Transverse strength of railway tracks: part 1. Planning and experimental setup

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ABSTRACT. Several studies have been carried out until now by various Research Agencies and Railway Administrations to quantify the effects of the track-bed geometrical characteristics on the transverse strength of the track. Unfortunately, not all the possible scenarios in terms of track components, track-bed cross profile, operating conditions etc. have been investigated and not all the relevant variables have been directly measured. Therefore data available from the literature have different degrees of reliability.
With the aim of enlarging the knowledge on the track stability and covering much of the possible relevant scenarios, an experimental research program has been developed in the framework of a cooperation between RFI, Italcertifer and DII.
In order to perform the investigation under quite general conditions and to reduce the experimentation costs, n. 28 significant scenarios have been identified and reproduced on as many independent track segments. By applying on each track segment a transversal load, the strength of the ballast-sleeper interface has been determined. The results relative to the first four scenarios are presented in terms of applied load vs. lateral track displacement diagrams and in more synthetic numerical tables.

KEYWORDS. Ballast resistance; Track stability; Full scale test; CWR track; Railway track.

INTRODUCTION

From the analysis of the technical literature concerning the continuous welded rail (CWR) problems, it can be inferred that together with the noteworthy advantages that it offers when compared to the traditional solution, in terms of both maintenance, comfort and performance, some essential precautions are needed. Among these, the most important from the structural design point of view is related to the track buckling (usually in the horizontal plane, although the phenomenon can occur also in the vertical plane [1]) caused by the rail temperature increases due to sun irradiation or train induction brakes [2].

The phenomenon takes place especially in presence of eccentricity due to track misalignments, in the neighbourhood of bends, bridges and other track singularities or when the neutral temperature is decreased due to creep [3, 4]. This latter is an effect particularly important near tunnels, in correspondence of strong gradients or in bents [2]. Also if the track neutral temperature can be restored to a safe value by periodic maintenance, very often the effects of local variability cannot be eliminated [4].

When rail temperature exceeds the maximum allowable value it is mandatory to reduce the rolling stock speed.

Furthermore, several authors have pointed out that loads (included the longitudinal ones) exerted on the track by trains can contribute to exceed the lateral strength limit [6], also due to the up-lift: design data for high speed trains and examples of horizontal track loads evaluation are also reported in [6].

In [6-8] it is demonstrated that track lateral strength offers a safety margin against lateral buckling and that most of the track strength is due to the friction between the sleepers base and the ballast; other important lateral strength contributions are given by the presence of ballast near the heads of the sleepers, the ballast parts included between successive sleepers and the ballast shoulders. The relative importance of these strength contributions depends on the track weight [6]. However, it is very difficult to trace a curve representative of the weight effect also because of the experimental data lack: until now direct measurements of track lateral strength have been carried out only with no more than two different weights of the track. Other parameters that can affect the lateral strength are time, since the ballast mechanical properties degrade with time and, finally, the sleeper shape that affects the resultant friction force against the ballast.

Also the kind of fastening system between sleepers and rails can affect the track lateral strength [9]. When the track moves sideways, sleepers can remain parallel to each other or show a relative rotation [10, 11]. Which of these behaviours predominates depends on the ballast strength and the primary and secondary twisting stiffness of the fasteners. However, it has not been possible to the authors finding in literature test data parameterized with fastener stiffness.

In consequence of ballast maintenance operations, the lateral strength can be reduced up to the 40% of its full value. Therefore, some operations cannot be carried out when the rail temperature is high, while some others are done imposing a reduced train speed until the ballast is consolidated [12].

A reliable solution to improve the track lateral stability is the adoption of sleeper anchors; unfortunately they involve additional costs.

A related problem also very often examined is the track displacement in curves due to the thermal deformations of the CWR. It lays down precise limits to the CWR construction: curves having radius less than a given threshold value cannot be made by the continuous rail.

Several studies have been carried out on the contributions brought to the lateral strength by the geometrical details of the track [3, 6, 12]. Most of them do not cover all the aspects involved: very often the scheduled experimental activities were not finished [6]. The tests usually were not repeated, when they were, the number of repetitions was quite low or however aprioristically fixed. Sometimes, the reported experimental results are partially censored (See, f.e., [3]); in addition, data are referred to an uniform ballast also if generally the presence of water pockets [6] or other singularities can alter the ballast behaviour.

On the basis of these data, that have limited and different reliability, several theoretical models and design software's have been developed in order to make deterministic and probabilistic previsions about the CWR buckling behaviour (See, f.e., [3, 5, 7, 8, 11, 13, 14, 15]) and to establish an allowable buckling risk [1, 2, 5, 16], if the risk based approach is adopted. In addition to the buckling phenomenon probability, this latter approach takes account of the seriousness of its consequences [5].

In order to improve the reliability of the aforementioned tools adopted for the prediction of the ballast behaviour, an experimental activity wider and more realistic than those usually carried out till now by the Institutions interested in this topic and in funding such research programs is needed.

Starting from this latter observation, RFI and DII have shown their interest in sharing resources and competences to develop a demanding research program. Together with Italcertifer, Italian Institute of Railway Research and Certification, they are partners in a research project whose main aim is a program of full scale tests on a great number of infrastructure archetypes simulating real scenarios of the track service conditions.

EXPERIMENTAL PROGRAM

From the analysis of both data required to identify the critical service conditions for the type of tracks described in the Technical Specification (elaborated *ad hoc* by RFI [17]) and those gathered in literature, useful guidelines have been drawn in order to plan out the type of tests and their number. This information is necessary to define the range of variation of all the parameters on which the aforementioned critical situations depend. The parameters are:

- Type of sleeper (A_i);
- Degree of ballast compaction (B_i);
- Shoulder dimension (C_i);
- Distance of the end of the sleeper from the ballast retaining wall (D_i);
- Height of the ballast in correspondence of the ends of the sleeper (E_i);
- Type of the anchor of the sleepers (F_i);
- Effect of the superelevation-cant (G_i);
- Lowered ballast profile between two sleepers for a width of 2 m (1 m for each side in respect to the track axis) (H_i);
- Height of ballast under the sleeper (I_i);
- Applied vertical load (L_i);
- Type of ballast material (M_i).

The combinations of all these parameters would obviously lead to define an onerous number of scenarios to be reproduced in the experimentation if the subscript "i" assumes at least 3÷4 different values, therefore it is compelled to make a trade-off choice in order to realize a narrow number of tests, but sufficiently significant to make, on the basis of the results obtained from them, both numerical and mathematical models able to effectively simulate all the scenarios corresponding to the parameter values belonging to the predetermined fields of variation.
On the basis of significance and representativeness considerations of the chosen track service conditions, as well as of economies of scale, 28 scenarios have been selected; they are summarized in Tab. 1.

M1, C2, H1, E1, A1, I1, B1, L1	M1, C2, H1, E1, A2, I1, B2, L2	M1, C2, H1, E1, A2, I3, B2, L1	M1, C2, H1, E1, A1, I3, G2, B1, L1
M1, C2, H1, E1, A1, I1, B1, L2	M1, C2, H1, E1, A1, I1, B2, L1	M1, C2, H1, E1, A2, I3, B2, L2	M1, C2, H1, E1, A1, I3, G2, B2, L1
M1, C2, H1, E1, A2, I1, B1, L2	M1, C2, H1, E1, A1, I1, B2, L2	M1, C2, H1, E1, A2, I3, B1, L1	M1, C2, H1, E1, A1, I3, G2, B2, L2
M1, C2, H1, E1, A2, I1, B1, L1	M1, C2, H1, E1, A1, I3, D3, B2, L1	M1, C2, H1, E1, A2, I3, B1, L2	M1, C2, H1, E1, A1, I3, F2, B2, L2
M1, C2, H1, E1, A2, I1, D3, B2, L2	M1, C2, H1, E1, A1, I3, D3, B2, L2	M1, C2, H1, E1, A1, I3, B1, L1	M1, C2, H1, E1, A1, I3, F2, B2, L1
M1, C2, H1, E1, A2, I1, D3, B2, L1	M1, C2, H1, E1, A1, I3, B2, L1	M1, C2, H1, E1, A1, I3, B1, L2	M1, C2, H1, E1, A1, I3, F1, B2, L1
M1, C2, H1, E1, A2, I1, B2, L1	M1, C2, H1, E1, A1, I3, B2, L2	M1, C2, H1, E1, A1, I3, G2, B1, L2	M1, C2, H1, E1, A1, I3, F1, B2, L2

A1 = RFI 230 pre-stressed concrete sleepers; A2 = RFI 240 pre-stressed concrete sleepers.
B1 = de-consolidated ballast bed; B2 = DTS consolidated ballast bed.
C2 = 60 cm ballast shoulder.
D3 = ballast retaining wall 60 cm apart from the sleeper end.
E1 = regular ballast shoulder top profile.
F1 = sleeper anchors at every 2^{nd} sleeper; F2 = sleeper anchors at every sleeper.
G2 = canted track.
H1 = non lowered ballast profile.
I1 = 30 cm ballast thickness; I3 = 60 cm ballast thickness.
L1 = unloaded track; L2 = loaded track.
M1 = regular ballast material.

Table 1: Scenarios included in the testing plan: characterizing parameters.

In order to establish a future correlation between test results and geometrical, mechanical and behavioural characteristics of all components and related materials used during testing, it has been decided to perform also a series of characterization tests on the components and materials that were not already tested by the suppliers. On the basis of the choices made to define the scenarios, the ballast was the only material/component that needed a special investigative attention; for it both a geometrical characterization test program, to be carried out in the laboratory on the aggregate, and a series of loading and seismic tests in the service conditions (on the instrumented track) have been defined. In particular, the latter tests have been planned in order to evaluate those parameters that can affect the ballast capacity of constraining in the long run the displacements of the sleepers in their axial direction, under the action of the destabilizing forces acting on the rails.

EXPERIMENTAL METHODOLOGIES AND TESTING PLAN

In the laboratory the following characterization tests, in accordance with the Standard shown in brackets, have been planned for the rocks that compose the ballast:

- Granulometric properties of Ballast grains (UNI EN 933-1 4/99);
- Shape index (UNI EN 933-4 4/01);
- Apparent particle density of ballast grains (UNI EN 1097-6 Ann. B 2/02);
- Los Angeles-test (UNI EN 1097-2);

In order to characterize *in situ* the ballast, in other words on the instrumented permanent way, the following tests have been introduced in the plan:

- Dynamic plate load test;
- Seismic tests.

The chosen kind of seismic test is the Seismic Refraction Profile in P and S wave velocities and has an investigation depth of 1 m. It consists in positioning along a line-up (sub horizontal and straight – for instance parallel and external to the track) n. 12 seismic sensors (geophones), 0.5 m far-between them and fixed in the ballast; along this alignment, n. 5 explosion points for the P-wave are positioned, two of which placed outside the furthest geophones (G1 and G12 in Fig. 1) at 0.25 m from them, one placed at the centre of the alignment and two in-between the furthest and the central explosion points.

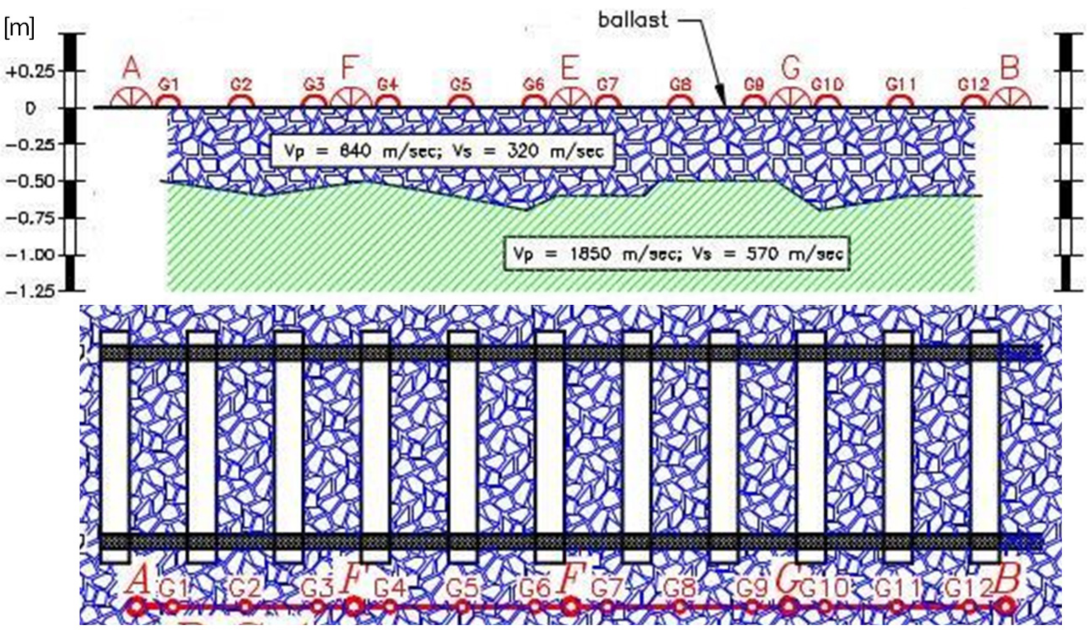

Figure 1: Arrangement layout of the geophones and the explosion points in the seismic tests.

Also, n. 2 explosion points for the S wave outside the furthest geophones (coincident to the first two for the P wave) will be realized by whacking with a hammer the vertical faces of a metallic plate having parallelepiped shape.

To understand, then, the influence of other structural parameters of the tracks on the stability of the system, tests on track panels reproducing the planned scenarios have been scheduled. These tests consist in applying on the rails a load

orthogonal to them and parallel to the running plane, until extended flows in the ballast, corresponding to yielding of the ballast at the interface with the sleeper, occurs.
Track panels are composed of n. 4 sleepers at least and extracted from a continuous track built according to the prescriptions needed to reproduce in each of them a scenario different from all others. The use of the track panels allows to test several sleepers at the same time reducing the total time of the experimentation. Moreover, the goodness of the results is not affected by this approach since the results, which are referred to a general sleeper belonging to a given scenario, are computed averaging the results of all sleepers of the scenario tested under the same conditions
For the chosen series of geometrical configurations of the track and for one ballast material, by means of these tests, the strength offered by the ballast against the longitudinal displacement of the sleeper, crosswise the permanent way, under loading and unloading conditions, is determined.
Full-scale tests on railway sections have been carried out according to the following practice:

1. a structure for load-transfer (cluster) is constrained to the track in at least n. 8 points;
2. a tensile load, transversal to the track and parallel to the running plane, is applied on the aforementioned system, until a displacement greater than 30 mm is produced, acquiring both load and displacement values with a sampling rate high enough to plot the load-displacement curve;
3. the contiguous track is loaded, symmetrically to the load axis of the cluster system, by means of a 2 t mass/sleeper;
4. the test load is applied as in point 2 and the load-displacement curve is acquired.

To carry out these tests - in addition to, obviously, the hydraulic ram, the load cell, the displacement transducer and the high frequency data acquisition system - the following equipments are needed: - a constraining structure; - block shaped masses, up to a total of 2 t/sleeper, laying on the track with the centre of mass in correspondence of the loading axis of the cluster system; - an interface structure between rail/loading blocks that allows loading and centring of the masses.

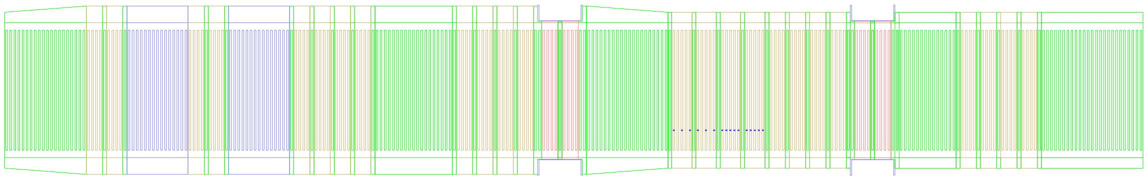

Figure 2: Schematic top view of the tested track segment (not in scale).

To conduct the full-scale tests in the same place for the different scheduled scenarios, the testing plan on the track schematized in Fig. 2 has been designed. In this figure different colours represent different zones. In particular, the green blocks represent the transition zones between two contiguous scenarios, while the blue one refer to canted track scenarios (only for RFI 230 sleepers). Red and cyan blocks represent scenarios with ballast retaining wall and anchors mounted on ties, respectively, while the brown one represents "classical" scenarios, namely straight track without accessories (such as anchors).

TESTING RIG

To implement the testing plan, an area of the Naples Campi Flegrei railway station has been prepared for the experimental activities. From two old tracks two segments having length equal to about 200 m are removed. A new track is rebuilt in place of the old ones, in such a way to match the specifications for the 28 scheduled tests (Fig. 3).
The construction details of the testing plant and the procedure adopted to carry out the tests on all the selected scenarios will be published shortly together with the acquired results. In the present paper, some graphs related to the first results acquired during the transverse tests carried out on four of the most common scenarios are reported (see Fig. 4). In particular, the curves depicted in the aforementioned graphs refer to the scenarios reported in the figures with the abbreviations LRS01, LRS04, LRS06, LRS07, which correspond to the following configurations, respectively:

- LRS01: n. 4 RFI 230 sleepers, 60 cm ballast shoulder, 30 cm ballast thickness, de-consolidated ballast bed.
- LRS04: n. 4 RFI 240 sleepers, 60 cm ballast shoulder, 30 cm ballast thickness, de-consolidated ballast bed.
- LRS06: n. 4 RFI 240 sleepers, 60 cm ballast shoulder, 30 cm ballast thickness, DTS consolidated ballast bed, ballast retaining wall.
- LRS07: n. 4 RFI 240 sleepers, 60 cm ballast shoulder, 30 cm ballast thickness, DTS consolidated ballast bed.

Figure 3: Photographic top view of the chosen testing field.

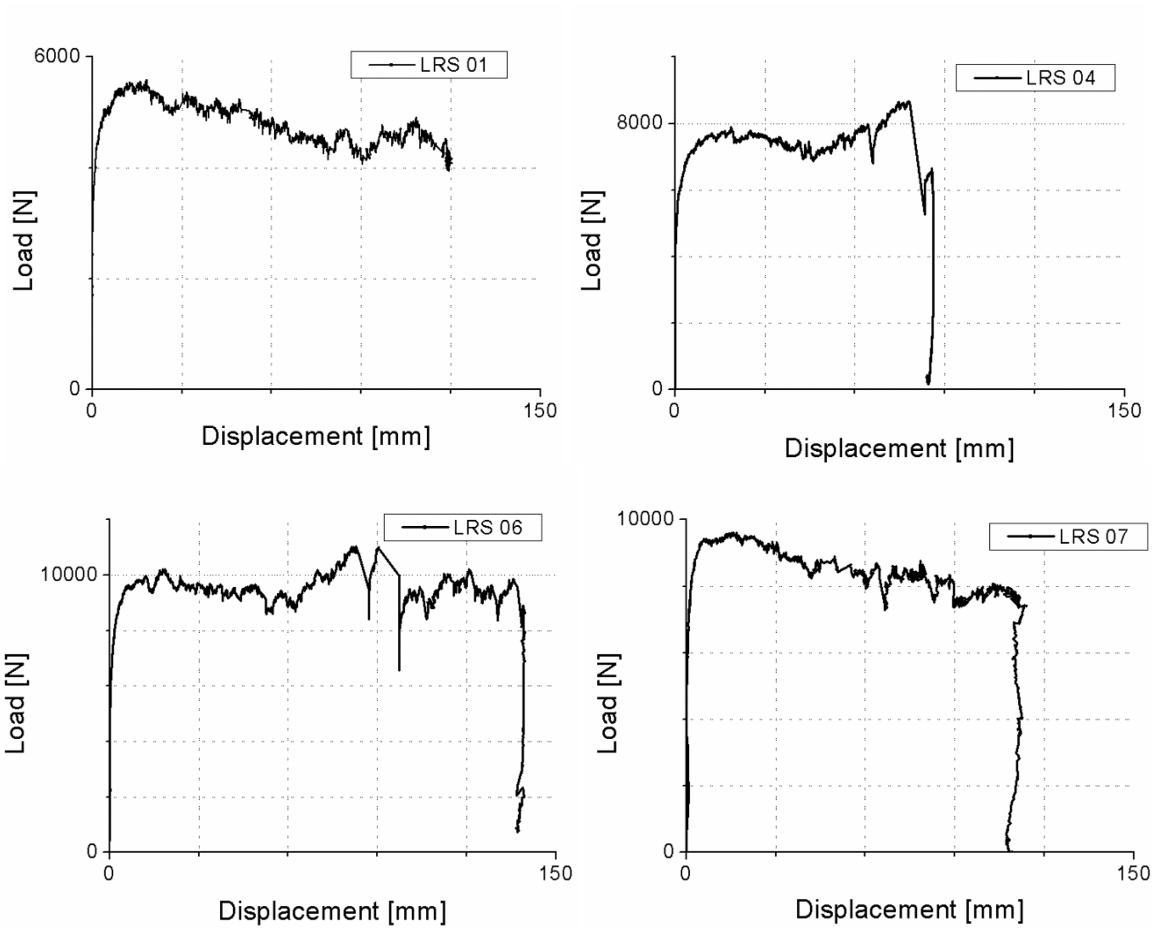

Figure 4: Load *vs.* track displacement curves for some typical scenarios.

The different components of the track panels are listed in Tab. 2. The maximum values of the ballast resistance, corresponding to a single sleeper, together with the limit values which correspond to the sliding of the sleeper on the ballast due to pseudo plastic failure of this latter, are reported in Tab. 3. The interpretation and the use of these results will be widely discussed in other papers, once the test campaign is completed.

Name	*Type*	*Reference Standards*
Rail	60E1	EN 13674-1
Fastening system	elastic type	EN 13481-2, EN 13146-1÷7
Concrete Sleeper	RFI 230 RFI 240	EN 13230-2:2002

Table 2: Track components.

	Scenario			
	LRS 01	*LRS 04*	*LRS 06*	*LRS 07*
Peak Resistance [N]	5˙545	7˙715	10˙000	8˙840
Limit Resistance [N]	4˙370	7˙100	9˙100	8˙100

Table 3: Peak and limit values for scenarios of Fig. 4.

The presented experimental test program, besides being a collection of raw test data (obtained with a substantial funding) driven by the need to expand the field's knowledge, will be a source of results directly useful for building up and validating a reliable CWR track model for a wide range of service conditions in terms of both scenarios and mechanical as well as environmentally induced loads that are able to produce the buckling phenomenon.

CONCLUSIONS

A relevant set of data concerning lateral track strength, directly useful for track design and maintenance, will be obtained through a series of full scale tests carried out on a number of different track layouts with various geometric configurations. In the present paper planning of the experimental activities as well as some details of the testing types and methodologies were described. As an example, the results of the first transverse tests carried out on four track panels corresponding to just as many scenarios were reported. The characterization of both materials and components used for the tested infrastructure will allow to identify a correlation between the parameters determining their mechanical behaviour and results obtained from full-scale testing. These latter will be used as starting point for the numerical modelling activity of the track system and for the final validation of a new track model, which is the true final aim of the present activity, offering to the railway technicians a more versatile and reliable tool for the design and management of the railway service.

BIBLIOGRAPHY

[1] Sung, W., Shih, M., Lin, C., Go, C.G., The critical loading for lateral buckling of Continuous Welded Rail, Journal of Zehjiang University Science, 6A (8) (2005) 878-885.
[2] UIC Code 720 R, Laying and maintenance of CWR track (2005).
[3] Improved knowledge of CWR track, Coenraad Esveld.
[4] Read, D.M., Kish, A., Clark, D. W., Optimized readjustment length requirements for improved CWR neutral temperature management, In: AREMA Conference, (2007)
[5] Kish, A., Samavedam, G., Risk analysis based CWR: track buckling safety evaluations, In: Proceedings of the International Conference on Innovations in the Design & Assessment of Railway, (1999).
[6] ERRI DT202/DT363, Improved knowledge of forces in tangential tracks including switches, Determination of lateral and longitudinal ballast resistance of a railway track by experimental tests, Utrecht, (1997) 2.
[7] Kish, A., Samavedam, G., Wormley, D., New track shift safety limits for high speed rail applications, In: Proceedings of World Congress on Railway Research, Cologne, Germany, (2001).

[8] Analyses of track shift under high speed vehicle-track interaction, US Department of Transportation, DOT/FRA/ORD-97/02, DOT VNTSC-FRA-97-3 (1997).
[9] Lim, N. H., Sung, I. H., Thermal buckling behavior of continuous welded rail track, Steel Structures, 4 (2004) 111-119.
[10] Poonia, R.S., Understanding Long Welded Rail, Permanent Rail Bulletin, Indian railways, 34 (1) (2007).
[11] Van, M.L., Buckling Analysis of Continuous Welded Rail Track, Heron [0046-7316], 41 (1996) 3.
[12] Sussmann, T., Kish, A., Investigation on the influence of track maintenance on the lateral resistance of concrete tie track, TRB Annual Meeting, (2004).
[13] A new set of computer models for analyzing, CWR, Coenraad Esveld, Esveld Consulting Services.
[14] Esveld, C., A better understanding of continuous welded rail track, Rail Engineering International Edition, 4 (1996).
[15] Lim, N. Y., Parametric study on stability of continuous welded rail track-ballast resistance and track irregularity, Steel Structures, 8 (2008) 171-181.
[16] Kish, A., Sussmann, T., Trosino, M., Effects of maintenance operations on track buckling potential, In: Proceedings of International Heavy Haul Association, (2003).
[17] Technical Specification, RFI, Rome, (2008).