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On the lateral stability of the sleeper-ballast system

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Abstract

The lateral stability of railway tracks depends on all track components: rails, fastening systems, sleepers, ballast bed and substructure. Among them, the ballast is the weakest one and, due to its granular nature, experimental data obtained in line from full-scale tests, rather than based on analytical formulations, are used to describe its behavior. Until now, several studies have been carried out to quantify the effects of the track-bed geometrical parameters on the transverse strength of the track, but unfortunately not all the possible scenarios have been investigated. To fill this gap, a numerical-experimental research program of in-line tests has been developed in the framework of a cooperation between the Italian State Railways (RFI) and the Department of Industrial Engineering (DII) of the University of Naples Federico II. An *ad hoc* experimental testing plant, which is able to apply in a more realistic way the testing loads in field conditions, has been designed and realized. In the present paper, the test field is described, and both the features of the new testing plant and the advantages that this new system offers are detailed. Finally, from the analysis of the experimental data obtained from in-line tests carried out on some track panels representative of real scenarios, and with the help of atypical lateral resistance tests, an interesting property is utilized to predict *a priori* the lateral resistance curves of non tested scenarios.

Keywords: Thermal track buckling; railway track stability; CWR; full scale test; field test; sleeper-ballast lateral resistance; DCPPT

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1. Introduction

Despite the continuous welded rail (CWR) offers remarkable advantages in terms of maintenance, comfort, and performances when compared to the traditional solutions, some drawbacks still exist, among which the most important is the buckling tendency (Kerr (1978); Sussmann et al. (2003); Gong et al. (2016); Kish et al. (1991)). This phenomenon occurs mainly in the horizontal plane when the rails temperature increases beyond a critical value, or when the rail neutral temperature decreases under the actions exerted by the trains passages (UIC (2005); Esveld et al. (1998); Read et al. (2007); Sluz et al. (1999); Harrison et al. (2012)).

So, the ballast lateral resistance plays a crucial role on the track safety against the thermal buckling phenomenon, and this resistance strongly depends on track geometry, track components, and ballast bed compaction level. In fact, it is generally recognized the ballast bed offers a 60 % contribution to the lateral strength of ballasted railway tracks, compared to about 30 % and 10 % provided by the fastening systems and the rails, respectively (De Iorio et al (2014a)) .

The high number of mechanical and geometrical parameters, together with the costs of experimental activities carried out on full-scale track sections, probably justifies the limited availability in literature of a useful tool for the choice of the optimum set of parameters that ensures railway technicians a better economy and a higher safety. Experimental data acquired during full-scale tests conducted in USA (Kish et al. (1998); Kish et al. (2013); Jeong (2013)), UK (Sinclair (1996); Shrubsall et al. (2001)), Australia (Wu et al. (2012)), Italy (De Iorio et al. (2014a-c); Pucillo et al. (2018)), and the one carried out by ERRI, the European Rail Research Institute (ERRI (1995a-b)), were obtained with particular track configurations and, as a consequence, it is not possible to use them in scenarios different from those from which they were derived if no data processing or manipulation is done. This lack of information has also conditioned the activities of researchers dealing with the problem of the track analytical or numerical modeling (Kerr (1974); Kerr (1978); Kish et al. (1998); Pucillo (2016); Gesualdo et al. (2017); Penta et al. (2017); Pucillo (2018); Gesualdo et al. (2018a-b)).

In this study, in order to contribute to reduce the existent gaps in the knowledge of the ballast mechanical behavior, a new in field experimental methodology, which is able to give useful data for assessing the safety margins against the thermal buckling of a given number of scenarios is presented and discussed.

2. Experimental methods for the evaluation of the sleeper-ballast lateral resistance

Two experimental techniques are mainly used for determining the ballast lateral strength: the Single Tie Push Test (STPT, see Fig. 1a) and the Discrete Cut Panel Pull Test (DCPPT, see Fig. 1b).

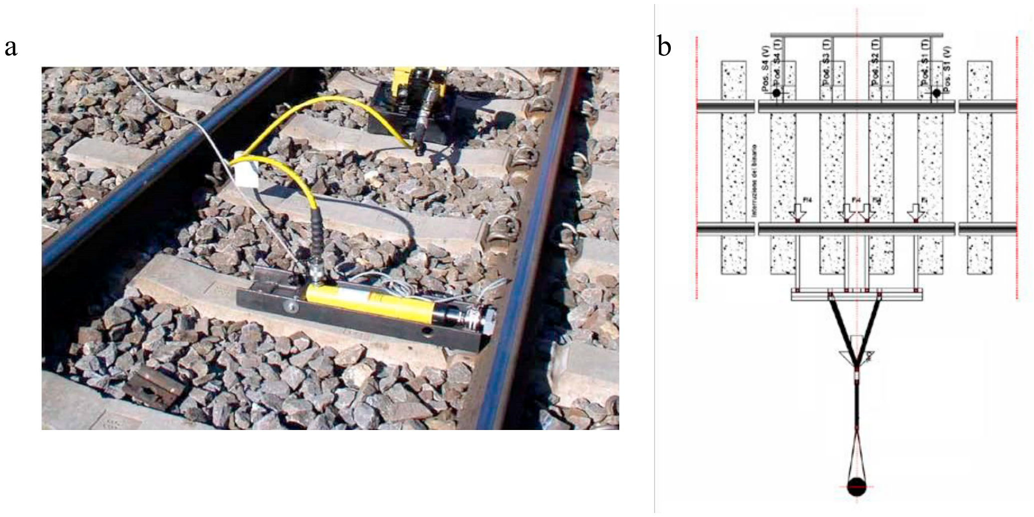

Fig. 1. STPT (a) and DCPPT (b) layouts.

With the STPT, a lateral displacement is imposed to a single sleeper, and the corresponding values of the resistance exerted by the ballast bed are recorded (Samavedam et al. (1995)). As shown in Fig. 1a, the tested sleeper is first disconnected from the track, then it is moved in the lateral direction by an actuator whose body is fixed to the sleeper; the piston rod of the actuator pushes against the continuous rail, which works as a fixed constraint.

In this case, however, the load is applied nominally along a direction that is tangent to the sleeper upper surface, with an arm that is equal to the distance between the actuator axis and this surface (when the parallelism between the load direction and the upper sleeper surface is guaranteed). Before the test, in addition to the fastening systems, the rails pads are also removed. During the tests carried out in loaded track conditions, the rail pads are replaced by lubricated steel plates of the same thickness. Since the vertical load is realized by positioning a wagon axle in correspondence of the sleeper, the steel plates transfer to the sleeper the maximum part of the vertical load applied to the rails (Fig. 2).

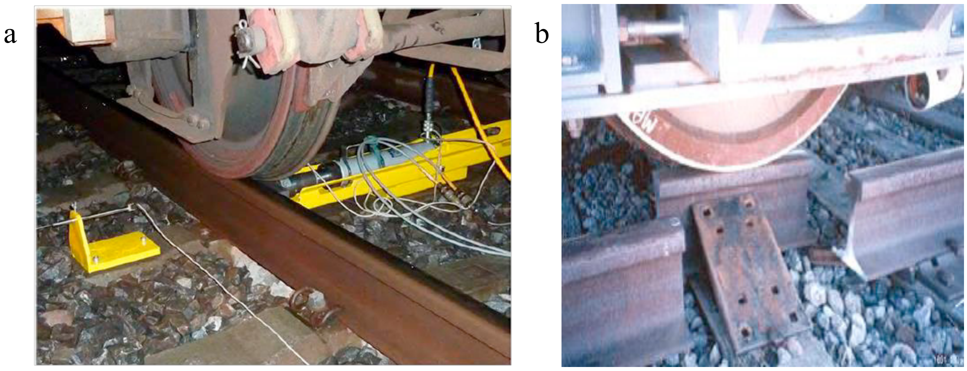

Fig. 2. STPT configuration for loaded track conditions in the case of continuous track (a) and cut track (b).

The STPT technique has several advantages, the most important of which are the cost and the operative simplicity. However, this method leads to results that are affected by uncertainty, mainly due to the following reasons:

- the border effects, due to the presence of the adjoining sleepers to the one under test, are not taken into account;
- the applied load can have a parasitic component which is orthogonal to the sliding plane of the sleeper, whose amplitude and application point are difficult to evaluate;
- in loaded track conditions, it is very difficult to accurately evaluate the effective value of the load that is transferred to the sleeper, both when the vertical load is applied to a continuous rail (Fig. 2a) and when a sectioned track is used (Fig. 2b). Moreover, when the STPT is carried out on a continuous track, the frictional forces arising from the interaction between the rails, the plates, and the sleepers are not considered, whereas during the tests performed on sectioned track the torsional resistance of the wagon is totally neglected.

Compared to the STPT, the DCPPT technique (ERRI (1995a)) is highly destructive and more expensive, because it requires the sectioning of a short track segment to which a lateral displacement is imposed. The track segment usually includes four or five sleepers, and both the type of sleepers and the track conditions and geometry (ballast thickness, subgrade thickness and composition, shoulder width, ballast retaining wall, etc.) are representative of specific track conditions. The typical setup includes an actuator pushing on one of the two rails of the track segment by means of a cluster fixture. An example of this type of fixture is sketched in Fig. 1b.

Despite the DCPPT is characterized by a more complex testing setup, it offers the possibility of performing the tests in presence of a vertical load in a very simple manner (Fig. 3b), and allows analyzing the experimental data in a direct way, without adopting particular hypotheses to estimate the ballast contribution to the lateral strength (ERRI (1995a)). Moreover, only with this technique it is possible to measure the ballast strength along the axial direction (De Iorio et al. (2018)), and the border effects are less pronounced compared to the STPT.

For these reasons, within the framework of a numerical-experimental research program on the track stability under thermal loads, developed thanks to the cooperation between the Italian State Railways (RFI) and the Department of Industrial Engineering (DII) of the University of Naples Federico II, the DCPPT technique has been chosen to perform full scale lateral resistance tests in field conditions (De Iorio et al. (2014a-c)).

The test system is an alternative to those described above, and has been fully discussed in a previous paper (De Iorio et al. (2014a)). It is configurable up to a maximum of five loading lines, and each loading lines is composed by an electromechanical actuator, two load cells, and a displacement transducer (Fig. 3). All the actuators are handled by a programmable digital controller. The tests scheduled in the research program have been performed under displacement control, with a speed of 2 mm/s, whereas loads and displacements data have been acquired with a sampling frequency equal to 2 Hz.

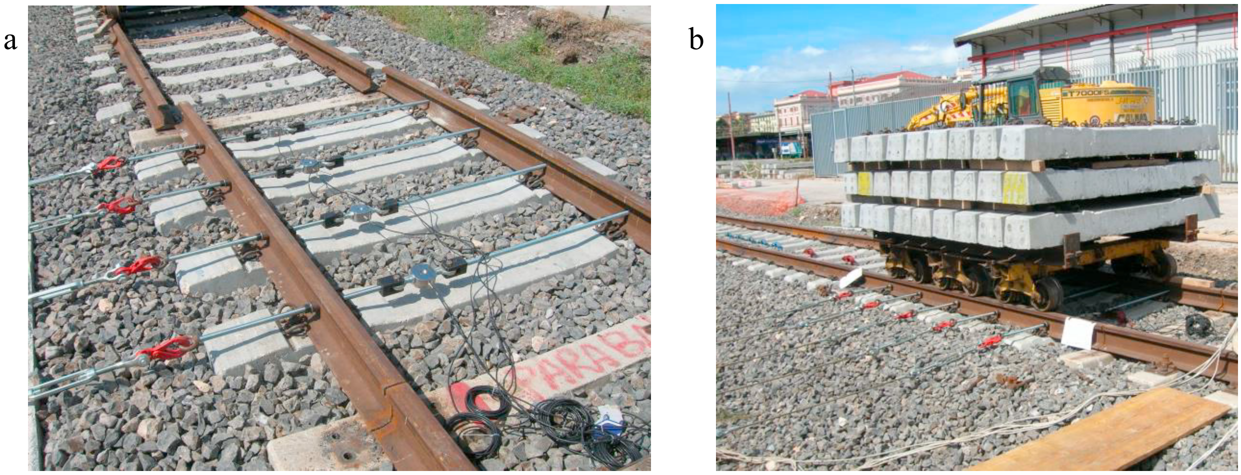

Fig. 3. DCPPT arrangement for unloaded (a) and loaded (b) track conditions.

3. Test Field

Due to granular nature of the ballast bed, experimentally data obtained in line from full-scale tests, rather than based on analytical formulations, are usually used to describe its behavior. The lateral resistance of the sleeper-ballast system depends on several geometrical and structural parameters; typical operational conditions of railroad tracks were included in the research program as track parameters (De Iorio et al. (2014c)):

- type of sleepers;
- degree of ballast compaction;
- shoulder width;
- distance of the sleeper end from the ballast retaining wall;
- height of the ballast at the ends of the sleepers;
- type of sleeper anchor;
- effect of cant;
- lowered ballast profile between two sleepers;
- ballast thickness under the sleeper;
- applied vertical load;
- type of ballast material.

Considering 3÷4 different values for each parameter, it would have been too expensive the experimental evaluation of their specific contribution on the total lateral resistance For this reason, a limited - but significant -

number of scenarios was realized, and from the analysis of the experimental data useful information have been found to evaluate the lateral resistance curves for non tested scenarios.

3.1. Full scale experimental results ad isomorphism of the sleeper-ballast lateral resistance curves

Taking into account the more important service conditions of actual railway tracks, n. 28 scenarios were chosen. They are those reported in Table 1 of De Iorio et al. (2014b). Full scale tests were performed on a track section of about 200 m located near the Campi Flegrei Railway Station in Naples (Italy). The test site (see, e.g., Fig. 4) included the following track parameters: - compacted and tamped ballast conditions; - loaded (2 t/sleeper) and unloaded tracks; - cant; - two different sleeper types; - two different values of the ballast thickness underneath the sleepers; - sleeper anchors; - ballast retaining wall. More details on the complete experimental activity are reported in De Iorio et al. (2014a-c)

The diagram of Fig. 5a shows the force–displacement curves obtained from lateral resistance tests carried out on classical (no ballast retaining wall, no sleeper anchors) scenarios in tamped ballast conditions and without vertical load. Note that in this diagram the experimental results refer to similar scenarios, with two sleeper types and two ballast thickness values as varying track parameters, as discussed above. Similar diagrams were collected also for the remaining scenarios: - with vertical load and in tamped ballast conditions; - in compacted ballast conditions, with and without vertical load; - that included sleeper anchors or ballast retaining wall, with or without vertical load; for a total of eight diagrams.

From the analysis of each diagram, an interesting property was found. If the ordinates of all the load–displacement curves are normalized to unity, the curves belonging to the specific diagram appear almost indistinguishable, as it can be seen in Fig. 5, e.g., where row (Fig. 5a) and normalized (Fig. 5b) experimental data are compared. And this happen also for the remaining seven diagrams, for a total of eight normalized, or characteristic, curves, as detailed in De Iorio et al. (2017).

At this point, the lateral resistance curve of a specific scenario "*S*" not belonging to the 28 tested scenarios can be obtained multiplying the ordinate values of the characteristic curve to which the scenario "*S*" is similar, by the peak values of the lateral resistance associated to the considered scenario "*S*". So, if only the peak value of any track scenario is know, the complete lateral resistance curves can be predicted *a priori*.

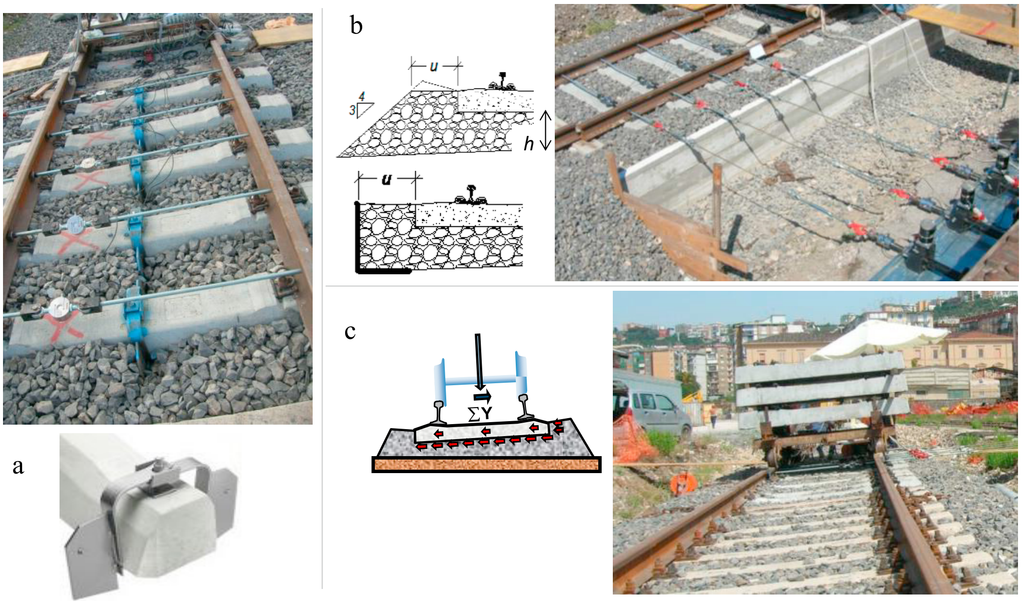

Fig. 4. Some examples of operational conditions in railroad tracks: (a) sleeper anchors; (b) ballast retaining wall; (c) cant.

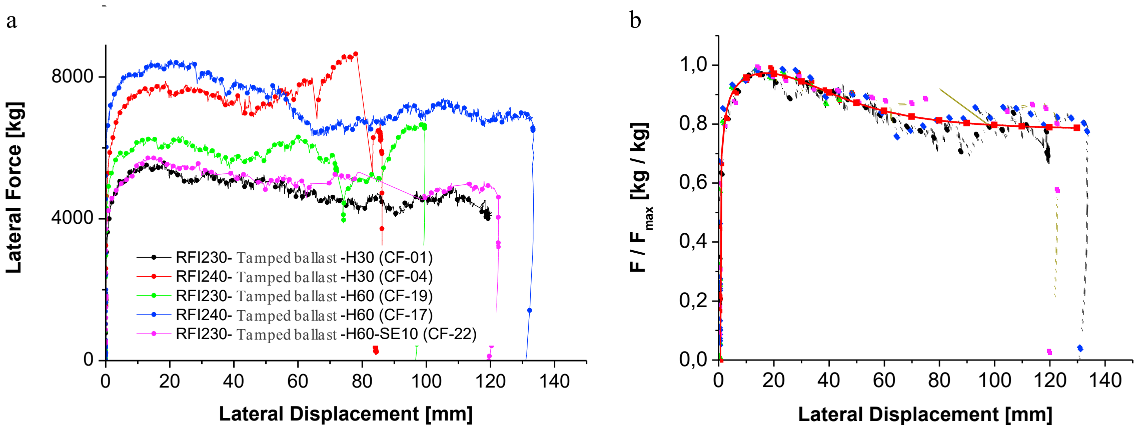

Fig. 5. Lateral resistance test results for tamped track without vertical load: row (a) and normalized (b) data.

3.2. Contribution of the crib, the base, and the shoulder to the lateral resistance

To estimate the contributions to the peak value of the lateral resistance arising from the interaction between the ballast bed and each sleeper face contacting the ballast, additional and atypical lateral resistance tests were performed in Traccia, near the Naples Central Train Station (De Iorio et al. (2018)). For this purpose, n. 4 track panels were realized by removing the crib ballast and/or the shoulder were removed, as shown in Fig. 6, for the purpose of evaluating the contributions offered by the base, the ballast between the sleepers, and the ballast shoulder to the total lateral resistance. This is a common experimental practice followed by various authors to extend the obtained results to scenarios similar to the tested ones (Le Pen et al. (2011); ERRI (1997)), although they differ in terms of shoulder height, shoulder depth, ballast thickness under the sleeper, etc., namely the volume and the shape of the ballast bed surrounding the sleepers. From the lateral resistance tests, the contributions to the total lateral resistance provided by the crib, the base, and the shoulder were found to be, respectively, approximately 50 %, 25 %, and 25 %, in good agreement with literature data (Le Pen et al. (2011); Kabo (2006)).

Fig. 6. Lateral resistance layouts for track panels: (a) without ballast crib; (b) with base contribution only; (c) without shoulder; (d) with ballast everywhere (De Iorio et al. (2018)).

4. Conclusions

Within the framework of a cooperation between the Italian State Railways (RFI) and the Department of Industrial Engineering (DII) of the University of Naples Federico II, a numerical-experimental research program on the track stability under thermal loads has been developed.

A relevant set of data concerning the lateral track strength has been obtained for n. 28 different track geometries, in tamped ad compacted ballast conditions, with and without a vertical load.

Taking advantage of the isomorphism of the lateral resistance curves, and with the help of additional atypical lateral resistance tests, it is show how the database of lateral resistance curves can be extended to other non tested scenarios.

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