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Razvoj novih i poboljšanje postojećih elastičnih pritiskalica za pričvršćenje tračnica

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Subject review

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Development of a new and modification of existing elastic clips for rails fastening

One of the problems of railway fastening systems (fastening system) that occurs due to the development of railways is the damage of the elastic clips, which leads to the loss of structural integrity between the rail and the base. Therefore, there is a need to develop new clips or improve existing ones. The paper describes the contribution and role of each component of the fastening system in different loading cases. As a tool whose parameters can affect the efficiency of the fastening system, special attention is given to the clips. Finally, an example is briefly described for creating numerical models that can be used to perform parametric analyses in order to develop new clips or improve existing ones.

Key words:
rail fastening system, elastic clip, CAE, FEM, numerical model, computer experiments

Pregledni rad

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Razvoj novih i poboljšanje postojećih elastičnih pritiskalica za pričvršćenje tračnica

Jedan od problema sustava za pričvršćenje tračnica na podlogu (sustav pričvršćenja) koji se javlja s razvojem željeznica jest oštećenje elastičnih pritiskalica, čime se gubi konstrukcijski integritet između tračnice i podloge. Stoga postoji potreba za razvojem novih ili poboljšanjem postojećih pritiskalica. U radu je kroz dosadašnja istraživanja opisan doprinos i uloga pojedinih komponenata sustava pričvršćenja pri djelovanju raznih slučajeva opterećenja, a kao alatu čijom se promjenom parametara može utjecati na učinkovitost sustava pričvršćenja, posebno je usmjereno na pritiskalice. Detaljno je opisan postupak izrade numeričkih modela kojima je moguće provođenje parametarskih analiza za razvoj novih ili modifikaciju postojećih pritiskalica za pričvršćenje tračnica.

Ključne riječi:
sustav pričvršćenja tračnica, elastična pritiskalica, CAE, MKE, numerički model, računalni eksperimenti

1. Introduction

With the development and progress of modern railways in recent decades, traffic speeds and axle loads acting on the track structure as the wheels of the railway vehicle pass over the rails have increased. Hence, there has been an increase in vertical and horizontal loads and the amplitude and frequency of dynamic forces transmitted from the rail through the fastening system to the sleepers and onto other track structure components and layers. If the track structure has high stiffness, the dynamic forces may permanently deform and damage track components due to fatigue and may eventually deteriorate the entire railway track. From an economic perspective, the cost of maintenance and the life cycle of the track structure are the most critical parameters in the design of this type of structure, along with safety and railway passenger comfort [1, 2]. To mitigate the dynamic forces and avoid the mentioned problems, the stiffness of the track must be reduced to an optimal value, which is achieved by choosing the appropriate track component type and dimensions [3, 4]. The static vertical stiffness of the classical ballasted track superstructure, the most widely used track type in the world, can be represented by a mathematical model as the serial sum of the stiffness of its layers (Figures 1.a and 1.b), namely: rail, fastening system, prestressed concrete sleeper, ballast bed of stone aggregate, sub-ballast, and subgrade layer [4]. When analysing the behaviour of a railway track under dynamic forces, more complex models are used, which consist of masses connected by pairs of springs and dampers (Figure 1.c) [5, 6]. The stiffness values of the individual layers shown in Figure 1.c indicate that the track's global stiffness can be partially reduced by installing a fastening system that elastically connects the rails to the sleepers through the interaction of several components [5]. For the classical fastening system, the most common components are elastic clips, rail pad, steel washers, screws, and angle plates (Figure 2).

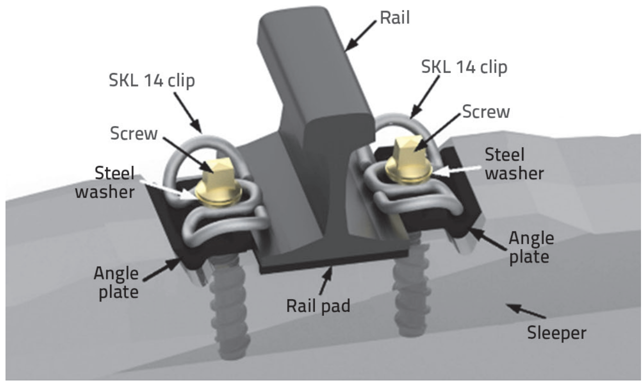


Figure 2. Vossloh W14 fastening system and its components

1.1. Problems related to the fastening system

The fastening system is an essential part of the railway track, as evidenced by the fact that most damage and defects in the track structure are directly related, and most train derailments are directly or indirectly related to fastening system damage [8]. The occurrence of characteristic problems in the fastening systems is mainly related to the increased traffic speeds and axle loads of modern railway tracks. Any defect or damage in any of the fastening system components can lead to a change in track geometry, wear of the rail, and loosening or failure of the rail fastening point [1, 9]. For example, permanent deformation of the clips, caused by material fatigue, often reduces the fastening force or, in the latter case, breaks the clip (Figure 3.a) [10-20]. This damage can lead to a loss of structural integrity between the rail and sleeper. Thus, the fastening system loses not only the fundamental property of stability and safety but also the property of elasticity, which can lead to the deterioration of the ballast bed and layers of the track substructure [14, 21]. The problems related to the track ballast bed made of stone aggregate and an overview of its numerical modelling are explained in detail in [22].

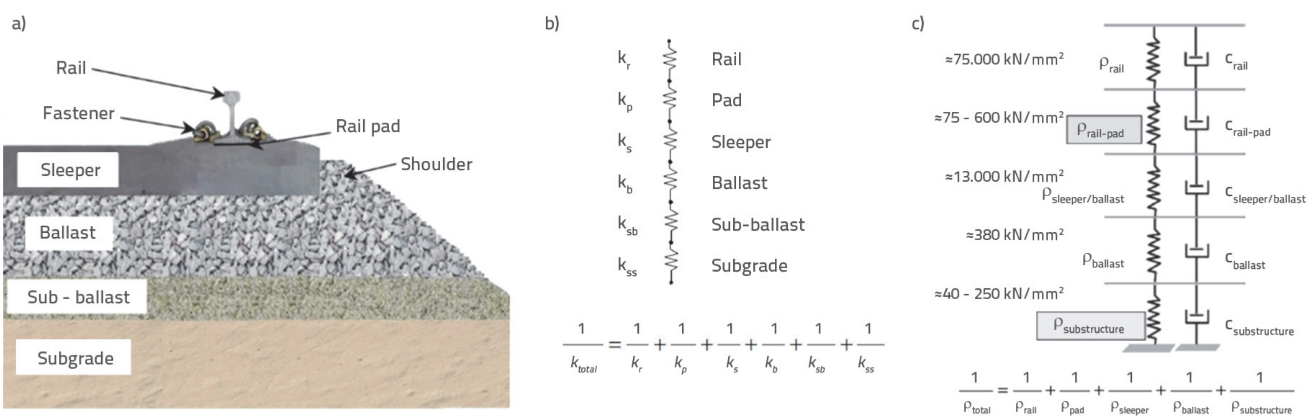


Figure 1. a) Cross section of a classic railway ballasted track structure with associated layers [7]; b) mathematical model of the ballasted track for static stiffness determination [4]; c) mathematical model for a combination of static and dynamic loads [6]

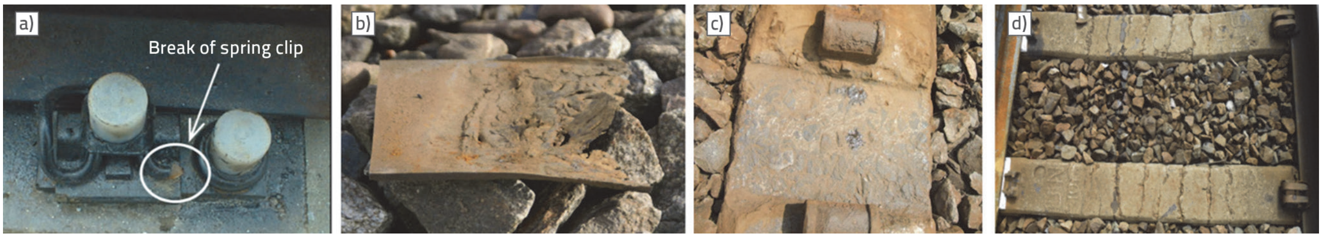


Figure 3. a) Example of clip breakage [10]; b) rial pad wear [20]; c) rail seat deterioration[23]; d) concrete sleeper breakage [23]

For example, the magnitude of the fastening force must be sufficient for all loading conditions, including the wear of individual components due to material fatigue [1, 10]. Therefore, special attention must be given to the clips and the influence of their mechanical behaviour on the behaviour of the whole fastening system in all loading cases must be investigated [11, 12]. In addition to clip damage, the fastening force can also be reduced by the wear of the rail pads (Figure 3.b), the rail seat deterioration (Figure 3.c), or the breakage of the concrete sleepers (Figure 3.d) [20, 23, 24]. The fastening force at the contact between the rail foot and clip can also be loosened by their degradation, which can change the mechanical properties of the clip and, consequently, the behaviour of the entire fastening system. This situation can be caused partly by phenomena such as stray currents if not prevented in time [25].

1.2. Requirements for modern fastening systems

Because of the abovementioned problems, stricter requirements have been imposed on all components of the railway track structure, including the fastening system. To adapt to the increased traffic loads, speeds, and general efficiency requirements, fastening systems are continuously improved by increasing the fastening force or the fatigue life of their components. Therefore, many different types and shapes of elastic clips and fastening systems have been developed, differing by durability, elasticity, ease of maintenance, fastening force at the clip-rail contact, construction cost, installation method, and protection against vandalism [26]. Precisely because of this shape variety, there are no prescribed design calculations. However, before being put into service, the fastening systems should meet safety and laboratory quality assessment standards, such as the European standards [27, 28], Manual for Railway Engineering published by AREMA - American Railway Engineering and Maintenance-of-Way Association [29], the Japanese regulations JIS (Japanese Industrial Standards), and the Australian regulations [30]. As the essential function of the fastening system is to ensure the stability of the track, the main requirement of all the standards mentioned above is that the fastening system must have sufficient elasticity to allow movements in the loading directions and adequate stiffness to contain these movements within certain limits. Thus, the elasticity of the fastening system is a measure that allows vertical and lateral displacement and rotation of the rail at its fixing point to the sleeper [2, 31]. It should be noted that the components of the superstructure, such as the fastening system, are critical in sudden actions, such as earthquakes, and the selection of the fastening system components in seismically active areas is also an essential step in the track structure design process [32].

Developing a new fastening system or improving an existing one usually starts with several initial variants. For each of the variants, an initial assessment using prescribed test procedures is necessary, making these processes time consuming and expensive. For this reason, Gutierrez Romero et al. [26] illustrated the necessity of a method that compares the properties of various types of fastening systems and accurately analysis different variants to improve their mechanical properties. The authors also stated that one of the ways to compare fastening systems is to study their mechanical behaviour and elasticity under different load cases, that is, how large is the possible displacement or rotation angle of the rail at its support. They simultaneously considered that another way is to analyse the fatigue strength of the individual fastening system components. Therefore, recent findings that describe the behaviour of fastening systems using various numerical modelling approaches can be divided into two groups. The first group studies the mechanical behaviour of the clips and/or the entire fastening system under the forces acting in different directions to determine the system's elasticity and resistance, and the second group studies the fatigue strength of the clips from perspective of fracture mechanics and the frequency domain.

2. The role of components in the mechanical behaviour of the fastening system

The forces transmitted from the rail to the sleepers through the fastening system when the wheels of the vehicle pass on the rail are static and dynamic and vertical, transversal, rotational (in both planes), and longitudinal depending on the direction of action [1, 2, 26] (Figure 4).

The response of the fastening system to these loads is complex because the forces are transmitted through its several components, which together form the structural and elastic connection between the rail and its base. Therefore, when analysing the behaviour of such a system, it is necessary to observe the transmission of forces through the entire system [33-35] and to include all components in the calculation [36].

For an appropriate fastening system design, the mechanical properties of its two main components, the elastic clips and rail pad [6] must be well understood. The rail pad, usually made of polymeric material, reduces the noise generated by the rail-wheel contact due to its elasticity and mitigates the static and dynamic forces and impact loads transmitted from the rail to the sleepers [1, 37, 38]. During installation, the fastening force at the rail foot is achieved by the deformation of the clip made of steel springs, thus ensuring constant contact between the rail and sleeper, damping vibrations and achieving rail titling resistance [10].

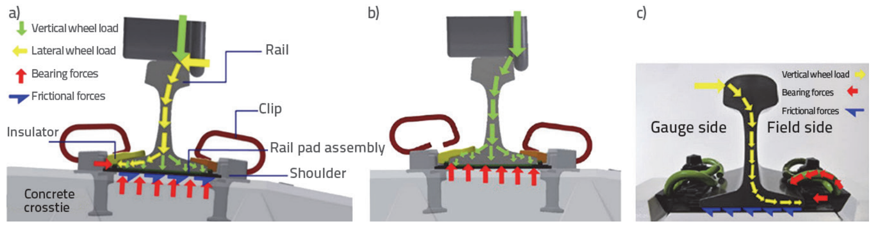


Figure 5. Force transmission through the fastening system: a) the biaxial axle load [33]; b) vertical force component [34]; c) lateral force component [35]

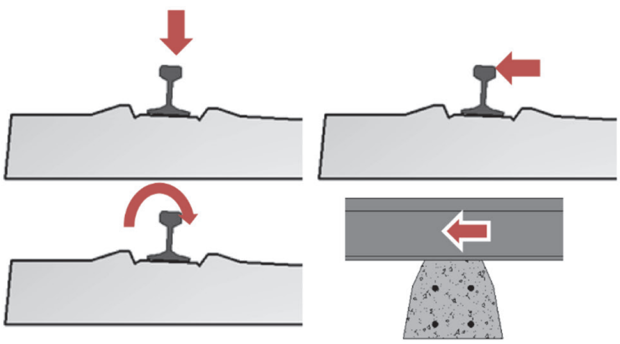


Figure 4. Basic loading directions on the rail during the passage of a railway wheel: vertical direction, lateral direction, torsional and bending moment, and longitudinal direction [2]

2.1. Longitudinal resistance of the fastening system

Due to creep, relaxation, rail thermal expansion or contraction of the rail, acceleration or deceleration of the railway vehicle, large longitudinal forces occur that can cause longitudinal movement of the rail within its support. The fastening system should have sufficient longitudinal resistance under such a load, which can be provided by an adequate fastening force. This force will also prevent the risk of crack initiation and growth that may lead to rail fracture [10, 39, 40]. According to the European standard EN 13481-2 [27], the maximum longitudinal force determined according to EN 13146-1 - Determination of longitudinal rail restraint [40] should not be less than 7 kN. For fastening systems intended for high-speed railway traffic with speeds exceeding 250 km/h, this value should be at least 9 kN. However, for conventional longitudinal loads, the fastening force and stiffness of the clip contribute most to the resistance of the fastening system. For braking or acceleration forces combined with impact loads, the frictional force between the rail and rail pad and between the rail pad and sleeper has the most significant influence on the rail displacement within its support, whereas the stiffness of the clip in the longitudinal direction has less influence [41].

2.2. Resistance of the fastening system to rail tilting

At the contact between the wheel of the railway vehicle and rail, a biaxial load occurs where the ratio of the lateral and vertical force components (L/V) is an important parameter, especially for a small curve radius where the lateral component L becomes dominant. When the biaxial loading occurs, the fastening system must have sufficient resistance to the tilting of the rail about its longitudinal axis [1, 6], because a large tilt angle can lead to wheel derailment. The transmission of forces through the fastening system under biaxial loading is shown in Figure 5.a, and the transmission of vertical and lateral force components is shown in Figures 5.b and 5.c, respectively. As seen in the mathematical model in Figure 6.a, the resistance of the fastening system to the tilting of the rail is mainly achieved by the stiffness of the clips on uplift and the stiffness of the rail pad under a compressive load [42]. Due to the elasticity of the fastening system, rail tilting is possible only to a limited extent. In this process, the contact point of the clip and rail foot is lowered or raised and depending on the vertical displacement of the contact point, the fastening force, deformations, and stresses of the individual parts of the clip change [43]. This change in the fastening force, stresses, and deformations depends on the magnitude and position of the axle load on the rail head and the gauge side of the rail on which the clip is located (the inner or outer gauge side) [43, 44]. The curves in Figure 6.e. illustrate the influence of the L/V ratio on the lateral displacement of the rail head and the rail foot. The critical L/V ratio decreases as the stiffness of the rail pad decreases, and for some fastening systems with a soft rail pad and L/V > 0.4, the maximum stresses in the clip can exceed the yield strength while the deformation in the clip remains permanent, which may reduce the fastening force [23].

2.3. Resistance of the fastening system to the uplift of the rail

The passage of the railway vehicle along the track moves the rail upward in front of and behind the wheels [1]. In this case, the elastic clips play an essential role, that is, their stiffness and the magnitude of their rail fastening force [2]. The magnitude of the fastening force is determined by laboratory tests such the standard EN 13146-7 (Figure 6.f) and is essential for ensuring load transfer to the sleepers. Therefore, it is necessary to ensure

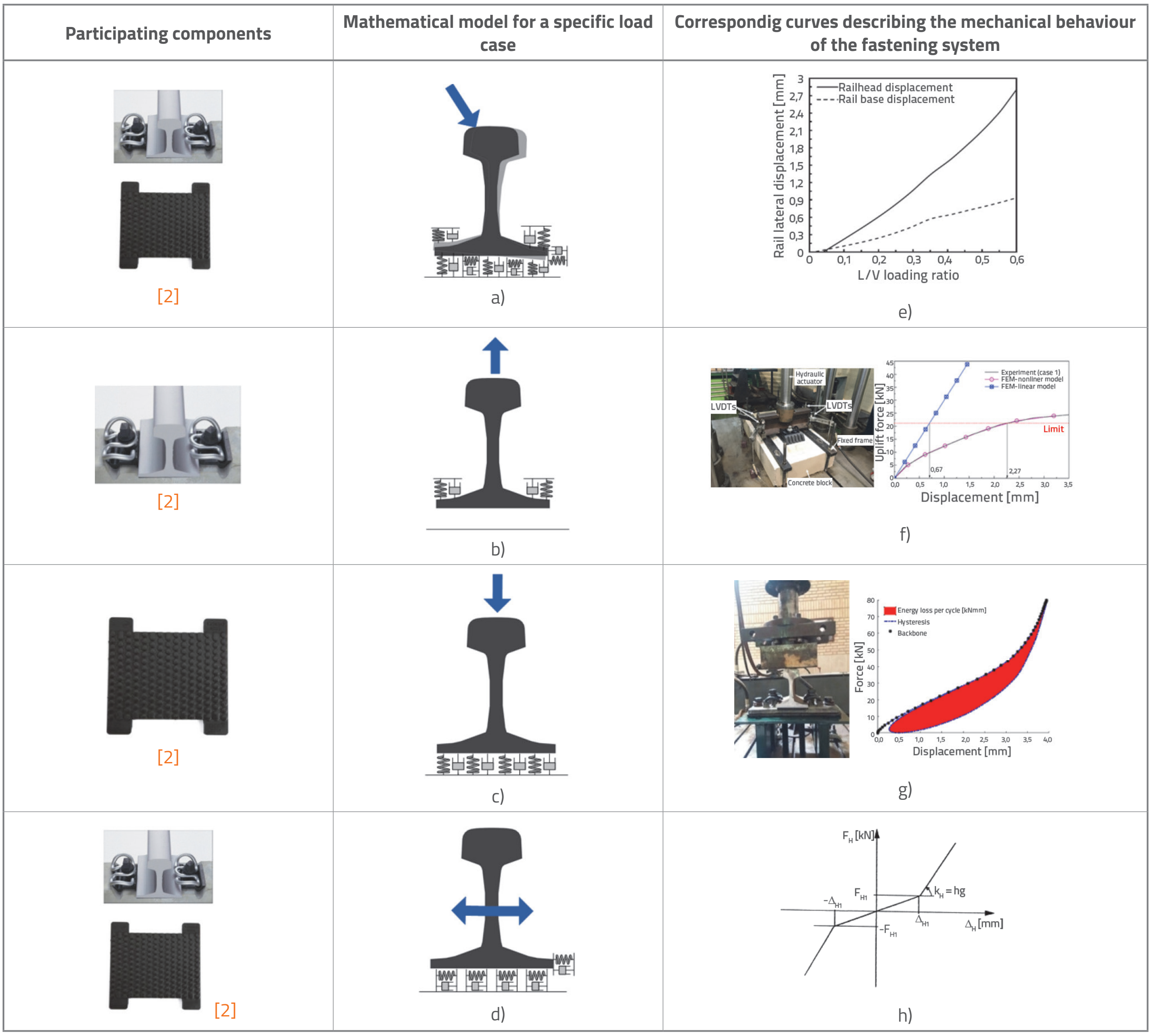


Figure 6. Mathematical models of the fastening system for different load cases: a) biaxial axle load; b) rail uplift; c) vertical force component in the downward direction; d) lateral force component; and corresponding curves describing the mechanical behaviour of the fastening system under the load cases: e) torsional rail tilting [47]; f) rail displacement in the upward direction [46]; g) rail displacement in the downward direction [48]; h) lateral rail displacement [42]

that the minimum fastening force is maintained throughout the life cycle of the fastening system. For this reason, the fastening force is usually determined before and after the test of the effect of repeated loading [45]. The behaviour of the fastening system under the uplift force can be described by the mathematical model shown in Figure 6.c, where the clips are modelled by a pair of springs and dampers. The relation curve between the uplift force and vertical displacement of the rail foot is shown in Figure 6.f. This curve indicates that the mechanical behaviour of the fastening system is nonlinear. Therefore, this type of behaviour must be considered in the numerical analysis of the fastening system [46].

2.4. Vertical stiffness of the fastening system

The behaviour of the fastening system under the vertical load can be described mathematically by the model shown in Figure 6.c. In general, the response of the fastening system to vertical static actions differs from the dynamic ones by the shape of the hysteresis curve [49], which is determined, for example, by the compression test of the fastening system according to the European standard EN 13146-9 [50] (Figure 6.g). Depending on the vertical compressive load, quasi-static or low, medium, or high-frequency load, the static or dynamic stiffness of the fastening system is determined

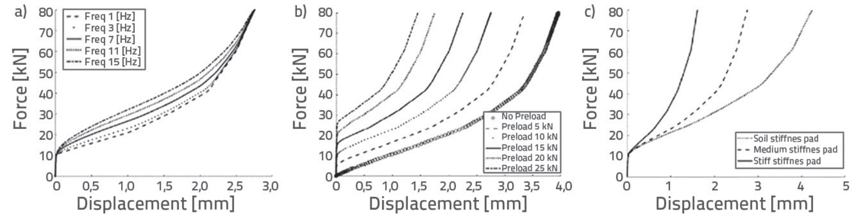


Figure 7. a) Effect of the load frequency; b) effect of the fastening force magnitude, c) effect of the rail pad stiffness on the shape of the hysteresis backbone curve [48]

from the hysteresis curve [48, 49]. The dynamic response of the fastening system to harmonic displacement excitation is nonlinear and consists of elastic and damping forces. In addition, the dynamic stiffness and energy loss are directly dependent on temperature, the material properties of the elastic rail pad, the magnitude of the fastening force, dynamic amplitude, and load frequency [51, 52]. Examples of the effects of some of the abovementioned parameters on the change in the shape of the hysteresis backbone curve are shown in Figures 7.a, 7.b, and 7.c.

2.5. Resistance of the fastening system to the action of the lateral component of the load

Figures 6.d and 6.h show the case where the lateral component of the load acts. In this case, the resistance of the fastening system to the rail movement depends on the stiffness of the clip in the lateral direction, the frictional force between the bottom face of the rail pad and sleeper, and the resistance of the angle plate in the lateral direction. However, when the vertical load component is small and the lateral force transmitted from the rail through the fastening system exceeds the frictional force between the rail pad and sleeper, the rail moves in the lateral direction without tilting [53]. In this case, the angle plate takes over the lateral force, which was investigated in detail in Ref. [54] by static laboratory tests of the W 40 fastening system on a test track model. The same is stated in the technical brochure of the Vossloh system, which includes SKL-type clips [39].

When the wheel is at the furthest point from the rail fixing point during the passage of a rail vehicle, the lateral component of the load causes a torsional moment in the plane parallel to the bottom face of the rail foot. This moment can cause the rail to lose stability due to tilting. To ensure that the fastening system continues to keep the stability of the rail, the European standard [55] prescribes the test procedures for quality and safety assessment for the above load cases.

3. Elastic clip – a tool to improve the fastening system efficiency

3.1. Elastic clip

The most common railway elastic clip shapes, installed on more than 90 % of the world's rail networks, are wire-shaped clips made of round cross-section steel bars, for example, SKL clip, Fastclip or e-clip; and plate-shaped clips with higher stiffness than wire-shaped ones, for instance, Nabla or K-clip (Figure 8.a). As the fastening force is achieved by the clip deformation, the change of its geometry and/or material properties significantly influences the clip's mechanical properties. This influence can be seen in Figure 8.b by comparing the toe force-toe displacement curves of different types of clips with different shapes and dimensions (Figure 8.a). The force-displacement curve is determined by a quasi-static test in which a force is applied to the clip toe, as shown by the example of the SKL 1 clip in Figure 9.a and the corresponding force-displacement curve for the same example (Figure 9.b). The force-displacement curve describes the static behaviour of the clip and provides information about its static stiffness, which significantly influences the static and dynamic behaviour of the entire fastening system.

Figure 9.b shows the changing point of the curve slope, called the second contact, which is characteristic of SKL-type clips. Therefore, it is often said that this type of clip has secondary stiffness, which is an advantage because secondary stiffness ensures high resistance to rail tilting and lifting [6, 56].

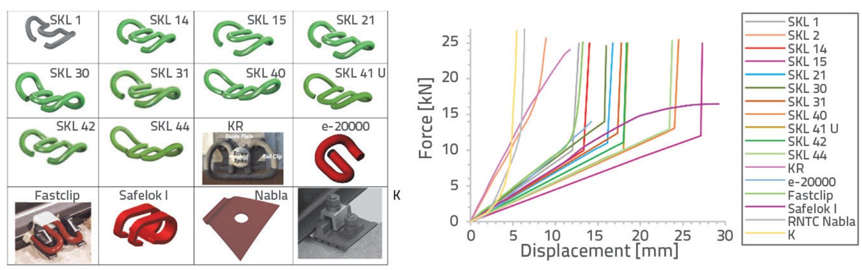


Figure 8. a) Different types of elastic clips; b) toe force-toe displacement curves (data from [56, 59-61, 63])

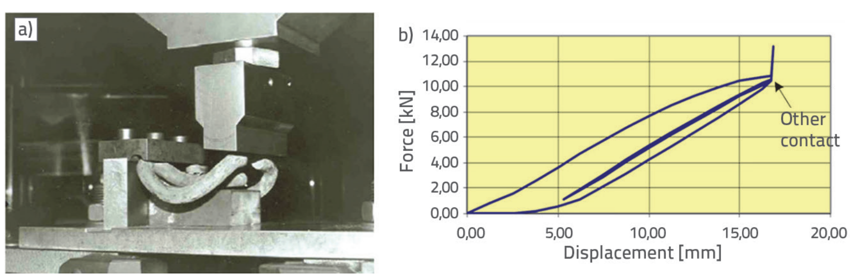


Figure 9. a) Example of laboratory quasi-static clip test; b) relation between toe force and toe displacement of a SKL-1 clip [10]

Changing the clip's geometry and material properties, changes not only the clip's stiffness, but also the magnitude of the fastening force. This is illustrated by the fastening force for a given displacement of the top face of the rail foot in the clip's force-displacement curve. Fastening force requirements depend on the rail size, railway vehicle type and speed, track characteristics and geometry, rail thermal variation, etc. [62]. It is important that the magnitude of the fastening force is achieved by a large clip deformation during installation. Satisfying this condition ensures that the magnitude of the fastening force varies as little as possible during the change in the rail pad thickness under different load cases and with the wear of individual components during the fastening system's lifetime [6, 57]. In most cases, a fastening force per clip in the range of 7.5 to 12.5 kN is achieved with deformations of the clip toe between 5 and 15 mm [58].

3.2. Dynamic strength assessment of the clips

Although the clips are elastic, they sometimes exhibit plastic deformation during installation and service. Therefore, conventional standard EN 13146-4 [64] methods for assessing the fastening system fatigue limit may not be applicable [17, 18]. Many experts perform analyses using different approaches to obtain the best possible assessment method for the dynamic strength of a particular clip type. Therefore, previous research in this area can be divided into two groups.

During operation, the elastic clips are subjected to a combination of static (fastening force at the rail foot) and dynamic loading (the passage of the railway vehicle); thus, they are consequently subjected to fatigue damage risk [15, 16, 18], and the formation of a critical crack in the clip represents a failure of the entire fastening system. In general, the operating range of the clip corresponds to high-cycle fatigue ($N > 10^6$); that is, material fatigue and the level of damage to an individual component of the fastening system depend on the load amplitude and frequency [15]. Accordingly, the first research group uses approaches based on fracture mechanics for clip dynamic strength assessment, where crack initiation and propagation in structural components are analysed by applying relevant parameters (stress intensity coefficient, J-integral, CTOD). For example, in articles [13, 17, 18, 65, 66], the high-cycle fatigue of the clip material is analysed using the stress-life (S-N) method, where the number of cycles to failure for a given stress amplitude was determined from Wöhler's (S-N) curves. In general, from an engineering perspective, a combination of expressions by Goodman and Gerber [66], showing the effect of mean stress on the clip's dynamic strength, is the most reliable method for the assessment of the clip's dynamic strength when the S-N method is used. In Ref. [67], crack growth was analysed by Paris' law using linear elastic fracture mechanics (stress intensity coefficient). In the papers [15, 68], the Rainflow method was applied, which is suitable for assessing dynamic strength under random loading, such as the passage of the railway vehicle.

At high speed of the railway vehicle, the rail head may be damaged or the rail running surface may corrugated. These changes are analysed by numerical calculations in Ref. [69]. The passage of wheels on such damaged rail sections causes vertical and horizontal high-frequency and large-amplitude dynamic forces (greater than 100 g) [5, 70]. Therefore, it is important to know not only the static but also the dynamic parameters of the fastening system, such as modal shapes, natural frequencies, dynamic stiffness, and the damping factor, which are significantly influenced by the fastening force and clip stiffness [71-73].

Therefore, the second research group includes the approach for the dynamic strength assessment of the clips from the frequency domain perspective [14, 19, 74]. In most cases, the clip is in direct contact with the rail and may vibrate in resonance with the rail, which can damage the clip, reduce the required fastening force magnitude force, or eventually cause the breakage of the clip [19, 74, 75]. Problems related to irregularities on the wheel surface, rails, and some track components are mainly caused by vertical forces, which are most significant up to 1500 Hz. Inertial forces that are partially transmitted through the wheels to the axle, suspension, and vehicle and through the track to the subgrade have a significant frequency of about 500 Hz [5]. Many field measurements have shown that clip damage is mainly caused by vibrations with frequencies lower than 1000 Hz, which are generated by the wheel-rail interaction [14]. However, a study on the dynamic parameters of the clip from the frequency domain perspective states that the frequency range in which the natural frequencies of the clip should be investigated is 0–1000 Hz [14, 74], and the study [19] indicates up to 2000 Hz. Previous research studies that analysed the fastening system, including all components, if noise is ignored, were performed in the range of 100–1000 Hz [71, 73, 76]. Therefore, the relationship between the clip's and rail's natural frequencies in response to the dynamic forces generated during rail-wheel contact must be understood. Therefore, Sun et al. [14] reported that the first important step in clip analysis is determining its modal parameters, including the natural modes and frequencies. Moreover, procedures that avoid clip and rail resonance should be considered in the early stages of clip development [14].

In both research groups, the magnitude of the fastening force, clip's geometry and material properties, and operation loads are the most critical parameters affecting the static and dynamic properties of the entire fastening system [12]. Therefore, changing these parameters can improve the fastening system's efficiency [77]. Consequently, the shape and dimensions of the existing clips as well as their material properties must be optimized [66, 68].

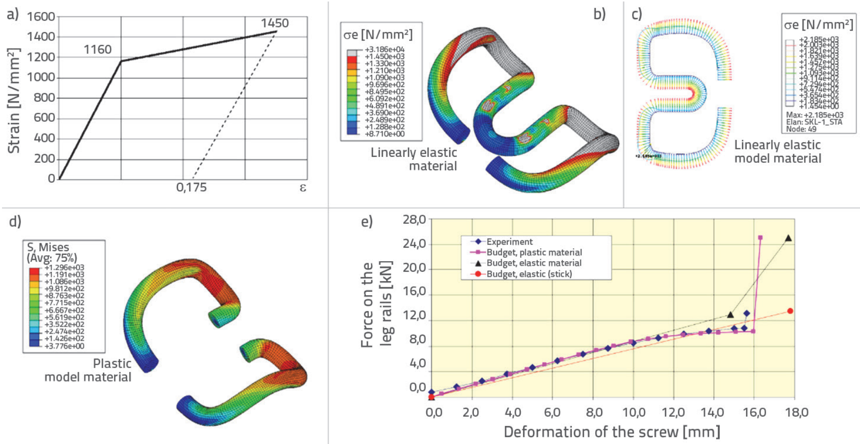


Figure 10. a) Elastoplastic material model; b) Spatial stress distribution of a linear elastic material clip obtained with the FE model; c) Stress distribution of a linear elastic material clip obtained with the beam model; d) spatial stress distribution with an elastoplastic material model; e) force-displacement curve for different SKL1 clip models [10]

3.3. Numerical models of elastic clips and fastening systems

As the clips were initially modelled by mathematical models containing only an elastic spring or a spring and damper pair, it was difficult to understand stress distributions in the clip, as well as the locations of the maximum stress due to their complex geometry. Moreover, determining the relation between the clip's geometrical and static and dynamic properties and fastening force was almost impossible, which could affect the mechanical behaviour of the fastening system.

Inspired by the above drawbacks of the then-existing assessments methods of clip mechanical properties and by the increasingly frequent occurrence of their breakage, Lakušić et al. performed clip static analyses using computer-aided engineering (CAE) tools and three-dimensional finite element (FE) models of elastic clips using the finite element method (FEM) [78]. The study showed that such an approach is reliable for analysing clips to evaluate their static behaviour. Moreover, the clip's spatial stress distribution can be used to predict where material fatigue damage may occur. In this study, the material model of the clip is defined as linear elastic. Therefore, the advantage of using the elastoplastic (Figure 10.a) over the linear elastic material model was highlighted Ref. [10], as well as the use of three-dimensional FE models (Figures 10.b and 10.d) over the beam models (Figure 10.c). This advantage was established by comparing the force-displacement curves for each analysed SKL 1 clip model (Figure 10.e).

Solving the common problems of fastening systems and understanding that a good grasp of the complex mechanical behaviour of the fastening system (which could only be determined by long-term and financially expensive tests) can provide the possibility to improve its efficiency have intensified research using FE models and CAE tools in the last two decades [10-16, 18, 19, 23, 47, 74, 79, 80]. Moreover, efficiency improvement is often achieved using parametric analysis by changing the geometry of the clip to extend its durability as well as the durability of the fastening system [77, 80, 81].

3.3.1. Example of the development of a numerical model of a clip and fastening system

Developing an FE model for an assembly, such as a fastening system, is a complex procedure involving several steps. The goal is to obtain numerical results that simulate the physical

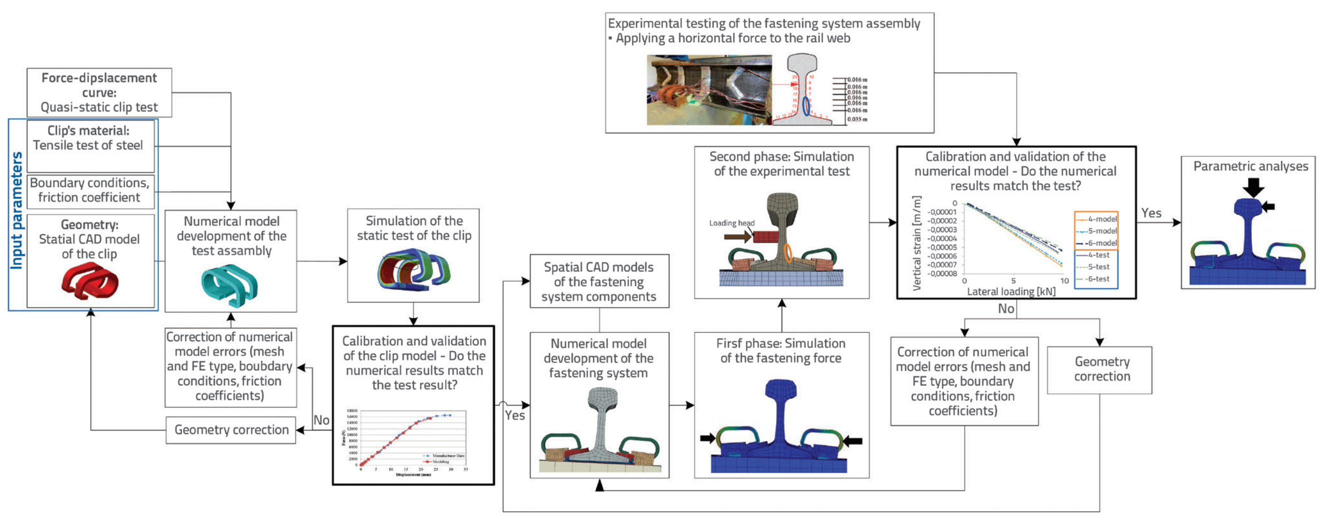


Figure 11. Flowchart of the FE model development of the fastening system based on the research reported in [23, 63, 84, 85]

Table 1. Overview of the clip types and steel material used for the numerical models in the reviewed literature

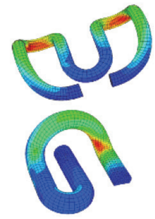
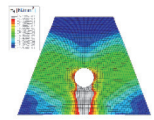
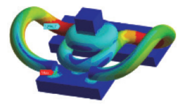
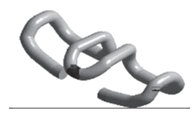
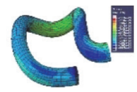
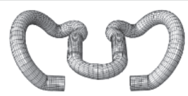
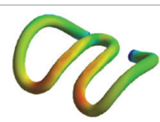
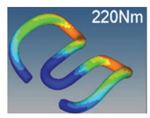
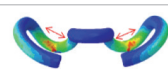
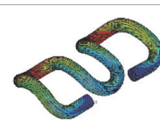
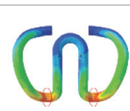
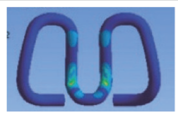
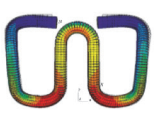
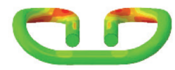
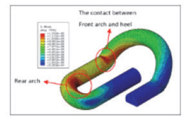
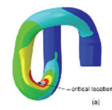
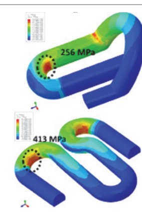
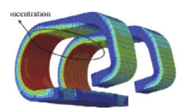
Clip type	Material	Modul of elasticity [MPa]	Material density [kg/m³]	Poisson's ratio	Yield strength [MPa]	Tensile strength [MPa]	Clip model	Ref.
SKL 1 SKL 12	steel	205000	7850	0.3	-	1450		[78]
SKL 1 e-2000 RNTC Nabla	steel	210000	7850	0.3	1160	1457		[10]
SKL 1	steel 38Si7	-	-	-	1077	1291		[66]
SKL 12	steel	210000	7850	0.313	-	1590		[44]
SKL 14	steel	200000	-	0.3	1300	-		[67]
SKL 14	steel	180000	7800	0.3	-	-		[47]
SKL 15	steel	21000	27146	0.313	-	1590		[11]
SKL 15	steel	200000	7850	0.27	1000	1300		[88]
SKL 15 SKLB 15	steel 38Si7	200000	-	0.27	≥1150	1300-1600		[18]
SKL 15	steel 60Si2Mn 38Si7	206000	7800	0.3	-	-		[68]
SKL 15	steel 38Si7	183333	7800	0.26	1242	1375		[89]
SKL 15	steel 38Si7	205000	7800	0.3	-	-		[77]
W rail clip	steel	210000	7500	0.3	-	-		[74]

Table 1. Overview of the clip types and steel material used for the numerical models in the reviewed literature - nastavak

Clip type	Material	Modul of elasticity [MPa]	Material density [kg/m^3]	Poisson's ratio	Yield strength [MPa]	Tensile strength [MPa]	Clip model	Ref.
KR	SPS9A	205000	-	-	1377	1509		[60]
e-clip	steel	206 000	7800	0.3	1176	1274		[19]
e-clip	steel 60Si2Mn	206000	7800	0.3	1200	1300		[13]
e-clip	steel SUP10	210000	-	-	-	-		[86]
Fastclip e-clip	steel	216700	7850	0.3	1311.3	1470.3		[87]
Safelok I	steel	158585	-	0.29	1261	1393		[85]
"-" - not specified in the literature								

phenomena of the physical model. Therefore, it is often said that a numerical model is a digital prototype of a physical model, and numerical simulations with numerical models are called computer experiments [82]. Such an approach saves time and money. Thus, in recent research studies on clips and fastening systems, simulations of the test procedures according to the standards are increasingly performed [48, 66, 77, 83]. An example of developing a detailed numerical model for the Safelok I fastening system is shown in Figure 11, and the procedure is described in detail in the research studies [23, 63, 84, 85].

Numerical simulations of laboratory tests of the fastening system and clips are usually divided into two phases. The first phase represents the simulation of the fastening force, that is, the introduction of a static stress state in the clip and fastening system. Depending on the simulated test, the second phase is the numerical simulation of the test load [10, 48, 66, 77, 78, 83]. In some studies, traffic load simulations have been performed as amplified static forces to simulate dynamic and impact loads [16, 75, 86], and recently, with the progress of computer technology, dynamic analyses are becoming more common [41, 87].

In most cases, the geometry of the clips is complex. Therefore, before creating the clip model in one of the computer-aided design (CAD) tools, a 3D scan of the actual model is often performed [18, 19, 67, 88]. The CAD model is then imported into one of the CAE computer tools to obtain a three-dimensional numerical model of the clip with the highest possible geometric accuracy. Material property is an essential input parameter for numerical analysis of clips and fastening systems. Therefore, tensile tests on the steel material of the clip have been performed in some studies [17, 66, 87, 89], and usually, they are 38Si7 or 60Si2Mn spring steel [90]. An overview of the clip types and steel material used in the reviewed literature and the properties of the steel are given in Table 1.

The reliability of numerical results describing the mechanical behaviour of a system depends mainly on input parameters such as geometry, material properties, and boundary conditions [91]. Numerical simulations usually contain idealisation and discretisation errors. Idealisation errors are also referred to as modelling errors and can include an approximation of a nonlinear problem by a linear problem, ignorance of the material and geometric nonlinearities, incorrect contact model definitions, treating a dynamic problem as a static one, etc. Discretisation errors arise from creating a finite element mesh that depends on

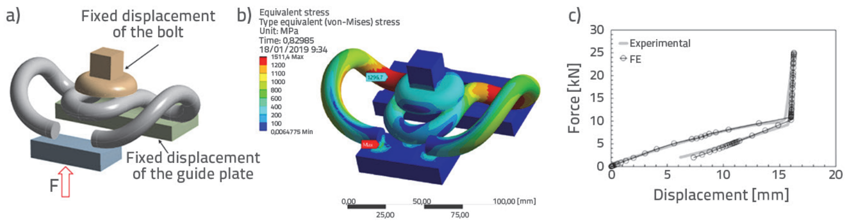


Figure 12. a) Quasi-static test of SKL-1 clip; b) the spatial stress distribution; c) validation of the numerical model of the clip [66]

the type, order, and number of finite elements used to discretise the geometry of the structural element under consideration.

To confirm the accuracy of the numerical results, the chosen finite elements, boundary conditions applied, material properties, friction coefficients and the like must be validated. In addition, it is necessary to analyse the convergence of the numerical results by performing analyses with different types of finite element mesh. Applied numerical algorithms must be verified if the results differ significantly from the experimental data.

The clip's numerical model accuracy is usually validated by comparing the results obtained by a numerical simulation of a force applied on the clip toe with the force-displacement curve obtained by an experimental quasi-static test using a physical test model (Figure 12). Some examples of static calibration and validation of clip models can be found in SKL 1 [10, 66], SKL 14 [15], and Safelok I clip [85] studies.

As the clip geometry is complex, the shape boundaries of the model often deviate from the actual model and fit the shapes of the finite elements. Therefore, an error due to the approximation of the geometry of the model may occur during its discretisation [91]. To minimise these errors and achieve timeous numerical analysis with sufficient numerical accuracy, it is possible to perform the FE mesh sensitivity analysis concerning the number and type of finite elements, as shown in the clip example in Figure 13.

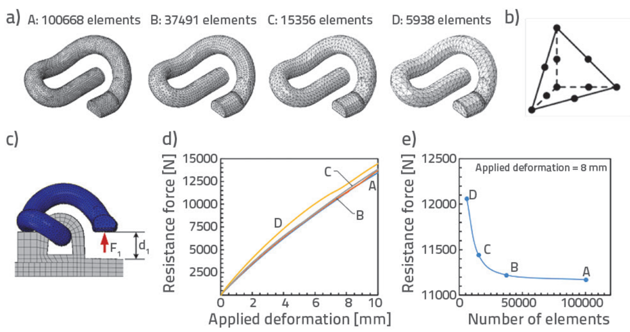


Figure 13. a) FE model of the e-clip with a different number of finite elements; b) tetrahedral finite element with ten nodes chosen for the discretisation of clip geometry; c) displacement applied to the clip toe; d) applied toe displacement – resistance force curves for each clip model; e) comparison of resistance forces at an applied displacement of 8 mm [16]

In this analysis, it was concluded that, for example, using tetrahedral elements with 10 nodes, 37491 finite elements are required for

a)

b)

Modal order	**Experimental model** [Hz]	**Simulation model** [Hz]
1	584	579
2	685	692
3	1455	1465
4	1512	1535
5	1726	1738

c)

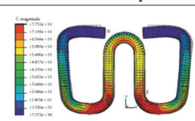
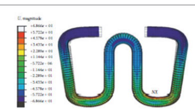
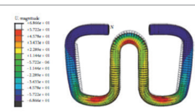
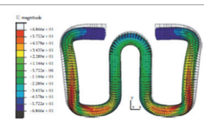
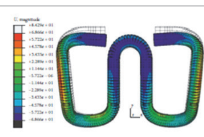
Mode	**Bolt force** [kN]	**Clip frequency** [Hz]	**Mode shape**
First	20-33	160-182	
Second	20-33	286	
Third	20-33	520-636	
Fourth	20-33	680-702	
Fifth	20-33	934	

Figure 14. a) Assembly modal test of the clip; b) comparison of natural frequencies of the numerical model and modal test; c) natural frequencies and modal shapes obtained with the numerical analysis of the W1 clip [74]

a reasonable approximation of the clip model's geometry [16]. In the research [66], a similar procedure was performed where hexahedral finite elements were chosen to approximate the geometry of the SKL 1 clip. The total number of finite elements in the numerical model of the test assembly (Figure 12) was 49,097, and the total number of nodes was 190,060. In this study, the size of the finite elements was gradually reduced until the variation in the von Misses stresses was less than 5 %.

When considering the dynamic behaviour of the clip, the clip's numerical model can be validated by comparing dynamic parameters such as the natural frequencies and modal vibration shapes of the clip obtained by numerical calculation with the data obtained, for example, by experimental modal analysis [14, 74]. An example of the dynamic calibration of the clip's FE model is shown in Figure 14.

If the behaviour of the fastening system is observed, especially in the case of lateral or longitudinal loading, the resistance of the system to rail displacement is partially achieved by the frictional force [41]. In this case, it is important to define the contact model between the individual components correctly. For such a model, except for validation of the numerical results at the level of one component, the numerical model must be calibrated at the level of the entire fastening system. This way, the friction coefficients that minimise the difference between the numerical and test results on the physical model can be determined. An example of such a calibration is shown in Figure 11.

After the calibration and validation of the clip's and/or fastening system's numerical model, parametric analyses can be performed. The most frequently considered parameters are the dimensions, shape [[16, 74, 77, 80] and material properties of the clip [68], the magnitude of the axle load and its position on the rail running surface [23, 47], and the distance of concrete sleepers, that is, the distance of the rail supports [23], the change in the stiffness of the rail pad [48, 49].

4. Conclusion

The progress of computers in the last two decades has prompted intensive computer experiment research on complex systems. These studies attempt to describe the mechanical behaviour of these systems as faithfully as possible to determine the parameters of specific components that significantly affect the efficiency improvement of the whole system.

The advantage of computer experiments is also recognised in the numerical calculations of fastening systems. These experiments simplified the calculations while being less expensive and time consuming to investigate the causes of problems in fastening systems that occur with the progress of railways. Hence, individual components and the mechanical properties of the entire fastening system can be improved through parametric analysis. The elastic clip is recognised as a critical and vital component that significantly affects the static and dynamic behaviour of the fastening system, for example, by changing the geometry and/or material properties of the clip. The following were drawn after a comprehensive review of the research area:

- The fastening force at the rail foot is achieved by the deformation of the clip. Therefore, the geometry of the clip and the properties of its material can significantly influence the mechanical properties of the fastening system and optimise its efficiency.
- When analysing the fastening system under an axle load, the stress in the clips depends on the size of the L/V ratio (the ratio of the lateral and vertical force components) and the position of this load on the rail running surface, as well as the rail side the clip is clipped on. For some fastening systems and clip types, the stress in the clip at an axle load with a higher L/V ratio may exceed the yield strength, resulting in permanent deformation, more rapid development of microcracks, and damage to the clip.
- The S-N method is reliable for high-cycle fatigue analysis for the elastic clip material, whereby data on the number of cycles to failure for a given stress amplitude is obtained from Wöhler's S-N curves. It was also shown that when the S-N method is used to evaluate the dynamic strength of the clip, the combination of Goodman's and Gerber's expressions showing the effect of mean stress on the clip dynamic strength is the most reliable.
- As the rail and clip can vibrate in resonance, it is very important to study not only the static but also the dynamic parameters of the fastening system, such as the modal modes of vibration and the significant natural frequencies of the clip, which range from 0 to 1000 Hz.

Recommendations for further research:

- The influence of specific geometrical parameters of the clip on its static parameters as well as its dynamic strength must be investigated. At the same time, evaluation methods from the fracture mechanics perspective should be applied, and if a certain section of a railway line is studied, the evaluation must be conducted in the frequency domain as well.
- Recently, clip and fastening systems testing procedures according to standards have been simulated. Hence, it can be said that virtual laboratories are gradually emerging, where the safety and quality of newly developed components and fastening systems can be initially evaluated. Hence, it is necessary to establish guidelines for the development of reliable digital prototypes for conducting computer experiments. These guidelines will ensure that when new fastening systems are developed or existing ones are modified, their stability and quality can be evaluated in accordance with the standards. In this way, the challenges of designing clip shapes and other components of the fastening system could also be overcome.

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REFERENCES

[1] Esveld, C.: Modern Railway Track, 2nd ed., Zaltbommel, The Netherlands, MRT Productions, 2001.

[2] Tzanakakis, K.: The Railway Track and Its Long Term Behaviour: A Handbook for a Railway Track of High Quality, 1st ed., Springer-Verlag Berlin Heidelberg, 2013, https://doi.org/10.1007/978-3-642-36051-0.

[3] Vaquero, C., Alfonso, I.: Optimización y análisis de comportamiento de sistemas de sujeción para vías de ferrocarril de alta velocidad española, Universidad de Cantabria, 2006.

[4] Berggren, E.: Railway track stiffness: dynamic measurements and evaluation for efficient maintenance, Royal Institute of Technology (KTH), 2009.

[5] Knothe, K.L., Grassie, S.: Modelling of Railway Track and Vehicle/Track Interaction at High Frequencies, Veh. Syst. Dyn., 22 (1993) , pp. 209-262, https://doi.org/10.1080/00423119308969027.

[6] Giannakos, K.: Secondary Stiffness of Fastening Clips: Influence on the Behavior of the Railway Track Panel, Materials and Infrastructures 2, 5B (2016), J. Torrenti, La Torre, F., John Wiley & Sons, Ltd, pp. 115-129, https://doi.org/10.1002/9781119318613.ch9.

[7] Sayeed, M.A., Shahin, M.A.: Design of ballasted railway track foundations using numerical modelling. Part I: Development, Can. Geotech. J., 55 (2017) 3, pp. 353-368, https://doi.org/10.1139/cgj-2016-0633.

[8] Sadeghi, J., Fesharaki, M., Khajehdezfuly, A.: Influences of train speed and axle loads on life cycle of rail fastening clips, Trans. Can. Soc. Mech. Eng., 39 (2015) 1, pp. 1-11.

[9] Xiao, X., Jin, X., Wen, Z.: Effect of disabled fastening systems and ballast on vehicle derailment, J. Vib. Acoust., 129 (2006) , pp. 217-229, https://doi.org/10.1115/1.2424978.

[10] Lakušić, S., Bartoš, D., Bajić, A.G.: Analysis of elastic fastening spring clips for rail fastening, ŽELJEZNICE 21, 7 (2008) 3, pp. 7-12.

[11] Choi, S.H., Park, B.H., Yun, K-M., Bae, H.U., Lim, N.H.: Behavior of Tension Clamp in Rail Fastening System, J. Korea Acad. Coop. Soc., 16 (2015) 12, pp. 8812-8819, https://doi.org/10.5762/KAIS.2015.16.12.8812.

[12] Baik, C.H., Joo, B.G., Choi, J.Y., Choi, I.Y., Park, Y.G. : The parametric study on the performance characteristics of elastic rail fastening system on the sharp curved track, in Proceedings of the KSR Conference, (2011) , pp. 2163-2173.

[13] Hong, X., Xiao, G., Haoyu, W., Xing, L., Sixing, W.: Fatigue damage analysis and life prediction of e-clip in railway fasteners based on ABAQUS and FE-SAFE, Adv. Mech. Eng., 10 (2018) 3, pp. 1-12, https://doi.org/10.1177/1687814018767249.

[14] Sun, L., Yan, Z., Xiao, J., Fang, H., Cui, S.: Experimental analysis of the modal characteristics of rail fastening clips, Proc. Inst. Mech. Eng. Part F J. Rail Rapid Transit, 234 (2020) 2, pp. 134-141, https://doi.org/10.1177/0954409719834784.

[15] Mohammadzadeh, S., Ahadi, S., Nouri, M.: Stress-based fatigue reliability analysis of the rail fastening spring clip under traffic loads, Lat. Am. J. Solids Struct., 11 (2014) 6, pp. 993-1011, https://doi.org/10.1590/S1679-78252014000600006.

[16] Hasap, A., Paitekul, P., Noraphaiphipaksa, N., Kanchanomai, C.: Analysis of the fatigue performance of elastic rail clip, Eng. Fail. Anal., 92 (2018) , pp. 195-204, https://doi.org/10.1016/j.engfailanal.2018.05.013.

[17] Tamagawa, S.: A fatigue limit diagram for plastic rail clips, COMPRAIL 2014, pp. 839-848, 2014., https://doi.org/10.2495/CR140701.

[18] Park, Y.C., An, C., Sim, H.B., Kim, M., Hong, J.K.: Failure Analysis of Fatigue Cracking in the Tension Clamp of a Rail Fastening System, Int. J. Steel Struct., 19 (2019) 5, pp. 1570-1577, https://doi.org/10.1007/s13296-019-00231-5.

[19] Xiao, H., Wang, J.B., Zhang, Y.R.: The fractures of e-type fastening clips used in the subway: Theory and experiment, Eng. Fail. Anal., 81 (2017) , pp. 57-68, https://doi.org/10.1016/J.ENGFAILANAL.2017.07.006.

[20] Oregui, M., Li, Z., Dollevoet, R.: An investigation into the modeling of railway fastening, Int. J. Mech. Sci., 92 (2015) , pp. 1-11, https://doi.org/10.1016/j.ijmecsci.2014.11.019.

[21] Kaewunruen, S.: Experimental and numerical studies for evaluating dynamic behaviour of prestressed concrete sleepers subject to severe impact loading, University of Wollongong, 2007.

[22] Sluganović, V., Lakušić, S., Lazarević, D.: Track ballast modelling by discrete element method, GRAĐEVINAR, 71 (2019) 7, pp. 589-600, doi: https://doi.org/10.14256/JCE.2350.2018

[23] Chen, Z., Shin, M., Andrawes, B., Edwards, J.R.: Parametric study on damage and load demand of prestressed concrete crosstie and fastening systems, Eng. Fail. Anal., 46 (2014), pp. 49-61., https://doi.org/10.1016/j.engfailanal.2014.08.002

[24] LoPresti, J., McHenry, M.: Detection of Concrete Tie Rail Seat Deterioration, Washington DC, 2019.

[25] Vranešić, K., Lakušić, S., Serdar, M.: Corrosion and stray currents at urban track infrastructure, GRAĐEVINAR, 72 (2020) 7, pp. 593-606, doi: https://doi.org/10.14256/JCE.2909.2020

[26] Gutierrez Romero, M., Edwards, J.R., Barkan, C.P.L., Wilson, B., Mediavilla, J.: Advancements in fastening system design for North American Concrete crossties in heavy-haul service, Proceedings of the AREMA 2010 Annual Conference & Exposition, Orlando, FL, USA, 2010 .

[27] CEN: EN 13481-2 Željeznički sustav - Željeznički gornji ustroj - Zahtjevi za izradbu kolosiječnog pričvrsnog pribora - 2.dio: Kolosiječni pričvrsni pribor za betonske pragove, Brussels, 2017.

[28] CEN: HRN EN 13146 - Željeznički gornji ustroj - Ispitne metode za kolosiječni pričvrsni pribor - 1.-9. dio, (2019), CEN, 2019.

[29] American Railway Engineering and Maintenance-of-Way Association (AREMA): Chapter 30 Ties, Manual for Railway Engineering - Volume 1, 2019.

[30] Standards Australia: AS1085.19 Railway track material - Part 19: Resilient fastening assemblies, 2003.

[31] Hay, W.W.: Railroad engineering, 2nd ed., John Wiley & Sons, 1982.

[32] Lakušić, S., Haladin, I., Vranešić, K.: Railway infrastructure in earthquake affected areas, GRAĐEVINAR, 72 (2020) 10, pp. 905-922, doi: https://doi.org/10.14256/JCE.2967.2020

[33] Williams, B., Holder, D.E., Dersch, M., Edwards, R., Barkan, C.:Quantification of Lateral Forces in Concrete Crosstie Fastening Systems, Transportation Research Board 94th Annual Meeting, Washington D.C., 2015.

[34] Manda, K.R., Dersch, M., Kernes, R., Edwards, R.J., Lange, D.A.: Vertical Load Path Under Static and Dynamic Loads in Concrete Crosstie and Fastening Systems, 2014 Joint Rail Conference, Colorado Springs, Colorado, USA, 2014., https://doi.org/10.1115/JRC2014-3832.

[35] Holder, B.G.J., Qian, Y., Dersch, M.S., Edwards, J.R.: Lateral load performance of concrete sleeper fastening systems under non-ideal conditions, RailTEC Faculty and Student Papers and Presentations IHHA 2017, Cape Town, 2017.

[36] Chen, Z., Andrawes, B.: A mechanistic model of lateral rail head deflection based on fastening system parameters, Proc. Inst. Mech. Eng. Part F J. Rail Rapid Transit, 231 (2017) 9, pp. 999-1014, https://doi.org/10.1177/0954409716642485.

[37] Kaewunruen, S., Remennikov, A.: Dynamic properties of railway track and its components: a state-of-the-art review, Weiss, BN (ed) New Research on Acoustics, Nova Science Publishers, Hauppauge, New York, pp. 197-220, 2008.

[38] Sol-Sánchez, M., Moreno-Navarro, F., Rubio-Gámez, M.C.: The use of elastic elements in railway tracks: A state of the art review, Conpp. Build. Mater., 75 (2015), pp. 293-305, https://doi.org/10.1016/j.conbuildmat.2014.11.027.

[39] Vossloh Fastening Systems GmbH: System W 14, 2019., www.vossloh.com/en/products-and-solutions/product-finder/product_11018

[40] CEN:EN 13146-1:2019 Željeznički sustav - Željeznički gornji ustroj - Metode ispitivanja za kolosiječni pričvrsni pribor - 1. dio: Određivanje otpora uzdužnomu pomicanju tračnice, 2019.

[41] Zhang, Z.: Finite element analysis of railway track under vehicle dynamic impact and longitudinal loads, Doktorski rad, University of Illinois at Urbana-Champaign, 2015.

[42] Turek, J.: Non-linear Response of the Track, Veh. Syst. Dyn., 24 (1995) 1, pp. 265-279, https://doi.org/10.1080/00423119508969630.

[43] Hasap, A., Noraphaiphipaksa, N., Kanchanomai, C.: Influence of malposition on the performance of elastic rail clip: Toe load, stress, and friction, Structures, 28 (2020), pp. 2661-2670, https://doi.org/10.1016/J.ISTRUC.2020.10.073.

[44] Lee, D.W., Choi, J.Y., Baik, C.H., Park, Y.G.: Influence of initial clamping force of tension clamp on performance of elastic rail fastening system, J. Korean Soc. Civ. Eng., 33 (2013) 3, pp. 1243-1251, https://doi.org/10.12652/Ksce.2013.33.3.1243

[45] CEN: EN 13146-7 Željeznički sustav - Željeznički gornji ustroj - Metode ispitivanja za kolosiječni pričvrsni pribor - 7. dio: Određivanje pričvrsne sile i otpornosti prema izdizanju, 2019.

[46] Sung, D.: Nonlinear Analysis Method for Serviceability Investigation of Bridge Deck Ends with a Concrete Slab Track, Adv. Civ. Eng., 2018 (2018), pp. 1-9, https://doi.org/10.1155/2018/6075686.

[47] El-sayed, H.M., Zohny, H.N., Riad, H.S., Fayed, M.N.: A three-dimensional finite element analysis of concrete sleepers and fastening systems subjected to coupling vertical and lateral loads, Eng. Fail. Anal., 122 (2021) 105236, pp. 1-14, https://doi.org/10.1016/j.engfailanal.2021.105236.

[48] Sadeghi, J., Seyedkazemi, M., Khajehdezfuly, A.: Nonlinear simulation of vertical behavior of railway fastening system, Eng. Struct., 209 (2020) 110340, pp. 1-13, https://doi.org/10.1016/j.engstruct.2020.110340.

[49] Liu, Y.: Experimental and numerical analysis of nonlinear properties of rail fastening systems, Doktorski rad, Université Paris-Est, 2015.

[50] CEN:EN 13146-9 Željeznički sustav - Željeznički gornji ustroj - Metode ispitivanja za kolosiječni pričvrsni pribor - 9. dio: Određivanje krutosti, 2020.

[51] Wang, S.W., Luo, Y.Y., Li, L., Liu, L.: Dynamic Property Analysis of Rubber Absorber in Rail Fastenings of Different Force Condition, Vibration, Structural Engineering and Measurement II, 226 (2012), pp. 877-880. https://doi.org/10.4028/www.scientific.net/AMM.226-228.877.

[52] Luo, Y., Liu, Y., Yin, H.P.: Numerical investigation of nonlinear properties of a rubber absorber in rail fastening systems, Int. J. Mech. Sci., 69 (2013) , pp. 107-113, https://doi.org/10.1016/j.ijmecsci.2013.01.034.

[53] Boon, J., Kesler, C., Hayes, W.F., Whitten, B.T.: High Speed Rail Tilt Train Technology: A State of the Art Survey, United States Department of Transportation, Federal Railroad Administration, 1992.

[54] Holder, D.E., Csenge, M.V., Qian, Y., Dersch, M.S., Edwards, J.R., Van Dyk, B.J.: Laboratory investigation of the Skl-style fastening system's lateral load performance under heavy haul freight railroad loads, Eng. Struct., 139 (2017) , pp. 71-80, https://doi.org/10.1016/J.ENGSTRUCT.2017.02.039.

[55] CEN: EN 13146-2 Željeznički sustav - Željeznički gornji ustroj - Ispitne metode za kolosiječni pričvrsni pribor - 2. dio: Određivanje otpora zakretanju tračnice, 2012.

[56] Vossloh Fastening Systems GmbH: Conventional Rail: Innovation for the rail of tomorrow, www.vossloh.com, 2019.

[57] Profillidis, V.A.: Railway Management and Engineering, 3. ed., Taylor & Francis Group, 2017.

[58] FIB - The International Federation for Structural Concrete: FIB 37: Precast concrete railway track systems, 2006., https://doi.org/doi.org/10.35789/fib.BULL.0037.

[59] Vossloh AG: Products & solutions: Rail fastening systems, www.vossloh.com , 2021.

[60] Kim, S.H., Fang, X.J., Park, Y.C., Sim, H.-B.: Evaluation of Structural Behavior and Fatigue Performance of a KR-Type Rail Clip, Applied Sciences, 11 (2021) 24, https://doi.org/10.3390/app112412074.

[61] Tomičić-Torlaković, M. Ranković, S.: Gornji stroj železnica, Beograd: University of Beograd, 1996.

[62] Esveld, C.: Geometrisch en constructief ontwerp van wegen en spoorwegen: Part D, Railway Structural Design, Delft University of Technology, Delft, 2004.

[63] Chen, Z., Shin, M., Andrawes, B.: Finite element modeling of the fastening systems and the concrete sleepers in North America, Proceedings of the 2013 International Heavy Haul Association Conference, New Delhi, India, 2013.

[64] CEN: EN 13146-4 Željeznički sustav - Željeznički gornji ustroj - Metode ispitivanja za kolosiječni pričvrsni pribor - 4. dio: Utjecaj ponavljanja opterećenja, 2020.

[65] Deshimaru, T., Tamagawa, S., Noguchi, M., Kataoka, H.: Improving the Performance of Rail Fastening System, Quarterly Report of RTRI, 59 (2018) 3, https://doi.org/10.2219/rtriqr.59.3_181.

[66] Ferreño, D. et al.: Experimental and finite element fatigue assessment of the spring clip of the SKL-1 railway fastening system, Eng. Struct., 188 (2019) , pp. 553-563, https://doi.org/10.1016/J.ENGSTRUCT.2019.03.053.

[67] Mohammadzadeh, S., Ahadi, S., Keshavarzian, H.: Assessment of fracture reliability analysis of crack growth in spring clip type Vossloh SKL14, Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability, 228 (2014) 5, pp. 460-468, https://doi.org/10.1177/1748006X14527926.

[68] Wang, P., Zhao, C., Lu, J., Yao, L., Ming, X.: Analysis on the Effects of Material Parameters on the Fatigue Performance of Novel Anticorrugation Elastic Rail Clips, Shock Vib., 2020 (2020), pp. 1-11, https://doi.org/10.1155/2020/5416267.

[69] Ovchinnikov, D., Bondarenko, A., Kou, L., Sysyn, M.: Extending service life of rails in the case of a rail head defect, GRAĐEVINAR, 73 (2021) 2, pp. 119-125, doi: https://doi.org/10.14256/JCE.2860.2019

[70] De Man, A.P.: Dynatrack: A survey of dynamic railway track properties and their quality, Doktorski rad, Delft University Press, Delft, 2002.

[71] Thompson, D.J. Verheij, J.W.: The dynamic behaviour of rail fasteners at high frequencies, Appl. Acoust., 52 (1997) 1, pp. 1-17, https://doi.org/10.1016/S0003-682X(97)00016-9.

[72] Vincent, N., Thompson, D.J.: Track Dynamic Behaviour at High Frequencies. Part 2: Experimental Results and Comparisons with Theory, Veh. Syst. Dyn., 24 (1995) 1, pp. 100-114, https://doi.org/10.1080/00423119508969618.

[73] Valikhani, M., Younesian, D.: Application of an optimal wavelet transformation for rail-fastening system identification in different preloads, Measurement, 82 (2016), pp. 161-175, https://doi.org/10.1016/j.measurement.2015.12.039.

[74] Gao, X., Wang, A., He, Y., Gu, X.: Structural Improvement of the ω-Type High-Speed Rail Clip Based on a Study of Its Failure Mechanism, Shock Vib., 2019 (2019) , pp. 1-14, https://doi.org/10.1155/2019/4127065.

[75] Ling, L., Li, W., Shang, H., Xiao, X., Wen, Z., Jin, X.: Experimental and numerical investigation of the effect of rail corrugation on the behaviour of rail fastenings, Veh. Syst. Dyn., 52 (2014) 9, pp. 1211-1231, https://doi.org/10.1080/00423114.2014.934844.

[76] Oregui, M., Li, Z., Dollevoet, R.: Identification of characteristic frequencies of damaged railway tracks using field hammer test measurements, Mech. Syst. Signal Process., 54-55 (2015) , pp. 224-242, https://doi.org/10.1016/J.YMSSP.2014.08.024.

[77] Cheng, Y.C., Kuo, C.M., Lee, C.K., Xie, M.S.: Optimization design of rail clip in Vossloh fastening system by uniform design and grey relation analysis, Proc. Inst. Mech. Eng. Part C J. Mech. Eng. Sci., 235 (2021) 21, pp. 5639-5652, https://doi.org/10.1177/0954406221995529.

[78] Lakušić, S., Bartoš, D., Bajić, G. A.: Experimental and numerical analysis of the rail fastening spring clips types SKL1-SKL12, 22nd DANUBIA-ADRIA Symposium on Experimental Methods in Solid Mechanics, Parma, University of Parma, pp. 248-249, 2005.

[79] Lakušić, S., Bartoš, D.: Numerical analysis of rail fastening spring clips, European Modelling Symposium, 2006.

[80] Todorov, G., Kamberov, K., Pantaleev, T., Kopralev, N.: Elastic rail clip design development, based on virtual prototyping, The 10th International Symposium Machine and Industrial Design in Mechanical Engineering, 393 (2018) 12120, Novi Sad, Serbia, https://doi.org/10.1088/1757-899x/393/1/012120.

[81] Gao, X., Wang, A., Liu, L., He, Y., Ju, L.: Analysis of failure mechanism of W1-type fastening clip in high speed railway and structure study of damping composite, Eng. Fail. Anal., 118 (2020) 104848, pp. 1-14,https://doi.org/10.1016/j.engfailanal.2020.104848.

[82] Santer, T.J., Williams, B.J., Notz, W.I.: The Design and Analysis of Computer Experiments, 2nd Ed., Springer Science+Business Media, LLC, New York, USA, 2018., https://doi.org/10.1007/978-1-4939-8847-1.

[83] Song, X.L., Qian, Y., Wang, K., Liu, P.: Effect of Rail Pad Stiffness on Vehicle-Track Dynamic Interaction Excited by Rail Corrugation in Metro, Transp. Res. Rec. J. Transp. Res. Board, 2674 (2020), pp. 1-18, https://doi.org/10.1177/0361198120918584.

[84] Bizarria do Carmo, T.: Multifaceted Aproach for the Analysis of Rail Pad Assembly Response, Diplomski rad, University of Illinois at Urbana-Champaign, 2014.

[85] Chen, Z., Shin, M., Wei, S., Andrawes, B., Kuchma, D.A.: Finite element modeling and validation of the fastening systems and concrete sleepers used in North America, Proceedings of the Institution of Mechanical Engineers Part F J. Rail Rapid Transit, 228 (2014) 6, pp. 590-602.

[86] Hasap, A., Paitekul, P., Noraphaiphipaksa, N., Kanchanomai, C.: Influence of toe load on the fatigue resistance of elastic rail clips, Proceedings of the Institution of Mechanical Engineers Part F J. Rail Rapid Transit, 232 (2018) 4, pp. 1078-1087, https://doi.org/10.1177/0954409717707834.

[87] Liu, Z., Tsang, K.S., Liu, Y., Pang, J.H.L.: Finite element and experimental study on multiaxial fatigue analysis of rail clip failures, Fatigue Fract. Eng. Mater. Struct., 43 (2020) 10, pp. 2390-2401, https://doi.org/10.1111/ffe.13310.

[88] Cho, J.G., Kim, J.W., Koo, J.S.: A Study on Fatigue Strength Improvement for Tension Clamp of Railway Using Work Hardening, IOP Conference Series: Materials Science and Engineering, 491 (2019) 12028, pp. 1-8, https://doi.org/10.1088/1757-899x/491/1/012028.

[89] Liu, Y., Li, Q., Jiang, X., Liu, H., Yuan, X., Zhu, Z.: The Effect of Material Static Mechanical Properties on the Fatigue Crack Initiation Life of Rail Fastening Clips, Adv. Civ. Eng., 2021 (2021) 1366007, pp.1-14, https://doi.org/10.1155/2021/1366007.

[90] CEN: EN 10089 Hot rolled steels for quenched and tempered springs - Technical delivery conditions, 2003

[91] Dvornik, J., Lazarević, D.: Manjkavost proračunskih modela inženjerskih konstrukcija, GRAĐEVINAR, 57 (2005) 4, pp. 227-236.