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About the Impact Behaviour of Railway Fastening Systems

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***Abstract*— On the basis of what established by the Product Technical Specifications - Specifiche Tecniche di Prodotto RFI (STP) - regarding the performance requirements that fastening systems between sleepers and rails should meet to be homologated, a test plant was designed and a procedure to determine the capabilities of the above-mentioned systems to lessen the effects of impact loads was defined. Moreover, specific guidelines concerning the ways in which impacts are generated are not supplied by the same STP. Issues arise in designing the test plant due to the need of guarantee a certain adjustment margin on the drop height as well as on the determination of the weight of the *drop mass*. Before building the plant, to check that it could perform impact tests in compliance with the Norms specifications, a massive numerical simulation campaign have been carried out. Numerical results allowed to solve optimally the design problem of the test apparatus here proposed.**

***Index Terms*— Railway, Infrastructure, Railway Fastening, Impact Load, Full Scale Test, Aided Design, Numerical Simulation of Tests.**

I. Introduction

THE Product Technical Specifications, drawn up to comply with European Regulations, identify the performance requirements of all components of the Railway Infrastructure.

Among them, one of the most complex is the one dealing with the attenuation of impulsive loads by means of the fastening systems located between sleepers and rails [1]. In fact, in order to determine the attenuation capabilities of these systems, a particular test set up able to induce in the railway ties, on which the fastening system will be installed, strains whose magnitude is not specifically assigned is needed. The magnitude of the aforementioned strains has to be experimentally obtained from the results of another static test, which is included in the certification tests set of the sleeper.

On the basis of the aforementioned considerations, a particular test plant together with a procedure through which determines the capability of the fastening system to lessen the effects of impact loads is a needed.

The problem was faced and solved with the aid of a numerical simulation of all the plant building phases and of suitable preliminary tests, aiming at designing a plant which is compliant with the Norms requirements as well as to simplify the experimenters task in the activities dealing with the certifications of the different types of fastening systems (railroad switches, AV, etc.) and the different types of sleepers (in terms of sizes and material).

Numerical analyses were performed with two finite element commercial codes in order to simulate static and impact tests.

The design phases of the test plant were followed since the beginning and therefore it was possible to check that its goals were achieved.

In the present paper a detailed description of all design phases have been discussed, in order to make the work useful to both young mechanical designer as well as skilled experimenters.

II. Test Procedure and Virtual Experimentation

Certification tests aiming at quantifying the absorption capabilities of the mechanical vibrations induced by the passage of trains are based on the comparisons between mat performances, which is the component of the fastening system which should be homologated and those of another mat taken as "reference", which is sufficiently harder than the previous one. The control parameter consists of deformations, measured on the longitudinal faces of the sleepers, induced by an impulsive load. This is produced making a mass having the shape of a puncheon falling down on the head of the rail, fastened to the sleeper through a fastening system to be homologated and vertically pre-loaded with two springs under the action of a load equal to 50 kN.

However, the Norms require that the deformation levels obtained in this way are at the most equal to 80% of those obtained during other tests to be performed on sleepers. This implies that, changing the type of fastening and/or the type of sleeper, the corresponding test setup should result different in terms of mass and height of the falling body, with inevitable disappointment by operators and running the risk not to be suitable to meet, for another sample to be tested, the plant requirements requested by the Norms.

In order to avoid this inconvenience and not to proceed with the a *trial-and-error* approach, concerning the fine tuning of the test set up, it was decided to preliminary

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perform a numerical simulation of the behaviour of the component to be tested, so that to have an estimation of the deformation values which arise in the sleeper, at the instrumented points for the impact test, under the action of the loads applied during the bending test of the sleeper [1 ÷ 3].

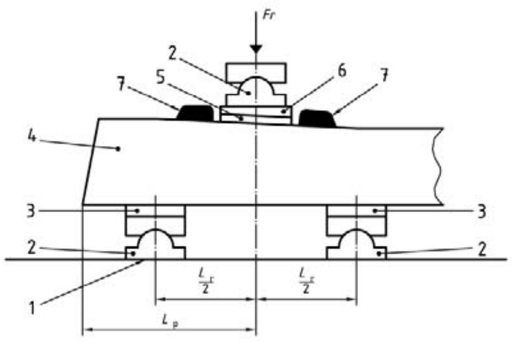
A. Numerical Simulation of the Sleeper in the Bending Moment at Rail Seat Test

The bending static test in the rail seat section [1 ÷ 3] gives the deformation values at the same points which are instrumented in the impact test. Such values have to be read and recorded when the applied bending moment, Md_r, reaches the value of 19 or 21 kN·m, depending on whether the sleeper is, respectively, of the type 240 or 260 RFI.

The test is performed according to the *tree point bending* scheme reported in [3 ÷ 5] (Fig. 1), by applying a vertical load, Fr_0, at the rail seat section by mean of an articulated support and locating the other two cylindrical supports – between each support and the sleeper a rubber plate is inserted – at a distance, L_r, which is function of the sleeper geometry (Table I). The load value, Fr_0, expressed in kN, is calculated with the following formula [2]:

$$Fr_0 = \frac{4Mdr}{L_r - 0{,}1}$$

which, in the examined case (RFI 260 sleeper and L_p > 0.45 m), gives a value of 168 kN.



Key
1. Rigid support
2. Articulated support
3. Resilient pad
4. Prestressed monobloc sleeper
5. Standard rail pad as defined by the purchaser
6. Tapered packing
7. Lateral stop

Fig. 1. Configuration for the bending moment at rail set test [1 ÷ 3].

TABLE I
L_R VALUES IN FUNCTION OF LP [1 ÷ 3].

L_p [m]	L_r [mm]
$L_p < 0.349$	0.3
$0.350 \le L_p < 0.399$	0.4
$0.400 \le L_p < 0.449$	0.5
$L_p \ge 0.450$	0.6

Taking into account both the geometrical and loading conditions symmetries, with respect to the vertical plane passing at the load application line and perpendicular to base of the sleeper, only one half of the model was simulated. Calculations were performed with a commercial finite element code and an implicit type solver, using 3-D 8-node structural solid elements, with 3 translational degrees of freedom (d.o.f.) per node. An isotropic, elastic and linear behaviour was assumed for all materials (Table II). Fig. 2 shows an image of the model with an indication of the load uniformly applied on the upper surface of the steel plate, with a resultant equal to 168 kN.

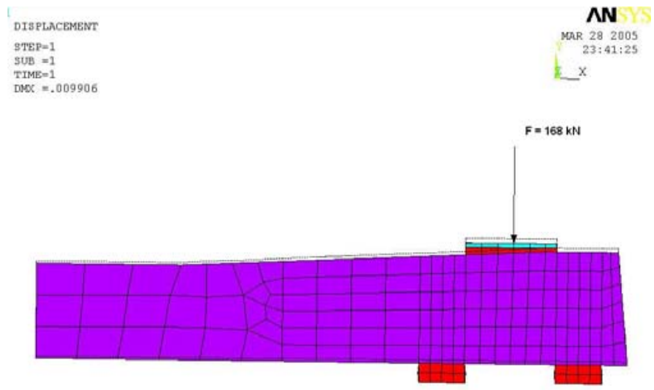


Fig. 2. Mesh, load and constraint hypotheses in the bending moment at rail seat test.

TABLE II
MECHANICAL PROPERTIES USED IN THE MODEL

Component		Ties	Shaped Plates	Elastic Elements
Modulus of Elasticity [N/mm²]	E	30000	210000	37.5
Poisson's ratio [mm/mm]	υ	0.3	0.3	0.3

Fig. 3 shows the contour plot of longitudinal strains produced by the test load, from which it is possible to obtain the strain values at the instrumented points of the lateral sides sleeper.

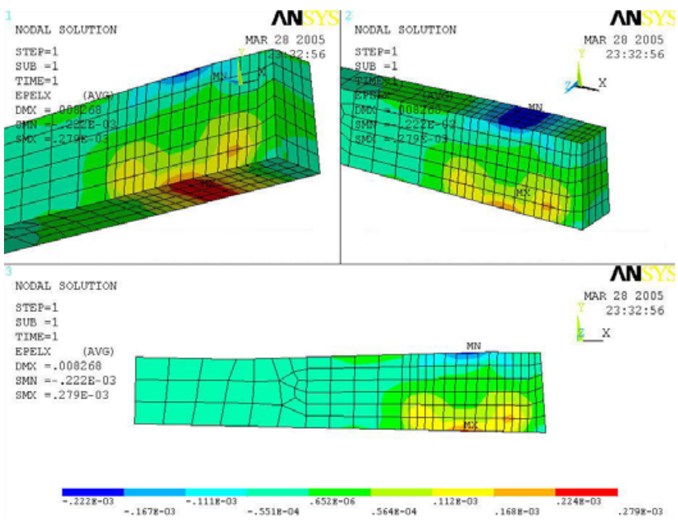


Fig. 3. ANSYS results: contour plot of the longitudinal (X) strain in the sleeper.

The sleeper material was considered isotropic and linear elastic, although it is anisotropic, for the following reasons:

1) the deformations to be calculated, both in the rail seat

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bending static test and the impact test, mainly derive from the bending moment, *Mz*, so that the contribution to longitudinal strains, ε_x, given by the transverse components of the stress tensor is less important in respect to the one due to the longitudinal component of the same tensor, σ_x, which implies that the values of the above-mentioned deformations do not vary significantly if the Young's modulus are different (anisotropic material) or equal (isotropic material) among them in the three directions, provided that the one of the modulus in the longitudinal direction of the sleeper is correct;

2) although it is not known in advance, the mistake which is made in the choice of the value to be assigned to the Young's modulus of the reinforced concrete sleeper has likely the same importance on the mistake which is made in the calculus of deformations obtained in both the above-mentioned tests.

Moreover, being the FEM modelling goal that to evaluate, for the impact test, the mass and the relative drop height for which induced strains do not exceed the 80% of the values recorded in the instrumented points during the bending moment at rail seat test, the inherent mistake in this evaluation - due the simplifying hypotheses performed on the material - should result quite small, if we suppose that for the above-mentioned goal the magnitude of the numerical mistake in the evaluation of strains values has the same order of magnitude in the simulation of both the static and impact tests.

B. *Numerical Simulation of the Impact Test*

In order to analyze the response under impulsive loads, a finite element commercial code with an explicit solver, dedicated to the solution of non-linear problems and widely used in the presence of impulsive load conditions, was used.

The results of the dynamic analyses are synthesized within the family of curves in Fig. 4, parameterized in mass and drop height, which supply the strain values reached in correspondence of the points to be instrumented, that are located symmetrically about a plane normal to the base of the sleeper and passing through the centre of the rail seat.

The model is very similar to the one used for the static test, and also in this case both geometrical and boundary conditions symmetries were employed, applying constraints which prevented perpendicular translations to the above-mentioned symmetry plane, which coincides with the longitudinal plane of the sleeper (Fig. 4).

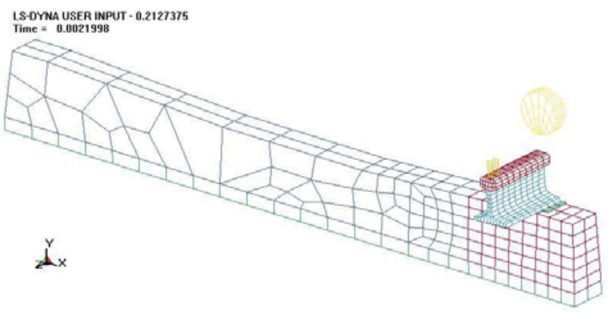

Fig. 4. Mesh used in the simulation of the impact test.

The solid elements used to model the rail, the sleeper and the rubber mats are the *solid 164* (equivalent to *solid 45* used in the implicit code), while the effect of the springs was simulated with the one-dimensional elements *combin 165*, with two nodes and three degrees of translational freedom per node. To these elements the value of the spring stiffness can be assigned, which, in the examined case, corresponds to the one requested by the Standard: 500 N/mm. The elastic modulus of the under-rail pad was so assigned that its vertical stiffness could be higher than the minimum value requested by the Standard, which is $K_{pad} \geq$ 500 MN/m. On the other hand, the only requirement for the rubber bed concerns the deflection, δ, which must be limited in the range $0.1 \leq \delta \leq 0.5$ mm when the preload varies from 50 to 60 kN. The values of elastic properties adopted in the numerical analyses in correspondence of the conditions which meet the above mentioned requirements are reported in Table III.

TABLE III
MECHANICAL PROPERTIES USED IN THE CALCULATIONS.

Component	Rail under pad	Sleeper under rubber bed	Preload springs
Modulus of Elasticity [N/mm^2]	100	14	
Stiffness [N/mm]			500

The punch was still modelled with elements *solid 164*, but considering the material of such elements with a stiff behaviour. This assumption, which is justified by the presence of other materials much more deformable than the one of the impact mass, served mainly to easily change the punch weight by changing its inertial properties without modifying its dimensions. The contact between ram and rail was implemented adopting a ‘Surface to Surface’ algorithm, already implemented in the FE code.

Fig. 5 shows the curves related to strains as a function of time, for upper and lower strain gages, and for a certain test configuration, that is for a given mass and drop height value.

Fig. 6 shows the curves related to numerically obtained peak values and parameterized as a function of the drop mass and the drop height value, the former, in the range 10 ÷ 100 kg and, the latter, in the range 10 ÷ 125 cm.

In Fig. 7 the 3D CAD model together with some pictures of the test plant are shown. The system here discussed is able to carry out impact tests with the drop height range showed in Fig. 6.

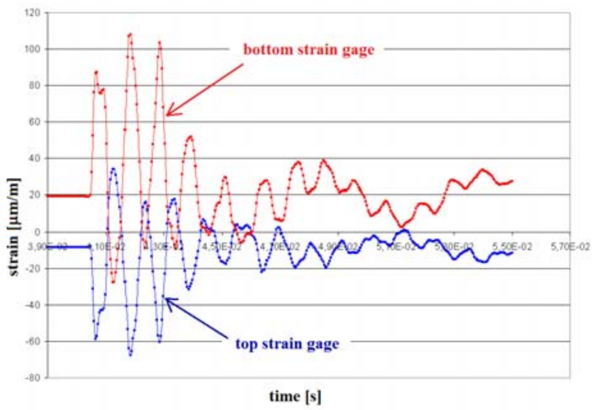

Fig. 5. Numerical strains calculated at the strain gages-instrumented points for a drop height of 25 cm and a drop mass of 50 kg.

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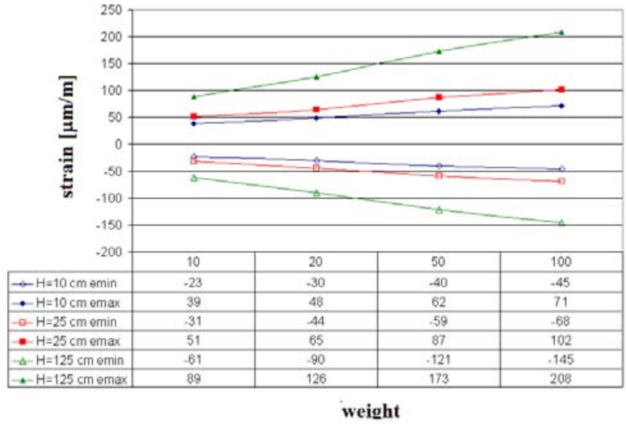

	10	20	50	100
H=10 cm emin	-23	-30	-40	-45
H=10 cm emax	39	48	62	71
H=25 cm emin	-31	-44	-59	-68
H=25 cm emax	51	65	87	102
H=125 cm emin	-61	-90	-121	-145
H=125 cm emax	89	126	173	208

Fig. 6. Numerical strains obtained in the sleeper points instrumented with strain gages.

Fig. 7. Plant for impact tests on rail fastenings.

III. Preliminary Tests

The impact test is preceded from the "vertical stiffness test" of the reference pad, from the calibration of the spring pack, by which the fastening system in the impact test is preloaded, from the verification of the under sleeper pad stiffness, and from the bending moment at rail seat test. Below is a short description of all these tests.

A. Vertical Stiffness Test for the Reference Pad

In accordance with what provided for in [1], the reference pad stiffness must be higher than 500 MN/m. It has been determined in accordance with [2].

The reference pad was placed between an enough stiff steel plate and a rail section 500 mm long. A load of 85 kN was applied on the rail head, perpendicular to the rail seat, with at a rate of 45 kN/min, by using a punch ended in a spherical cap as an interface (Fig. 9). Relative displacements between the rail foot and the plate were measured by means of 4 laser displacement sensors, connected to the plate and pointed to the rail (Fig. 9). The force and displacement signals were acquired with a sampling frequency of 2 Hz.

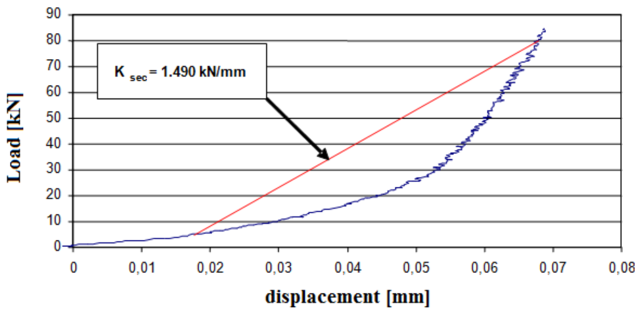

Fig. 8. Load-displacement curve registered during the vertical stiffness test.

Fig. 9. Test arrangement and laser disposition during the vertical stiffness test.

The secant stiffness, which the Norm identifies as the pad's vertical stiffness, obtained experimentally, was 1490 kN/mm (Fig. 8), so the pad meets the requirements specified in EN 13146-3.

B. Spring-pack Calibration

The springs used for applying the preload on the rail section (then on the underlying fastening system), in the impact test, are *mould springs* of the *extra-strong loads* series, and are marked by a nominal stiffness of 480 kN/m. Their calibration was carried out by means of the test machine adjusted on load control, by inserting each spring between two enough stiff steel plates. Apart from verifying the spring feature (Fig. 10), the calibration allowed to obtain the values for the deformation to impose on each of the four springs, in order to reach the total preload value of 50 kN and 60 kN to be applied during the test.

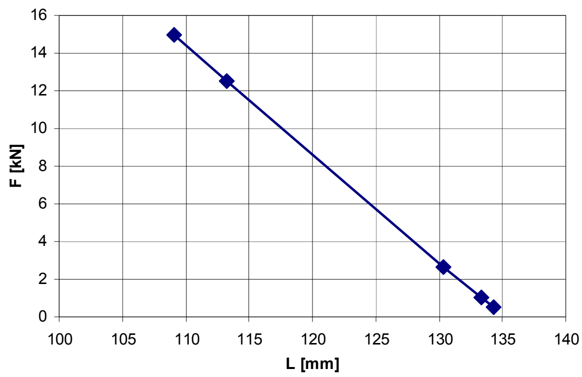

Fig. 10. Spring's characteristic curve.

C. Sleeper Under Pad Test

According to the norm, the under sleeper pad can be used in the *setup* of the impact test, if it allows a decrease, δ, between 0.1 mm and 0.5 mm when the tie, lying on it, is su1bject to an increase in preload from 50 kN to 60 kN.

The test was carried out with the impact test machine and

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the reduction was measured by means of two centesimal comparators (Fig. 11). The mean decrease registered by the two comparators was of 0.18 mm, then compliant for the impact test, and the deformations induced in correspondence of the points instrumented with strain gages were -19.5 μm/m and 28.05 μm/m for upper and lower strain gages respectively, when the preload reached 50 kN.

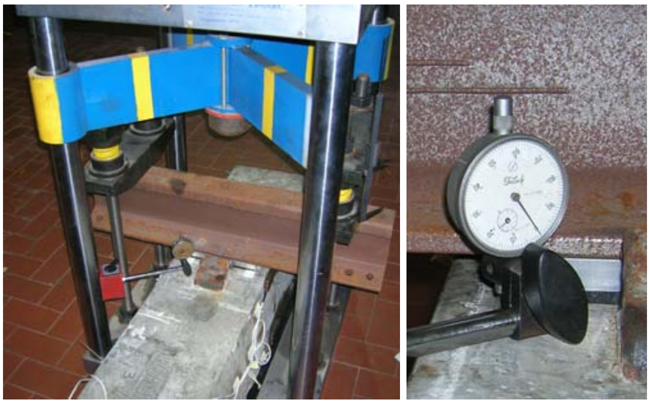

Fig. 11. Initial positioning and resetting of comparators.

D. Rail Seat Section Bending Test

Fig. 12 shows the setup for the sleeper under static test; the load was applied at a rate of 120 kN/min, and the sampling frequency was 2 Hz.

The corresponding deformations-load diagram is shown in Fig. 13, while Table IV summarizes the maximum values, in μm/m, registered by the four strain gages, as well as the average values, ε_{ft} and ε_{fb}, corresponding to the average maximum deformations registered by the couple of upper and lower strain gages, respectively. The static bending test in the rail seat section allowed to establish the strains in correspondence of the same points of the impact test. The 80% of such values represent the maximum limit for the deformations that can be registered during the impact test.

Fig. 12. Layout for rail under static test and strain gages readings.

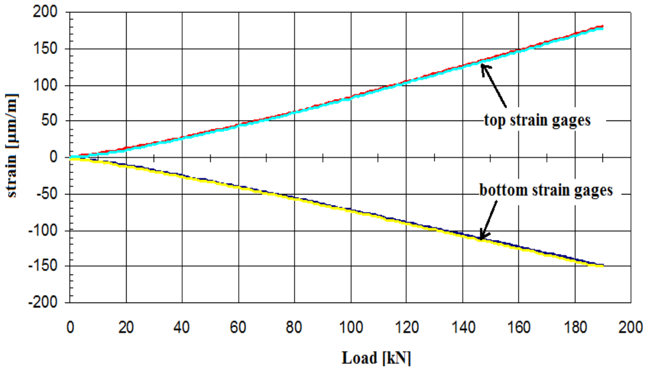

Fig. 13. Strain gages data during the bending test.

TABLE IV
MAXIMUM DEFORMATIONS REGISTERED IN THE RAIL SEAT STATIC TEST

	Def. due to preload	Left side		Right side		Average values [μm/m]
		Label	Value [μm/m]	Label	Value [μm/m]	
Upper Extensimeters	ε_{ft}	E3	-152.5	E1	-150.1	**-151.3**
Lower Extensimeters	ε_{fb}	E4	181.8	E2	183.3	**182.6**

IV. Impact Test and Comparison between Physical and Virtual Simulations

The calculated value of the drop mass for the impact test is about 80 kg, while the drop height is between 150 and 200 mm. After some preliminary tests, a height of 160 mm was found in correspondence of which the measured deformations on the sleeper were about 65% of those obtained during the static bending test.

The subsequent experimental phases, preliminary to the impact test, is a sort of trial stage, and consists in carrying out a minimum number of launches, equal to fifty, aiming at verifying, and ensuring, the repeatability of measures, when the fastening system includes the reference pad. In particular, the Norm requires that, during the last fifty impacts, the five maximum deformations registered, one every ten launches, shall fall in their average, at less than 10%.

The real testing phase, then, consists in obtaining experimentally the maximum deformation averages registered with the reference pad, ε_{pcr} (Fig. 14), and with the pad to be homologated, ε_{pc} (Fig. 15), as it is assumed, by the Norm, that the percentage variance of the latter compared with the former is the parameter characterising the damping capability of the fastening system. The results are expressed in terms of strains, $\varepsilon(t)$, registered by the two couples of strain gages on the side faces of the sleeper, in correspondence with the rail seat section [2].

Observing the results obtained experimentally with the reference pad (Fig. 14) and those obtained by simulating the same test numerically (Fig. 5), a substantial concordance between curves can be observed. This result proves, then, the effectiveness of the numerical-experimental approach proposed to carry out a test plant, enough well-structured and able to take different test configurations, each of them linked to the specific combinations between fastening system and sleeper, for the fastening systems currently on the market.

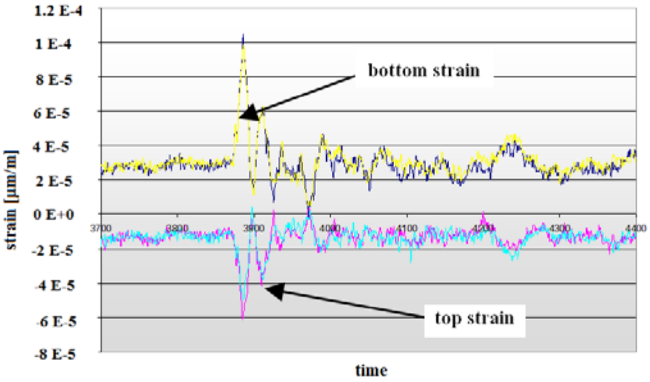

Fig. 14. Results of the impact test with the reference pad.

The ease of use of the whole test system, and above all the repetitiveness of the measures that was observed during the tests, allow ensuring reliable results in the experimental campaigns for the homologation of the fastening systems.

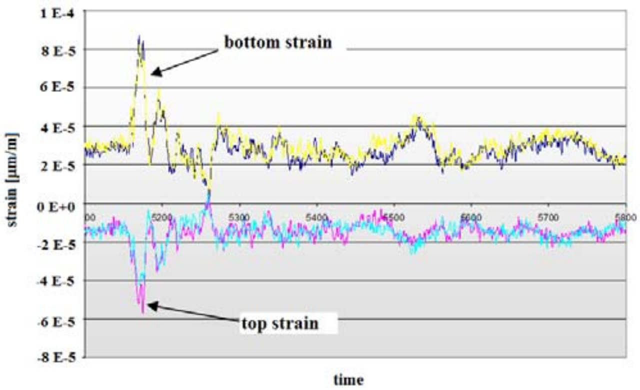

Fig. 13. Results of the impact test with the pad to be homologated.

V. Conclusions

Within the activities for homologating components of the rolling stock and of the railroad equipment, the problem of designing a test plant and defining an operational procedure for the homologation of railway components has been solved. In particular, the study deals with the experimental evaluation of the performances of the sleeper-to-rail fastening systems in attenuating impact loads, as required by the current European Standards.

The work was supported by a significant numerical activity of simulation of a series of additional preliminary tests to carry out, in order to verify, at each step of design, that the above mentioned requirements were met. The carrying out of the designed plant allowed to verify the efficiency of the procedure and the effectiveness of the virtual experimentation supporting the design.

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