WARSAW UNIVERSITY OF TECHNOLOGY Index 351733
FACULTY OF CIVIL ENGINEERING
COMMITTEE FOR CIVIL AND WATER ENGINEERING
POLISH ACADEMY OF SCIENCES ISSN 1230-2945

DOI: 10.24425/ace.2025.155122

ARCHIVES OF CIVIL ENGINEERING

Vol. LXXI ISSUE 4 2025

pp. 5 –29

Review paper

Ballastless track on railway bridges

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Abstract: This study focuses on problems related to the application of ballastless track on railway bridges. The different kinds of this track are presented, along with their advantages and disadvantages. Special attention is given to the generated vibration and noise by moving trains and their influence on the behaviour of the bridge structure. Methods of dumping are presented too. Transfer of longitudinal forces in the lateral and longitudinal directions is given. The interaction between the continuous welded rail and the bridge structure is written. Longitudinal resistance of the fastening system for ballastless track is also given. The use of a sealing layer between the track and the bridge deck is considered. Problems relating to the uplift of the girder ends are given. Cracks in the concrete elements of ballastless track on the bridge structure are considered. Some of the solutions to the problems mentioned above are given in general design rules produced by different organizations, and some are or will be given in current or prepared standards.

Keywords: ballasted track structure, bridges, rail fastening system, viaducts, vibroacoustic isolators

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1. Introduction

Modernization of railway infrastructure is combined with an increase in train velocity to 350 km/h [1]. It is strictly connected with the improvement or exchange of bridge structures, including track. The most popular kind of track is ballasted (Fig. 1), but because of maintenance costs, it should be applied at a velocity equal to 200 km/h. This estimation is taken into account mostly in Far East countries, but not necessarily in Europe.

Any kind of track should:

- carry on trains on the rails,
- transfer loads from trains through wheels to the track,
- take over and dump dynamic loads.

The railway track should be:

- durable,
- robust,
- reliable,
- keep geometry unchangeable in all directions.

Fig. 1. The ballasted track on the viaduct near Zawiercie, Poland

The investigation confirms that the ballast is the weakest element of the track. The vibrations generated by travelling trains develop durable deformations of the ballast, which change dumping characteristics along the length of the track.

The railway grid (rail plus connecting elements plus sleepers) acts in an elastic–plastic state, generating vertical and horizontal deformations, which weakens the stability of the ballast.

Additionally, the train travels at high velocity because of the rising pressure of the wind (and underpressure behind the train), causing lifting of ballast.

Therefore, it is obligatory to perform frequent and costly maintenance work.

This situation requires looking for new kinds of tracks, especially on the bridges and in tunnels.

This alternative solution is a ballastless track (Fig. 2). It ensures better cooperation between bridge and track structures, especially in the carry over of dynamic loads. The reduction of vertical elastic deformations is the most effective way to do it. In practice, it means that the track should not settle. In the case of bridges, it is necessary to design the structure with as small a deflection as possible. Therefore, the requirements concerning deflection of high-speed bridges are much stricter than for traditional railway bridges.

Unfortunately, there is a problem combining in one code all the requirements needed to design and build a ballastless track system. Additionally, in many countries, different rules and standards are used.

For example, the load model of the trains is not used in the same way for track components, which are specified with the local forces, and for bridge structures, for which the distribution of wheel load over long spans must be specified. Moreover, some track components are qualified with performance tests and not with design analysis. So it is useful to decide for which parts of the ballastless track the different rules should be applied.

Dynamic actions on railway bridges play a more important role than on highway bridges. This is the result not only of a larger mass of trains but also of the specificity of the traffic. The trains are moving on the rails only in their direction. The imperfection of the rails and clearance between rails and edges of wheels generate dynamic actions which rise together with the rise in the velocity of the train.

Fig. 2. The ballastless track on the viaduct in Gdańsk, Poland

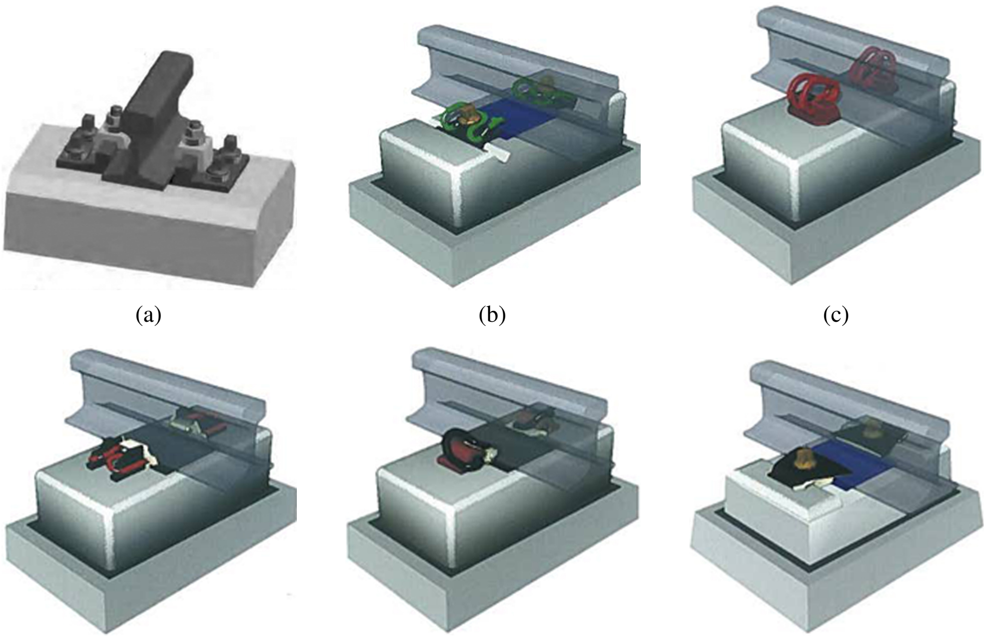
2. Structure of ballastless track on bridges

Any kind of railway track consists of rails and fixing devices. They are mounted to sleepers in ballasted track and to reinforced concrete slab in ballastless track. In the case of ballasted track, a so-called "ballast trough" is placed on the bridge. In the case of ballastless track, the concrete slabs are prefabricated or done on-site. It is necessary to add that ballastless track is applied only on concrete decks. There are no such solutions on the orthotropic decks.

Reinforced concrete slab of ballastless track:

- Ensure horizontal and vertical stability of the railway grid,
- Having slopes ensures dewatering of the slab,
- Make possible adjustment of the rails.

The fastening of rails ensures the lateral, normative inclination of rails and reduces the vibration of the track and bridge. Examples of fastenings are shown in Fig. 3.



(a) (b) (c) (d) (e) (f)

Fig. 3. Types of fastening of rails: (a) Stiff (type K), (b) Spring (SKL type Vossloh), (c) Spring DE (Deenikp Eisses), (d) Spring (Pandarol Tastclip), (e) Spring (Pandrol), (f) Spring (Nabla)

The need for the limitation of deformations of the track and the increase in lateral stiffness of the track caused the exchange of the ballast for a concrete slab.

The stages of development of ballastless track are presented in Fig. 4.

1. sleepers in cross direction,
2. sleepers in longitudinal direction,

3. sleepers connected in “skew” direction,
4. concrete slabs,
5. continuous monolithic slab.

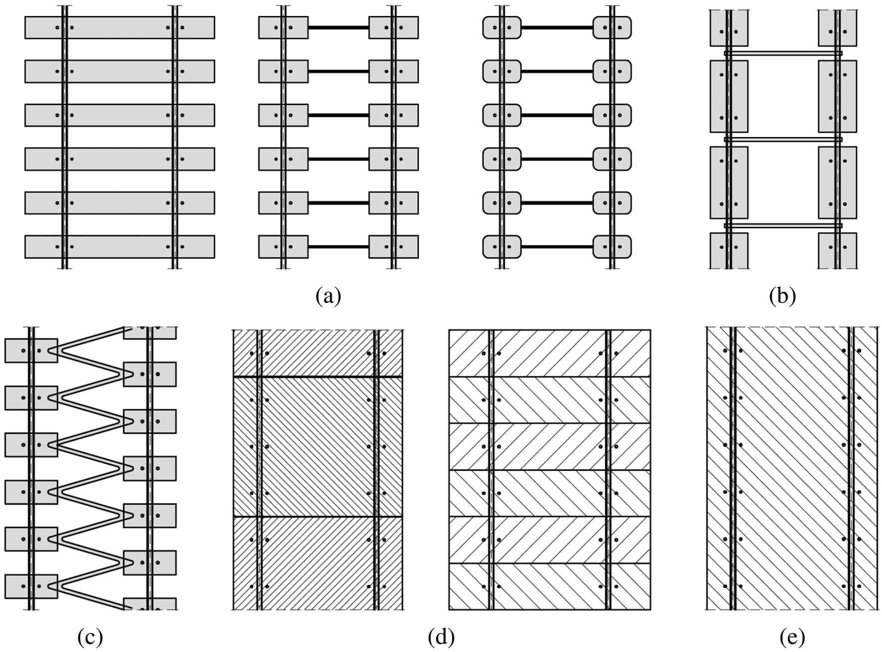


Fig. 4. Development of the ballastless track [2]

3. General rules of the design of ballastless track on bridges

The ballastless track is supported by the bridge deck. Structural elements that are part of the track are subjected to mainly compression forces, though uplifting forces can also occur at the bridge ends. The design of all components of the ballastless track has to ensure that the vertical and horizontal forces are transmitted and resisted in a safe manner.

Each railway track should be designed individually, taking into account the following parameters:

– kind of bridge structure,
– structural material,
– statical scheme,
– length of spans,
– load capacity of the bridge,
– velocity of trains on a particular railway line,
– annual loading of the railway line,
– kind of traffic (cargo, passenger, mixed).

For the good design of the railway track on the bridge, it is necessary to:
- fulfil sufficient cooperation between the deck and track (composite action),
- decide whether the deck will or will not be covered with insulation,
- fulfil requirements related to the safety of exploitation, especially in the case of derailment of the train,
- assume distribution of loads through the concrete slab of the track and bridge deck with an angle of 45°.
- Fulfill requirements related to thermal expansion of rails, which means:
  - using continuous rails,
  - avoiding making connections of rails on the bridge and at least 6.0 m behind it,
  - ensure the possibility of longitudinal movement of the bridge structure relative to the track when the length of span is 20–60 m,
  - using elongation joints on the steel bridges with spans above 60 m,
- ensure the execution of the elements about 3.5 m,
  - ensure efficient dewatering of the track combined with the system of dewatering of the bridge deck,
  - determine the time difference between the construction of the bridge structure and the ballastless track.

4. Advantages and faults of ballastless track on bridges

Compared to ballasted track, the ballastless track is characterized by:
- smaller deformation modulus,
- more uniform distribution of loads on the bridge structure,
- bigger thermal elongation,
- bigger flexibility against dynamic actions,
- more difficult dewatering of the track,
- smaller structural depth,
- bigger lateral stiffness.

Its advantages are:
- there is no problem with the shock wave generated by the traveling train,
- big stability and accuracy of mounting of rails,
- continuous fixing of rails reduces the consumption of their material over time,
- there is no problem with the settling of the ballast,
- lower cost of maintenance,
- where there is no need to close a track during maintenance works.

They are also following faults:
- higher cost of design, construction, and repair (e.g., after derailment of train),
- more difficult construction works,
- limited possibility of correction of the geometry of rails
- often small cooperation between the track and the bridge deck, especially in the lateral direction, and the need to use connectors,
- generation of a higher level of noise.

5. Types of ballastless track on the bridges

Different types of ballastless tracks are presented in Fig. 5–11.

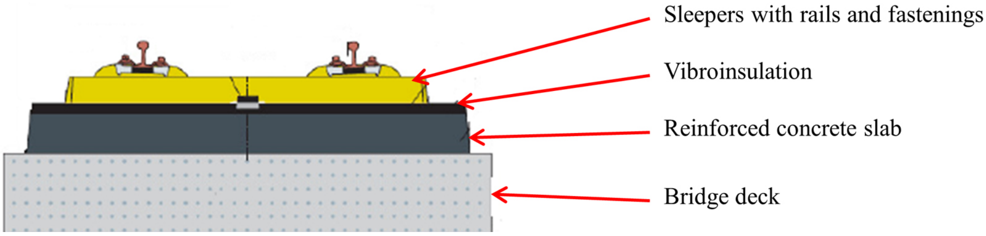


Fig. 5. The ballastless track with rails fixed to sleepers. They are located on the upper slab

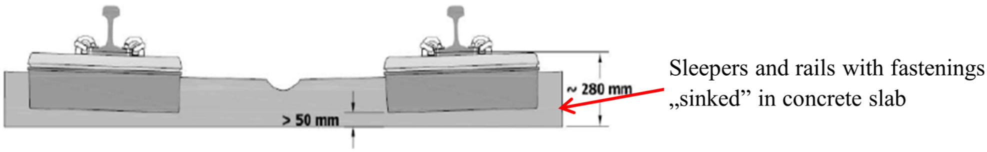


Fig. 6. The ballastless track with rails fixed to sleepers

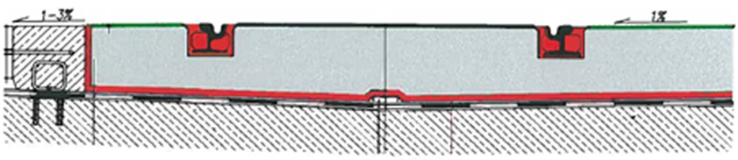


Fig. 7. The ballastless track with Embedded Rail System (ERS)

Fig. 8. The ballastless track with prefabricated slab of track in HSR in Taiwan

Fig. 9. System Bögl

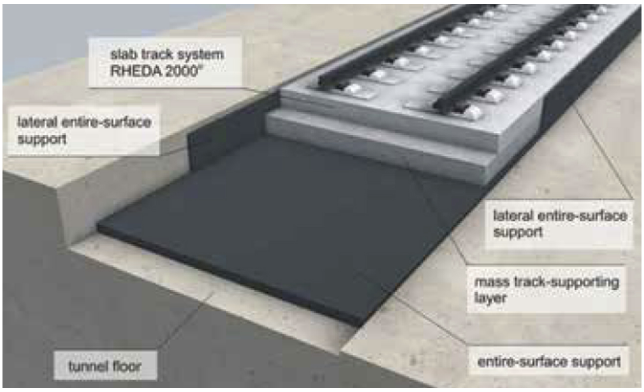


Fig. 10. System Rheda 2000 [3]

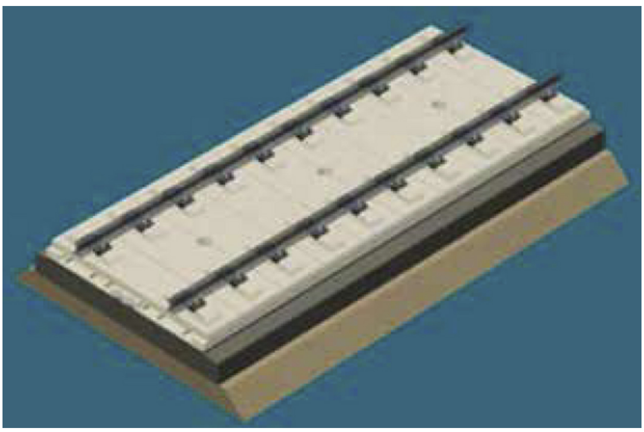


Fig. 11. System FFB [3]

Rails are “sinked” in channels made in a concrete slab and covered by polyurethane resin. They are fixed linearly (ERS – Embedded Rail System) with a reinforced concrete slab, and Vibroisolation (USM – Under Slab Mat) covers the bridge deck. Under the rail rusher are placed to adjust slope and to dump vibration.

System Bögl (FFB) (Fig. 9) consists of prefabricated reinforced or prestressed slabs. They are connected to each other with longitudinal steel ribs. The spacing between slabs is 5.0 cm. This solution keeps the geometry of the track and dumps vibration generated by high-speed trains.

Rail is fixed at a point to the concrete slab, Fig. 9–11. Also, elongation joints of the railway track are placed between slabs. Vibroinsulation covers the bridge deck.

6. Transfer of longitudinal forces in the lateral and longitudinal directions

Transmission of horizontal forces may need special devices, such as stoppers or anchors, connected to sleepers or prefabricated slabs with the bridge deck [4]. The problem is the determination of the value of the horizontal force. It is the sum of the breaking force and the acceleration force, as well as generated by the temperature difference (uniformly distributed temperature).

For “short” bridges (up to 30 m), the longitudinal horizontal forces can be assumed to be resisted by the track only, and therefore, the upper slab of the ballastless track can be continuous over the whole length of the bridge. The slab is free to slide in the longitudinal direction, thus allowing the bridge to move independently, provided there is no bond between the bridge deck and the slab track.

For “long” bridges (spans) (continuous or single supported structures) with expansion length greater than 30 m, the longitudinal horizontal forces need to be resisted by special construction details (stoppers and/or anchors). It is advised to construct the upper slab in sections with a length of 4.0 to 6.0 m. Each of them will individually transmit the longitudinal forces to the lower slab, which means the bridge deck, depending on the type of slab track and sealing layer. In this case, the ballastless track cannot move separately from the bridge. Instead, only the individual short slabs can do it.

Special attention should be taken to the account at the end of the bridge (span) to ensure that the abutment wall or the space between two bridge deck ends on the bridge pier, the opening between bridge ends, stays within permissible maximum and minimum limits. This problem is strictly combined with the correct calculation of the thermal displacement of the bridge deck and the angle of rotation. According to German experience, the minimum joint width shall not be less than 20 mm at the time when creep and shrinkage are no longer relevant. The maximum joint width shall be such that the distance between the rail fastenings on either side of the joint width does not exceed 650 mm or the applicable standard spacing of the rail fastenings.

Another important problem is ensuring the common transfer of longitudinal forces, which means the coordination of the action of expansion joints of the track with the action of the expansion joints of the bridge as a whole.

In the case of skew or curved in-plan bridge structures, lateral forces are developed. They should be transferred into the bridge structure and resisted by guiding blocks along the length of the slab, or by forming a tongue and groove-like shape under the upper slab, or by any other guiding structure details.

Additionally, correlation between statical scheme of the bridge and the length of the span has to be taken with method of fixing of rails to the upper slab (point or continuous).

In a long span bridge (continuous beam), the distance between the railway equalization devices of the track should also be considered.

7. Use of a sealing layer

In some countries [4], the sealing layer is used to cover the bridge deck. In that case, a special provision is made to transmit the horizontal forces to the bridge structure. The 110 mm thick protective concrete layer placed over the sealing layer is connected by reinforcement to the edge capping beam, which in turn is rigidly connected to the bridge deck (Fig. 12).

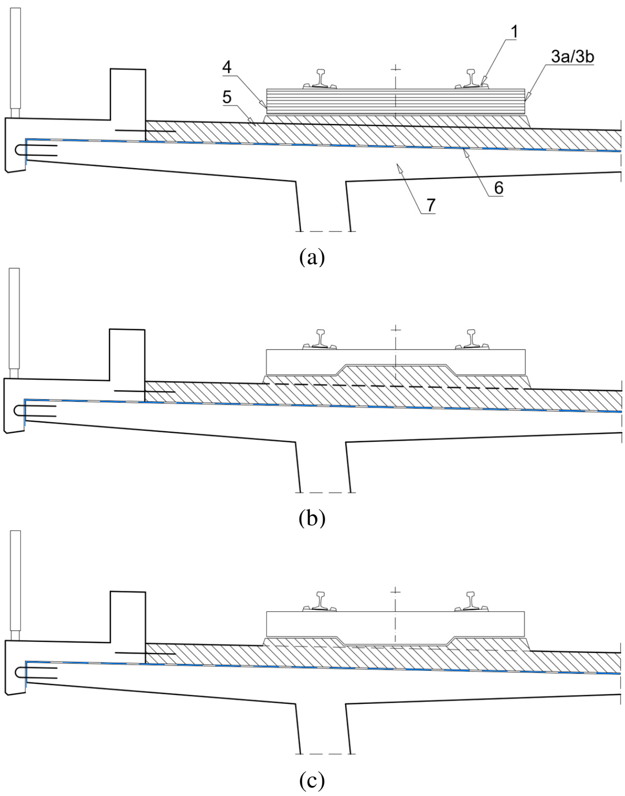


Fig. 12. Slab track with in-situ concrete ("monolithic" type) or with precast elements with sealing layer on bridge deck [4]: (a) Protective concrete layer integral with lower slab, (b) protective concrete layer integral with lower slab (using a stopper as restraint), (c) protective concrete layer integral with lower slab (using a recess as restraint); 1 – Rail fastening, 2 – Embedded sleeper, 3 – Slab with embedded sleeper, 3a – Upper slab with in-situ concrete but not embedded sleeper, 3b – Upper slab, constructed with precast elements, 4 – Lower slab, can incorporate restraint detail (not shown) 5 – Protective concrete layer (part of lower slab), 6 – Sealing layer of the bridge deck, 7 – bridge deck

8. Cracks in the concrete elements of the ballastless track on the bridge

One of the important factors which make influence on durability of bridges with ballastless track are cracks of concrete as well in slab of track as bridge deck [4]. The standard procedure which should be implement during design is to take adequate class of concrete and to apply sufficient structural and against shrinkage reinforcement. The maximum of divergence of cracks is 0.3 mm. The minimum thickness of the slab is 18 cm. The grade of reinforcement should be a minimum of 0.9–1.0 %. The tolerance of slab dimensions should be ±2 mm.

The concrete of the slabs of the railway track should have at least class C40/50. It assures sufficient tightness and freeze resistance and limits absorbability.

9. Longitudinal resistance fastening system for ballastless track

In ballastless track [4], the support is designed for very high longitudinal resistance, and longitudinal forces in rails will depend strongly on the longitudinal resistance of the fastening system.

Low longitudinal resistance fastening systems can be used in ballastless track to limit longitudinal forces in rail, especially in the case of interaction between tracks and bridges with expandable length and without an expansion joint. If buckling risk does not really exist with ballastless track, a neutral temperature of continuous welded rails can be chosen, unlike for ballastless track, and a particular requirement for temperature variation can exist.

The neutral temperature is determined by different technical and practical aspects. Proper choice of it is very important for ballasted track because of the high risk of rail buckling and possible catastrophe of the train. But, because in a ballastless track, in reality, this risk does not exist, different neutral temperatures can be chosen. This can have a major influence on the choice of fastening system on the bridge. On the other hand, practical aspects should not be neglected. Rail laying and rail replacement should remain possible.

Longitudinal resistance shall be measured as longitudinal rail restraint, possibly with additional provisions to prevent rotation.

Low-restraint fastening is used in some parts of expansion devices with creep resistance between 0 and 5 kN per baseplate.

A minimum longitudinal resistance is required to manage rail breaking risk. In case of rail breaking, with temperature lower than the neutral temperature of continuous welded rail, the gap that appears depends on longitudinal resistance (sliding limit and longitudinal stiffness). It is necessary to know that for safety reason in many countries the rules for maintenance give speed restriction of train depending of the gap.

Low longitudinal resistance fastening systems should be designed to get longitudinal rail restraint, e.g., for a value of force equal to 6.0 kN (according to EN 13146-1 [5]).

Low longitudinal restraint can be obtained by reducing toe load while modifying the geometry of the fastening system. For instance, by modifying rail pad height or putting shims at the appropriate place under clips. But usually, a low longitudinal resistance fastening system is achieved by modifying the metallurgy of the clip (stiffness), but not its geometry. So it is required to have special marks to recognize this system.

10. Interaction between continuous welded rails and bridge structure

The effects of track-bridge interaction on the track are controlled [4], principally, by limiting the "additional stress" or force in the rail due to thermal and vehicle loading (traction, braking, and bridge deck bending forces) effects, attributable to the presence of the bridge. This is the additional axial tensile stress or compressive force in the rail, which shall be added to the axial tensile stress or compressive force that would be expected with the same track system and the same vehicle loading, but not on the bridge.

For rails on the bridge and on the adjacent abutment, the permissible additional stress in the rail due to the combined response of the structure and track to variable actions should be limited to the design value of 112 N/mm^2 in tension or compression

The limiting values for the rail stresses are valid for a track complying with:
- rail profile 60E1 or 60E2 of grade R260 or better,
- straight track or track radius $R \geq 1500$ m.

The limiting values of displacement due to traction and braking, δ_B [mm], shall not exceed the following values:
- 5 mm across the joint for continuous welded rails at the joint (no rail expansion devices at the joint),
- 30 mm across the joint where there are rail expansion devices in all rails at the joint.

For ballastless track, the displacement due to traction and braking shall be limited in order to ensure compatibility with the design characteristics of the rail fastening system.

For ballastless track, the longitudinal displacement due to vertical traffic actions (up to two tracks loaded with Load Model 71 (and where required SW/0)) shall not exceed the following values:
- 8 mm when the combined behaviour of structure and track is taken into account (valid when there is only one or no expansion devices per deck),
- 10 mm when the combined behaviour of the structure and track is neglected.

The relative longitudinal displacement at the level of the bottom surface of the ballast layer, due to vertical deformation of the bridge deck, is measured:
- between the end of the deck and the adjacent abutment, or
- between two consecutive decks.

For ballastless track, the longitudinal displacement due to vertical traffic actions, δ_H [mm] shall be limited in order to ensure compatibility with the design characteristics of the rail fastening system. In the absence of any specific data, limiting values for ballasted track should be applied to ballastless track.

The vertical displacement of the upper surface of a deck relative to the adjacent construction (abutment or another deck) δ_V [mm] due to variable actions shall not exceed the following values:
- 3 mm for a Maximum Line Speed at the site of up to 160 km/h,
- 2 mm for a Maximum Line Speed at the site over 160 km/h.

For ballastless track, the uplift forces (under vertical traffic loads) on rail supports and fastening systems shall be checked against the relevant limit state (including fatigue) performance characteristics of the rail supports and fastening systems.

Calculation methods should enable the combined response of the track and structure to be checked against the design criteria, which may be summarized as:
1. Longitudinal relative displacement at the end of the deck split into two components to enable comparison with the permitted values: δ_B due to braking and traction and δ_H due to vertical deformation of the deck.
2. Maximum additional stresses in the rails,
3. Maximum vertical relative displacement at the end of the deck, δ_V,
4. for ballastless tracks, if δ_V is greater than 0,5 mm, an additional check on uplift forces is required.

For a superstructure comprising a single deck (simply supported, continuous spans with a fixed bearing at one end or continuous spans with an intermediate fixed bearing) it is not necessary to check the rail stresses provided that
- the substructure has sufficient stiffness, K, to limit δ_B, the displacement of the deck in the longitudinal direction due to traction and braking, to a maximum of 5 mm under the longitudinal forces due to traction and braking. For the determination of the displacements, the configuration and properties of the structure should be taken into account,
- for vertical traffic actions δ_H, the longitudinal displacement at the upper surface of the deck at the end of the deck due to deformation of the deck does not exceed 5 mm,
- the effective expansion length L_J at the joint is less than 40 m.

The limits of validity of the calculation method is given in EN 1991-2 [6].

11. Uplift of the bridge ends

For ballastless track uplift at bridge ends must be designed with consideration of fastening system capacities, which implies that track and bridges are not designed separately (Fig. 13) [4].

Calculation of the deformation of the system shall be done with the global track stiffness (due to track components), and the real behavior of the fastening system [4]. Calculation at the lower support point shall be done to check the ability of the fastening support to withstand both forces and displacements. To reduce the tension forces in the transition area at the bridge ends, it is necessary to make at least one of the following measures:
- Shortening of the cantilever end at the bridge deck,
- Increasing the stiffness of the bridge structure,
- Choice of the bridge system, which means a continuous or single span structure,
- Application of a compensation plate.

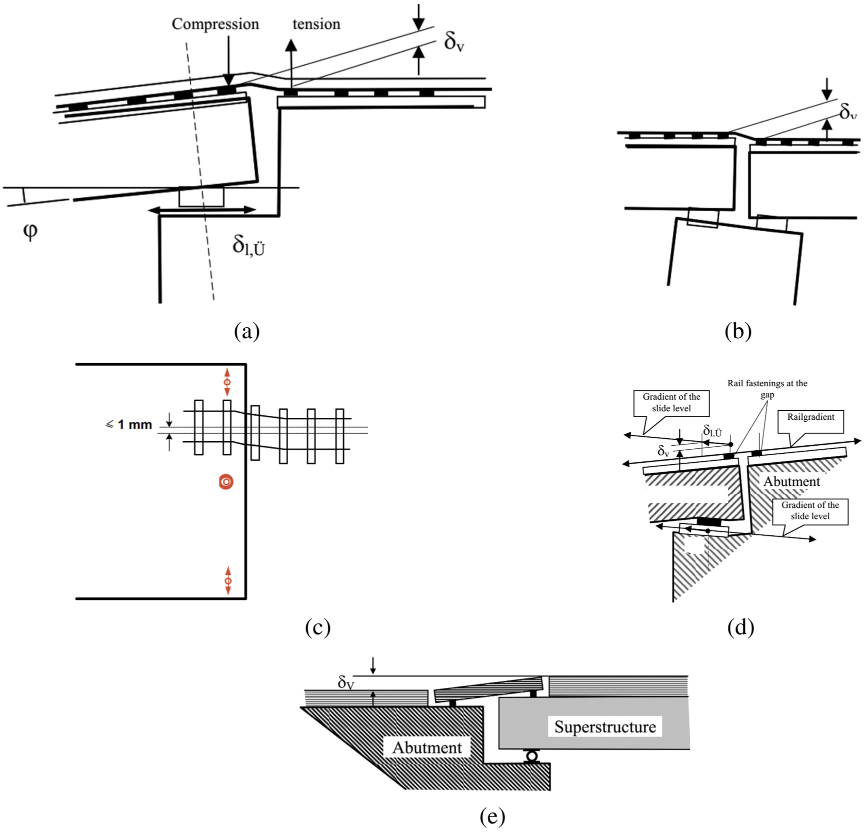


Fig. 13. Rotation of bridge end: (a) Correct settlement of pier, (b) Uneven settlement of pier, (c) Horizontal displacement, (d) Reducing vertical displacement for track with grade, (e) Eliminating and rotation with compensation slab [4]

12. Standardization process of design, construction, and maintenance of ballastless track located on bridges

For many years standardization of ballastless tracks was limited to particular countries. In 2008 UIC implemented their recommendations [4] but more important step was done by CEN preparing standard EN 16432 – Part 1, 2 and 3 [7–9]. Now, the EN 16432 – Part 4 [10] is under preparation, which is directly devoted to special ballastless track systems for attenuation of vibration, including those located on bridges. Except for general assumptions for design, determination of all kinds of actions, and taking into account problems of dynamic actions and fatigue behavior, procedures were given related to the calculation of internal forces in all elements of ballastless track, and information on how to implement co-operation between the bridge deck and ballastless track, especially with the rail concrete slab. It will provide information devoted to vibration and noise and their dumping.

13. Dumping of vibrations generated by traveling trains

Application areas of vibroacoustic isolators in railway tracks are given in Fig. 14 and may include the following elements [11]:

1. Resilient fastening (fixing) of rail foot: resilient clamps or grouting;
2. Resilient fastening (supporting) of rail foot: rail pad, continuous rail pad, discrete or continuous grouting;
3. Resilient fixing in indirect rail fastening system: tension clamps, anchor bolts with compression spring;
4. Resilient support of rail supporting structure in indirect rail fastening system: base plate pad, discrete grouting;
5. Resilient support or fixing of rail supporting structure (sleeper or block): under sleeper pad, under block pad, grouting;
6. Resilient fixing and support of railway track: under-ballast mats or slab-track mats – which, with the rail track structure, compose a floating slab track system;
7. Filling gaps between fishplate and rail web (noise reduction): grouting or rail web filler block.

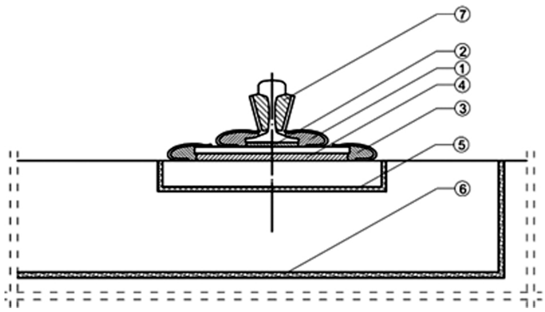
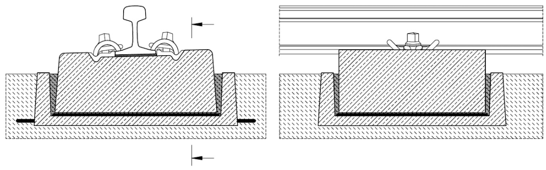


Fig. 14. Application areas of vibroacoustic isolators in railway tracks [11]

From the listed components of rail track structure, the rail fastening system demonstrates the greatest diversity of design solutions that constitute the basis for differing classifications [11, 12]. This is particularly the case with ballastless track structure, where resilient of load-bearing capability necessary for the proper functioning of the system must be provided by variously solved resilient elements of rail fastening system. The variety of possible design solutions is result of dynamic development of material engineering.

One of the basic classification criteria of rail fastening systems is their continuity in the rail track. It is illustrated in Fig. 15, where two kinds of rail fastening systems are defined: discrete and continuous.

Another basic classification of rail fastening systems is classification due to the criterion of fixing the rail with the rail supporting structure. Fastening systems, where rail is directly fixed to the supporting structure by anchors, bolts, or screws, are described as a direct rail fastening system (Fig. 16). However, if rail is fixed to the supporting structure with usage of additional element (i.e. ribbed base plate), then those systems are describes as indirect rail fastening system (Fig. 17).



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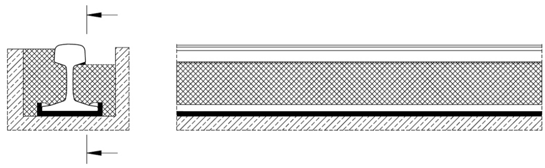
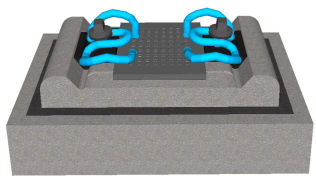


(b)

Fig. 15. Illustration principle of classification of rail fastening systems due to the criterion of their continuity occurrence in the rail track: (a) discrete rail fastening (i.e., rail fastening in Embedded Blocks System – EBS); (b) continuous rail fastening (i.e., Embedded Rail System – ERS) [11]

(a)



(b)

Fig. 16. Illustration principle of classification of rail fastening systems due to the criterion of fixing rail with rail supporting structure – direct rail fastening system: (a) SB fastening system, (b) embedded blocks system with tension clamps type Skl 14 [11]

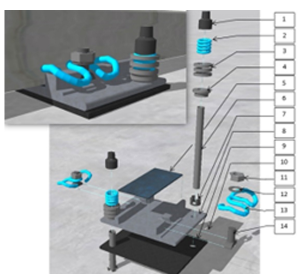


Fig. 17. Illustration principle of classification of rail fastening systems due to the criterion of fixing rail with rail supporting structure: rail sleeper or track base plate (as an example – indirect fastening system). Key: 1 – protection cap, 2 – compression spring, 3 – correction bush, 4 – collar bush, 5 – rail pad, 6 – anchor bolt, 7 – centering cup, 8 – baseplate, 9 – baseplate pad, 10 – concrete track base plate, 11 – nut, 12 – washer, 13 – tension clamp type Skl 12, 14 – T-bolt [11]

The term of rail fastening system used in standard EN 13481-5 [13] requires a more detailed description of its two main functions specified in that standard as rail support and rail fixation.

Rail support system provides absorption of vertical loads and transfers them to the ballast layer (ballasted track system) or substructure – concrete base plate (ballastless track system). The rail support force vector (connected to the stiffness of the rail supporting structure) acts from top to bottom.

Elements of the supporting rail system (both continuous and discrete) are rail pads, resilient railfoot profiles, resilient elastomeric grout based on polyurethane reins, and other items that are included (i.e., ribbed base plate, elastic pad). Material features of rail supporting system components also have an impact on their functions: static and dynamic stiffness of support, protection against stray current, and restraint against longitudinal rail displacements.

Rail fixing is the function of the rail fastening system, which ensures:

1. clamping force that acts on the rail foot;
2. restraint against longitudinal rail displacements (effect of clamping force and friction coefficient);
3. torsional resistance against rail rollover (effect of lateral shear resistance of anchor elements);
4. electrical insulation between rail and supporting structure (sleeper, block, or concrete slab), providing protection against stray current.

Presented variants of classification of rail types fastening systems, apart from the classical division into direct and indirect, the following systems can be specified due to design solution and interconnectedness of rail supporting and fixing:

1. discrete rail fastening system – discrete both rail support and rail fixing, i.e., Embedded Blocks System (EBS);
2. continuous rail fastening system – continuous both rail support and rail fixing, i.e., Embedded Rail System (ERS);
3. mixed rail fastening system – continuous rail support and discrete rail fixing, i.e., direct rail fastening to concrete slab with continuous grout – Fig. 18).

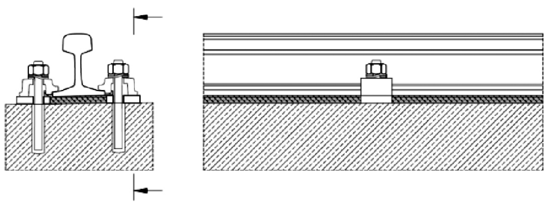


Fig. 18. Mixed rail fastening system (direct rail fastening to concrete slab) [11]

Details of the support block in EBS (Embedded Block System) and components of the rail fastening system are given in Fig. 19. The Rail supporting structure in the Embedded Block System is an example of a floating slab track system, where a heavy support block is set on a resilient under-block pad. Significant vibration damping in the EBS system is also attained due to the elastic fixing of the support block in the socket by means of grouting, which serves as a support block coating.

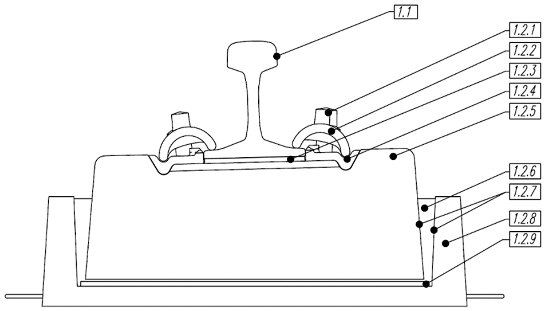


Fig. 19. Detail of support block in Embedded Block System (EBS) – Key: 1.1 – Vignole rail, 1.2.1 – sleeper screw; 1.2.2 – tension clamp type Skl-14; 1.2.3 – rail pad (resilient rail support), 1.2.4 – angled guide plate Wfp; 1.2.5 – reinforced concrete block; 1.2.6 – resilient compound; 1.2.7 – adhesive material; 1.2.8 – prefabricated concrete tray or concrete slab; 1.2.9 – resilient under block pad [11]

Resilient mats in railways are used for vibration isolation of the railway track by reducing the dynamic effects of rail traffic. The reduction relates mainly to vertical and transverse material vibration, but also to structure-borne noise.

Resilient mats in railways are used as well as in ballast and ballastless track systems. In ballast track systems, under-ballast mats are applied in the track superstructure on engineering structures such as bridges, track troughs, and tunnels. They increase resilience between the ballast and the track, and reduce vibrations emitted into the environment, which is especially important in cities. Characteristics of resilient mats important for vibration isolation and their test methods were given in standards [14–17] and [18–21].

In a ballastless track system, resilient mats have a similar purpose as an under-ballast mat, but are always an individual engineering solution for a particular application.

In a slab track system, resilient mats are applied horizontally and vertically directly below and from the sides of the concrete track base plate to provide a resilient support layer for the railway track. The resulting floating slab track system is effective in mitigating vibrations, especially in low frequencies, and achieves a significant reduction in vibrations and structure-borne noise emissions at excitation frequencies above $\sqrt{2}$ times the tuning frequency [22–26].

Resilient mats can be classified according to different criteria – i.e., range of applications, kind of material from which they are made, production technology, or structure of finished product.

They can be grouped into two categories because of the range of applications in various types of railway track construction:

a) Under-Ballast Mats (UBM)/ Sub-Ballast Mats (SBM) or ger. Unterschottermatten (USM) – used in ballast railway track; among which two varieties can be classified due to the main purpose of their use:
   - used primarily for isolation from vibration,
   - used primarily for stress reduction in ballast.
b) Under-Slab Mat (USM)/Slab-Track Mats (STM) – used in ballastless railway track (applied under or from the sides of concrete track base plate), with three varieties of slab support system according to standard [16, 17]:

- discrete support (steel springs or elastomeric pads),
- linear support (strip mats),
- continuous support (elastomeric mats).

It should be noted that, under-ballast mats can be sufficiently used instead of slab-tack mats in floating slab track systems, but not the other way round. Slab-track mats must be protected against damage from the sharp edges of the gravel by an additional protective layer (i.e., geosynthetics).

Due to the materials and production technologies used, resilient mats can be grouped into mats made of various kinds of elastomers (elastomeric mats) or mineral wool mats. Elastomeric mats can be divided into two groups:

– mats based on polyurethane in versions with closed or open pores;
– rubber mats (composites based on blends of natural rubber and/or synthetic rubber), whose resiliency is ensured by shape (channels, grooves, or protrusions of different shapes) and cross-sectional structure of the mat (density and pore volume).

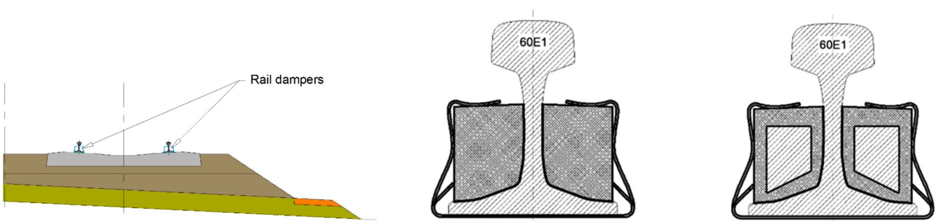
Resilient mats can have a uniform (homogeneous) or a layered structure (sandwich cross-section with layers of different materials and features).

14. Dumping of noise generated by traveling trains

Increased train velocity has significant negative effects, such as increased noise emission. It affects both people and the environment. There are various methods to minimize this phenomenon, such as noise barriers placed along railway lines. For many reasons, such a solution may not be used. In some countries, different solutions are proposed and implemented, like rail dampers ("absorbers") [27], porous concrete sound (noise) absorbing panels [28], and low-height noise barriers. The first two of them will be presented in this paper.

There are at least 20 patents of rail dampers developed in countries such as Germany, France, the USA, China, Japan, South Korea, and the European Union. The most important reason to create such a structure was the construction of high-speed railways.

Rail dampers are elements that are fixed to both sides of the rail (the rail web and/or rail base and, in some cases, even to the bottom part of the rail head. They are attached to the rail by gluing or using additional elastic clamping elements. Rail dampers are usually placed at equal intervals along the rail (Fig. 20) between rail fastenings.



(a) (b) (c)

Fig. 20. Prototype rail dampers: (a) Schematic location within the ballasted track structure, (b) cross-section of a "static damper", (c) cross-section of a "dynamic damper" with steel insert and an elastic cover based on rubber granulate [27]

All of these proposals differ with:
- Methods fixing dampers to the rails,
- Kind and composition of the elastomer,
- Shape and kind of material of the inserts of dampers,
- Methods and range of tuning of dampers for required frequencies.

The main aim of rail dampers is to accelerate the decay of vibration induced in the rail (along its length) and to thereby reduce the level of noise. There are two types of rail dampers: static and dynamic [27].

- Dampers with an elastic cover that either fully or partially fulfils the rail chambers or/and covers the surface of the rail base. The rail cover exhibits the same characteristics of vibration as the rail. Therefore, it does not change the general dynamic characteristics ot he rail systems. This type of damper is referred to as "static damper" (Fig. 21).
- Dampers with an element or group of elements with a certain mass that are distributed between the fixing of the rail and glued (usually polyurethane resin) to the rail with an elastomeric layer. The elastically attached damping mass (usually a steel insert) is exited by the traveling trains. The induced vibrations can undergo a phase shift compared to the rail vibrations due to the elastic layer. This phenomenon changes the general dynamic characteristics of the rail and thereby suppresses the acoustic wave emitted by the rail, especially its web. This type of damper is referred to as "mass damper" or "dynamic damper" (Figs. 22 and 23).

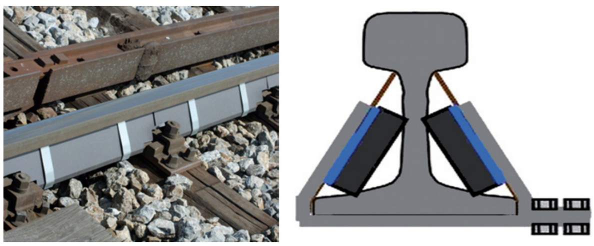


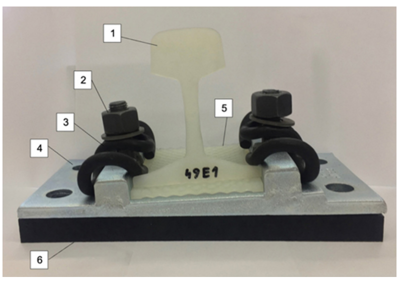
Fig. 21. "Static damper" (product of SEKISUI CHEMICAL GmbH)

Fig. 22. "Dynamic damper" (product of TATA Steel C)

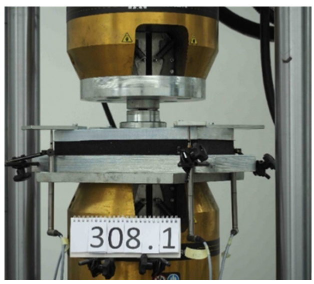
Fig. 23. Application of "dynamic damper" (product of STRAIL Co.)

The effectiveness of rail dampers depends on various aspects, as mentioned above. It can be verified by direct measurements or determined based on dynamic characteristics analysis TDR (Track Decay Rate [29], EN 15461 [30]). According to many studies, this effectiveness is between 2 and 6 dB, depending on the type and velocity of the trains. The biggest influence is for velocities of 40 ÷80 km/h. Above this range, the damping effectiveness is constant and independent of the train velocity. Moreover, the studies revealed that the roughness of the rails and wheel running surfaces does not affect the mentioned above factor.

European norm EN 17495 [31] specifies laboratory test procedures to determine a high-frequency dynamic stiffness, "acoustic stiffness", of resilient components of rail fastening assemblies. This document is applicable to complete rail fastening assemblies and to pad components of fastening systems, including both discrete (Figs. 24 and 25) and continuous fastening systems. It is applicable to the measurement of the dynamic transfer stiffness under a prescribed pre-load and the associated hysteretic damping loss factor. It provides measurement methods and pre-load, excitation, and frequency range conditions for application to ground-borne and structure-borne noise, as well as for rolling noise.

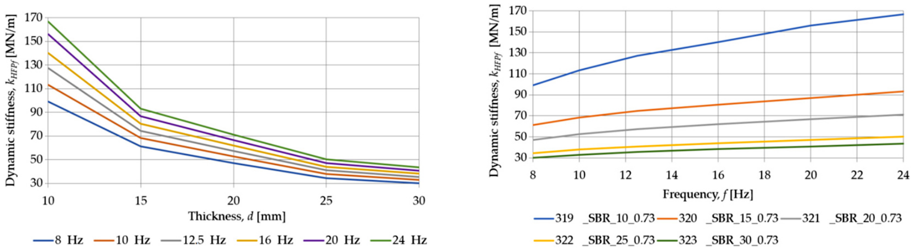


(a)



(b)

Fig. 24. Scheme of the discrete resilient rail fastening system for ballastless tracks: (a) View of the whole system; Symbols: 1 – Vignole rail with a 49E1 profile; 2 – alloy T-bolt and nut with washer; 3 – elastic rail clip/tension clamp type Skl 12; 4 – baseplate type Pm49; 5 – shaped rail pad type PAK; 6 – vibration isolation/baseplate pad (made of SBR granules – recycling material); (b) Test stand at the Faculty of Civil Engineering of the Warsaw University of Technology for determination of static and dynamic elastic characteristics of discrete elastic supports of the baseplate/rail: SBR-based specimen, 30 mm thick [12]



(a) (b)

Fig. 25. High-frequency dynamic stiffness (acoustic stiffness) of resilient components of rail fastening assemblies: (a) influence of the pad thickness on its dynamic stiffness at high frequencies determined for SBR-based samples, (b) influence of the load frequency on the dynamic stiffness at high frequencies determined for SBR-based samples [12]

Porous concrete sound (noise) absorbing panels (Figs. 26 and 27) are elements that create a noise-dampening layer placed on the upper surface of sleepers or on the concrete slab in ballastless track.

– They are installed between the rails that make up the track, as well as outside the rails and optionally in the track spacing.
– The mechanism of operation of track silencers involves partly absorbing and partly dispersing sound waves. Therefore, they do not affect the source of sound, but lie in its path.
– They owe their effectiveness to the location of the damping element on top of the track structure, very close to the noise source, where its intensity is greatest.

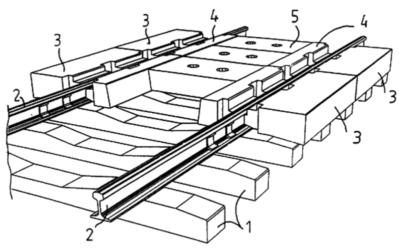


Fig. 26. Idea of structure of porous concrete sound (noise) absorbing panels according to Nederlander patent no NL194553 (B): 1 – sleepers, 2 – rails, 3 – side damping element, 4 – internal damping element, 5 – internal positioning element

Fig. 27. Prototype sound (noise) absorbing panels made of porous concrete during acoustic tests at the Faculty of Civil Engineering of the Warsaw University of Technology [28]

The most popular materials used for prefabricated elements located between rails are:
- porous concrete,
- rubber.

Investigation done inside passenger trains proved the efficiency of rail dampers 3 dB in a tunnel and 1 dB in an open area for a train velocity of 60 km/h. Generally, it depends on the velocity of the traveling train and its type.

15. Conclusions

Application of ballastless track is grooving especially on bridges and in tunnels. In some countries, the knowledge and experience of using it is better than in others. But the development of high-speed railways increases the need for its dissemination. This paper summarizes what was done in the world in this area of science and industry. Hopefully, it will help in the development of railway technique.

Funding: This paper was co-financed under the research grant of the Warsaw University of Technology supporting scientific activity in the discipline of Civil Engineering, Geodesy, and Transport.

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Nawierzchnie torowe o konstrukcji bezpodsypkowej na obiektach mostowych

Słowa kluczowe: bezpodsypkowa nawierzchnia torowa, mosty, system przytwierdzenia szyny, wiadukty, izolatory wibroakustyczne

Streszczenie:

W artykule przedstawiono problematykę nawierzchni torowych o konstrukcji bezpodsypkowej na obiektach mostowych. Pokazano zróżnicowane rodzaje nawierzchni torowych oraz ich wady i zalety. Szczególną uwagę poświęcono drganiom (wibracjom i hałasowi) generowanymi przez przejeżdżające pojazdy szynowe. Przedstawiono wpływ tych niekorzystnych oddziaływań dynamicznych na zachowanie się konstrukcji mostowej i jej otocznie, a także stosowane na świecie w praktyce inżynierskiej sposoby tłumienia drgań w postaci izolatorów wibroakustycznych w konstrukcji nawierzchni torowej. Opisano zagadnienie transferu sił podłużnych zarówno w kierunku podłużnym jak i poprzecznym do konstrukcji mostowej i związane z tym zjawisko interakcji z nią toru bezstykowego. Zwrócono także uwagę na fakt wpływu elementów przytwierdzeń szyn na wielkość sił oporu podłużnego zarówno w wersji sztywnej jak i sprężystej. Sprowadza się to do zapewnienia w jak największym stopniu współpracy między nawierzchnią bezpodsypkową i konstrukcją mostową. Przedstawiono również zagadnienia wpływu izolacji wibroakustycznej m.in. w postaci mat podtorowych montowanych na pomoście obiektu na generowanie wibracji i hałasu. Rozważano także problem unoszenia konstrukcji przęseł na przyczółkach obiektu i wpływu tego zjawiska na dobór urządzeń dylatacyjnych konstrukcji mostowej i urządzeń wyrównawczych nawierzchni torowej. Przedstawiono także wymagania odnośnie wielkości rys w betonowych blokach podszynowych pełniących funkcję podparcia szyny. Niektóre z rozwiązań wyżej wymienionych zagadnień inżynierskich są przedstawione w rekomendacjach lub specyfikacjach opracowanych przez różne instytucje np. Międzynarodowy Związek Kolejowy (UIC), a inne są zawarte w najnowszych normach europejskich (np. serii EN 16432) – obowiązujących lub będących w trakcie przygotowania.

Received: 2025-08-20, Revised: 02.09.2025