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Analysis of carrying capacity of concrete sleepers for switches and crossings under static and dynamic load

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Professional paper

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Analysis of carrying capacity of concrete sleepers for switches and crossings under static and dynamic load

The testing of bearing capacity under static and fatigue loading is mandatory in case of prestressed concrete sleepers for switches and crossings. The authors present the static testing required according to EN13230-4:2009, and the optional dynamic testing of sleepers for switches and crossings, which is conducted at the customer's request only. The criterion for positive evaluation in accordance with the standard is met based on static test results. The determinants from EN13230-2: 2009, with deviations in the number of load cycles, are applied during dynamic testing.

Key words:
railway, switches, crossings, prestressed concrete sleeper, static and dynamic testing

Stručni rad

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Analiza nosivosti betonskih pragova za skretnice i križišta pri statičkom i dinamičkom opterećenju

Obavezna ispitivanja prednapetih betonskih pragova za skretnice i križišta jesu ispitivanja nosivosti pragova pri statičkom opterećenju i opterećenju na zamor. U radu je prikazano obavezno statičko ispitivanje prema normi EN13230-4:2009 i dinamičko ispitivanje pragova za skretnice i križišta koje nije propisano, nego se provodi isključivo na zahtjev kupca. Na osnovi rezultata statičkog ispitivanja ispunjen je kriterij za pozitivnu ocjenu u skladu s normom. Pri dinamičkom ispitivanju su korištene odrednice EN13230-2:2009, uz odstupanja u broju ciklusa opterećenja.

Ključne riječi:
željeznica, skretnice, križišta, prednapeti betonski prag, statičko i dinamičko ispitivanje

Fachbericht

Enes Curić, Dragoljub Drenić, Zoran Grdić

Analyse der Tragfähigkeit von Betonschwellen für Weichen und Kreuzungen unter statischer und dynamischer Belastung

Erforderliche Prüfungen von Spannbetonschwellen für Weichen und Kreuzungen umfassen die Prüfung der Tragfähigkeit unter statischer Belastung sowie unter Ermüdungsbelastung. In dieser Arbeit werden Bahnschwellen für Weichen und Kreuzungen betreffende statische Prüfungen, die der Norm EN13230-4: 2009 folgend obligatorisch sind, und dynamische Prüfungen, die nicht vorgeschrieben sind, sondern ausschließlich auf Wunsch des Kunden durchgeführt werden, dargestellt. Auf den Ergebnissen der statischen Versuche beruhend, sind die Bedingungen für eine positive Bewertung im Sinne der Norm erfüllt. Für dynamische Prüfungen sind die Richtlinien EN13230-2: 2009 angewandt worden, unter Abweichungen bezüglich der Lastwechselanzahl.

Schlüsselwörter:
Eisenbahn, Weichen, Kreuzungen, Spannbetonschwellen, statische und dynamische Prüfung

1. Introduction

Prestressed concrete sleepers are characterized by a high carrying capacity which, in addition to ensuring a more uniform load distribution and transfer to the underlying base, also provides a highly enjoyable ride to passengers. This is due to a considerable mass and the vertical and lateral stability of concrete sleepers [1, 2]. The use of new types of sleepers as a replacement for wooden ones [3], both for straight tracks and for switches and crossings, is becoming indispensable for most modern railway lines on which a high speed traffic is operated. One of possible solutions is the use of concrete sleepers, which is why it is necessary to determine their resistance to static and especially to impact (dynamic) loads [4]. Based on an appropriate design documentation [5], and after having gained experience in production of straight tract sleepers [6], the concrete factory in Stalać, Serbia, also adopted the technology for the production of sleepers for switches, ranging from 2600 to 4700 m in length, for switches with the maximum axle load of 250 kN, and for speeds of up to 200 km/h, all in accordance with EN13230-1:2009 [7], EN13230-2:2009 [8] i EN13230-4:2009 [9]. In addition to the control of the manufacturing process, these standards also require control of the quality of prestressed concrete sleepers and, in that respect, appropriate tests are conducted to check the design, while routine tests are also made to ensure respect of adequate quality standards. Obligatory tests aimed a proving adequacy of the design of sleepers for switches and crossings are the tests of sleeper behaviour when subjected to static load and fatigue load. The dynamic testing of sleepers for switches and crossings is not required as per EN13230-4:2009 [9] which regulates sleepers for switches, and is conducted at the client's request only, based on EN13230-2:2009 [8]. The static and dynamic testing of sleepers for switches was conducted, without fatigue testing, at the laboratory of the Faculty of Civil Engineering and Architecture of the University of Niš, Serbia, in the early 2014 [11].

2. Static testing of prestressed concrete sleepers for switches

The static testing was conducted using a traditional jack for the application and measurement of force and this for the positive and negative bending moment, and for the centre section (in the normal and inverse position), according to EN13230-4:2009 [9], and for the rail seat section according to EN13230-2:2009 [8]. Only one test can be conducted for each sleeper [9]. At least twelve sleepers are needed for static testing: six sleepers for the rail seat section, three sleepers for the sleeper centre section in normal position, and three sleepers for the same section in inverse position. The tested sleepers were manufactured in the period from 1 Sep. 2013 to 25 Dec. 2013. As different length sleepers are used for switches and crossings, the sleepers 2.6, 3.4 and 4.0 m in length were selected for representative samples.

2.1 Load at rail seat section

The initial design force for testing cross-section of the sleeper for switches to positive bending moment at the rail seat section is calculated according to EN13230-2:2009 [8]:

$$F_{br0} = \frac{M_{dr}}{L_r - 0{,}1} = 4\frac{16{,}59}{0{,}6 - 0{,}1} = 132{,}64\ kN$$

Lr - Design distance between the articulated supports centre lines for the test arrangement at the rail seat section, in m

Fulfilment of criteria for positive assessment of tested switch-sleepers for a given section:

- all test results show that the quality of sleepers is uniform,

Table 1. Switch sleeper static testing results for the rail seat section

Test force [kN]		LOAD AT RAIL SEAT SECTION (positive design load at rail seat section tested on 8.2.2014.)						Average values of safety coefficients $k_{bxs,sr}$	Minimum allowable values of safety coefficients $k_{bxs,doz}$
		SP-I/1 L = 2,6 m	SP-I/2 L = 3,4 m	SP-I/3 L = 4,0 m	SP-II/1 L = 2,6 m	SP-5 L = 3,4 m	SP-6 L = 4,0 m		
STATIC TESTING	F_{br0}	132,50	132,50	132,50	132,50	132,50	132,50		
	F_{br}	195,00	205,00	225,00	185,00	215,00	240,00		
	$F_{br\,0,05}$	365,00	380,00	360,00		365,00	345,00		
	$F_{br\,0,5}$	405,00		460,00	380,00	460,00			
	F_{brB}	614,00	650,00	480,00	450,00	550,00	530,00		
	$k_{b1S} = F_{br\,0,05} / F_{br0}$	2,75	2,86	2,86	2,60	2,75	2,60	2,736	>1,80
	$k_{b2S} = F_{br\,B} / F_{br0}$	4,64	4,90	3,62	3,39	4,15	4,0	4,116	>2,50

F_{br0} - Positive initial reference switch-sleeper test load for the rail seat section [kN],
F_{br} - Positive test load which produces first crack formation at the bottom of the rail seat section [kN],
$F_{br\,0,05}$ - Positive load at which the crack 0.05 mm in width occurs and remains unchanged [kN],
F_{brB} - Maximum load at rail seat section which cannot be increased due to fracture [kN],
k_{bxs} - Static safety coefficient
$k_{bxs,sr}$ - Average static safety coefficient

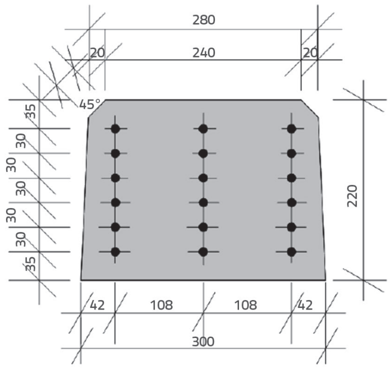

Figure 1. Cross-section of sleeper for switches

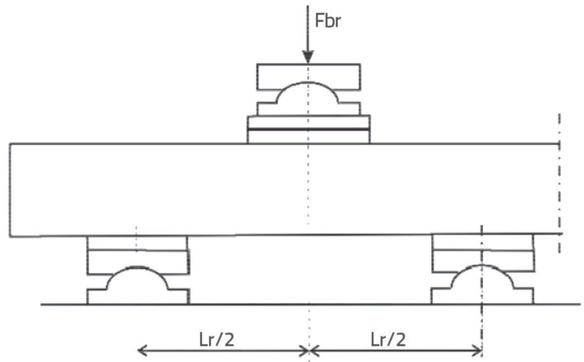

Figure 2. Load application diagram [8]

- average value of the force F_{br} is 210.8 kN > F_{br0} = 132.5 kN,
- average values of static coefficients $k_{b1s,sr}$ and $k_{b2s,sr}$ are much higher that the minimum allowable safety coefficients which clearly shows why this testing is not required in the standard.

2.2. Load at centre section

2.2.1. Sleeper in normal position and positive moment

During the positive and negative moment testing, the calculation of initial force for testing switch-sleeper section to positive and negative moment in the sleeper centre section must be compliant with EN13230-1:2009 [7], and is conducted according to EN13230-4:2009 [9]. The calculation was also made according to [8] in order to check and compare the moment values. A good correspondence of results was obtained during this comparison.

$$F_{b0} = \frac{M}{0{,}35} = \frac{19{,}90}{0{,}35} = 56{,}86\ kN; \quad F_{b0} = \frac{M_{dr}}{L_c - 0{,}1} = 4\frac{19{,}90}{1{,}5 - 0{,}1} = 56{,}86\ kN$$

The mean value of the force F_{br} is compliant with requirement given in standard [9]:

$F_{br,sr}$ = 73,3 kN > F_{b0} = 56,86 kN

The coefficient k_{bn} is determined by the purchaser, and is calculated as follows:

$k_{bn} < F_{bB,sr} / F_{b0}$ = 111,67/56,86 = 1,96

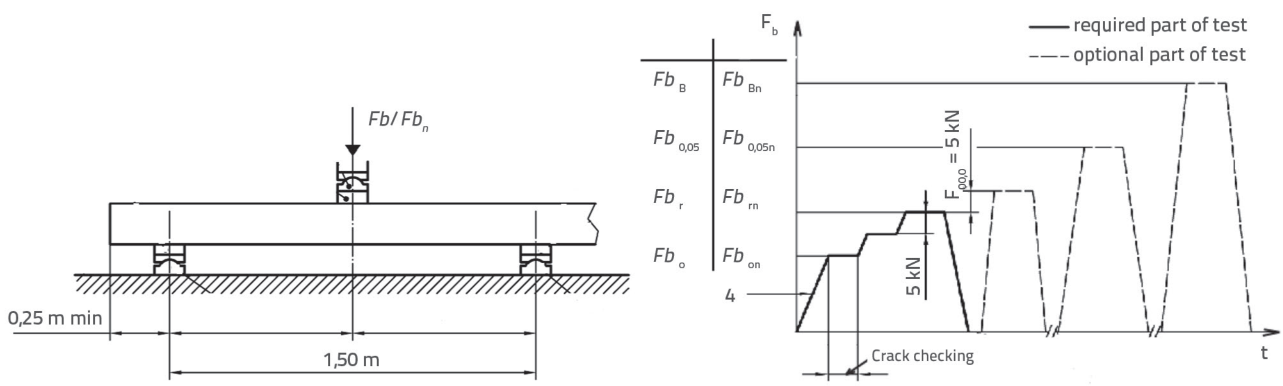

Figure 3. Load application sequence for positive and negative moment [9]

Table 2. Results obtained by static testing of switch-sleeper to positive moment

Test force [kN]	**POSITIVE DESIGN MOMENT** **sleeper in normal position - load in the sleeper centre section**		
	L = 2,60 m (15.2.2014.)	**L = 3,40 m (15.2.2014.)**	**L = 4,00 m (15.2.2014.)**
$^{*}F_{bo,n}$	5,00	5,00	5,00
F_{bo}	56,86	56,86	56,86
F_{br}	75,00	70,00	75,00
F_{bB}	115,00	120,00	100,00
$F_{br} > F_{bo}$	75,00 > 56,85	70,00 > 56,85	75,00 > 56,8

$^{*}F_{bo,n}$ - force increase increment during the testing from F_{bo} to F_{bB}.

Table 3. Switch-sleeper static test results for centre section section

Test force [kN]	NEGATIVE DESIGN MOMENT sleeper in inverse position - load in the sleeper centre section		
	L = 4,00 m (15.2.2014.)	L = 3,40 m (15.2.2014.)	L = 2,60 m (15.2.2014.)
F_{bon}	114,00	114,00	114,00
F_{brn}	117,00	116,50	118,00
F_{bBn}	125,00	119,00	125,00
$F_{brn} > F_{bon}$	117,00 > 114,00	116,50 > 114,00	118,00 > 114,00

F_{b0n} - Negative initial reference switch-sleeper test load [kN],
F_{brn} - Test load which produces first crack at the top of the bearer [kN],
F_{bBn} - Maximal test load which cannot be increased when the top of the bearer is cracked [kN],
Average value of the force $F_{brn,sr}$ = 117,2 kN > F_{b0n} = 114,0 kN

2.2.2. Sleeper in inverse position, negative moment

Initial design force for the switch-sleeper section (Table 3) testing to negative moment at the centre sleeper section, calculated according to [9, 8], for checking and comparison purposes:

$$F_{b0n} = \frac{M_n}{0{,}35} = \frac{39{,}90}{0{,}35} = 114{,}0\ kN; \quad F_{b0n} = \frac{M_{dn}}{L_c - 0{,}1} = 4\frac{39{,}90}{1{,}5 - 0{,}1} = 114{,}0\ kN$$

Note: No values for calculating negative moment in sleeper centre section (M_n) are set in [9] for switch-sleepers. Instead of that, expressions for straight tracks are therefore applied to sleepers for switches [8]. This can not be correct, as it is not right that F_{br0} = 132,64 kN > F_{bon} = 114 kN.

2.2.3. Influence of static load on sleepers for switches

Based on the detailed analysis of static test results, extended as per requirements contained in the standard [9], it can be concluded that the tested sleepers for switches and crossings meet requirements set for reaching the positive assessment (opinion) about behaviour of tested sleepers for switches subjected to static load.

3. Dynamic load testing for prestressed concrete sleepers for switches

The standard [9] requires the static load testing and fatigue testing, while the dynamic testing of sleepers for switches is conducted only if requested by the customer, based on test program supplied by the customer, according to the standard [8]. The dynamic testing implies testing behaviour of samples subjected to load ranging from minimum force to the force that causes fracture, in three cycles (5000 cycles are anticipated in standard [8]), with the frequency of up to 2 Hz, which is followed by the relaxation of load. The minimum force is defined by the designer and amounts to 50 kN for positive load and 5 kN for the application of negative load on the sleeper. The testing of positive load on rail seat is defined by the standard for the testing of concrete sleepers [8], wile the testing in the sleeper centre section (for negative and positive moments, in the normal and inverse positions) is the product of analogy set by the test supervisor. The deviation from the standard [8] with regard to 5000 load cycles, is due to the customer's request and because the dynamic testing is not obligatory [9]. Despite the deviation, the force values at which typical cracks occur were obtained, and values of dynamic safety coefficients k_{1d} and k_{2d} were defined, which gives a certain level of safety to the manufacturer that it can continue with production, and prepare sleepers for fatigue testing. Figures 4.a and 4.b show the way in which measurement strips were connected in accordance with the designer's instructions. The measurement strips were glues at specified points, i.e. two on the surface of every sleeper subjected to testing, one in the top zone and one in the bottom zone, and they were identified with the mark MT(n).

In parallel with the dynamic testing, the ultrasound measurement was made on three sleepers of varying lengths, in order to check compactness of concrete and the strength of prestressed concrete sleepers for switches (Table 4). This non-destructive method enabled approximate determination of uniformity in the quality of

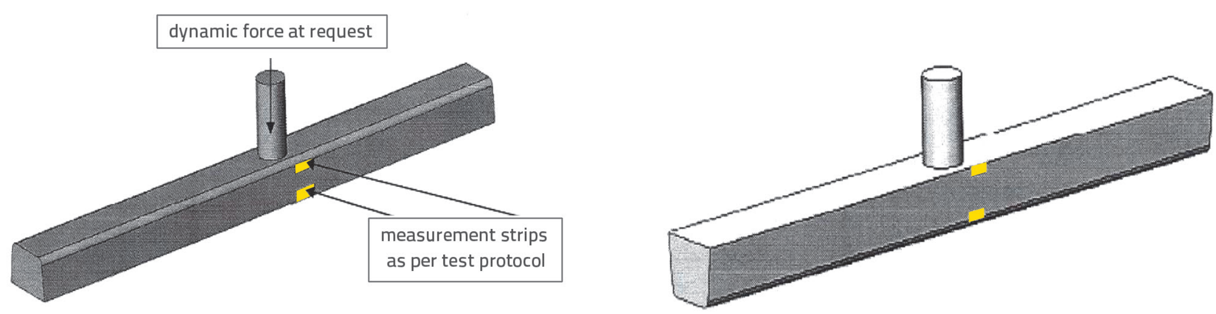

Figure 4. Sleeper for switches: a) sleeper in normal position; b) sleeper in inverse position

Table 4. Ultrasound measurement results for sleepers for switches

SLEEPER	t_1 [μsec]	t_2 [μsec]	t_3 [μsec]	V_1 [m/s]	V_2 [m/s]	V_3 [m/s]	σ_1 [MPa]	σ_2 [MPa]	σ_3 [MPa]	E_{d1} [GPa]	E_{d2} [GPa]	E_{d3} [GPa]
SP-1a	2890	1104	2810	260	260	260	61,8	61,8	61,8	39,5	39,2	37,4
SP-2a	1447	1104	2810	606	260	260	62,5	61,8	61,8	39,1	38,8	37,9
SP-4a	3250	3490	3150	260	658	189	61,2	59,5	62,5	38,3	38,4	40,20

Figure 5. Dynamic load testing: a) sleeper support method; b) dynamic loading of sleeper

sleepers. Measured concrete strengths are above the values set in the design (Table 4).

The dynamic testing was conducted after the measurement strips were positioned at points defined in the protocol. Each sample was loaded using an appropriate force distribution system, and the sleeper was held in place by a support (Figure 5.a). The hydraulic cylinder applies force via the load cell C6 500 kN manufactured by Hotinger Balidwin Messtechnik (HBM) on the computer Apple Mackintosh 520c using the software BEAM ver. 3.1, produced by Hotinger Balidwin Messtechnik (HBM). In parallel with the force measurements, the computer also registers sleeper expansions, as measured using the measurement strips. Test results are presented in form of diagrams showing dependence between force and expansion over time. As a very big number of diagrams with test results were obtained, it was necessary to restrict this number to just a few examples, as shown below.

3.1. Results and graphical presentation of measurement results

3.1.1. Load at rail seat section

The dynamic testing of sleepers for switches and crossings at rail seat was conducted on six sleepers. The results are shown as time diagrams presenting typical forces and their increase over time, with the occurrence of cracks as defined in the standard. Figure


Figure 6. Failure at dynamic testing of representative sleeper L= 4,0 m at maximum force F_{rB} = 570 kN

Table 5. Dynamic testing results for sleepers for switches, subjected to load at rail seat section

FORCE	Switch-sleeper SP-1a (L = 2,60 m)	Switch-sleeper SP-1b (L = 2,60 m)	Switch-sleeper SP-2a (L = 3,40 m)	Switch-sleeper SP-2b (L = 3,40 m)	Switch-sleeper SP-4a (L = 4,00 m)	Switch-sleeper SP-4b (L = 4,00 m)	Average values of dynamic safety coefficient $k_{xd,sr}$	Minimum allowable values for dynamic safety coefficient $k_{xd,doz}$
F_{r0}	132,50	132,50	132,50	132,50	132,50	132,50		
F_{rr}	312,50	312,50	312,00	312,00	332,50	339,00		
$F_{r\,0,05}$	392,00	358,00	352,00	338,00	332,50	339,00		
$F_{r\,0,5}$					532,00			
F_{rB}	570,00	550,00	570,00	480,00	600,00	550,00		
k_{1d}	2,95	2,70	2,65	2,55	2,51	2,55	**2,65**	**> 1,50**
k_{2d}	4,30	4,15	4,30	3,62	4,52	4,15	**4,17**	**> 2,20**

6 shows a typical example of dynamic testing until failure, while Figure 7 shows a testing diagram for a representative sleeper.

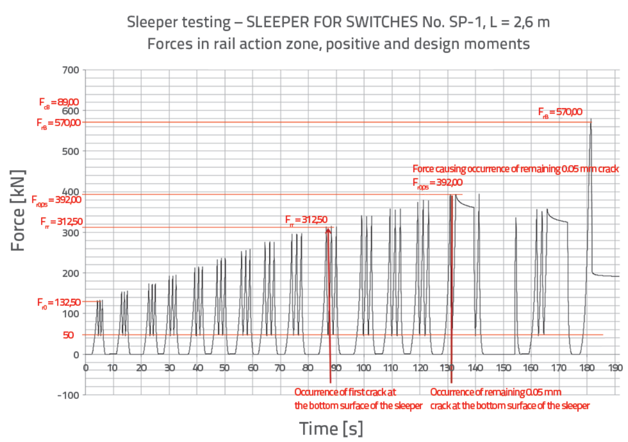

Figure 7. Time diagram for dynamic testing of a representative sleeper with typical forces and force increase over time

Results obtained by dynamic testing of sleepers to determine the positive design moment clearly indicate that the obtained average dynamic (impact) safety coefficients $k_{1d,sr}$ and $k_{2d,sr}$ greatly exceed maximum allowable values, thus showing that the length of sleeper does not play a significant role in the distribution of forces in the rail action zone. The value of force $F_{r0,5}$ is higher when compared to the limit state F_{rB} at static testing, which clearly points to the increase in the bearing capacity of the section in case of dynamic loading.

3.1.2. Load in centre section of the sleeper, inverse sleeper position

Standards [8, 9] do not anticipate dynamic testing of section in the centre of the sleeper for the negative design moment. The testing was conducted (Figure 8) based on a separate analogy, in order to determine why this testing was left out of the standard. Two sleepers were tested (Table 6).

Table 6. Dynamic testing results for sleeper for switches, sleeper in inverse position

FORCE	Switch-sleeper SP-3 (L = 4,00 m)	Switch-sleeper SP-5 (L = 2,60 m)
$F_{con,n}$	5,00	5,00
F_{con}	55,00 (113,71)	55,00 (113,71)
F_{crn}	155,00	215,00
F_{cBn}	210,00	262,00
$F_{crn} = F_{con,r} > F_{con}$	155,0 > 113,71	215,00 > 113,71

F_{c0n} - Negative initial reference test load at the centre section of the sleeper (sleeper in inverse position) [kN]

F_{crn} - Negative test load which produces first crack formation at the centre of the sleeper (sleeper in inverse position) [kN]

F_{cBn} - Maximum negative test load at the centre section which cannot be increased (sleeper in inverse position) [kN]

Figure 8. Failure for dynamic testing of sleeper for switches SP-3 at F_{cBn}=210 kN

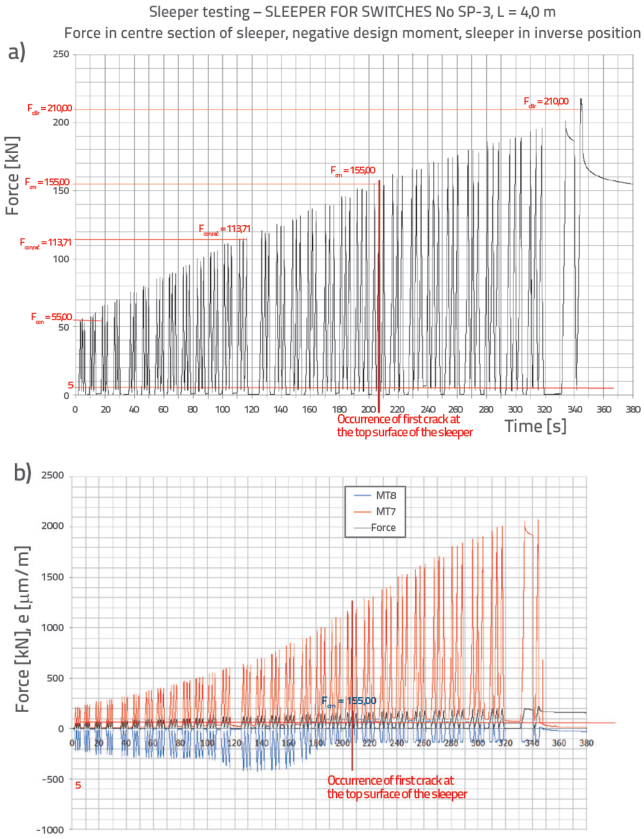

Figure 9. Dynamic testing of sleeper for switches SP-3: a) force, time; b) force, expansion, time

3.1.3. Load in centre section of sleeper, normal sleeper position

As this testing is also not anticipated in the standard, it was conducted based on a separate analogy.

The sleeper for switches SP-8 (L = 2.60 m) is the only sample that was subjected to dynamic cross-section testing at the centre section of the sleeper (Table 7), for positive design moment, sleeper in normal position. The load was applied in the centre section of the sleeper (Figure 10 and Figure 11).

Table 7. Dynamic testing results for sleeper for switches, sleeper in normal position

FORCE	Switch-sleeper SP-8 (L = 2,60 m)
$F_{co,n}$	5,0
F_{co}	27,50 (56,86)
F_{cr}	117,5
F_{cB}	248,0
$F_{r\,0,05}$	162,5
$F_{cr} = F_{co,r} > F_{co}$	117,50 > 56,86

F_{c0} - Positive initial reference test load at the centre section of the sleeper (sleeper in normal position) [kN]

F_{cr} - Positive test load which produces first crack formation at the centre of the sleeper. The load acts in the centre of the sleeper, at the top surface of the sleeper, for the positive bending moment (sleeper in normal position) [kN]

F_{cB} - Maximum positive test load which can not be increased and that acts in the centre of the sleeper, at the top surface of the sleeper, for the positive bending moment (sleeper in normal position) [kN].

Figure 10. Failure at dynamic testing of sleeper for switches SP-8, at max. force F_{CB}=248 kN

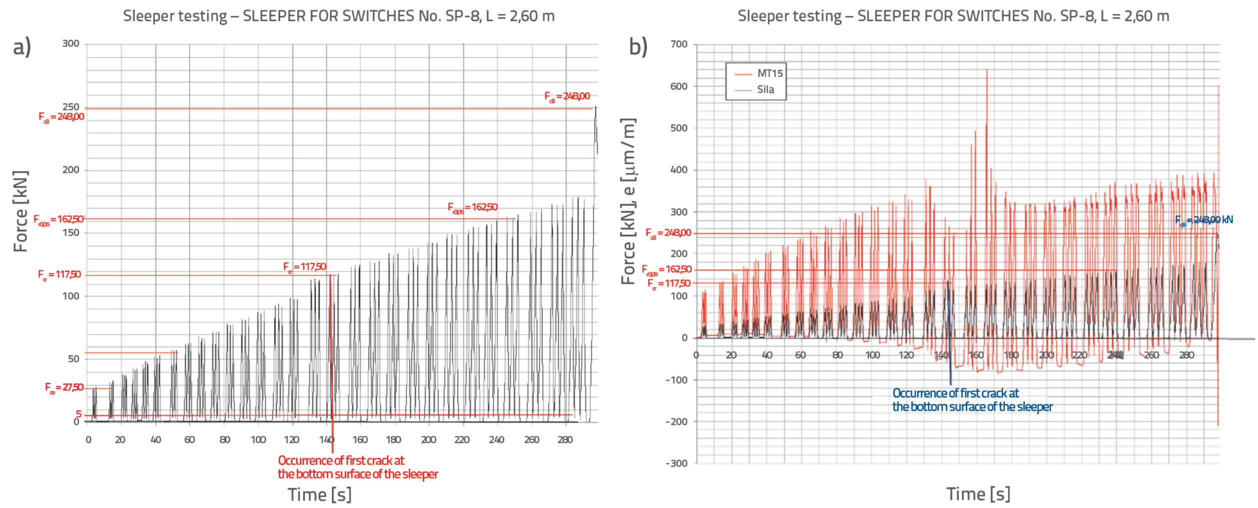

Figure 11. Dynamic testing of sleeper for switches SP-8: a) force, time; b) force, expansion, time (note: force is in the centre section of the sleeper, sleeper in normal position, positive design moment)

3.1.4. Discussion on dynamic testing

According to the standard, the dynamic testing is regarded as non-obligatory optional testing that is conducted at the request of the end-user. The results obtained confirmed the reasons why standards do not require dynamic testing: dynamic (impact) safety coefficients obtained in the testing, compared to maximum allowable values, are greater than the relationship between the static safety coefficients and maximum allowable static safety coefficients. It is clear that the effect involving increase of bearing capacity of prestressed concrete sleepers occurs at dynamic cyclic load.

4. Conclusion

Based on the specified and extended static testing for prestressed concrete sleepers for switches and crossings, it becomes completely clear why the standard EN 13230-4 does not require testing at rail seat. Average values of static coefficients $k_{b1s,sr}$ i $k_{b2s,sr}$ are much higher that the minimum allowed safety coefficients. For the cross-section in mid span, in normal and inverse sleeper positions, the results show fulfilment of all criteria set in the standard EN 13230-4 for positive assessment of sleepers. After dynamic testing of prestressed concrete sleepers for switches and crossings, the results show that there is a considerable reserve in the capacity of cross-section, which means that the existing reserve can be used either for assuming a greater locomotive axle load, or for rationalisation of cross section and this as to geometry of sleepers for switches, or as to the total prestressing force for sleepers for switches.

The tested sleepers for switches and crossings completely meet requirements set in EN13230-1 and EN13230-4 with regard to static and dynamic load, but with the mentioned deviations from testing method specified in EN13230-2.

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