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**Abstract**

Transition zones in railway tracks are locations with considerable variation in the vertical stiffness of supporting structures. Typically, they are located near engineering structures, such as bridges, culverts, tunnels and level crossings. In such locations, the variation of the vertical stiffness and the differential track settlement result in amplification of the dynamic forces acting on the track. This amplification contributes to the degradation process of ballast and subgrade, ultimately resulting in the increase of maintenance costs. The paper studies a corrective countermeasure that can mitigate the track degradation in transition zones when differential settlement appears. The countermeasure is the adjustable rail fastener and its working principle is to eliminate the gap under hanging sleepers by adjusting the position of shims (height of the fastener). The adjustable fasteners are first tested on three transition zones, wherein the adjusted heights of fasteners (accumulated voiding) are recorded after 2-month and 5-month operation. The test results show the adjustable fasteners are effective to mitigate the track degradation in the transition zones. The effect of the adjustable fasteners on the dynamic behaviour of transition zones is analysed using FE method. The results show that the adjustable fasteners are effective to reduce the amplification of wheel forces, achieve a better stress distribution in ballast, and decrease the normal stresses in rails in transition zones. Parametric studies are also performed to study the applicability of the adjustable fasteners.



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| **Keywords** | Adjustable fasteners; Railway track modelling; Transition zone; Corrective countermeasures; Finite element method. |
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14-Dec-2017

Dear Editors,

We wish to submit an original research article entitled "*Corrective Countermeasure for Track Transition Zones in Railways: Adjustable Fastener*" for consideration by *Engineering Structures*.

We confirm that this work is original and has not been published elsewhere, nor is it currently under consideration for publication elsewhere.

In this paper, we present a corrective countermeasure for transition zones in railway tracks. The corrective countermeasure is first tested in three transition zones. Then, its mechanical behaviour is studied using a FE (explicit dynamic) model which considers the nonlinear contact between sleepers and ballast during the trains passing process.

We believe that this manuscript is appropriate for publication by *Engineering Structures* because it possesses the novelty to study the mechanical behaviour of a new countermeasure for transition zones and fits the scopes of *Engineering Structures.*

There are 6,500 words in the article. We have no conflicts of interest to disclose. Thank you for your consideration of this manuscript.

Sincerely,

Ph. D candidate

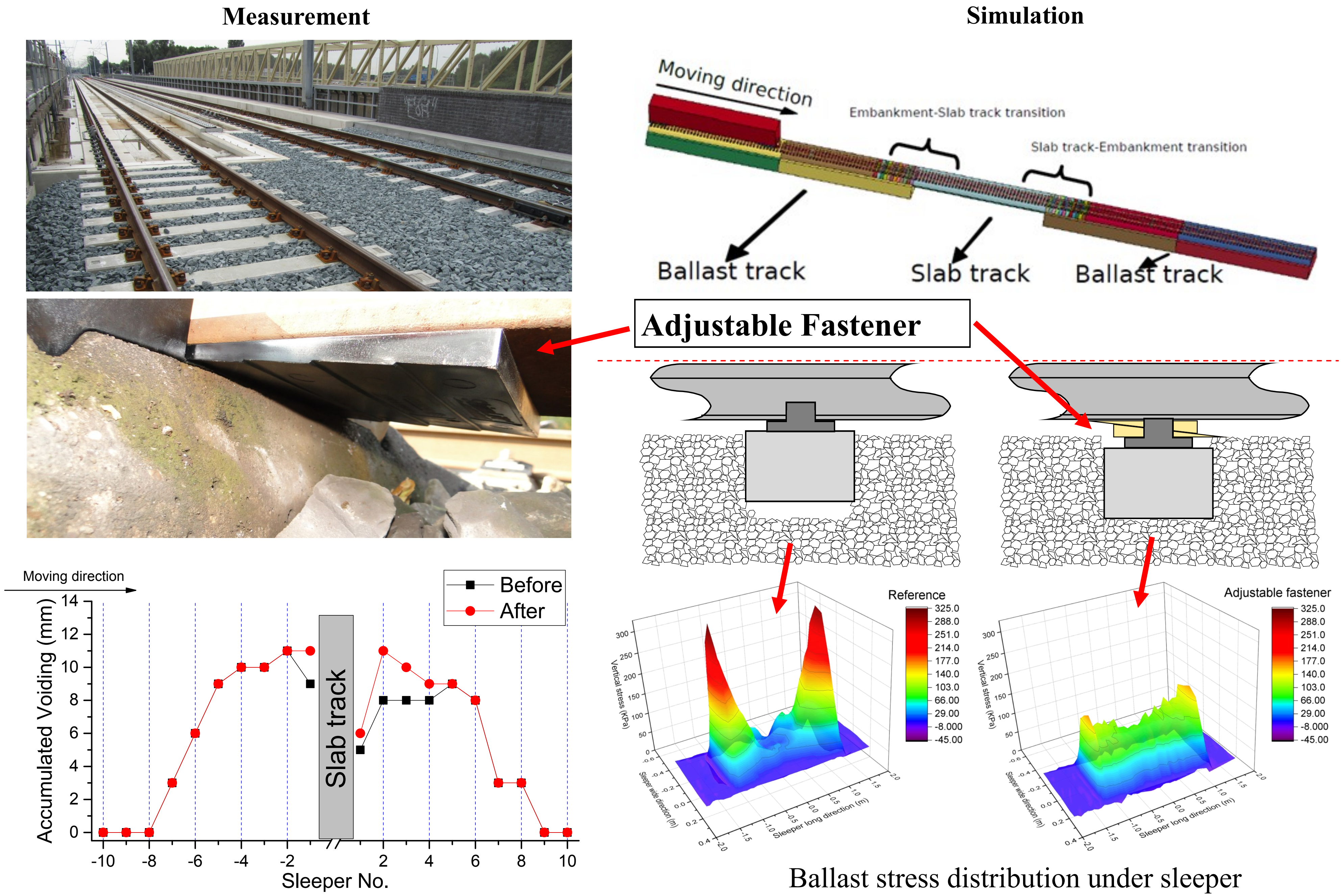
Structural Engineering department,

Civil Engineering and Geosciences faculty,

TU Delft (Delft University of Technology)

# Highlights

- The paper studies a corrective countermeasure (the adjustable fastener) that can mitigate the track degradation in transition zones when differential settlement appears.
- Field measurements of the adjustable fastener are performed in transition zones to test the value of accumulated voiding.
- Dynamic behaviour of transition zones with and without the adjustable fastener is compared and analysed using FEM.
- Since the nonlinear contact between the ballast and sleeper is considered, the hanging sleeper is modelled more accurately, and the stress distribution in ballast is analysed.



Measurement
Simulation
Moving direction
Embankment-Slab track transition
Slab track-Embankment transition
Ballast track
Slab track
Ballast track
Adjustable Fastener
Moving direction
Before
After
Slab track
Accumulated Voiding (mm)
Sleeper No.
Reference
Adjustable fastener
Vertical stress (KPa)
Sleeper wide direction (m)
Sleeper long direction (m)
Ballast stress distribution under sleeper

# Corrective Countermeasure for Track Transition Zones in Railways: Adjustable Fastener

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## Abstract

Transition zones in railway tracks are locations with considerable variation in the vertical stiffness of supporting structures. Typically, they are located near engineering structures, such as bridges, culverts, tunnels and level crossings. In such locations, the variation of the vertical stiffness and the differential track settlement result in amplification of the dynamic forces acting on the track. This amplification contributes to the degradation process of ballast and subgrade, ultimately resulting in the increase of maintenance costs.

The paper studies a corrective countermeasure that can mitigate the track degradation in transition zones when differential settlement appears. The countermeasure is the adjustable rail fastener and its working principle is to eliminate the gap under hanging sleepers by adjusting the position of shims (height of the fastener). The adjustable fasteners are first tested on three transition zones, wherein the adjusted heights of fasteners (accumulated voiding) are recorded after 2-month and 5-month operation. The test results show the adjustable fasteners are effective to mitigate the track degradation in the transition zones. The effect of the adjustable fasteners on the dynamic behaviour of transition zones is analysed using FE method. The results show that the adjustable fasteners are effective to reduce the amplification of wheel forces, achieve a better stress distribution in ballast, and decrease the normal stresses in rails in transition zones. Parametric studies are also performed to study the applicability of the adjustable fasteners.

**Keywords**: Adjustable fasteners; Railway track modelling; Transition zone; Corrective countermeasures; Finite element method.

# 1. Introduction

Transition zones in railway tracks are locations with considerable variation in the vertical stiffness of supporting structures. Typically, they are located near engineering structures, such as bridges, culverts, tunnels and level crossings. An example of a typical transition zone is shown in Figure 1.

Figure 1. Track transition zones

In those locations, the variation of the vertical stiffness together with the differential settlement of tracks (when the foundation settles unevenly) results in amplification of dynamic forces, which contributes to the degradation of ballast and subgrade, ultimately resulting in deterioration of the vertical track geometry or even the damage of track components. To keep track transition zones in operation, more maintenance is required as compared to free tracks [1, 2]. For instance, in the Netherlands, the maintenance activities on the tracks in transition zones are performed up to 4-8 times more often than that on free tracks [3, 4]. Transition zones in the other countries of Europe and the US also require additional maintenance [5, 6].

To mitigate the track degradation in transition zones, countermeasures have been proposed and analysed in a number of studies. In [7], some countermeasures including the auxiliary rail, sleeper with gradual increasing length, light sleeper and various combinations of them were studied using a 2D Finite Element (FE) model. In [8], countermeasures were studied using a 3D FE model, including reinforced backfill, lighter sleepers, sleeper with gradually increasing length, ballast with increasing thickness. Three types of the reinforced backfill (transition wedges) for the embankment-engineering structure transition were studied in [9]. Similarly, two types of reinforced backfill for the transition zone were analysed in [10]. A transition zone using under sleeper pads and reinforced backfill were studied in [11]. In [12], the transition zone using ballast with gradually changing stiffness and under sleeper pads were studied. In [13], the transition zone using the sleeper with gradual increasing length, auxiliary rails and reinforced backfill were studied.

Even though many countermeasures have been used in transition zones, severe track deterioration in transition zones is still often observed [8, 14]. In [15], three countermeasures including geocell, cement, and hot mix asphalt were applied on three similar transition zones. Compared to a plain transition zone (no countermeasure is applied) as a reference, it has been found that all countermeasures were not sufficient to reduce the settlement in the transition zones. In [16], the countermeasure, which uses an approaching slab linking the ballast track onto a concrete culvert, 'has exacerbated rather than mitigated the (transition) problem'. These findings are in agreement with [17], where the authors indicated that 'the problem of track degradation associated with stiffness variations is far from being solved'.

In most of the studies on the countermeasures for transition zones, the numerical models assumed that the tracks on the embankment (ballast tracks) and the tracks on the engineering structure have perfect vertical geometry, that is to say, the ballast track has no differential settlement with respect to the tracks on the engineering structure. However, such a perfect geometry only exists at the very beginning of the track operation. According to the settlement behaviour of ballast tracks [18-23] , the track settlement process can be divided into two stages (as shown in Figure 2). Stage 1 is the rapid settlement process, caused by the volumetric compaction and abrasion of ballast particles. Stage 2 is the standard settlement process (until the end of the maintenance interval) caused by the frictional sliding of particles. The settlement of ballast, subballast, and subgrade in Stage 1 is: (1) fast, which happens only after few months; (2) large, accounts for approximately 50% of the total settlement in a maintenance interval; (3) somewhat inevitable, which happens even though it was compacted. On the contrary to the large settlement appearing in ballast tracks, the engineering structures barely settle, which creates a considerable geometry irregularity (differential settlement). After the differential settlement appears (corresponding to the beginning point of Stage 2, see Point B in Figure 2), the rails are lifted up by the engineering structures, creating gaps under sleepers (also known as hanging sleepers or voiding) on the embankment side. Due to the existence of the gaps, the dynamic responses in transition zones are significantly increased [24, 25]. For instance, a 1mm gap can increase the sleeper-ballast contact force in adjacent locations by 70% [26]; and 2mm gap can lead to 85% increase of wheel forces [24]. It should be noted that the settlement curve in Figure 2 is only for free ballast tracks. Due to the differential settlement, the settlement curve for the tracks in transition zones and the dynamic track behaviour could be different. An example of the transition zone with a large differential settlement is shown in Figure 3.

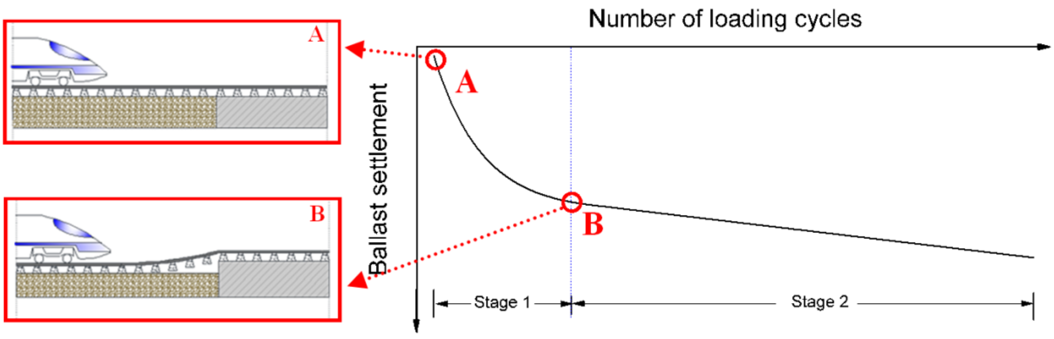


Figure 2. Schematic permanent settlement curve of ballast as a function of loading cycles (only for free ballast tracks).

Figure 3. Transition zone with a large differential settlement.

The countermeasures can be categorized into the preventive measures and corrective measures. The preventive countermeasures are implemented during construction prior to the track operation while the corrective ones are used when the track has already settled (the differential settlement is visible). The studies of the transition zones with the perfect geometry, i.e. considering the beginning point of Stage 1 (Point A in Figure 2), are more suitable for the preventive countermeasures; while for the analysis of the corrective countermeasures, the numerical models have to take the differential settlement into account. The corrective countermeasures that can timely mitigate the transition zone problems caused by differential settlement (at Point B in Figure 2) required further studies.

This study focuses on the corrective countermeasures for transition zones which should meet the following requirements:

- The corrective operations should be performed in short track possession windows manually or by using small machines.
- The corrective countermeasures should be able to mitigate the track degradation in transition zones.

The paper presents the experimental and numerical analysis of a corrective countermeasure - the adjustable fastener. The adjustable fastener intents to fill the partial gap between a sleeper and ballast by shims, whereas it prevents a large operation such as tamping. Even though (unloaded) track alignment is not restored, the hanging sleepers in the vicinity of engineering structures are eliminated, which can slow down the track degradation in transition zones.

The paper is organised as follows. The preventive and corrective countermeasures for transition zones are reviewed in Section 2, including the introduction of the adjustable fastener. The measurement results of three transition zones with the adjustable fasteners are discussed in Section 3. In Section 4, the dynamic behaviour of the transition zone (with differential settlement) with the adjustable fasteners is analysed using FE method. Finally, conclusions are given in Section 5.

## 2. Countermeasures for transition zones

The countermeasures for transition zones can be divided according to their application period, which is either the design stage (preventive measures) or the operation stage (corrective measures).

When designing a transition zone, the primary goal is to construct a zone with smooth changes of the vertical stiffness from the embankment to the engineering structure. A thorough review of the countermeasures for transition zones can be found in [27]. The countermeasures are applied to embankments or/and engineering structure. The intent of the countermeasures on the embankment is to reinforce the ballast track on different levels using various measures such as:

- Subgrade: the geocell, geotextile, cement, hot mix asphalt [15, 28], and transition wedge (special backfill) [29];
- Ballast: the ballast glue [30], under ballast mat [31], pile or steel bar underneath the ballast [8, 32], and ballast containment wall [33];
- Sleepers: sleeper modifications such as increasing its length and reducing the spacing [13, 33] and weight [34, 35].

The countermeasures on engineering structures are intended to decrease the stiffness of the tracks, for instance using rail pads [36], under slab pads [33] and under sleeper pads [10, 11]. In addition, some countermeasures increase the intergrade stiffness of transition zones such as using auxiliary rails [13, 33, 35] and approaching slabs [37]. In some cases, a combination of several countermeasures is used [27].

When the preventive countermeasures do not mitigate the track degradation efficiently, e.g. [15, 16], or no countermeasures are used, e.g. [14, 38], critical differential settlement may appear in a maintenance cycle. The differential settlement may result in the damage of track components and deterioration of the passenger's comfort. To mitigate the existing differential settlement, the corrective countermeasures are necessary. Besides, the hanging sleepers also appear in the vicinity of the engineering structure (0.9m [7] or 1.5m [39] from the engineering structure). However, due to the abutment or the transition structure, it is not always possible for tamping machines to perform track maintenance near engineering structures. In these situations, corrective countermeasures that can be performed manually or by small packing machines can be applied. The general principle of the corrective countermeasures is to fill the gaps between the sleepers and ballast to eliminate hanging sleepers.

One way to fill the gap under hanging sleepers is to use hand-held stoneblower [40, 41] or on-track stoneblower (when possible) [14, 42-44]. The principle is first to lift the sleeper to the required level with minimum disturbances; and then to blow a pre-determined quantity of stones into the void under the sleeper using compressed air. The amount of the added stones is determined by the basis of the sleeper displacement before the stone blowing (using the void meter) [40]. The size of the blown stones is 14-20mm, which is smaller than the ballast particle [41]. The principle of ballast blowing and a hand-held stoneblower are shown in Figure 4 [45].

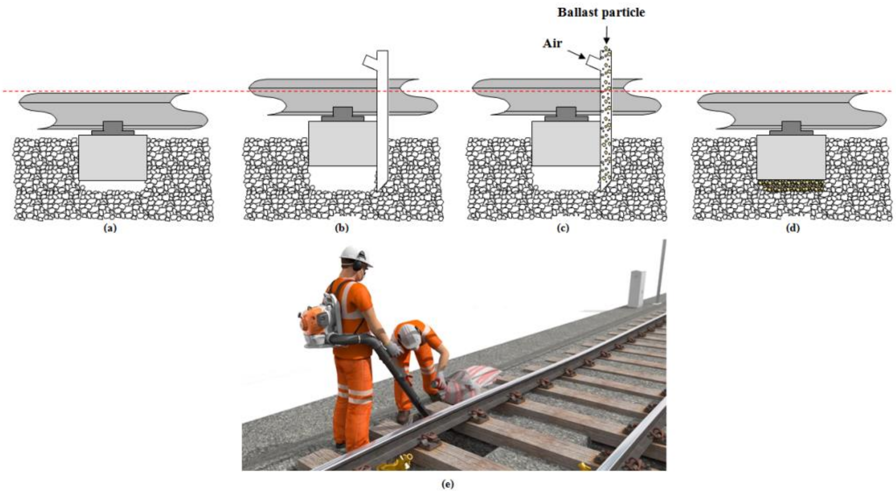


Figure 4. Schematic diagram of stone blowing: (a)-(d) Working principle, (e) is from Network Rail with permissions [45].

An alternative way to remove the gap under the hanging sleepers is by using adjustable fasteners which consist of two plastic wedges (shims) inserted between sleepers and rails (Figure 5). The height of the adjustable fastener can be changed by adjusting the position of the two wedges (shims) to fill the gap. As a result, the sleeper can be fully supported by the ballast under instead of hanging. The principle of using adjustable fasteners is shown in Figure 5(a) and (b). An example of the adjustable fastener used in the track is shown in Figure 5(c). The adjustable fasteners are called ShimLift®, developed by Movares Nederland B.V together with BAM Infra Rail BV [46] and produced by Kampa-International BV.

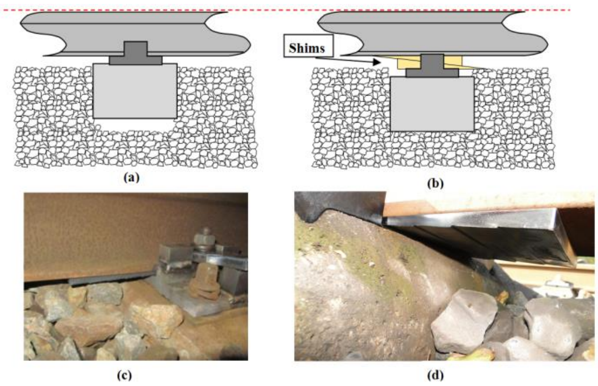


Figure 5. Schematic diagram of Adjustable fastener: (a)-(b) Working principle, (c)-(d) Examples of the adjustable fastener used in the track

## 3. Experimental analysis

To study the effectiveness of the adjustable fasteners, they were tested on three transition zones in the track between Utrecht and Houten, the Netherlands. Since the fasteners are adjusted to fill the gaps under sleepers, the adjusted height equals the accumulated voiding, which can represent the degradation process of tracks at the moment. Therefore, the adjusted heights of the fasteners are recorded to analyse the track degradation.

## 3.1.Measurement set-up

The measurements were performed on the transition zones which consist of ballast tracks and slab tracks (embedded rail system) [47]. The three (Embankment-Slab track-Embankment) transition zones are named Transition Zone A, B, and C, as shown in Figure 6.


Figure 6. Photographs of the measured transition zones.

The adjustable fasteners had been installed on ten sleepers on both sides of slab tracks when the tracks were constructed. At that moment, the fasteners were set to their lowest position (0mm). The new tracks including the transition zones were levelled and aligned by tamping before the tracks went into service, as shown in Figure 7.

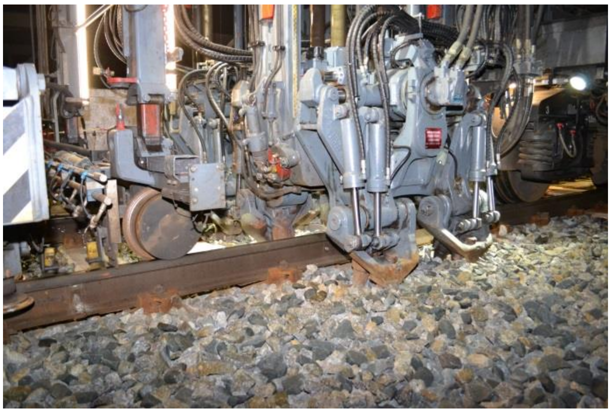

Figure 7. Tamping in a transition zone.

The fasteners were adjusted after 2-month operation and after 5-month operation. During the adjustments, the fasteners were first unfixed (see Figure 8(a)); then the rails were lifted to the required level by standard rail jacks (see Figure 8(b)) or hydraulic rail jacks. After that, the fasteners were adjusted to the desired height by sliding shims. The operation for one side of a slab track (ten sleepers) required approximately fifteen minutes with three or four working staff. The adjusted heights of fasteners after two months and five months were recorded to analyse the development of the settlement in transition zones. It should be noted that due to practical reasons the fasteners on the embankment-slab track side of Transition Zone A were not adjusted after five months.


Figure 8. Adjustment of the fasteners.

## 3.2.Results

The adjusted heights of fasteners (accumulated voiding) of Transition Zone A, B, and C are shown in Figure 9, Figure 10, and Figure 11, respectively.

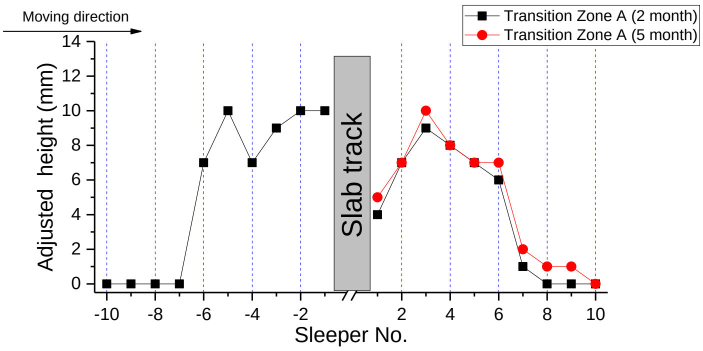


Figure 9. Adjusted heights of the fasteners in Transition Zone A.

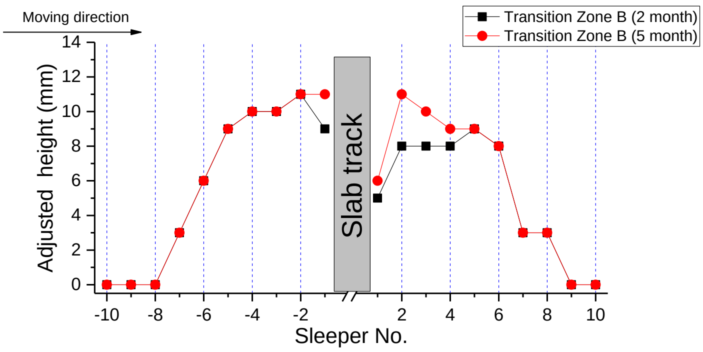


Figure 10. Adjusted heights of the fasteners in Transition Zone B.

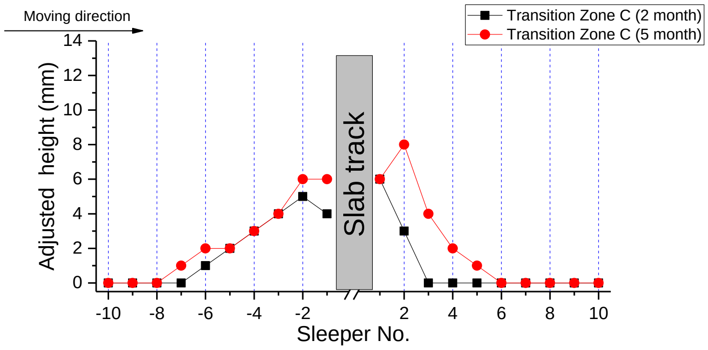


Figure 11. Adjusted heights of the fasteners in Transition Zone C.

As it can be seen from Figure 9-Figure 11, the settlement of ballast tracks appears after 2-month operation, where settlement values within 5-11mm can be found. This confirms the theory of the appearance of the different settlement in transition zones which is explained in Section 1 (Figure 2) that the settlement near engineering structures is much higher than that farther from engineering structures. The settlement patterns on both sides of the slab tracks are different.

After filling the settlement using adjustable fasteners, the growth of the settlement in ballast tracks is significantly reduced, which can be seen by comparing the accumulated settlement in 0-2$^{nd}$ month and that in 2$^{nd}$-5$^{th}$ month. It implies that the adjustable fasteners mitigate the track degradation in the transition zones.

# 4. Numerical analysis

Since the adjustable fasteners are proved to be effective in the field measurement, its effect on the dynamic behaviour of transition zones is analysed using FE method.

## 4.1.Introduction of FE model

The FE model is developed according to the measured transition zones, which has two ballast tracks and a slab track in the middle, as shown in Figure 12. When the railway vehicle moves from one ballast track to the other (from left to right), it is possible to analyse both the embankment-slab track and the slab track-embankment transition with a single calculation. In the model, the 'slab track' is symbolical and not analysed, because the purpose of the paper is to study the ballast track degradation in the transition zone rather than the slab track itself. The slab track is simplified to reduce calculation costs.

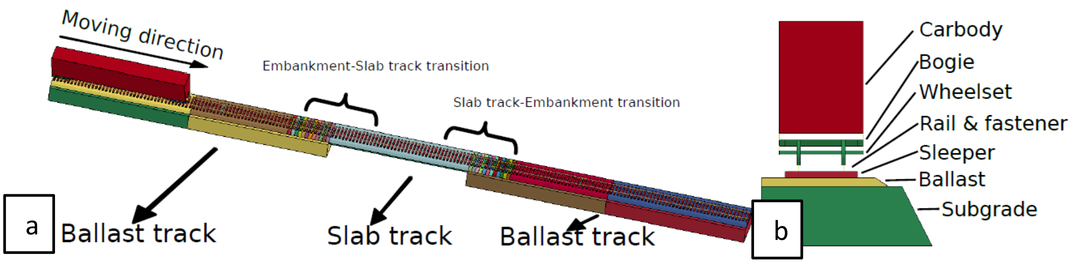


Figure 12. FE model of track transition zones: (a) Overview, (b) Side view.

As the length of the ballast track is 48m and the slab is 24m, thereby, the total length of the transition zone is 48+24+48=120m. The components of ballast tracks are rails, fasteners, sleepers, ballast, and subgrade. The rails are modelled by the beam elements with the cross-section and mass properties of the UIC54 rails. The adjustable fasteners are modelled by spring-damper elements which have bilinear material property. In compression, the elements can model elastic rail pads; and in tension, the elements can model the clamping effect of fasteners. In this way, hanging sleepers can be attached to rails, leaving gaps underneath.

Ballast, sleepers, and subgrade are modelled using the fully integrated solid elements with elastic material properties. The thickness of ballast and subgrade is 0.3m and 2m, respectively. Contact elements [48] are applied between the ballast and sleepers so that they are separable. The contact elements employ the penalty algorithm which searches for penetrations between the bottom surface of the sleepers and the top surface of the ballast at every time step during the calculation. When a penetration is detected, a force proportional to the penetration depth is applied to resist and ultimately eliminate the penetration. By the way, the impact of sleepers on ballast can be studied, which is proportional to the downward acceleration of the sleepers.

The railway vehicle is a passenger vehicle, which is idealized as a multibody system consisting of one carbody, two bogies, and four wheelsets. The parameters of the vehicle are based on [49] and adapted to a Dutch passenger train [2, 50]. The axle load of the vehicle is 210kN (21.4t). The velocity of the vehicle is 144km/h (standard operation velocity). The contact between the wheels and rails is modelled using the Hertzian spring [40]. The non-reflection boundaries [48] are applied to both ends of the model in order to reduce the wave reflection effect. The translation and rotation freedom of the nodes on the bottom of the subgrade and slab track are fixed. The material properties of the track components and the vehicle used in the model are collected in Table 1.

Table 1: Material properties of the track components.

| Parameter | Value |
|---|---|
| Sleeper Elastic Modulus (Pa) | 3.65E+10 |
| Sleeper Poisson ratio | 0.167 |
| ballast Elastic Modulus (Pa) | 1.20E+08 |
| ballast Poisson ratio | 0.250 |
| Subgrade Elastic Modulus (Pa) | 1.80E+08 |
| Subgrade Poisson ratio | 0.250 |
| Concrete slab Elastic Modulus (Pa) | 3.50E+10 |
| Concrete slab Poisson ratio | 0.167 |
| Fastening system Horizontal Stiffness (N/m) | 1.5E6 |
| Fastening system Horizontal Damping (N*s/m) | 5.00E4 |
| Fastening system Longitudinal Stiffness (N/m) | 1.5E6 |
| Fastening system Longitudinal Damping (N*s/m) | 5.00E4 |
| Fastening system Vertical (compression) Stiffness (N/m) | 1.20E8 |
| Fastening system Vertical (compression) Damping (N*s/m) | 5.00E4 |
| Fastening system Vertical (tension) Stiffness (N/m) | 1.20E11 |
| Fastening system Vertical (tension) Damping (N*s/m) | 5.00E4 |
| Distance between wheels (m) | 2.5 |
| Distance between axles (m) | 20.0 |
| Length of train body (m) | 23.0 |
| Primary suspension stiffness (N/m) | 4.25e5 |
| Primary suspension damping (N*s/m) | 1.00e6 |
| Secondary suspension stiffness (N/m) | 4.68e5 |
| Secondary suspension damping (N*s/m) | 6.50e4 |
| Secondary suspension Bending stiffness (Nm/rad) | 1.05e4 |

The differential settlement (settlement of Stage 1 as illustrated in Figure 2) has been added to ballast tracks, which is 8mm since the measurement results after 2-month operation is in the range of 5-11mm. At the equilibrium state of the model, due to separable contact between the sleepers and ballast, as well as the application of the gravity and the resistance of the rail, the gaps between the sleepers and ballast appear in the vicinity of the slab track, as shown in Figure 13(a). For convenience, the sleepers are numbered starting from the one closest to the slab track. They have the positive sign on the slab track-embankment transition and the negative sign on the embankment-slab track transition depending on the moving direction of the passing train (from left to right in the study). Note that there are no sleepers on the slab track. The hanging distance of Sleeper+1 is the highest and the hanging distance gradually reduces as the distance from the slab track increases. The hanging values of the sleepers are presented as the differences between the sleepers and ballast. The same situation is observed on the other side of the slab track. After the equilibrium state, the vehicle moves over the transition zone. The movement of a hanging sleeper (Sleeper+3) are shown in Figure 13(b).

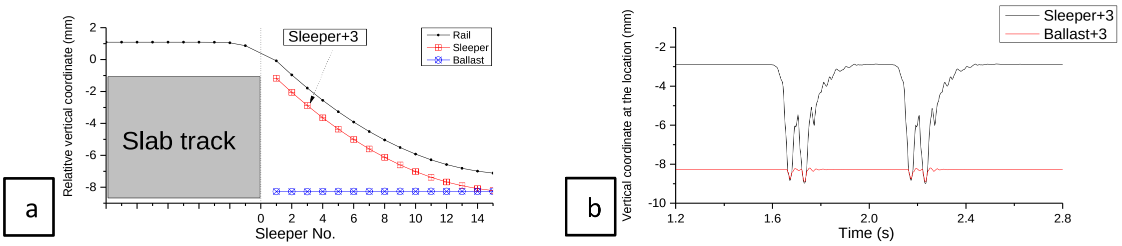


Figure 13: (a) Vertical coordinates of rail, sleepers and ballast due to 8 mm differential settlement; (b) Time history of vertical coordinate due to the passing vehicle at Sleeper+3.

The gap under the hanging sleeper is eliminated under train loads, where an increase of wheel-rail contact forces can be expected. When the sleepers contact the ballast, the penetrations between the bottom surface of the sleepers and the top surface of the ballast occur. The stress distribution in the ballast can be therefore calculated. Because the voids under sleepers are different depending on the location (see Figure 13(a)), the stresses in the ballast elements under different sleepers also vary according to their locations.

In the transition zone with adjustable fasteners, the spring-damper elements are extended to compensate the gaps between the sleepers and ballast, as shown in Figure 14. It should be noted that the adjustable fasteners are assumed to have the same material property as rail pad. The differential settlement is magnified in Figure 14. In the actual case, the differential settlement (8mm) is much smaller compared to the size of a sleeper (240mm in height).

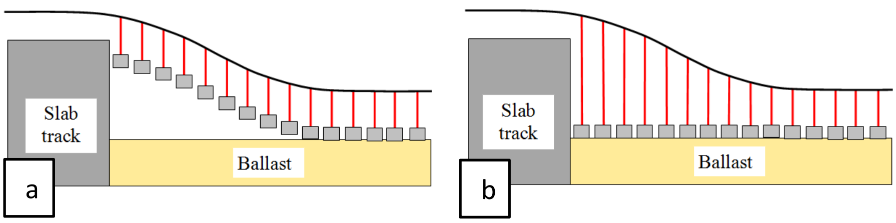


Figure 14. Schematic diagram of the simulation of the countermeasure: (a) Reference, (b) Using adjustable fasteners. Fasteners are indicated by the red lines.

## 4.2. Dynamic responses of transition zones with the adjustable fasteners

**Wheel force**

The calculated wheel forces of four wheelsets in the reference case and the adjustable fastener case are shown in Figure 15. The wheel loads on the slab track are not considered in this study and therefore their responses are covered by the shaded area. The maximal wheel forces acting on ballast tracks are collected in Table 2.

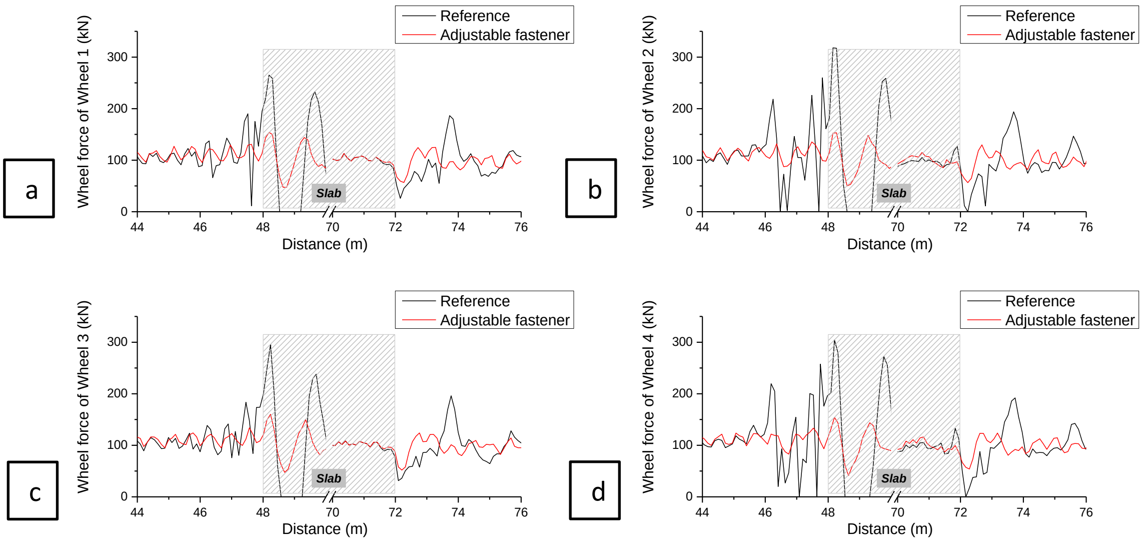


Figure 15. Wheel-rail interaction force of four wheelsets: (a) Wheel 1, (b) Wheel 2, (c) Wheel 3, (d) Wheel 4. The wheel loads on the slab track are covered by the shaded area.

Table 2. Maximal wheel forces in the ballast track in transition zones from Figure 15.

| Wheel No. | Embankment-Slab track transition | | | Slab track-Embankment transition | | |
|---|---|---|---|---|---|---|
| | Reference | Adjustable fastener | Reduction | Reference | Adjustable fastener | Reduction |
| 1 | 190.0 | 130.8 | 45% | 186.4 | 124.9 | 49% |
| 2 | 259.8 | 135.4 | 92% | 194.0 | 129.7 | 50% |
| 3 | 183.6 | 133.9 | 37% | 196.1 | 124.0 | **58%** |
| 4 | 257.6 | 133.3 | **93%** | 192.0 | 123.7 | 55% |

Figure 15 shows that the wheel loads are slightly vibrated around 105kN, which is the static wheel load (210/2=105kN); while they are increased considerably at both the embankment-slab track transition and the slab track-embankment transition in the reference case. This indicates the differential settlement lead to the amplification of wheel loads if no adjustable fastener is implemented.

Comparing to the reference case, the wheel loads are reduced significantly when adjustable fasteners are in use (see Figure 15 and Table 2). The reason is that the hanging sleepers in the transition zone are eliminated by the adjustable fasteners. This moment corresponds to the first adjustment of the fasteners in the measured transition zones after 2-month operation (Section 3). The decrease of the amplified wheel loads (in Figure 15 and Table 2) explains the substantial reduction of the track settlement growth (presented by the adjusted height of the fasteners) in the measurement after using the adjustable fasteners.

## Ballast stress

Since the ballast settlement depends on the ballast stress, the ballast stress in the transition zone is studied as well. It should be noted that the response of unbound granular materials like ballast is non-linear, which affects the calculated distribution of stresses inside the ballast. However, for the transient behaviour analysis in this study, the linear model is used as a first attempt, which is a typical approach, e.g. in [51, 52], due to the limitation of the computational power. Moreover, the ballast bed in this model is assumed to be well compacted (after the rapid compaction). At the moment the sleeper contacting the top of the ballast, the ballast on the top can be simplified as the linear material. In order to compare the ballast responses at the different locations, the ballast elements under one sleeper are considered as a group (unit), which are 416 elements (52*8=416, there are 8 elements on the wide side and 52 elements on the long side, see Figure 16).

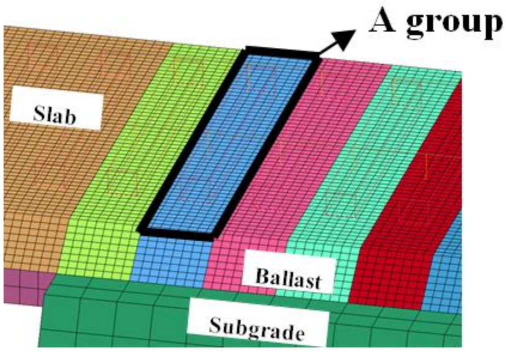


Figure 16. Collecting method for ballast stresses. Red lines are sleeper frames.

The vertical stresses in ballast under sleepers are analysed. The average and maximal stresses calculated for the ballast elements in each group along the track are shown in Figure 17.

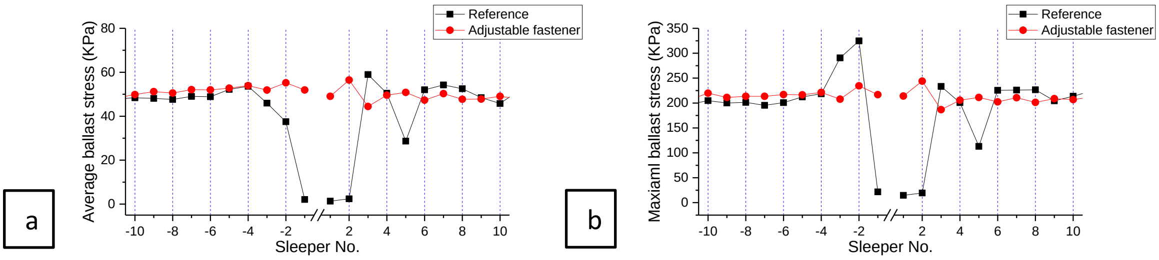


Figure 17. Ballast stresses along the track: (a) Average; (b) Maximal

It can be seen in Figure 17(a) that, after using the adjustable fasteners, the average of ballast stresses are more evenly distributed along the track. In the reference case, the ballast stress closer to the slab track is lower than that at a greater distance from the bridge. It is because the hanging values of the sleepers are so large that the bending stiffness of rails resists the sleepers to fully contact the ballast. The stresses in rails at the moment can be expected high which will be discussed later.

Due to the poor support condition (sleepers are evenly supported by ballast), the hanging sleepers can move irregularly, causing the stress concentrations in ballast, which can be proved by Sleeper-2 in Figure 17(b). The maximal ballast stress reaches 325KPa at Sleeper-2, which is approximately 60% higher comparing to that in a well-supported location. The stress distributions in ballast under

Sleeper-2 in the two cases are shown in Figure 18. The reduction of ballast stresses can be clearly seen from Figure 18, where the maximal stress in ballast is reduced from 325KPa to 235KPa. A similar situation can also be found under Sleeper+3, as shown in Figure 19, where the maximal stress in ballast is reduced from 233KPa to 187KPa. Since the ballast stress is proportional to the settlement rate of ballast [53, 54], the amplified stress may lead to the permanent settlement in ballast, which indicates the settlement (track degradation) in the transition zone may increase continuously if the adjustable fasteners are not implemented.

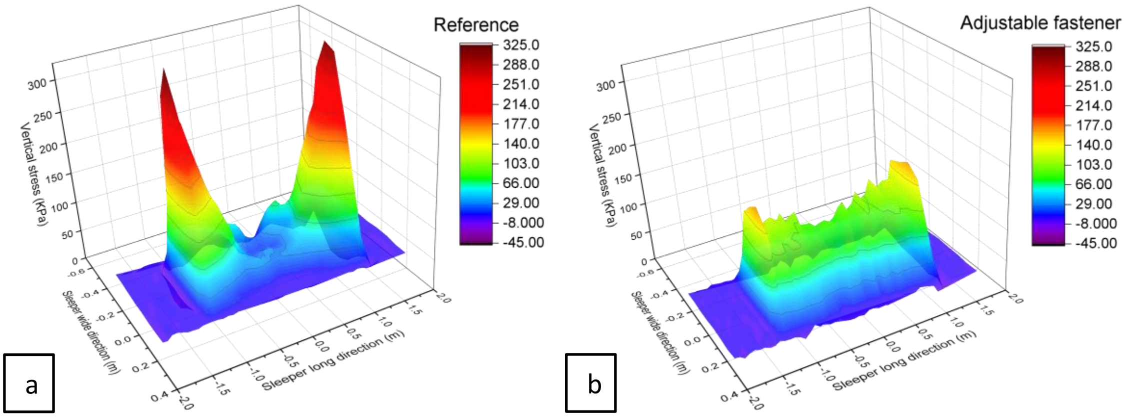


Figure 18. Stress distribution in ballast under Sleeper-2: (a) Reference case, (b) Using adjustable fasteners.

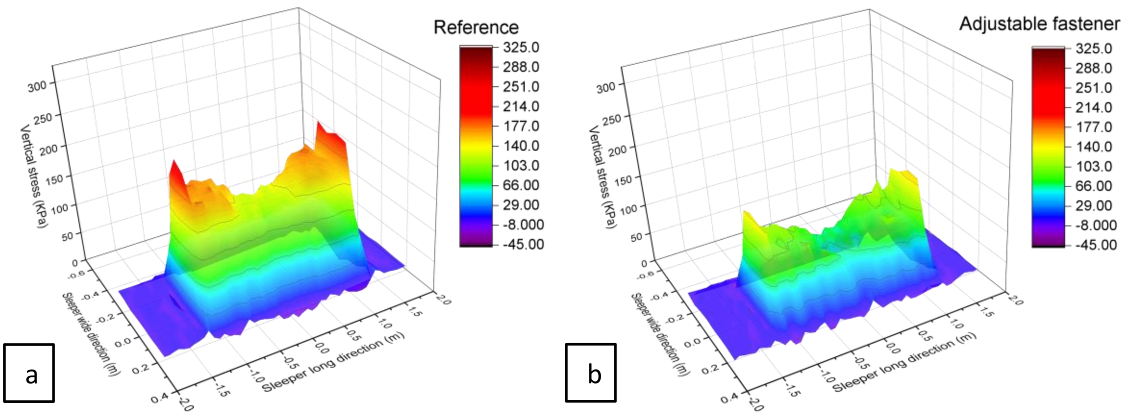


Figure 19. Stress distribution in ballast under Sleeper+3: (a) Reference case, (b) Using adjustable fasteners.

**Rail stress**

The maximal normal stresses in rails in the two cases are shown in Figure 20. The rails are simulated by the beam elements with the length of 75mm (eight elements in a sleeper space). As expected, the results show that the normal stresses in rails in the reference case are amplified near the slab track. When the adjustable fasteners are in use, the normal stresses are again decreased significantly. It shows the adjustable fasteners are also beneficial to rails.

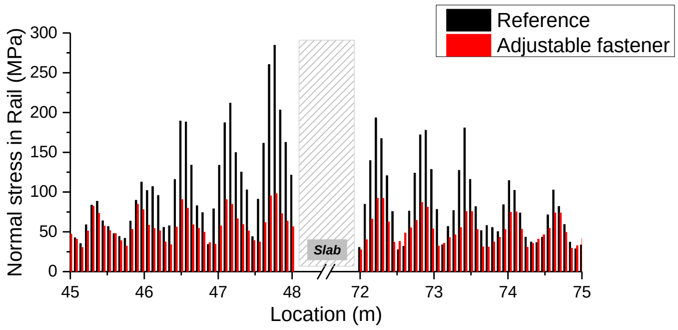


Figure 20. Normal stresses in rails in the reference case and the adjustable fastener case.

To conclude, the adjustable fasteners are effective to reduce the amplification of the wheel forces, to achieve a better ballast stress distribution under the hanging sleepers, and to decrease the normal stresses in rails in transition zones.

## 4.3. Parametric study

**Differential settlement value**

Since the differential settlement value strongly depends on the material properties of tracks, the construction and operation condition, the differential settlement in transition zones may vary. To study the applicability of the adjustable fasteners, the transition zones with various differential settlements are modelled. Three values of the differential settlement are calculated, including 4mm, 8mm (the reference case in Section 4.2), and 12mm. The wheel forces of Wheel 1 in three cases are compared in Figure 21.

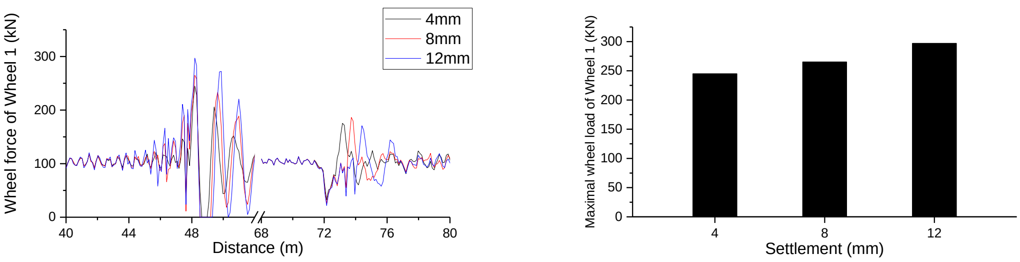


Figure 21. Wheel force of Wheel 1 in three cases: (a) Time history; (b) Maximum.

As it can be seen in Figure 21, the wheel forces are increased as the differential settlement value grows near the slab track. It indicates that the adjustable fasteners should be used in the early stage of the differential settlement initiation. It should be noted that since the rapid compaction stage (Stage 1 of the settlement in Figure 2) is somewhat inevitable, the fasteners should be adjusted as soon as the ballast track is compacted, namely, at the end of Stage 1 or the beginning of Stage 2. Stage 1 of the settlement ends at 0.5MGT according to [22]. Assuming five vehicles in a train, four trains in an operational hour, and fifteen operational hours in a day, it takes approximately twenty days to complete Stage 1 of the settlement.

The transition zones with adjustable fasteners in the cases of 4mm and 12mm are also studied. The wheel forces of Wheel 1 are shown in Figure 22. It shows that the adjustable fasteners can significantly reduce the amplification of wheel forces in both cases, which indicates the applicability of the adjustable fasteners is relatively large.

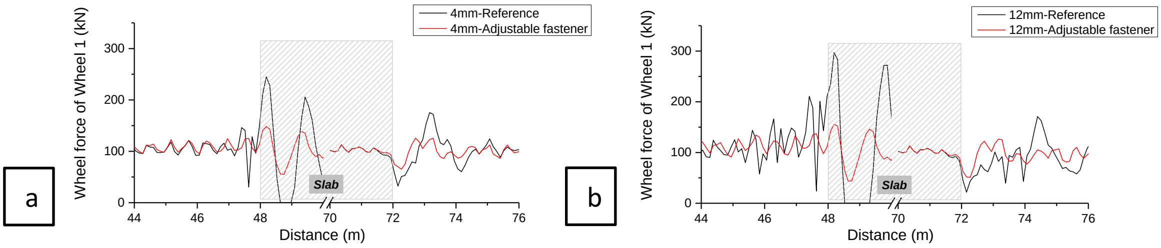


Figure 22. Wheel forces of the transition zones using adjustable fasteners: (a) 4mm differential settlement, (b) 12mm differential settlement.

**Velocity**

The effect of the adjustable fasteners is also studied in the cases of different velocities, including 90km/h, 144km/h (the reference case in Section 4.2) and 198km/h. The wheel forces of Wheel 1 in three cases are shown in Figure 23.

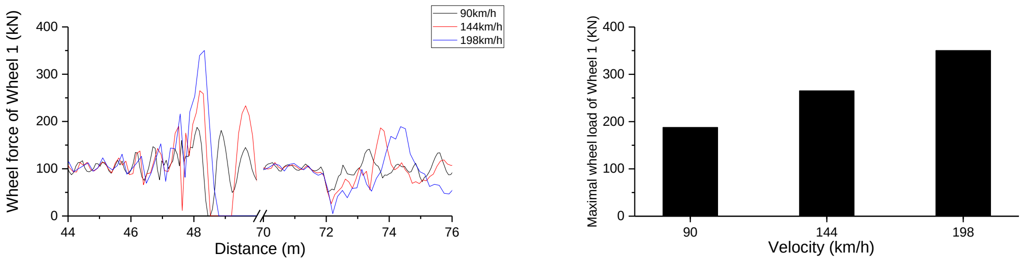


Figure 23. Wheel force of Wheel 1 in three cases: (a) Time history; (b) Maximum.

As expected, the wheel forces are amplified significantly near the slab track as the velocity increases, which can be seen in Figure 23. The comparison of the wheel forces in the transition zones with and without adjustable fasteners is shown in Figure 24.

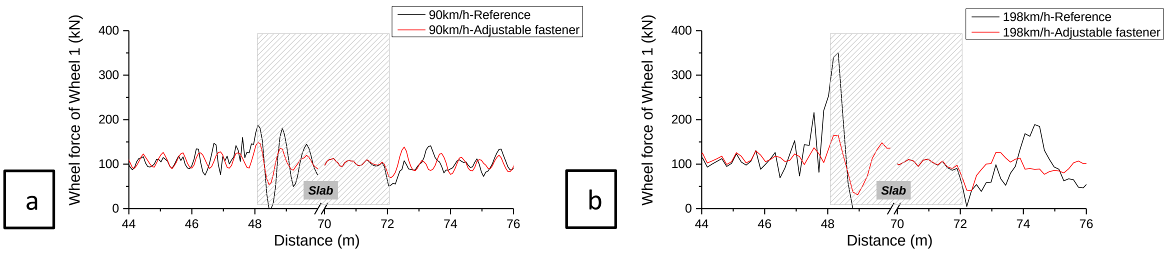


Figure 24. Wheel forces of the transition zones using adjustable fasteners: (a) 90km/h, (b) 198km/h.

Figure 24 shows the wheel forces are reduced in both cases. A considerable reduction can be found in the case of 198km/h, which is over 50%, from 350kN to 165kN. It indicates that the adjustable fasteners work in both low- and high-velocity range and their benefit are significant especially in the higher velocity cases.

# 5. Conclusions

The paper presents the experimental and numerical analysis of a corrective countermeasure - the adjustable fastener. Its working principle is to eliminate the gap under the hanging sleepers by adjusting the height of the fastener (relative position of two shims).

In the experimental study, the adjustable fasteners were installed on three transition zones and adjusted after 2-month operation and after 5-month operation. The results show that the differential settlements in the transition zones are ranged from 5mm to 11mm after 2-month operation. The settlement near engineering structures is much higher than that farther from engineering structures. After using the adjustable fasteners, the growth of the settlement of ballast tracks is reduced significantly.

In the numerical study, the effect of the adjustable fasteners on the dynamic behaviour of transition zones is analysed using FE method. The results show that the adjustable fasteners are effective to reduce the amplification of wheel forces, to achieve a better stress distribution in ballast, and to decrease the normal stresses in rails in transition zones.

The parametric studies show that the applicability of the adjustable fasteners is relatively wide. Since the wheel forces are increased with the value of the differential settlement, it is recommended that the adjustable fasteners should be adjusted as soon as the ballast track is compacted (20 days for the mentioned case). Moreover, the adjustable fasteners work in both low- and high-velocity range and their benefits are significant especially in the higher velocity cases.

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