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Increased Crack Resistance of Rail Reinforced Concrete Sleepers for Anchor Rail Fasteners

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Abstract. The study deals with the influence of the reinforcement layout in the cross-section and the fibre added to the concrete on increased crack resistance of reinforced concrete sleepers for anchor rail fasteners in the rail fastening zone. New methods of experimental research were developed. It has been experimentally established that increasing the reinforcement length and bringing the end reinforcement row as close as possible to the rail seat section can increase the sleeper crack resistance in the fastening zone (crack initiation moment) by 35%. It was also established that the addition of fibre can increase the concrete tensile strength, but practically does not increase the compressive strength, and in many cases even reduces it. The best indicators of increased crack resistance were obtained by adding basalt fibre and steel fibre with lengths of 24 mm and 6 mm, respectively, at contents of 6 kg/m³ and 26 kg/m³. The tensile strength in bending increased by 1.5 times, while the crack resistance criterion increased by 0.35, corresponding to an improvement of more than two fold. However, concrete with steel fibre undergoes electro-corrosive damage, so it is unsuitable for sleepers on electrified rail sections. As measures to increase the sleepers crack resistance with anchor rail fasteners in the fastening zone, it is proposed to extend the reinforcement with the approach of the end row of reinforcement to the rail seat section and/or introduce 24 mm long basalt fibres in the concrete.

1 Introduction

In Ukraine, approximately 20,900 km of continuous welded rail on reinforced concrete sleepers are used for public railways [1], which exceeds 77% of the total extended length of the railway lines. The total number of reinforced concrete sleepers for them is more than 44.3 million. Sleepers are made of concrete with compressive strength C32/40 and C35/45, pre-stressed, and with reinforced bundles of high-strength wire ∅3 mm. The entire reinforcement is prestressed.

The rails are attached to the reinforced concrete sleepers using the following rail fastener types:
- padded separable bolt-clamped fastening: a steel pad is placed between the rail and the sleeper via polymer and/or rubber gaskets and is fastened to the sleeper with anchor bolts, the rail is pressed against the pad with rigid or elastic clamps using clamp bolts (over 69%);
- unpadded solid anchor fastening: only a polymer gasket is laid between the rail and the sleeper, the rail is pressed against the sleeper with elastic clamps that are fastened to anchors concreted into the sleeper (about 20%);
- unpadded, solid dowel screw fastening: only a polymer gasket is placed between the rail and the sleeper, the rail is pressed against the sleeper with elastic clamps, which are pulled together by screws in polymer dowels concreted into the sleepers.

All of the above-mentioned types of rail fasteners ensure the functioning of signalling, centralisation and interlocking systems, as well as preventing traction current losses (leakage), by providing electrical insulation between the rail and the sleeper using gaskets, insulating washers, bushings and inserts.

The service life (durability) of sleepers is estimated by the tonnage, i.e., the total weight of the rolling stock over them, as well as their service life. The current national standard of Ukraine DSTU 9002 [2] establishes the frequency of overhaul with the replacement of the rail-sleeper grid as 800 million tons gross or 20 years. The removed sleepers are sorted and, if reusable, are laid again on sections of lower categories. During routine maintenance, individual replacement of sleepers with significant defects (damage) may also be carried out. Thus, most of the undamaged sleepers are used for several cycles. Overall, the number of reinforced concrete sleepers that are unsuitable for use due to damage does not exceed 0.12% on the railways. However, their significant absolute number – over 183,000 pieces – and the tendency for this number to increase make the issue of increasing the service life of concrete sleepers urgently pressing.

Damage sustained by sleepers as they accumulate tonnage is even catalogued in regulatory documents. The most common damage (defects) are cracks of various types and origins (Fig. 1) [3]: transverse and longitudinal cracks in different zones of the sleepers (Fig. 1, a–c); splits from which cracks develop (Fig. 1, d); a network of fine cracks from which larger cracks and splits subsequently develop (Fig. 1, b–d). Due to the peculiarities of interaction between fasteners and concrete, sleepers with unpadded solid anchor fasteners (Fig. 2, c, d) are somewhat more prone to cracking [3].

Thus, the vast majority of damage to sleepers is in the form of cracks, so the study aimed at higher the crack resistance of reinforced concrete sleepers is urgent.

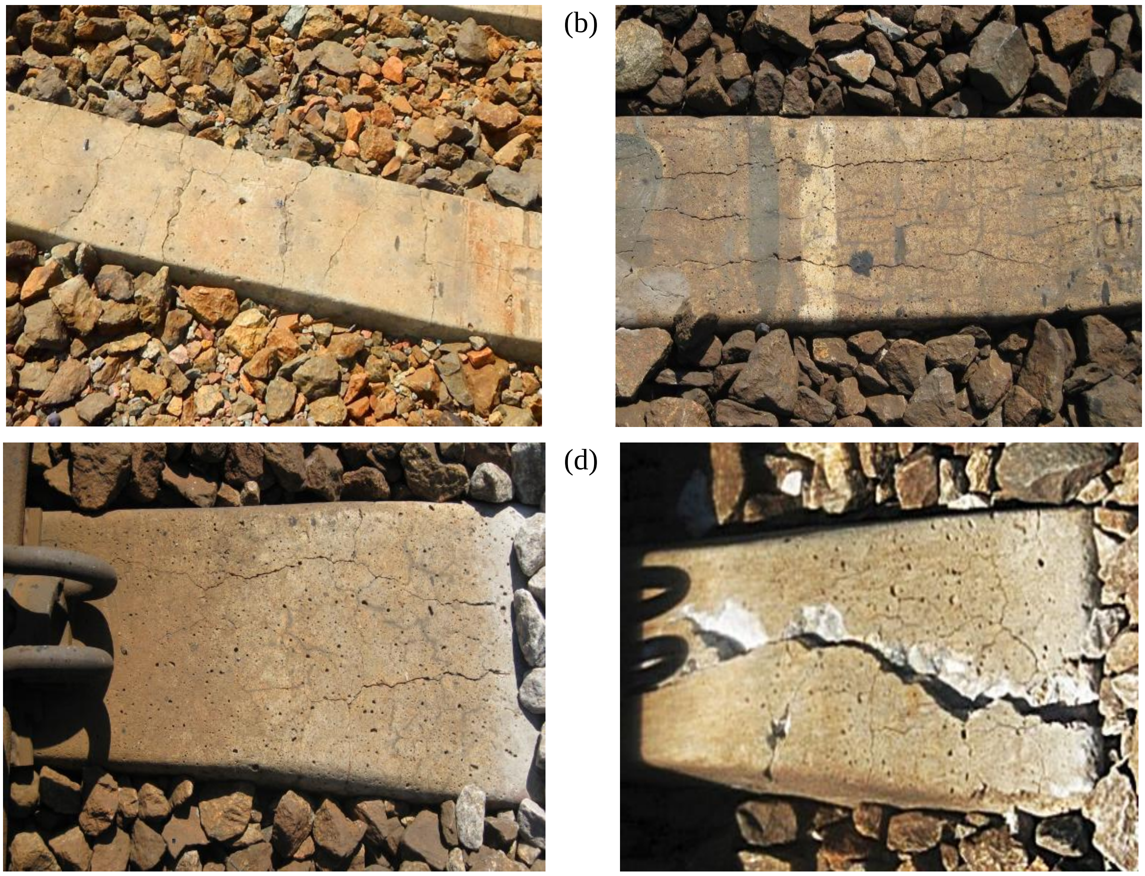
(a) (b) (c) (d)


Figure 1. The damage (defects) to sleepers

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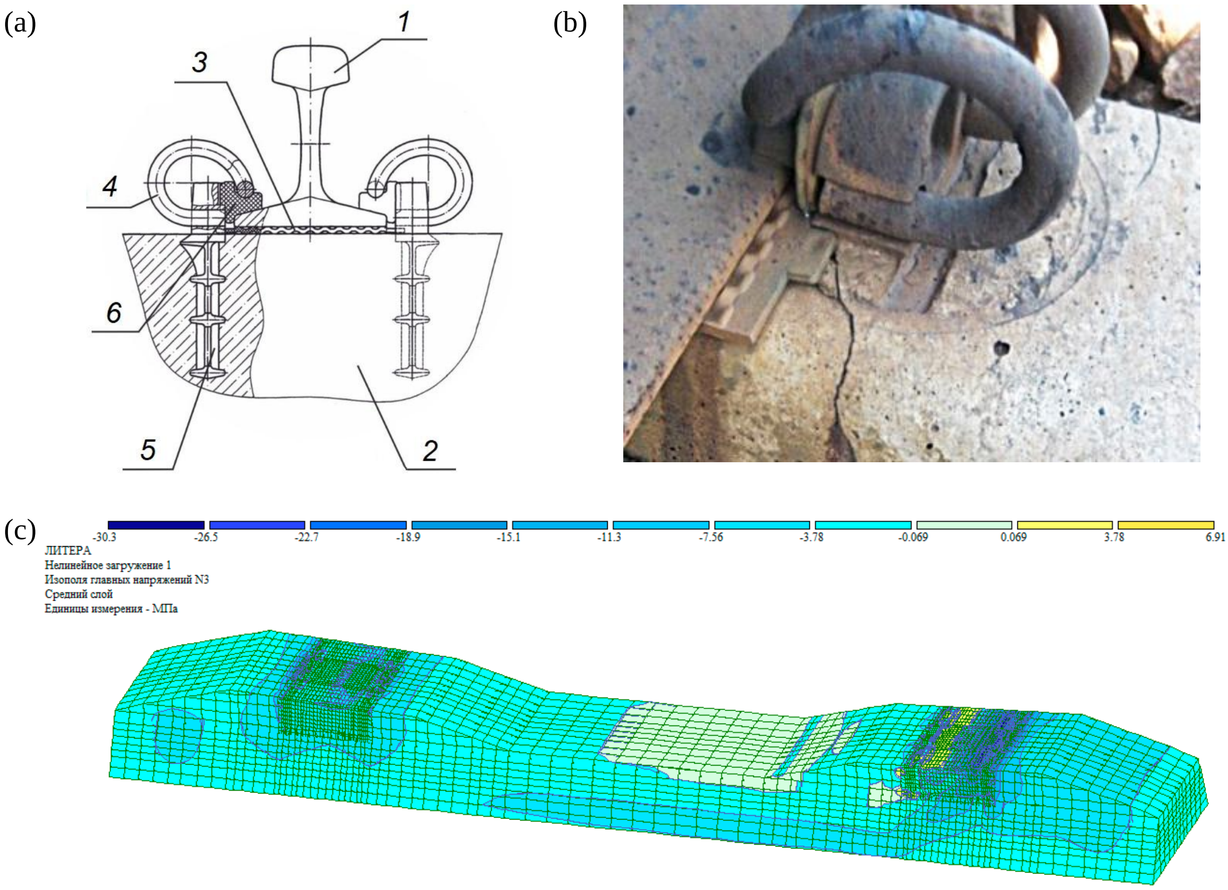


Figure 2. The unpadded solid anchor rail fastenings: a – fastener's design; b – cracks in sleepers in the fastening area: c – stress fields in the sleeper determined by the finite element method; 1 – rail; 2 – sleeper; 3 –rail pad; 4 – elastic clamp; 5 – anchor; 6 – insulating insert

Transverse and longitudinal cracks are often induced by force [3] except for crack networks (Fig. 1, b–d), which are formed as a result of internal corrosion of concrete due to the interaction between cement alkalis and reactive aggregates (Alkali-Silica Reaction – ASR) and are further promoted by processes caused by leakage currents [4, 5]. ASR contributes to the formation of stress cracks, from which they develop (Fig. 1, b, c). Prevention of cracks caused by internal corrosion is ensured by avoiding the use of cement with a high alkali content and reactive aggregates in manufacturing concrete sleepers, which is achieved through careful inspection of the materials [5, 6]. The absence of transverse reinforcement in sleepers contributes to the formation of longitudinal cracks, so connecting the working reinforcement with clamps and plates can prevent their formation. The formation of transverse cracks can be prevented by increasing the crack resistance of concrete. According to the results of research [3], in order to prevent the formation of cracks in sleepers during the revision of DSTU B V.2.6-209 [6, 7], the minimum concrete class was increased from C32/40 to C35/45.

In sleepers with anchor rail fasteners (Fig. 2, a), the load from the wheel sets of rolling stock, especially in curved sections of the track, creates lateral pressure on the anchors, which in turn create a bending moment and, accordingly, significant tensile stresses in the anchor zone. These stresses, according to the stress fields obtained as a result of calculations using the finite element method, can reach 7 MPa (Fig. 2, c), which exceeds the concrete tensile strength. However, the reinforcement of serial sleepers is located in the form of a package of parallel rods or wire, even the end row of which is remote from the most stressed area (Fig. 3). As a result, cracks often form in sleepers in the area of rail fasteners (Fig. 2, b). An increase in the crack resistance of this zone can be achieved by expanding the reinforcement in it.

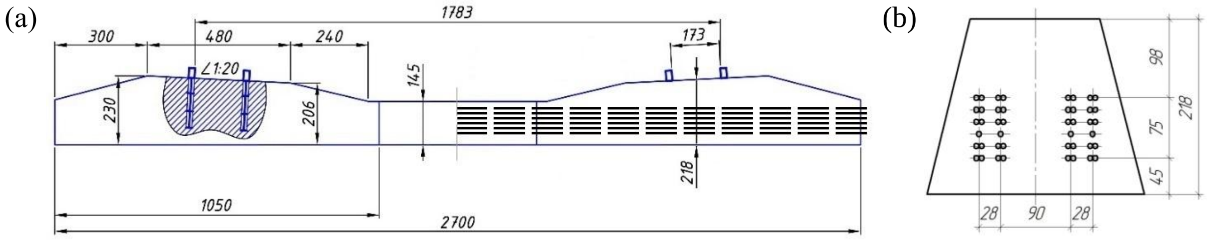


Figure 3. The reinforcement in serial reinforced concrete sleepers: a – in the longitudinal direction; b – in the rail seat cross-section

The crack resistance can also be increased by means of dispersed reinforcement of concrete, which is considered the most effective way [8]. In [9, 10], sleepers reinforced with steel and polymer fibres are studied. The authors obtained an increase in impact strength, wear resistance, water resistance, and frost resistance. However, the effect of dispersed reinforcement on the sleepers crack resistance, primarily in their local congested areas, is not studied. In [11] it is shown that steel fibre concrete is prone to electrical corrosion, and in [12] it is shown that in alkaline environments, including $Ca(OH)_2$, basalt fiber can be corroded. Therefore, these issues require additional research.

The objective of this investigation is to increase the crack resistance of reinforced concrete sleepers in the rail fastening zone by optimizing the reinforcement layout and applying dispersed reinforcement of concrete.

2 Research Methodology

2.1 Methodology for investigating the influence of reinforcement layout on sleeper crack resistance in the rail fastening zone

The influence of the reinforcement layout in the cross-section of sleepers was studied on models – beams with a size of 140×40×40 mm made of cement-sand mortar 1:1.53 with W/C = 0.42 (corresponding to mortar component of concrete) with a rod of composite epoxy-basalt reinforcement ∅8 mm (Fig. 4). The distance of the rod axis from the edge of the beam, which during the test was stretched for different models was 10 mm (Fig. 4, a), 20 mm (Fig. 4, b) and 30 mm (Fig. 4, c). The control beams were made without reinforcement.

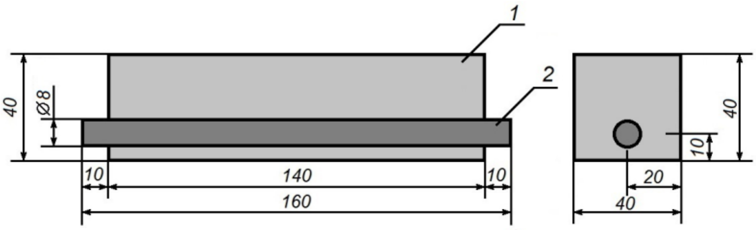
The models were formed in metal moulds for the manufacture of standard cement-sand beams with a size of 160×40×40 mm, fixing the position of the reinforcement using plywood inserts with a size of 40×40×10 mm with holes with a diameter of 8.5 mm (Fig. 5, a, b). After forming on a standard laboratory vibrating table, the models were subjected to heat and moisture treatment in a laboratory steaming chamber (Fig. 5, c).

The models were tested on a hydraulic press with a concentrated central load (Fig. 7). The distance between the supports was l = 0.1 m. Based on the test results, the crack initiation moment M_{cr} and the destructive moment M_d, corresponding to crack formation and model failure, respectively, was determined:

$$M_{cr} = P_{cr}l/4, \text{ kN}\times\text{m}; \quad (1)$$

$$M_d = P_d l/4, \text{ kN}\times\text{m}, \quad (2)$$

where P_{cr} and P_d are the force at which the crack was formed and the force at which the destruction occurred, respectively, kN,

(a)


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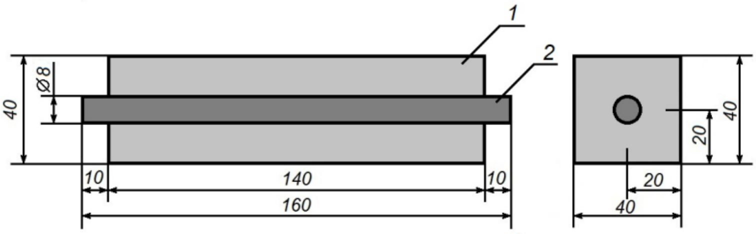


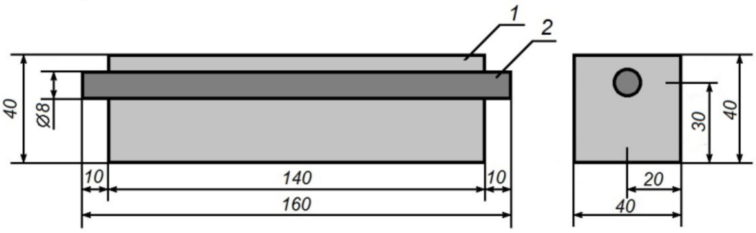
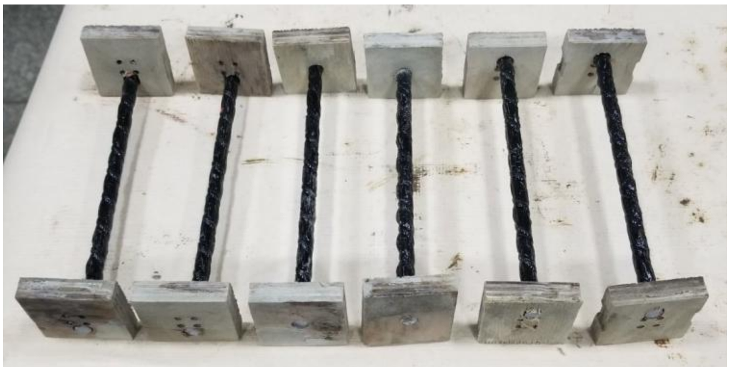
(c)


Figure 4. Beam models used for investigation of the influence of the reinforcement layout on sleeper crack resistance in the rail fastening zone: *1* – mortar component of concrete; *2* – reinforcing rod

(a)


(b)


(c)


Figure 5. The production of models for investigation of the influence of the reinforcement layout on sleeper crack resistance in the rail fastening zone: *a* – reinforcing rods in layout regulators; *b* – reinforcement in the design layout in moulds; *c* – moulds with models in the steaming chamber

Dependencies M_{cr} and M_d on the ratio a/h, i.e., the distance from the reinforcement axis to the stretched edge of the model were constructed and analysed. For models with a rod axis distance from the beam edge of 10 mm, 20 mm and 30 mm, the ratio a/h was 0.25, 0.5 and 0.75, respectively. For the control model without reinforcement adopted a/h = 1.

2.2 Methodology for investigating the influence of dispersed fibre reinforcement on sleeper crack resistance in the rail fastening zone

The influence of dispersed fibre reinforcement on concrete crack resistance was studied on beam models with a size of 140×40×40 mm from cement-sand mortar 1:1.53 with W/C = 0.42 (corresponds to the mortar component of concrete). The effect of polypropylene, basalt, steel fibres was studied. Properties of fibres and experimental compositions are presented in Table 1.

Table 1. The properties of fibres and experimental compositions

Fibre name, trademark	Fibre density, kg/m^3	Fibre length, mm	№	Recogni-tion	Fibre consumption per 1 m^3 concrete, kg	Strength enhancement factors		Crack resistance criterion	Criterion of improvement of crack resistance criterion
						K_{ft}	K_{fc}	f_t/f_c	$K_{ft/fc}$
Fibre-free	–	–	K	w/f	0	1.00	1.00	0.18	
Polymeric MicroArm 6	910	6	1	pp6.1	1	0.96	0.89	0.19	1.08
			2	pp6.2	2	1.13	0.64	0.31	1.76
			3	pp6.3	3	1.39	0.98	0.25	1.41
Polymer XMesh 23		23	4	pp23.1	1		0.81		
			5	pp23.2	2	1.14	0.84	0.24	1.36
			6	pp23.3	3	1.30	1.09	0.21	1.20
Basalt Technobasalt 24	2,850	24	7	bas24.3	3.13	1.00	1.00	0.17	
			8	bas24.6	6.26	**1.50**	**0.72**	**0.35**	**2.09**
			9	bas24.9	9.40	1.46	0.71	0.34	2.07
Steel	7,800	6	10	st6.9	8.57	1.71	0.92	0.31	1.87
			11	st6.17	17.14	1.29	0.89	0.24	1.44
			12	st6.26	25.71	**1.50**	**0.71**	**0.35**	**2.11**
		23	13	st23.9	8.57	1.50	0.90	0.28	1.67
			14	st23.17	17.14	1.07	0.76	0.23	1.41
			15	st23.26	25.71	1.21	0.94	0.21	1.29

The beam models were formed in metal moulds for the manufacture of standard cement-sand beams with a size of 160×40×40 mm. Fibre was added to the dry mixture while stirring cement and sand. After being formed on a standard laboratory vibration table, the models were subjected to prolonged natural curing at 18±2 °C and 100% relative humidity. The age of the models at the time of testing was 28 and 180 days. The models tested on a hydraulic press for bending with a concentrated central load with a distance between the supports l = 10 cm. The halves of the beams obtained after breaking were compressed through cover plates with an area of S = 25 cm^2. According to the test results, the tensile strength in bending and compressive strength were determined, respectively:

$$f_t = 0.0981 \cdot 3P_t l / 2bh^2, \text{ MPa}; \quad (3)$$

$$f_c = 0.0981 P_c / S, \text{ MPa}, \quad (4)$$

where P_t is the destructive force of the bend test, kgf; b is the width of the beam, 4 cm; h is the height of the beam, 4 cm; P_c is the destructive force of the compression test, kgf.

Based on the obtained values of tensile strength in bending f_t and compressive strength f_c, the following was determined:

- tensile strength in bending increase factor K_{ft} and the compressive strength increase factor K_{fc} due to the introduction of fibre:

$$K_{ft} = f_{ti} / f_{t0}; \quad (5)$$

$$K_{fc}= f_{ci} / f_{c0}, \quad (6)$$

where f_{ti}, f_{ci} is the mortar strength with the addition of fibre for tensile bending and compression, respectively; f_{t0}, f_{c0} is the strength of the initial mortar without fibre for tensile bending and compression, respectively;

- crack resistance criterion is the ratio of the tensile strength to the compressive strength f_t/f_c;
- crack resistance criterion increase factor $K_{ft/fc}$ due to the introduction of fibre:

$$K_{ft/fc} = (f_t/f_c)_i/(f_t/f_c)_0, \quad (7)$$

where $(f_t/f_c)_i$ is crack resistance criterion of the mortar with fibre; $(f_t/f_c)_0$, is the crack resistance criterion of the initial mortar without fibre.

3 Results and discussion

3.1 Influence of the reinforcement layout on the crack resistance of the sleeper model in the rail fastener zone

The results of the investigation of the influence of the composite reinforcement layout on sleeper crack resistance in the rail fastener zone of the models, obtained using the method described in Section 2.2, are shown in Figs. 6 and 7. Fig. 6 depicts the models during the formation of the primary crack and fracture; Fig. 7 shows the dependence of the crack initiation moment M_{cr} and f destructive moment M_d of the models from the ratio of the distance from the reinforcement axis to the stretched edge of the model to the height of the model a/h.

The pattern of destruction of models shown in Fig. 6 c, f and i shows that fracture with high cracking was observed not even at a/h = 0.75, as it was assumed, but at a/h = 0.5, therefore with the concentration of reinforcement around the neutral axis.

The dependencies of the fracture toughness moments M_{cr} and fracture M_d models on the distance between the reinforcement axis and the stretched edge of the model to the height of the model a/h are well approximated with the correlation coefficients R = 0.93 and 0.94 by linear equations.

For the sleeper rail fastener zone shown in Fig. 3, b, the ratio of the distance between the centre of the nearest row of the reinforcement and the edge of the rail seat foundation on which tensile stress concentrators are formed (Fig. 2, c) and cracks (Fig. 2, b) to the height of the entire section a/h is:

$$a/h = 98/218 = 0.45.$$

At a/h = 0.45 at according to the obtained regression equations for the studied models, the moments are:

$$M_{cr} = –0.2534·0.45+0.2562 = 0.142 \text{ kN·m};$$

$$M_d = –0.2371·0.45+0.2735 = 0.167 \text{ kN·m}.$$

These regression equations can be used to assess the potential increase in sleeper crack resistance in the rail fastener zone by shifting the end row of reinforcement toward this zone. For example, a decrease in a/h from 0.45 to 0.25 may cause new values of moments M_{cr} and M_d:

$$M_{cr} = –0.2534·0.25+0.2562 = 0.193 \text{ kN·m};$$

$$M_d = –0.2371·0.25+0.2735 = 0.214 \text{ kN·m}.$$

These values exceed M_{cr} and M_d for a/h = 0.45 by (0.193–0.142)·100/0.142 = 35.9% and (0.214–0.167)·100/0 .167 = 28.1%, respectively.

Consequently, the extension of the reinforcement with the maximum approach of the end row of reinforcement to the rail seat foundation can increase the sleeper crack resistance in the rail fastener zone (the cracking moment) by 35%.

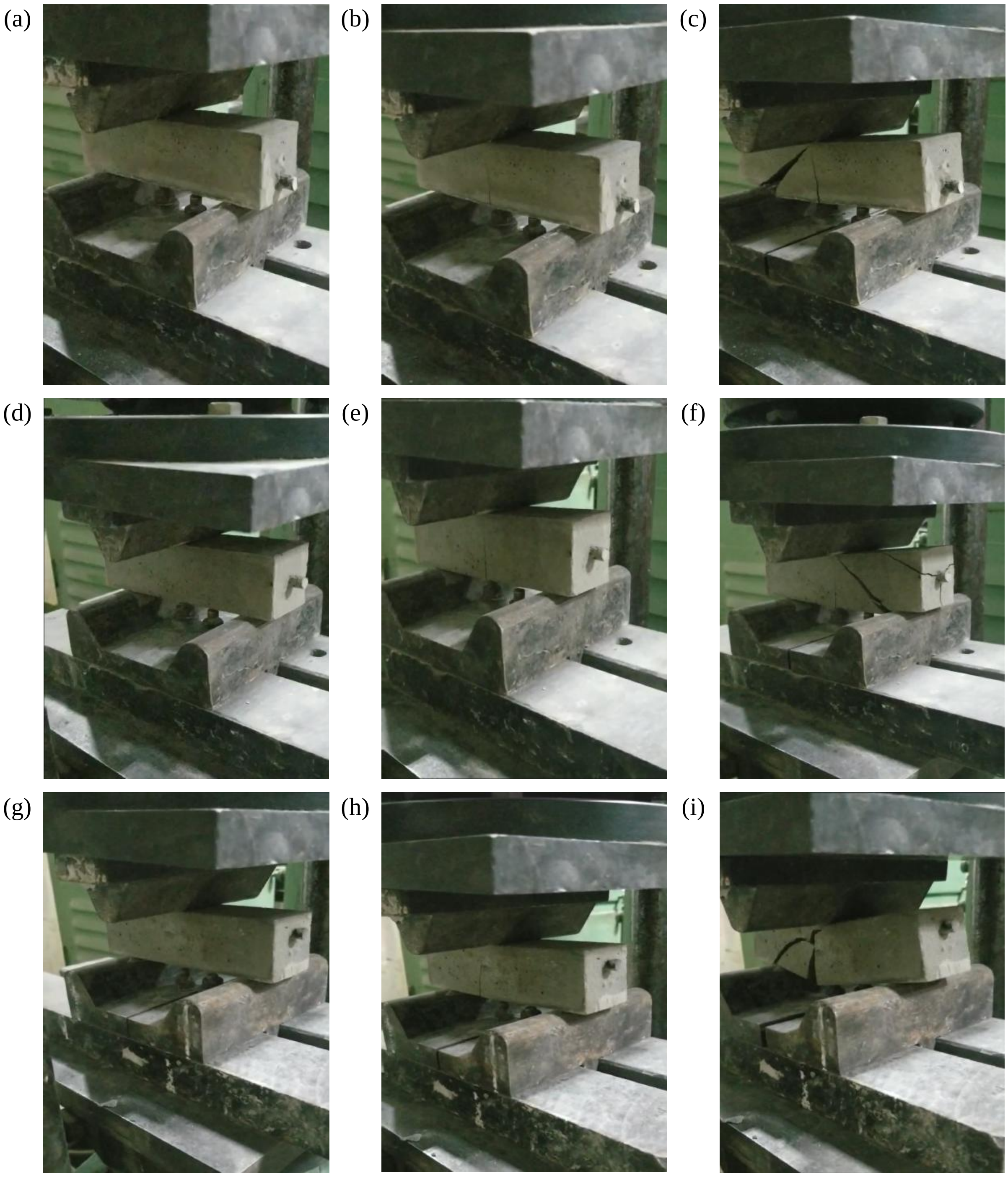


Figure 6. The testing of models: a – with the ratio a/h = 0.25, beginning of stress; b – the same crack opening; c – fracture; d – with the ratio a/h = 0.5, beginning of stress; e – the same crack opening; f – fracture; g – with the ratio a/h = 0.75, beginning of stress; h – the same crack opening; i – fracture

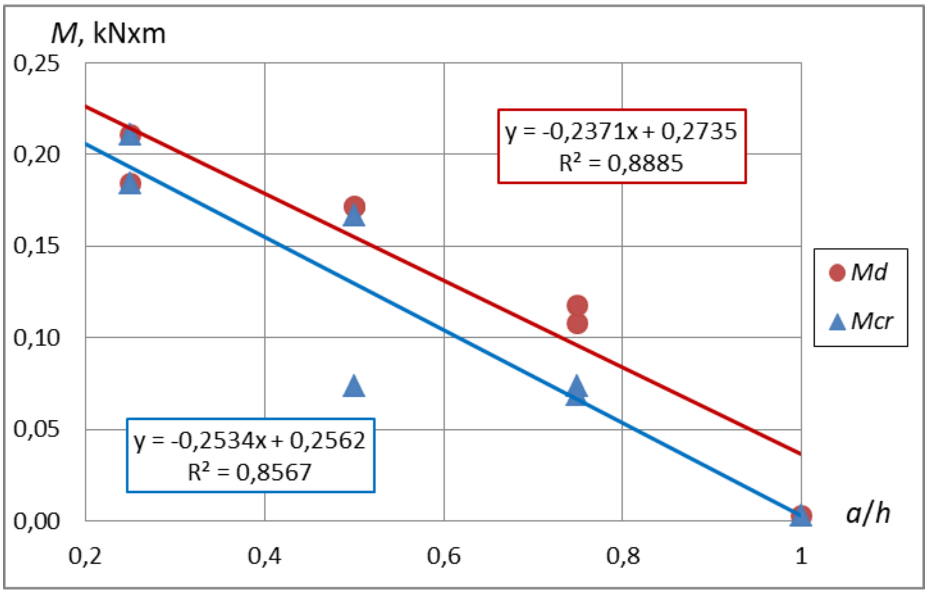


Figure 7. The dependence of fracture toughness moments M_{cr} and fracture M_d of models on the ratio of the distance from the reinforcement axis to the stretched edge of the model to the height of the model *a*/*h*

3.2 Influence of fibre addition on the crack resistance of the sleeper model in the rail fastener zone

The effect of fibre addition on the crack resistance of concrete, particularly the soluble component of sleeper concrete, was investigated using the method described in Section 2.2; the results for concrete aged 180 days are presented in Fig. 8 and Table 1.

As seen from Fig. 8 and Table 1, the introduction of fibres increases the tensile strength of the solution, but practically does not increase its compressive strength, and in many cases even reduces it. The best crack resistance improvement was achieved by adding fibre:

- basalt fibre with length of 24 mm in the amount of 6 kg/m^3;
- steel fibre with length of 6 mm in the amount of 26 kg/m^3,

which ensured a 1.5-fold increase in tensile strength in bending, a crack resistance criterion of 0.35 and its improvement by more than twofold.

However, as indicated in [11], concrete reinforced with steel fibre is susceptible to electro-corrosion damage and is therefore unsuitable for use in sleepers on electrified railway sections.

Therefore, according to the research results, as measures to increase the crack resistance of sleepers with anchor rail fasteners in the area of rail seat cross-sections, it is proposed to extend the reinforcement with the approach of the end row of reinforcement to the rail seat foundation (Fig. 9), and/or introduce into the concrete an additive of basalt fibres with a length of 24 mm in the amount of 6 kg/m^3.

A patent for a utility model of Ukraine was obtained for the design of the sleepers shown in Fig. 9 and the method of its production [13].

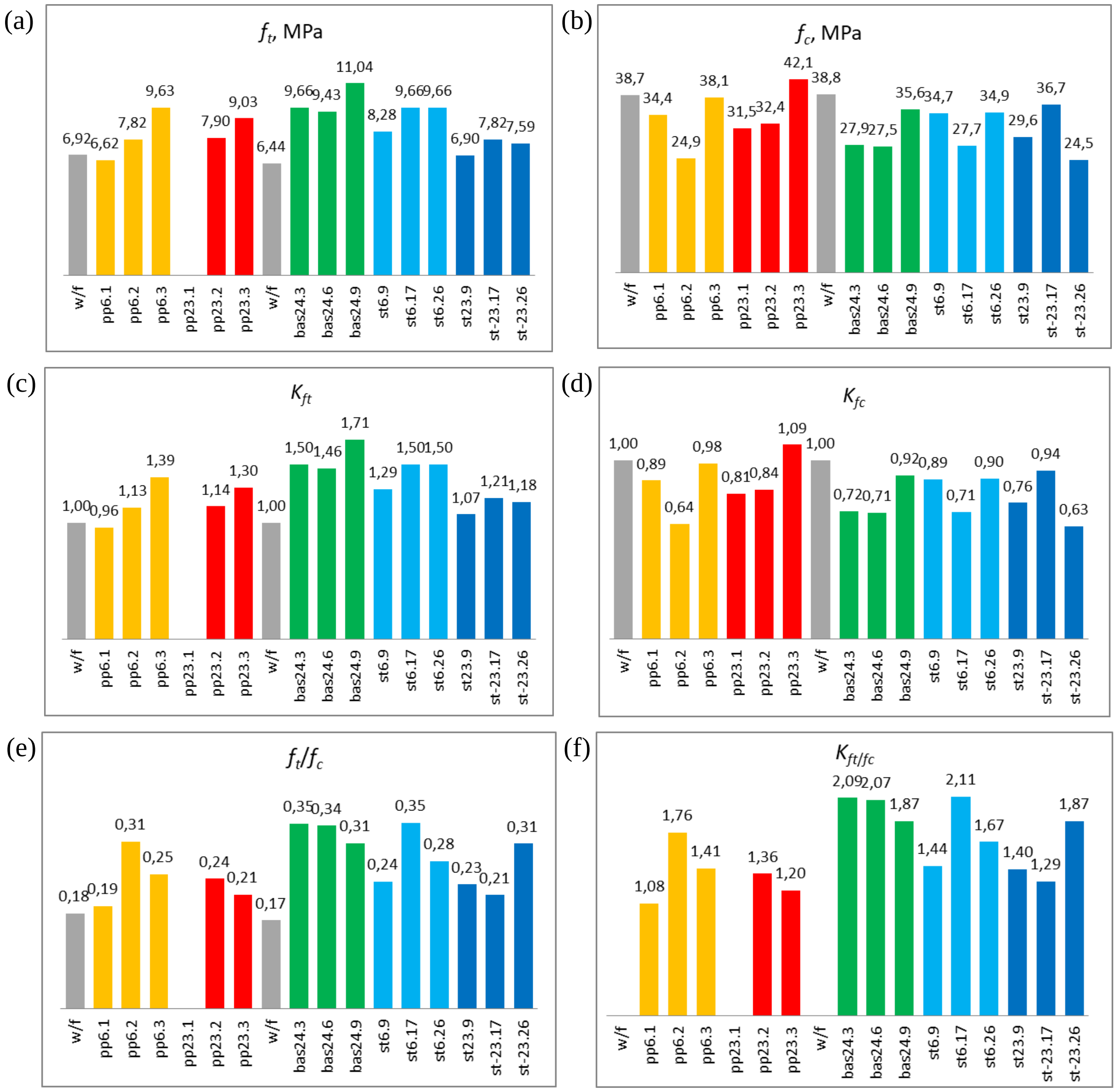


Figure 8. The indicators of physical and mechanical properties and crack resistance of fibre-reinforced compositions with various fibre types and contents (Table 1): a – tensile strength f_t; b – compressive strength f_c; c – tensile strength increase factor due to fibre K_{ft}; d – compressive strength increase factor due to fibre K_{fc}; e – crack resistance criterion, i.e., the ratio of the tensile strength to the compressive strength f_t/f_c; f – crack resistance criterion increase factor $K_{ft/fc}$

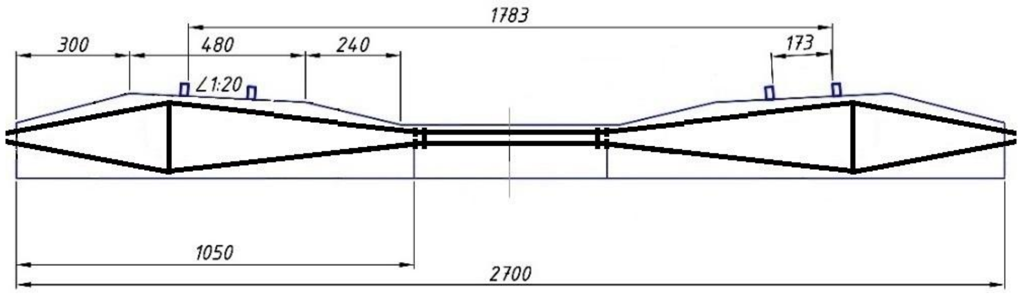


Figure 9. The sleepers for anchor rail fasteners with an extended reinforcement

4 Conclusion

Original experimental methods were developed to investigate the effects of reinforcement layout and fibre addition on sleeper crack resistance in the rail fastener zone.

The experimental studies demonstrated that extension of the reinforcement and maximum approximation of the end reinforcement row to the rail seat foundation increased the crack resistance of the sleeper in the anchor zone (crack initiation moment) by 35%.

It was found that the addition of fibre can increase the concrete tensile strength, but practically does not increase the compressive strength, and in many cases reduces it. The best indicators of increased crack resistance were ensured by the addition of basalt fibre with a length of 24 mm in the amount of 6 kg/m^3 and steel fibre with a length of 6 mm in the amount of 26 kg/m^3, which ensured an increase in tensile strength in bending by 1.5 times, a crack resistance criterion of 0.35 and its improvement by more than two fold.

As measures to increase the crack resistance of sleepers with anchor rail fasteners in the rail fastener zone, it was proposed to extend the reinforcement with the approach of the end row of reinforcement to the rail seat foundation, and/or introduce into the concrete an additive of basalt fibres with a length of 24 mm in the amount of 6 kg/m^3.

A patent for a utility model of Ukraine was obtained for the design of the sleepers and the method of its production.

5 Acknowledgment

The article uses the results of qualification studies of graduate students Serhii Musienko, Maksym Murygin, and Kyrylo Kutsyn.

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