagrams $\sigma_c$–$\varepsilon_c$, reinforcement – by the diagram $\sigma_c$–$\varepsilon_c$, without a yield point;

3) the pre-stress force of reinforcement was applied by the influence of negative temperatures;

4) the calculation was performed by the step-iterative method with two loading stages – pre-stress of reinforcement and load transfer, the number of loading steps of each stage – 50, the increment of loads at each step – non-uniform.

## 5. Results of investigating the strength, stiffness, and crack resistance of sleepers on models

### 5. 1. Results from the experimental comparative study of the physical and mechanical properties of steel and composite reinforcement

The results of the tests of steel and composite reinforcement are reported in the form of deformation diagrams $\sigma = f(\varepsilon)$ ("relative deformation $\varepsilon$ – stress $\sigma$") and are shown in Fig. 6.

The diagrams are fitted well to polynomials: steel wire – 5$^{th}$ power (with a correlation coefficient of 0.97), composite epoxy-basalt – 4$^{th}$ power (with a correlation coefficient of 0.99), which indicates their reliability.

However, from Fig. 6 it is seen that up to a stress of 1400 MPa the deformation diagram of steel wire is close to linear, the deformation at the linear stage is elastic. Upon reaching a stress of 1400 MPa, a developed yield point is observed, which ends with failure. The deformation diagram of composite epoxy-basalt reinforcement up to a stress of 540 MPa is also close to linear, the deformation is elastic. Upon reaching a stress of 540 MPa, a very short, barely noticeable yield point is observed, which ends with failure, which, accordingly, is almost brittle.

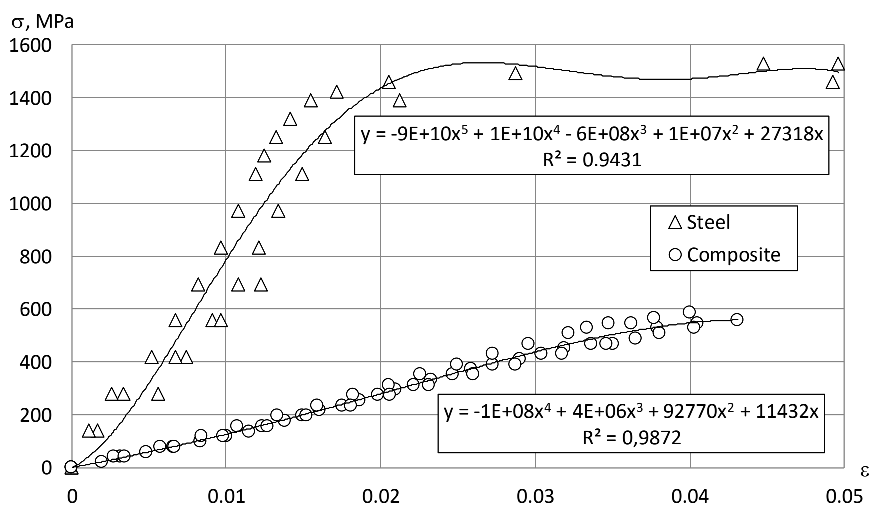



Fig. 6. Relative strain $\varepsilon$ — stress $\sigma$ diagrams of steel and composite reinforcement

The values of the modulus of elasticity $E$ determined from the deformation diagrams as the tangent of their slope angle at the linear stage were as follows: steel wire – 81,301 MPa, composite epoxy-basalt reinforcement – 14,981 MPa. The tensile strength limits f of the reinforcement were as follows: steel wire – 1,400 MPa, composite reinforcement – 540 MPa.

**5. 2. Results from the calculation and field experiments on loading models of sleepers made of concrete with steel and composite reinforcement**

The results of calculation and field experiments on loading models of sleepers made of concrete with steel and composite reinforcement according to the scheme in Fig. 1 are shown in Fig. 7–10 and given in Table 2.

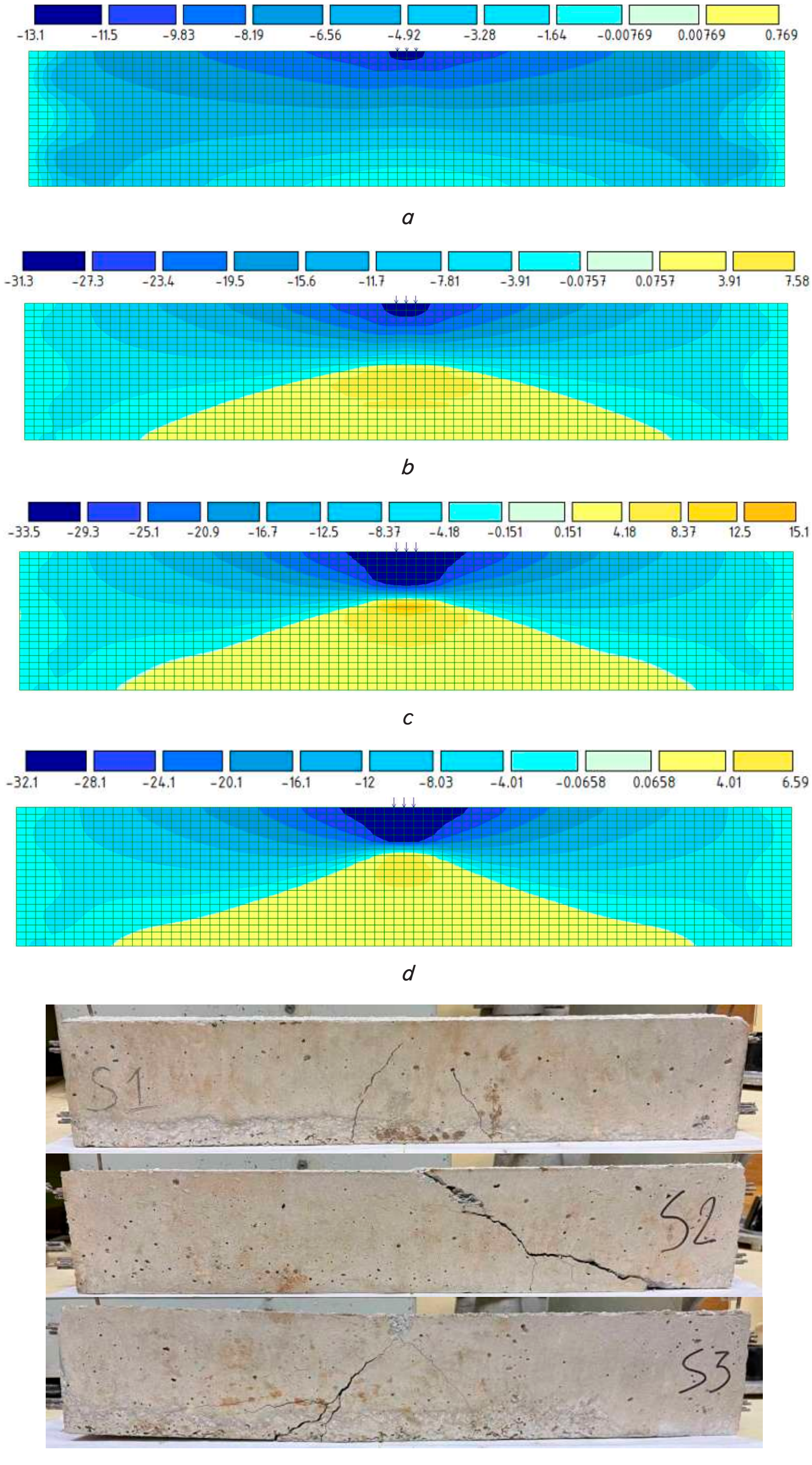



Fig. 7. Results from the calculation and full-scale experiments on loading models with steel reinforcement with a pre-stress force of the package of 29 kN: *a* – stress fields in the model at the moment of crack formation in the tension zone; *b* – the same at the moment of crack formation in the compression zone; *c* – the same during the formation of a plastic hinge; *d* – the same at the moment of failure; *e* – physical appearance of samples *S*1, *S*2, *S*3 of the model after failure

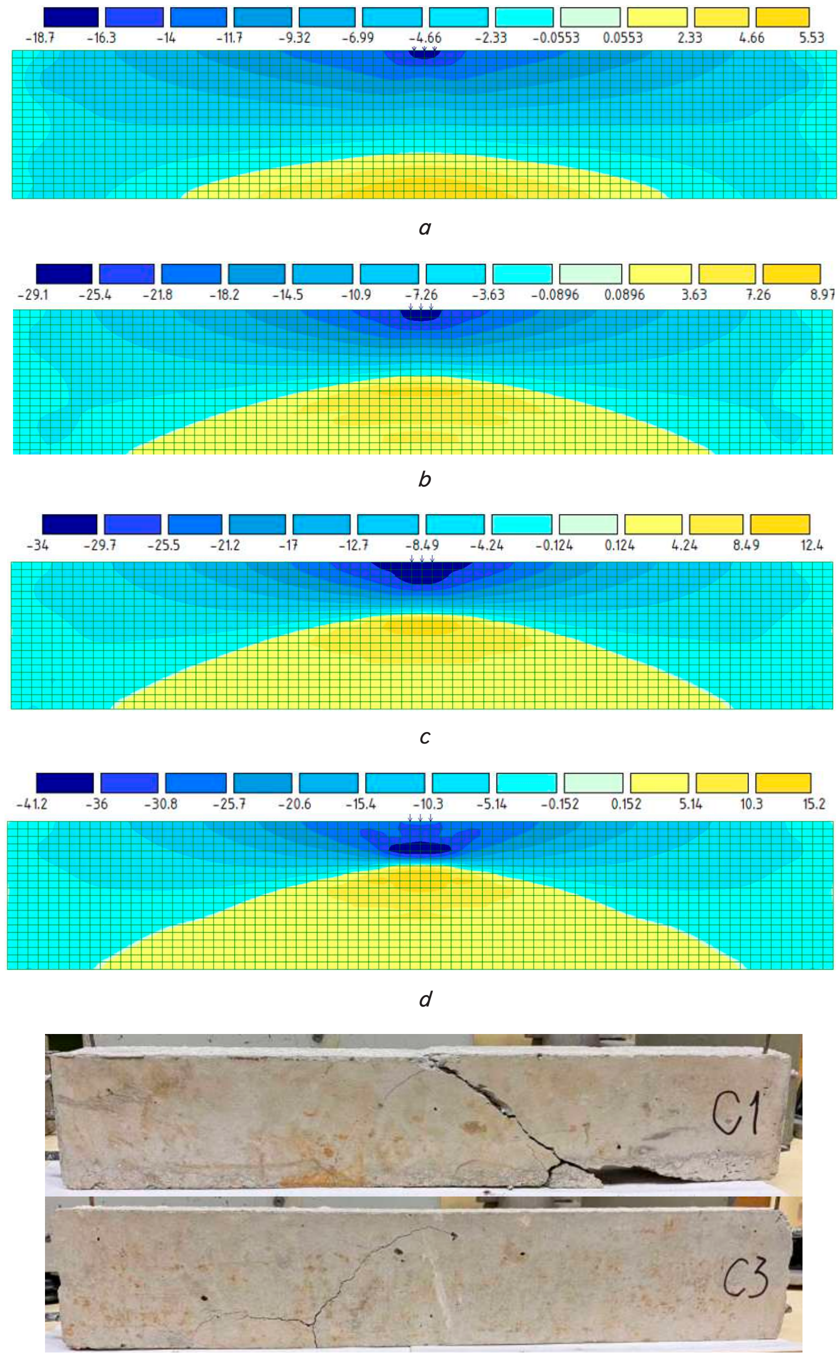



Fig. 8. Results from the calculated and full-scale experiments on loading models with composite reinforcement with a prestress force of the package of 23 kN: *a* – stress fields in the model during the formation of cracks in the tension zone; *b* – the same during the formation of cracks in the compression zone; *c* – the same during the formation of a plastic hinge; *d* – the same during failure; *e* – physical appearance of samples *C*1, *C*2, *C*3 of the model after failure

As a result of our calculation experiment, it was found that as all models are loaded and the moment from it increases, the deformation evolves to failure in stages:

1) formation of cracks in the tension zone;

2) formation of longitudinal cracks in the compression zone;

3) development of cracks in the tension zone to the formation of a plastic hinge (except for the model with composite reinforcement without tension);

4) complete failure.

In the model with composite reinforcement with a tension of 23 kN, compared to the model with steel reinforcement with a tension of 29 kN, the moments are lower:

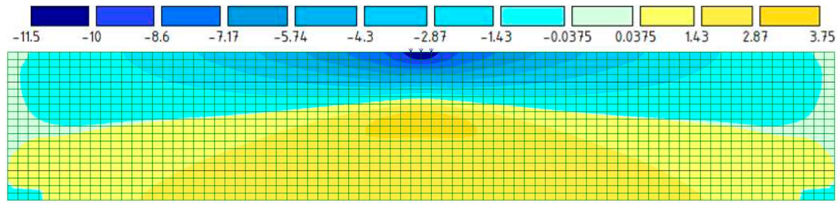
1) formation of cracks in the tension zone – by 18.2%;

2) formation of cracks in the compression zone – by 10.7%;

3) formation of a plastic hinge – by 12.1%;

4) failure – by 11.4%.

Therefore, the specified moments are 10.7–18.2% lower, which correlates with a 20.7% lower tension force of the reinforcement package.

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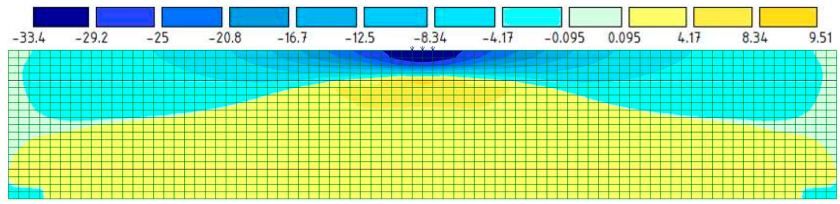


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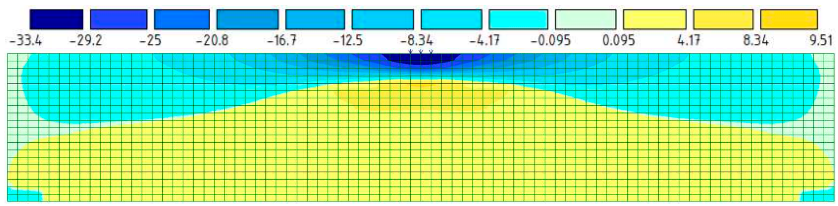


*c*


*d*

Fig. 9. Results from the computational and field experiments on loading a model with composite reinforcement without pre-stress: *a* — stress fields in the model at the time of crack formation in the tension zone; *b* — the same at the time of crack formation in the compression zone; *c* — the same at the time of fracture; *d* — physical appearance of the *C*2 sample of the model after fracture

Table 2

Comparing the results of computational and full-scale experiments

| Stage of model destruction | The indicator at which the stage of model destruction is reached | | Unit of measure | Value for model | | |
|---|---|---|---|---|---|---|
| | | | | With steel reinforcement with a tension of 29 kN | With composite reinforcement with a tension of 23 kN | With composite reinforcement without tension |
| Crack formation in the stretched zone | Moment | Estimated value | kN·m | 0.67 | 0.55 | 0,43 |
| | | Actual value (experimental) | " | 1.51 | 1.32 | 0,61 |
| | Deviation of the calculated value from the actual value | | % | −55,4 | −58.1 | −30.0 |
| | Correction factor to the calculated value | | Arbitrary unit | 2,24 | 2.39 | 1.43 |
| Crack formation in the compressed area | Moment | Estimated value | kN·m | 1.72 | 1.53 | 0,80 |
| | | Actual value (experimental) | " | Not determined | | |
| Formation of a plastic hinge | Moment | Estimated value | " | 2.02 | 1.78 | not determined |
| | | Actual value (experimental) | " | about 2.1 | about 1.8 | |
| Destruction | Moment | Estimated value | " | 2.15 | 1.90 | 0,98 |
| | | Actual value (experimental) | " | 1.93 | 1.85 | 1,10 |
| | Deviation of the calculated value from the actual value | | % | 11.5 | 2.5 | −11.1 |
| | Correction factor to the calculated value | | Arbitrary unit | 0.90 | 0.98 | 1.13 |

In the model with composite reinforcement without tension compared to the model with composite reinforcement with a tension of 23 kN, the moments are lower:

1) cracking in the tensioned zone – by 22.2%;
2) cracking in the compressed zone – by 48%;
3) fracture – by 48.4%.

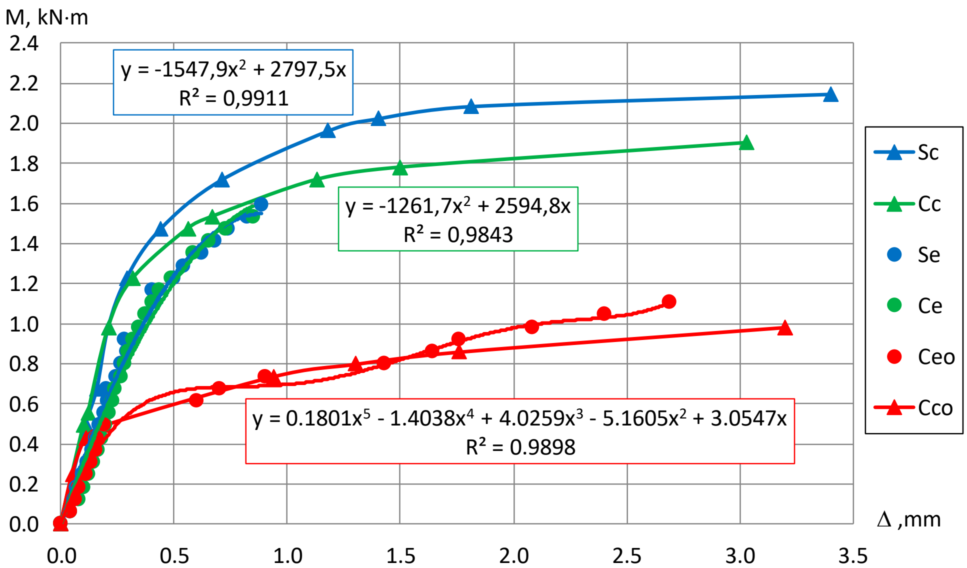


Fig. 10. Calculated (with indices "c") and experimental (with indices "e") dependences of the deflection arrow $\Delta$ on load $P$ (deformation diagrams) of the models: $S_c$, $S_e$ – with steel reinforcement with a pre-stress force of the package of 29 kN; $C_c$, $C_e$ – with composite reinforcement with a pre-stress force of the package of 23 kN; $C_{c0}$, $C_{e0}$ – with composite reinforcement without tension

According to the results of the calculation experiment, it can be stated that the type of reinforcement affects all moments characterizing the strength and crack resistance of the models to a much lesser extent than the pre-stress force of the reinforcement package.

As can be seen from the stress isofields shown in Fig. 7–9, in the model with composite reinforcement, compared to the model with steel reinforcement, the stretched zone is wider at all stages of loading, and the compressed zone is narrower. This indicates its lower stiffness and crack resistance approximately proportional to the difference in the pre-stress forces of their reinforcement packages. In the model with unstressed composite reinforcement (Fig. 9), the stretched zone is much larger, which confirms the conclusions of the quantitative analysis above.

If we accept the values of the stiffness, strength, and crack resistance indicators obtained by the full-scale experiment as actual, from Table 2 it is clear that the calculated values of the crack formation moments in the stretched zone are smaller than the actual values. In models with steel reinforcement with tension of 29 kN, these moments are lower by 55.4%, in models with composite reinforcement with tension of 23 kN – by 58.1%, in models with composite reinforcement without tension – by 30%. The values of the destructive moments differ from the actual values: models with steel reinforcement with tension of 29 kN – by 11.5% higher, models with composite reinforcement with tension of 23 kN – by 2.5% higher, models with composite reinforcement without tension – by 11.1%. Therefore, the calculated cracking moments for models with prestressed steel and composite reinforcement are significantly lower than the actual values – by 55.4–58.1%, for the model with unstressed composite reinforcement – by 30%. The calculated failure moments have a much better agreement with the actual values. The deviations are as follows: for the model with steel reinforcement with a tension of 29 kN – (+11.5)%, for the model with composite reinforcement with a tension of 23 kN – (+2.5)%, for the model with composite reinforcement without tension – (–11.1%).

Therefore, the specified moments are 22.2–48.4% lower. In the model with composite reinforcement without tension, the stage of plastic hinge formation was not observed.

## 6. Results of investigating the strength, stiffness, and crack resistance of sleepers on models: discussion

As can be seen from Fig. 6, the modulus of elasticity of composite reinforcement is 5.4 times smaller than the modulus of elasticity of high-strength steel wire. This will have a significant impact on the stressed-strained state of the models.

As a result of our full-scale experiment, it was established that the nature of crack formation in all models is similar – as the load increased, 2–3 perpendicular (in the middle) and inclined (closer to the edges) cracks opened in the stretched zone (Fig. 7, 8, *e*, 9, *d*). The formation of visible cracks in the compressed zone was not observed. The nature of the fracture is a sharp increase in deflection with a significant opening of one or two (on both sides) extreme cracks at an angle of about 45° without the destruction of the compressed zone. This indicates the failure of the models due to the slipping of the reinforcement in the concrete in one or both end sections above the supports.

In the model with composite reinforcement with a tension of 23 kN, compared to the model with steel reinforcement with a tension of 29 kN, the moments were lower:

1) cracking in the tension zone – by 12.8%;
2) fracture – by 3.7%.

In the model with composite reinforcement without tension, compared to the model with composite reinforcement with tension of 23 kN, the moments were lower:

1) cracking in the tension zone – by 53.5%;
2) fracture – by 40.5%.

From the above analysis of Fig. 10 and Table 2 it follows that in models with composite reinforcement the moments corresponding to all stages of deformation are smaller than in models with steel reinforcement. The values by which they are smaller correlate with the smaller tension force and modulus of elasticity of the reinforcement. This is explained by the smaller modulus of elasticity of composite reinforcement. However, all moments characterizing the strength and crack resistance of the models were less influenced by the type of reinforcement than by the pre-tension force. This is explained by the smaller tension force of composite reinforcement compared to steel, achieved during the experiment. This is to some extent a drawback of our research, which can be eliminated by conducting a new series of experiments with the same tension force of the reinforcement.

Unlike [5], in which the results were obtained for beams with non-stressed reinforcement, the deformation values, correction factors, and conclusions obtained in our study are suitable for analyzing the stressed-strained state of sleepers and the design of their structure. This was made possible by the pre-stressing of the reinforcement models in both the tension and compression zones, as in sleepers. The results of the analysis of the stressed-strained state, in particular the verification of the fulfillment of the requirements for the crack resistance of sleepers, will be reliable provided that the specified correction factors are included in the calculation. Their preliminary values are given in Table 2 but for practical purposes, they require experimental refinement using more representative samples of models and sleepers in full size.

Our results confirm the possibility of designing sleepers with composite reinforcement of the required crack resistance by finite element calculations according to [10]. A certain limitation is the need to artificially introduce correction factors into the calculations to determine the moments of crack formation in the sections. Such sleepers can be introduced after their experimental operation on an electrified load-stressed section of the railroad in the established manner, provided that they are not damaged more than is allowed by current standards.

To build on this study, it is advisable to load test sleeper samples in full size with measurement of deformations and stresses in concrete and reinforcement using strain gauges. The values will need to be compared with stresses and deformations in finite element models of sleepers during the corresponding computational experiment. However, conducting such studies is associated with difficulties, which involve the complexity of comparing the measured values of stresses in concrete and reinforcement with the values of equivalent stresses in the models.

## 7. Conclusions

1. As a result of our experimental studies, it was found that the deformation of composite epoxy-basalt reinforcement, like steel wire, is elastic but, unlike it, it has almost no yield point, and the fracture is brittle. The modulus of elasticity $E$ and the ultimate tensile strength $f$ of the reinforcement were as follows: steel wire – $E$ = 81,301 MPa, $f$ = 1,400 MPa; composite epoxy-basalt – $E$ = 14,981 MPa, $f$ = 540 MPa. The modulus of elasticity of composite epoxy-basalt reinforcement is 5.4 times smaller than the modulus of elasticity of high-strength steel wire, which will have a significant impact on the stressed-strained state of the models.

2. Physical models of concrete sleepers with composite and steel reinforcement have been constructed and manufactured; their finite element models were built. Calculation and full-scale experiments on their loading were performed. It was established that as all models are loaded and the moment from it increases, the deformation evolves to failure in stages. These are the following stages: the formation of cracks in the stretched zone; their development to the formation of a plastic hinge; complete failure due to the slipping of the reinforcement in concrete. In the model with pre-stressed composite reinforcement, compared to the model with steel reinforcement, the moments from the load, which correspond to the specified stages, were 11–18% lower. This correlates with a 21% lower tension force of the reinforcement package, taking into account the lower modulus of elasticity of the composite reinforcement. In the model with composite reinforcement without tension, compared to the model with steel reinforcement, the specified moments were 22–48% lower. Therefore, all moments characterizing the strength and crack resistance of the models were influenced by the type of reinforcement to a lesser extent than the pre-stress force of the reinforcement package.

## Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

## Funding

The research, results of which are reported in this paper, was partially funded by the UK-Ukraine R&I twinning grant scientific project: "Integrated rail freight optimization in Ukraine: "Railroad sleepers, rolling stock, and logistics" within the UK-Ukraine R&I twinning grants scheme("UUKi")" grants scheme, project 11150. The research was carried out as part of the authors' postgraduate studies.

## Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

## Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

## Acknowledgments

The research, the results of which are reported in this paper, was conducted within the framework of the UK-Ukraine R&I twinning grant scientific project: "Integrated rail freight optimization in Ukraine: "Railroad sleepers, rolling stock and logistics" within the UK-Ukraine R&I twinning grants scheme("UUKi")" grants scheme, project 11150 (ДРН 0123U102700, ДОН 0224U031548).

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