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Lateral Resistance of Railway Track

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1. Introduction

Increasing the speed limit of railway tracks is applicable by welding rail joints and employing Continues Welded Rails (CWR). Unfortunately, there are large numbers of curves with the radius less than 400 m in the most conventional railway tracks. Field investigations show that the lateral resistance of the railway track is not adequate for welding the rail joints in the mentioned railway tracks. In fact, elimination of rail joints causes huge longitudinal forces in the rails leading to the track lateral movement. There are several methods to increase the lateral resistance of the railway track such as employing winged sleeper, dual block sleepers, sleeper anchoring, frictional sleeper, Xi-track method and large sleeper [3, 18]. Various studies have been conducted to measure ballasted railway track characteristics [1, 10, 13, 14]. The main purpose of these studies is examining the possibility of track stability against longitudinal forces due to the changes in temperature. Former studies were usually conducted on ballasted tracks with conventional sleepers, and they often showed that enough lateral stability for the straight CWR tracks is applicable with reasonable dimensions in the ballast section. However, more arrangement is needed in curves according to these studies [11, 15].

The resistance between a simple mono-block concrete sleeper and the ballast bed mainly consists of three components: friction on both sides of the sleeper, passive pressure at both ends of the sleeper (shoulders) and friction at the bottom (figure 1). Components of the frictional resistance at the bottom of the sleeper are created with sliding the ballast particles on the relatively uniform surface of the concrete sleeper. The friction coefficient is measured to be around 0.5, while the internal friction of ballast particle is in the range of 0.9 to 1.4. [16]

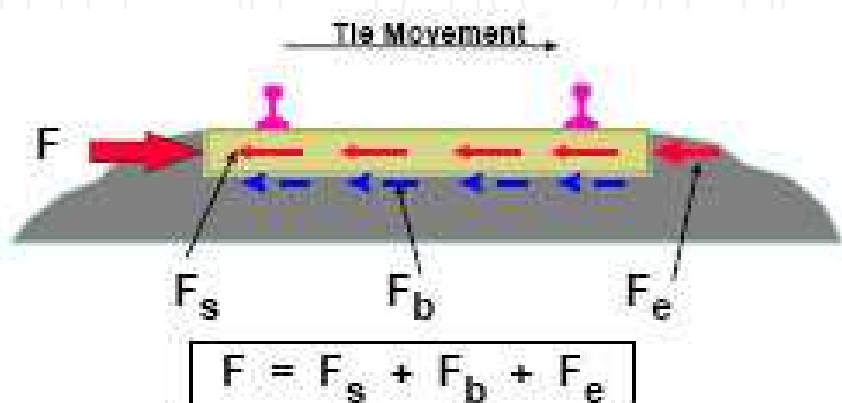


Fig. 1. Resistance between a simple mono-block concrete sleeper and the ballast bed

Near the rail joints of conventional railway tracks, different kinds of damages may occur: plastic deformation of head and sides of the rails, failure in sleepers and fasteners, ballast bed damage, lateral movement of railway track and etc. To reduce the enormous cost of maintenance and also take the advantage of the use of CWR, the track lateral resistance must be increased.

2. Measuring methods of lateral resistance

Determination of lateral resistance is one of the key points for safety and stability of railway tracks, which is influenced by: sleeper type, weight and dimensions of the sleeper, intervals, ballast gradation, ballast stone quality, ballast depth in the crib and the shoulder height from the bottom of sleeper, ballast compaction, rail and fasteners type.

The resistance to lateral displacement can be measured by the following methods [13]:

- Single sleeper (Tie) Push Test (so called STPT)
- Panel displacement test
- Mechanical track displacement test
- Continuous dynamic measurements of lateral resistance

These methods measure the force versus sleeper or track panel displacement.

Generally, the STPT is a laboratory method to determine the lateral resistance of a sleeper. In this method, the displacement of sleeper is measured proportional to the applied force by applying the force to the sleeper. Often, this displacement is recorded up to 0.2 mm.

In order to implement this test, the four fasteners of a sleeper must firstly be removed and then a hydraulic jack must be installed to the shoulder fasteners. Consequently, the sleeper is pushed against the rail with the help of a hydraulic device by applying the force to the shoulder fastener. On the other hand, a LVDT should be mounted on the sleeper (such as a hydraulic cylinder connection) to measure the amount of sleeper displacement by moving the sleeper and gauge returning and to record the lateral displacement of a sleeper by the processor.

In Panel displacement Test method, a frame of 4-6 meters is placed on the foundation, and then after applying the force to the panel, the displacement is measured. Thus, in this test, the lateral resistance of track panel is measured.

In Mechanical track displacement Test method, additional equipments are attached to the tamping machine, in which the track lining and lifting cylinders provide the lateral and vertical forces, respectively. The lining value transducers also measure the displacements in tamping machines.

The track lateral resistance can be measured by employing The Dynamic Track Stabilizer (DTS) with the additional equipments during the operation [11].

In figure (2) test results are presented by Plasser and Theurer [1] for different speeds and frequencies. As can be seen, the lateral resistance of the track has been increased by employing the dynamic track stabilizer after the tamping.

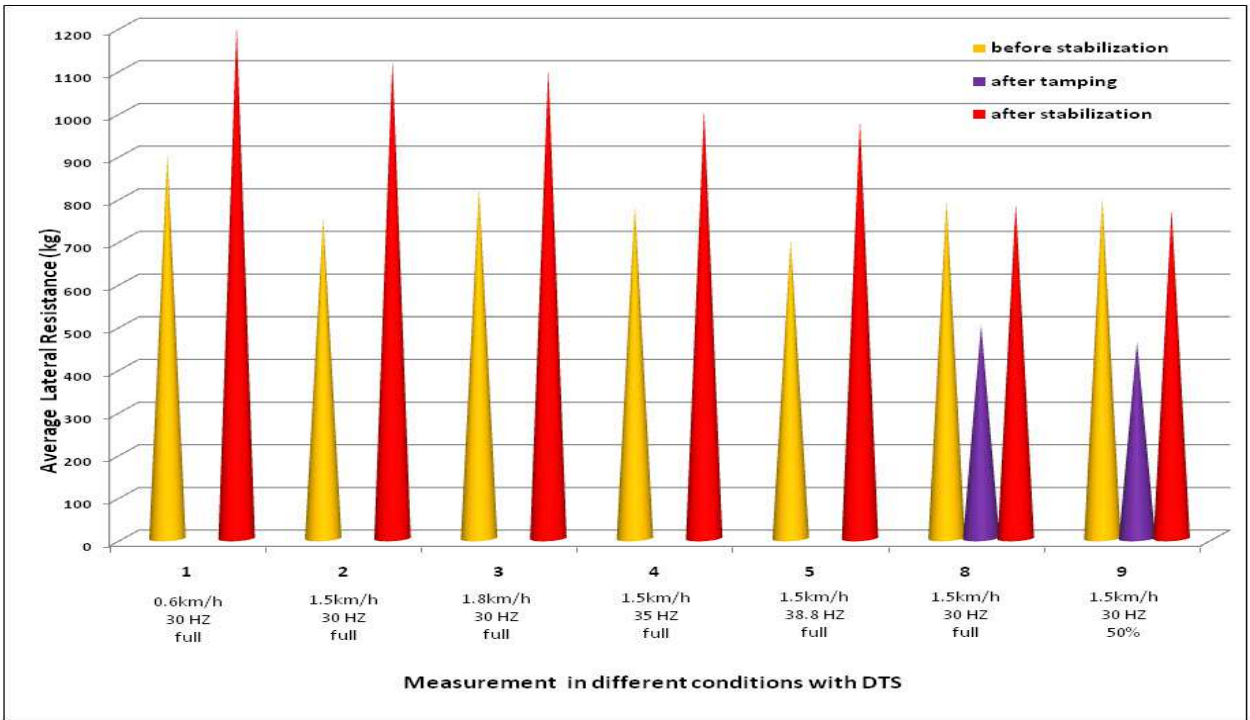


Fig. 2. Track lateral resistance, results measured by the DTS

Several studies have been carried out to measure the lateral resistance of the sleeper and railway track; among these studies the researches done by Plasser and Theurer [1] and the U.S department of transportation of federal railroad administration can be noted. The effect of maintenance involves the use of the following Tamping Machine, Dynamic Track Stabilizer and Ballast Regulator. [6, 7]

In this chapter, the frictional concrete sleepers and wing concrete sleepers will be introduced. It is important to note that the design and construction of wing concrete sleepers has been implemented before in China, but due to some executive problems it had no pervasive use in the actual railway tracks.

In this chapter, the results of tests conducted on the simple and frictional concrete sleepers [3, 9] in the actual railway track curve with radius of 250 meters have been presented and the impact of employing the frictional concrete sleeper has also been described.

This chapter also deals with the effect of vertical loads and running rolling stocks on track lateral resistance and on the change of stability in both frictional sleeper tracks (with ribbed bottom sleepers) and conventional sleeper tracks (with flat bottom sleepers). The results of the studies have indicated considerable increase in lateral resistance of track with frictional sleepers as well as track bearing under vertical loads.

3. Lateral resistance of ballast

Lateral resistance of the ballast is one of the most important factors to prevent the expansion and track buckling. According to the tests results, from the summation of the track lateral resistance it is known that the proportion of the ballast, rails and fastenings from the total lateral resistance are 65%, 35% and 10%, respectively.

Ballast section used in CWR tracks should be well constructed and compacted in accordance with standards.

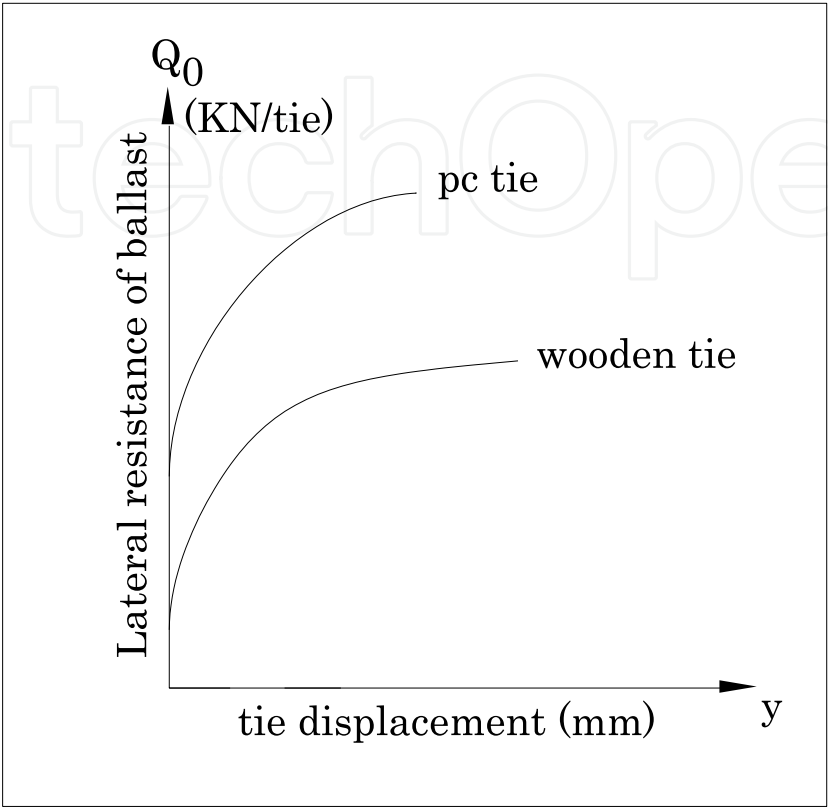


Fig. 3. The relationship between lateral resistances and displacement

In the lateral resistance of ballast tests, the lateral resistance of one sleeper is initially measured. The ballast resistance against the movement of a sleeper is shown by Q_0 . Experiments show that the Q_0 has a nonlinear relationship with the lateral displacement of the sleeper.

As shown in figure (3), Q_0 initially increases with the increase of y . But when the lateral displacement reaches to a certain level, the resistance of ballast will not increase and remains at a constant level. If more displacement occurs, the ballast bed will cause to failure.

The amounts of Q_0 depends on the type, weight, size, shapes and the cross section dimensions of sleeper, the aggregation of ballast and annual passing traffic. The resistance of the ballast is usually expressed in terms of unit length of the track. If it represented by q then:

$$q = \frac{Q_0}{a} (N / cm) \tag{1}$$

where a is the sleeper spacing.

As it has been mentioned, the value of q could be determined by the lateral displacements of sleepers, and the relationship between them is as follows:

$$q = q_0 - c_1 y + c_2 y^n \quad (2)$$

where y is the lateral displacement of the track and $q_0, c_1, c_2, n < 1$ are parameters obtained from experiments[18]. For instance, after implementation of several tests in China, the following relationships were presented for the lateral resistance of the ballast:

- For wooden sleepers, crushed stone ballast:

Ballast shoulder, 30 cm

$$q = 12.2 - 201.9y + 255.8y^{2/3} \quad (3)$$

Ballast shoulder, 40 cm

$$q = 12.2 - 201.7y + 290.1y^{2/3} \quad (4)$$

- For concrete sleepers, crushed stone ballast:

Ballast shoulder, 30 cm

$$q = 13.7 - 388.1y + 511.6y^{\frac{2}{3}} \quad (5)$$

Ballast shoulder, 40 cm

$$q = 14.7 - 435.1y + 571.3y^{\frac{2}{3}} \quad (6)$$

It should be noted that the lateral resistance provided by sleeper is different in respect to types of sleepers and the dynamic effects resulted from the passing vehicles. This is due to existence of positive curvature in the region ahead of the train wheels on rails while there are simultaneously negative curvatures of the rails between two bogies. Therefore, the lateral resistance decreases because of the loss of contact between the sleeper and the ballast. Also the rigidity of track (EI) is a parameter which reduces the deformation of the flexible track which is necessary for preventing the lateral track buckling. This resistance comes from two sources: one is the lateral bending rigidity of rails and the other is the torsion rigidity of fasteners. Fastener torsion resistance is depending on the kind of sleepers and fasteners, toe load, and the relative rotation between the sleeper and the rails. The lateral rigidity of track can be obtained as follows:

$$EI = \beta EI_y \quad (7)$$

in which EI_y is the lateral rigidity of each rail.

In this function, β is the conversion ratio. In wooden sleepers, because of the high relative rotation between the sleeper and the rail, the torsion resistance of fasteners is considered to be zero. Thus, the value of β is considered as 2.

3.1 The resistance of ballast between the sleepers (Crib)

The Resistance, which prevents the displacement of sleepers in the longitudinal direction, is provided by the ballast and can be calculated based on each sleeper resistance or resistance per unit length of the track. The resistance of ballast depends on ballast gradation, ballast quality, tamping quality and the weight of track panel. The resistance of ballast will increase as the displacement of sleepers increases. But after a certain value of displacement, the ballast between sleeper yields and the resistance of ballast will not increase. Usually in the calculations, the resistance of ballast is taken into account when the displacement of sleeper to ballast is equal to 2 mm.

It should be noted that the resistance of ballast is not the same in all tracks. Therefore, field investigations should be done for the calculation of ballast resistance, if necessary. The track maintenance operation disrupts the arrangement of the particles of ballast and decreases the resistance of ballast, which will be gradually compensated by the load of passing vehicles.

In real conditions, the resistance of ballast is caused by the relative motion between the sleeper and ballast.

3.2 The resistance of ballast shoulders

The upper part of the ballast that is between the end of sleepers and beginning of ballast slope is known as the ballast shoulder. The obvious solution to prevent the lateral movement of sleepers during the buckling, is the increase of track lateral stiffness. A method to increase the track lateral stiffness is increasing the width of the ballast shoulder and the ballast between the sleepers. Another method is to increase the lateral stiffness of the rail-sleeper structure. Germany and Austria railways attempted to increase the ballast shoulder width to 0.35 m, as can be seen in figure (4). In the former Soviet Union railways, in freight tracks with wood and concrete sleepers, the shoulder width of 0.45 m have been proposed like figure (5). [19]

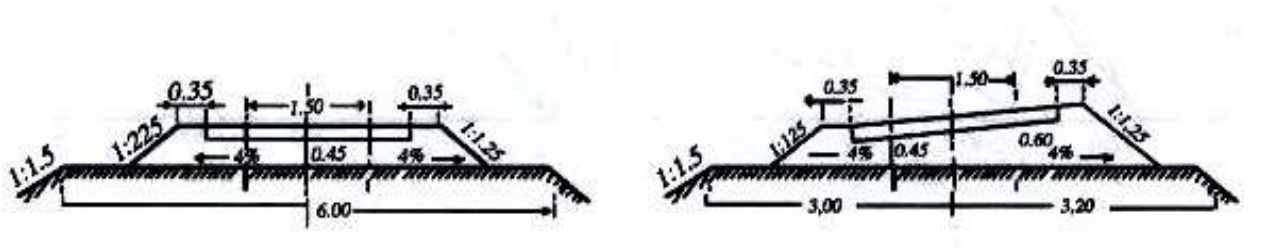


Fig. 4. Section of the different types of ballasted railway tracks in German (dimensions are in meters)

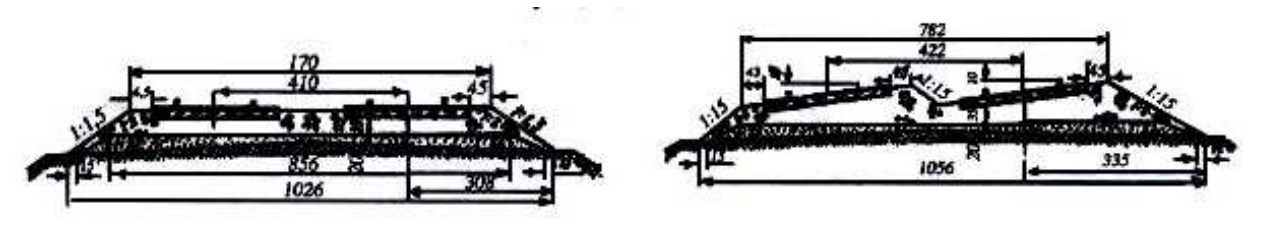


Fig. 5. Sections of railway track in the former Soviet Union (the dimensions are in cm)

In Japan, the width of ballast shoulders should be chosen at least 40 cm. In addition, ICE railways in Germany also use 50 cm wide shoulders. In 1970, the North American railways has been recommended to take the advantage of shoulders wider than 15.3 cm in straight tracks. In addition to reducing the risk of the track buckling, these shoulders reduce the deterioration of the track and maintenance costs. The reason refers to the movement of ballast particles under the load from the seat of rail to the areas of low stress. (Figure 6)

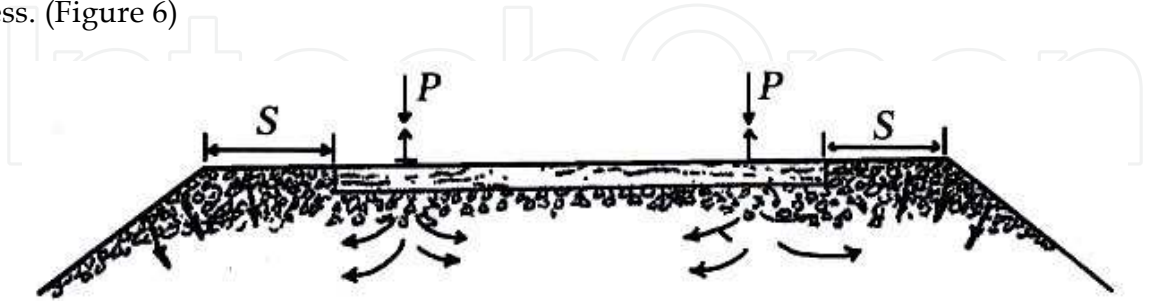
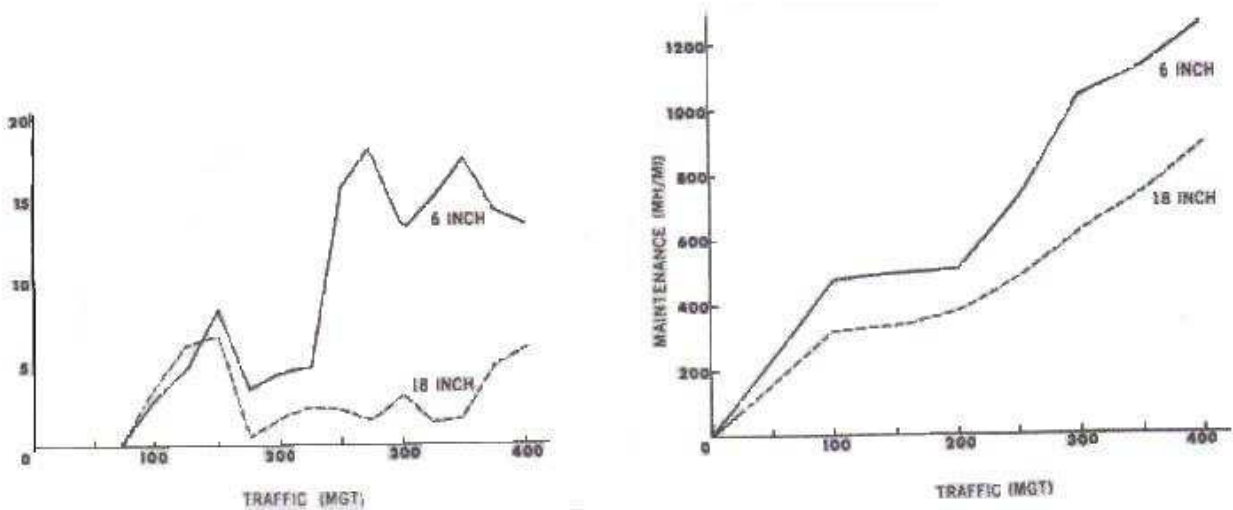


Fig. 6. Changing the location of ballast under the load of passing train

In this case, considering the wider shoulders create more resistance against the movement of particles. This theory was tested on the FAST tested track in the Colorado state. The results of the tests confirmed this theory. The main findings of the experiments are shown in Figure (7).



- a) Trying the maintenance of the track against the cumulative traffic passing (MGT)
- b) Change in the rail profiles to cumulative traffic passing (MGT)

Fig. 7. The results of the width of ballast shoulder on the FAST tested track

The results of these tests show that in addition to improve of the track safety against the buckling, the increase of ballast shoulder width is also effective in reducing the geometric deterioration of track and therefore, reduces the maintenance cost.

At the aim of reducing the buckling, German and Russian railways were recommended to use at least 35 cm ballast shoulder width in straight and curve tracks, but so far no action has been performed about shoulder width optimization to reduce the Superstructure deterioration.

Kind of sleeper	Ballast specification		Resistance per sleeper (KN)					
	Size (mm)	Density	Ballast shoulder :150mm		Ballast shoulder :230mm		Ballast shoulder :300mm	
			Total	Only ballast shoulder	Total	Only ballast shoulder	Total	Only ballast shoulder
Wood	38	Loose	2.12	0.1	2.46	0.44	2.71	0.69
	38	Dense	3.45	0.74	3.52	0.80	3.59	0.88
Concrete	38	Loose	3.41	0.15	3.72	0.46	4.39	1.13
	38	Dense	-	-	5.06	0.51	6.31	1.76
Concrete	75	Loose	-	-	3.24	0.13	3.48	0.10
	75	Dense	-	-	8.50	1.30	8.80	1.65

Table 1. The effect of increasing the ballast shoulder width on the lateral resistance of sleeper

4. The effect of operation and maintenance on the track stability

Maintenance operations, such as track laying, welding and other operations which are rising the rail neutral temperature will help to develop the potential of track buckling. However, stabilization of track after the maintenance operation increases the track safety factor against the buckling.

Tamping is a maintenance method that has an adversely affect on the lateral stability of the track because it distribute the ballast under the sleepers. The distribution of ballast leads to track vertical sinking and the lateral track defects. After tamping, often dynamic track stabilization method is used to re-dense the ballast.

The test was conducted using the Single Tie Push Test (STPT) to measure the variation in lateral resistance during a common track tamping operation. Lateral resistance was measured prior to tamping, after Tamping/before stabilization, and after stabilization. A sample of this device is shown in Figure (8).



Fig. 8. STPT Test Setup

The pre-tamping STPT measurements were made to characterize the condition of the track in operational condition [6]. Common characteristics of the pre-tamping tests are a steep initial slope, distinct peak, and a post-peak which decreases to an approximately constant value of lateral resistance for large deflections. (Figure 9)

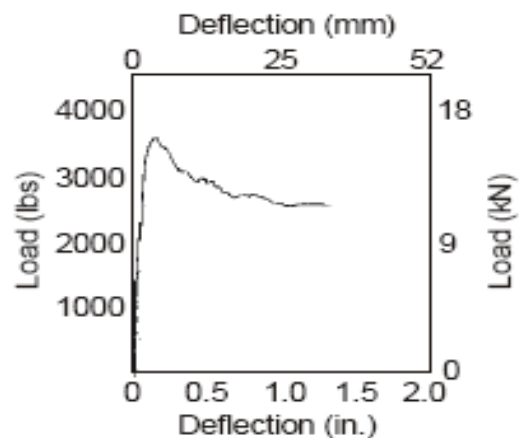


Fig. 9. Pre-tamping tests results

Figure (10) describes the measurements of STPT method after tamping and before stabilization. Specifications of these measurements are a gradual increase to a constant peak value. In this case, the lateral resistance of the conditions before tamping has been reduced by 43%.

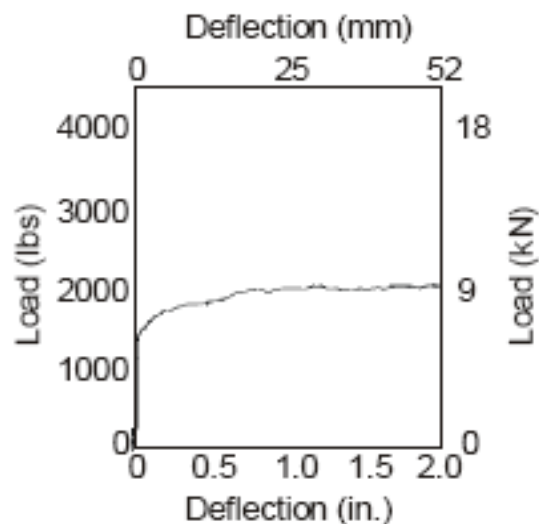


Fig. 10. Post-tamping and before stabilization tests results

The STPTs which has been conducted in the post-stabilization stage of the test, characterized the stability of the track after Tamping maintenance followed by the dynamic track stabilizer. This stage is just before subjecting the track to the revenue traffic. Common characteristics of the post-stabilization STPTs are a steeper initial increase than the pre-stabilization stage as shown in Figure 11. Stabilization produces an initial peak value similar to the trend of the data from the pre-tamping stage, but the peak value is significantly lower and less well defined than the pre-tamping stage peak. The increase in the initial slope (although less discernable) and thereafter, observance of a peak in load-deflection curve is consistent with behavior associated with the more dense, stronger and stiffer ballast. This represents an average increase in lateral resistance of approximately 31% over the post-tamping condition.

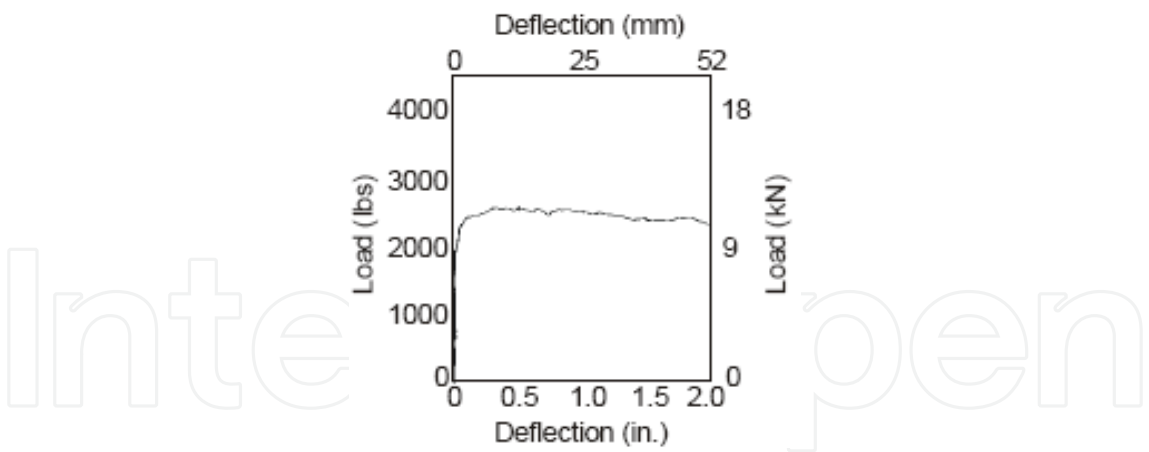


Fig. 11. Post-stabilization and before passing traffic results

5. The effect of elastic pads under sleepers on the lateral resistance of track

Now we describe the practical results of the effect of using under sleeper pads on the lateral resistance of track in Germany and Switzerland.[17]

5.1 Germany

One of the features of a modern ballast track is increasing the efficiency of track with improvements while introducing new components. Using elastic elements can be the best way to increase the track elasticity and damping. In the recent years, Germany Railways has tested the sleepers that are equipped with elastic pads under them. The results of field measurements, laboratory tests and theoretical evaluations have been very satisfactory. For example the maintenance period (tamping) has been increased.

Indeed, the substructure of ballasted railway tracks has two major problems: one is the difficulty contact of concrete sleeper with ballast, and the other is its rigid structure because of the new construction methods. These factors causing the deterioration of ballast, the speed limitation, and increasing the maintenance costs [20].

Using the elastic pads under sleepers has a satisfactory influence on the ballasted tracks, stability of tracks with longer durability, and lower life-cycle cost.

In recent years, in order to study the effect of elastic pads under sleepers on the lateral resistance of the track, field tests have been conducted on these type of sleepers in Germany [21].

After two years of track operation, lateral resistance of track has been measured for the conditions of with and without USP. The results are given in Table 2.

Under sleeper pads	non used	Stiff	SOFT
Stiffness (KN.mm)	-	70	30
Lateral resistance per rail (KN)	9.7	10.3	9.4

Table 2. Amount of the lateral resistant

It is concluded that the lateral resistance of both tracks with and without USP is the same, and does not change [17].

5.2 Switzerland

In early 2005, five types of USP in the Kysn test line, that were obtained from different plants, have been installed by the Switzerland Federal Railways headed by Mr. Schneider to assess the effects of elastic pads under sleepers on the railway tracks. USP specifications used are as follows:

USP	Brand	Manufacturer	measured Modulus (N/mm3)	
			Field	Laboratory
USP 1	SLB 3007G	Getzner/A	0.30	0.15
USP 2	M 01	Muller-RST/D	0.30	0.17
USP 3	S 01	Spreepolymer	0.35	0.38
USP 4	PRA	Sateba/F	0.30	0.14
USP 5	TR1-85M	Tiflex/UK	0.25	0.08

Table 3. USP specifications used in the Kysn test line

The length of each five track sections, where the USP has been installed, was 216m long. And the length of the sixth control section, where USP has not been installed, was 283m long. The test line was determined based on the UIC Classification system, with type of D4, with a maximum axial load of 22.5 ton. The objective of this test was evaluating the quality of tracks and increasing the tamping intervals.[22]

To measure the lateral resistance of each section, first, the fasteners were loosened to allow the concrete sleepers to have the lateral displacement and then replaced the rail pads with greased steel plate [14]. Second, the concrete sleepers were subjected to lateral load with a specially developed hydraulic device which is shown in Figure 12. Third, the force between the hydraulic cylinder and the rail was measured with minimal friction losses. Then, the amount of rail displacement has been recorded towards a reference fixed point on the front rail. In each section, four sleepers were measured in each part: with and without the USP.



Fig. 12. The Device that applied the lateral force to the track

As shown in Figure (13), the measurement of lateral resistance indicates that the lateral resistance against the displacement of sleepers with USP is less than those recorded from sleepers without USP. This means that the track lateral resistance with sleepers which are equipped with USP is less than the sleepers that are not equipped with USP. The Softest USP (USP 5), the lowest lateral resistance.[20]

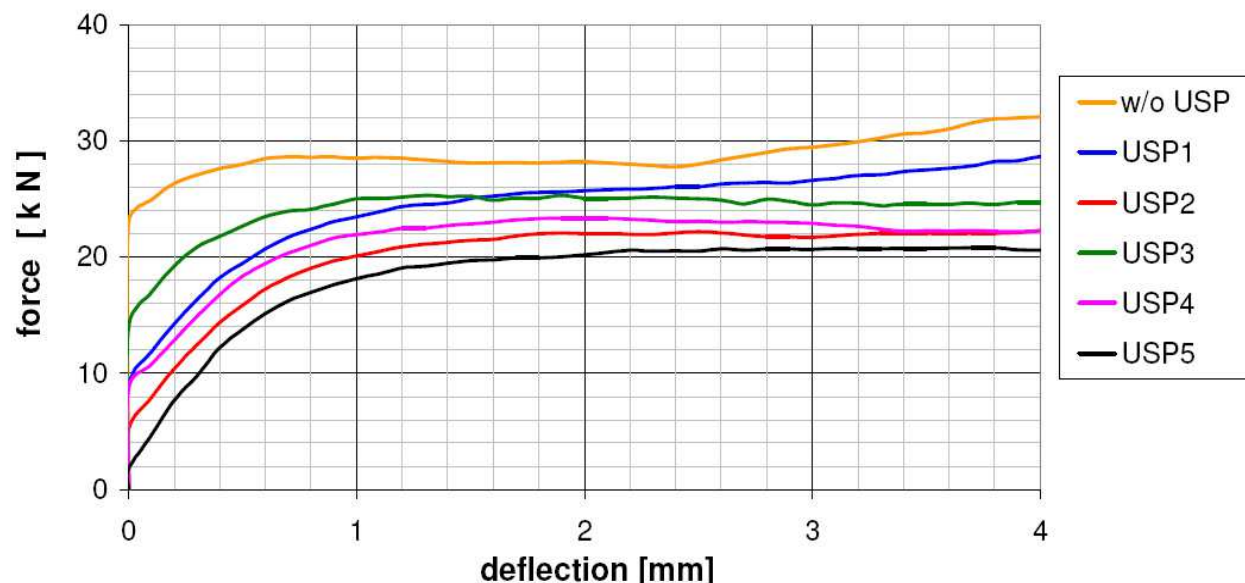


Fig. 13. Results of track lateral resistance at different sections

It should be noted that these results can be unrealistic, since the vertical axial load on the system has not been taken into account and also because of the test method. It is obvious that when a train passes, the vertical component of the load will increase, and consequently the amount of friction force will differ. Therefore, the role of pad below the sleeper in lateral resistance become important. This does not match with the resistance measured by STPT method.

Therefore, it can be said that the lateral resistance of the track equipped with USP is the same as the track without USP.

The results of the field investigations in SATEBA company under the supervision of International Union of Railways in 2006 indicates that using the elastic pads under the sleepers increases the lateral resistance of track approximately by 9%.

Laboratory investigations on the models which were built at the University of Zagreb in Croatia indicates that using the elastic pads under the sleepers increases the lateral resistance of track approximately by 9% (same as SATEBA results).

Further researches with the aim of studying the impact of these components on the lateral resistance of track have not been conducted yet. Other researches have implicitly reported the results in this aspect, and because of using various USP, the results of studies are different. In many cases, using the elastic pads under the sleepers increases the lateral resistance and in some other cases decreases the lateral resistance or has no impact.

Based on investigations conducted by the International Union of Railways and other researches on the track lateral resistance, it is demonstrated that the less hard pads under the sleepers, the less lateral resistance of railway track.

In all experiments, only STPT (Single Tie Push Test) has been carried out without any loading which may affect the results of these experiments.

The environmental temperature has a direct impact on the vertical hardness of the plate under the sleeper. Therefore, the selection of plate will be directly influenced by environmental conditions.

With regard to the positive effect of using USP in the reduction of environmental vibrations, it can be concluded that the existence of these pads (with the appropriate choice) will not create a problem for the track lateral stability.

6. Frictional concrete sleeper

Ballast is a layer of crushed stone particles with a diameter in range of 20 to 60 mm where the track panel including the set of sleepers, fasteners and rails are layed over. A frictional concrete sleeper has been designed to increase the involvement of ballast stone particles and sleeper base, the coefficient of friction beneath the base of sleeper, and to increase the lateral resistance of the track. As it shown in Figures (14) and (3), all parts of the frictional concrete sleeper is like a special mono-block concrete sleeper (B70) except that its beneath surface is trapezoidally- shaped. The dimensions of the height and the two small and large bases of the trapezoidal are 2.5cm, 6cm and 10 cm, respectively. It should be noted that the trapezoidal shape of the sleeper base has no effect on the maintenance operations [23].



Fig. 14. The bottom of frictional concrete sleeper

6.1 Field tests to determine the lateral resistance of railway track

Field tests were conducted on the curve of an actual railway track with a radius of 250m. First, the lateral resistance was measured on a track with B70 mono-block concrete sleepers. Then, the B70 mono-block concrete sleepers were replaced by the frictional concrete sleepers (B70-F) and the lateral resistance of the track was measured again. In the test process, the following conditions were maintained the same: 1) Weather conditions, and 2) Physical conditions of the railway track.

In order to maintain the same weather conditions, both tests (with simple concrete sleeper and frictional concrete sleeper) were conducted in equal atmospheric situations.

In order to maintain the same physical conditions, first the track have been tamped and then the Dynamic Track Stabilizer (DTS) has stabilized the track in both tests. Furthermore, other same track characteristics were: the ballast shoulder width, the slope of ballast layer on both sides, the depth of ballast in the crib zone, and the space between sleepers.

To carry out the field investigation, the panel displacement method was employed using a hydraulic jack. In this test, the lateral displacement was measured by the LVDT which was installed on pedestals along with the applied lateral force. As shown in Figure (15), for more establishments, the hydraulic jack has been installed with the buffer (to the inner rail).



Fig. 15. Installation of the hydraulic jack

Also, the jack's tip was perpendicular to the rail to insure a perpendicular lateral load. These procedures were the preliminary preparations to conduct the test. The test has been started by applying the lateral force to the inner rail at $t=0$. The time also has been recorded during the test. Simultaneously, the LVDT has recorded the displacements due to lateral force applied by the hydraulic jack. Therefore, displacements could be saved versus time.

In the second stage, the tests were repeated after the replacing simple concrete sleepers with frictional concrete sleepers. Finally, the data obtained from both test were compared.

Note that the effect of the vertical load was disregarded in this test.

The procedure of replacing the conventional railway track (with simple concrete sleepers) with the new railway track (with frictional concrete sleepers) is clearly shown in Figures (16) and (17).

Investigating the effect of frictional concrete sleeper on the track lateral resistance in curves, the results obtained from each stage are explained, interpreted and compared in the next subsection.



Fig. 16. Installation of railway track prepared with B70-F sleeper by employing 120- tons railway crane



Fig. 17. Tamping and stabilizing operations after the installation of the railway track with B70-F sleepers (before the second stage of test)

6.2 Results

In conventional railway tracks, there are many sharp curves with radius less than 400m. Therefore, it is impossible to remove all rail joints by welding due to the lack of lateral resistance. Investigations show that lots of damages occur near rail joints such as failure in fasteners, plastic deformation of head and sides of the rails, failure in sleepers, damage of ballast bed, lateral movement of railway track etc.

In this research, regarding the effect of using frictional sleepers on the lateral resistance of actual curves with radius of 250m, the use of the frictional sleepers instead of conventional sleepers has been recommended.

In summary, the test described in this research was conducted on a curve of an actual railway track with radius of 250m. In the first stage, the lateral resistance of a track with B70 mono-block concrete sleepers was first measured. In the second stage, the B70 mono-block concrete sleepers were replaced by the frictional concrete sleepers and the lateral resistance of the track was measured again.

In general, the test results show that the amount of the force which was necessary to displace the track with the frictional concrete sleepers at a specified value, is about 1.67 times greater than the force applied in a conventional track.

In conclusion, by employing the frictional concrete sleepers, the lateral resistance of a railway track will increase approximately by 67%. Thus, to insure the lateral stability of sharp curves (curve radius between 250m and 400m) of railway tracks, the use of frictional sleeper is recommended.

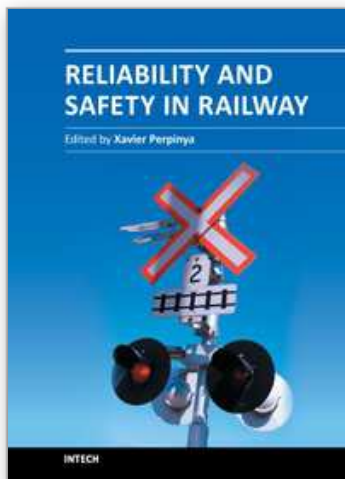
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In railway applications, performance studies are fundamental to increase the lifetime of railway systems. One of their main goals is verifying whether their working conditions are reliable and safety. This task not only takes into account the analysis of the whole traction chain, but also requires ensuring that the railway infrastructure is properly working. Therefore, several tests for detecting any dysfunctions on their proper operation have been developed. This book covers this topic, introducing the reader to railway traction fundamentals, providing some ideas on safety and reliability issues, and experimental approaches to detect any of these dysfunctions. The objective of the book is to serve as a valuable reference for students, educators, scientists, faculty members, researchers, and engineers.

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