Proceedings of the Sixth International Conference on
Railway Technology: Research, Development and Maintenance
Edited by: J. Pombo
Civil-Comp Conferences, Volume 7, Paper 7.6
Civil-Comp Press, Edinburgh, United Kingdom, 2024
ISSN: 2753-3239, doi: 10.4203/ccc.7.7.6

Design of Innovative Rail Pad Including Removable Sensor for Traffic-Track Monitoring

A. Guillen[1], M. Sol-Sánchez[1], O. Guerrero[1], G. Iglesias[2], F. Moreno[1] and M. C. Rubio[1]

[1]Engineering School, University of Granada, Spain
[2]NanoMag Laboratory, University of Granada, Spain

Abstract

In the need for more efficient and sustainable infrastructures, a promising solution could be to incorporate sensors for real-time monitoring. In this sense, the present paper focuses on a parametric study into the design of rail pad including piezoelectric sensors, to define the optimal conditions for the manufacturing and application of these smart elements. Particularly, this research aims to develop rail pads with a removable sensor-holder that allows for a versatile track component with capacity to be adapted depending on monitoring requirements, while allowing for future repair of sensor and/or its replacement to adapt future technologies. With this purpose, a series of laboratory tests (traffic load application and simulating train passage tests) were carried out to determine the optimal position of the sensor inside the rail pad and the impact of using a removable sensor-holder. Also, the optimization of the removable sensor-holder was determined, evaluating the thickness of the device, the design method and different types of pads for the insert to be employed. Results showed that the removable sensor could detect load changes and the train passage load, having the advantage of being removed from the pad for data extraction or changing the sensor type, as necessary for future studies.

Keywords: railway track, smart rail pads, removable sensors, piezoelectric, monitoring, vehicle-track interaction.

1 Introduction

Worldwide, extensive research endeavours have been seeking alternative methods for enhancing the efficiency and cost-effectiveness of infrastructure conservation. The need for effective maintenance and cost management considering that train traffic is hindered as little as possible optimizing the flexibility of conservation involves the design of new technologies capable of optimize the railway track maintenance status. [1-4]. One of the challenges lies in the need to provide a versatile device with the capacity for continuous monitoring while being able to adapt the technologies to possible changes in track requirements during monitoring operations [17].

Among these strategies, one approach to reduce the expenses associated with railway track maintenance lies in preventive measures. Innovative solutions have explored various methodologies[5-12]. On the other hand, an alternative for gaining advantages involves the integration of sensors directly into the railway infrastructure components [13-15] leveraging the existing materials as carriers for these sensors. This includes concepts such as incorporating sensors into the rail pad, both as an add-on sensing device or embedding them inside the rail pad material [13], [16- 18].

In this context, the focus of this article is to design a pad with removable sensors so that they can be used in the areas of the line to be monitored, using different technologies depending on the objectives of the supervision. Therefore, to design the pad with a removable sensor, three stages had to be carried out: 1st) defining the optimum configuration of the sensor (location inside the pad and how to embed) it); 2nd and 3rd) design and validation of the removable device. In the first section, after the introduction, it specifies the location of the sensor inside the plate based on different methods. The second section consisted of assessing the applicability of monitoring traffic conditions through laboratory tests under realistic traffic loads and track conditions. Subsequently, the third section delves into evaluating the durability of the removable sensor when applying the rail pad under repeated loads simulating train passing, simulating extreme climate conditions to evaluate their capacity, and studying the material stiffness when modifying its mechanical properties. The objective is to cultivate an instrument that not only improves design and production processes but also contributes to the advancement of real-time load monitoring within rail operations.

2 Methodology

The methodology section is structured into three key components: materials, testing plan, and methods.

2.1 Materials

To carry out this research, several types of rail pads were manufactured at the laboratory, evaluating different ways to insert the removable sensor-holder to define the optimal design. In Figure 1 it can be seen an example of the rail pad with and without carrying the removable sensor-holder.

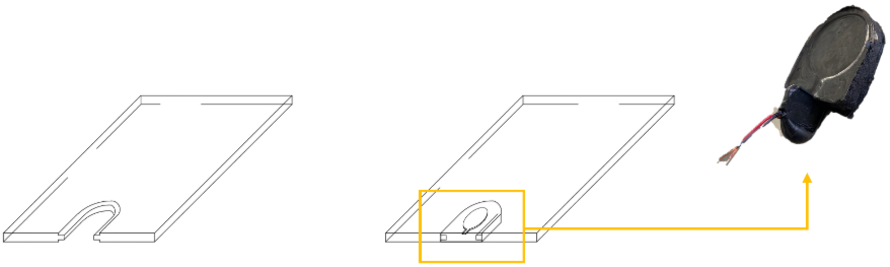

Figure 1: Rail pad with removable sensor-holder.

For this study, it was employed three types of material, the principal material of the study (R-PP/PE Pad) was mainly composed of a low-density polyethylene (LDPE) containing other polymers such as polypropylene (PP) obtained from recycling geomembranes used for waterproofing applications. As previous studies have shown its feasibility for use in pad fabrication [13], [14], this recycled component was selected as the main research material. The second and third material in use were a Recycled PE Pad and a SBS Pad, both with different chemical characteristics in order to be able to compare the sensitivity of the sensor-holder to detect load changes on the rail-track varying the stiffness of its composition.

The static and dynamic stiffness values of the three types of material used in this paper were as follow: the SBS Pad showed the higher values in the static stiffness, being 376 KN/mm and 455 KN/mm the dynamic stiffness. In the case of the Recycled PE Pad the values were 367 and 296 KN/mm and for the R-PP/PE Pad the values were 176 and 540 KN/mm.

As showed by prior studies [13], [14], the piezoelectric sensor has demonstrated its significant potential for detecting changes in strain and stresses of the rail pads they are embedded in. Also, ensuring a low-cost and easy to implement type of material. This sensor consisted of a 35 mm diameter metallic base and a 24 mm of the quartz sheet. Their thickness of 0.35 mm makes them appropriate to be embedded in the rail pads having a low impact in their shape. To measure the electrical changes due to variations in infrastructure/traffic characteristics, they were connected to a data logger with the capacity to directly measure the voltage generated by the piezoelectrics.

2.2 Testing plan

The testing plan was divided into three main stages: (i) Design of the pad to include sensors, aiming to define key parameters like optimal position of the sensor into the pad and procedure of embedding; (ii) Design of the removable sensor, defining geometric parameters of the removable sensor for optimization and (iii) validation of the mechanical behaviour and durability of the smart rail pad.

Table 1 displays the study steps of each stage as well as the variable assessed, and the tests carried out. For the first stage, the study focused on (a) the influence of the horizontal position of the sensor over the pad surface, and (b) influence of the incorporation of the sensor. Secondly, it was studied (c) the influence of the sensor thickness, and (d) the influence of the material stiffness. Thirdly, it was studied the (e) prove and validation of the smart pad by assessing the mechanical characteristics of the pad when including the sensor; its durability under fatigue tests and climate actions; and its functionality through full-scale tests simulating the passage of train wheels over the system.

	Study step	Variable of study	Test
Design of pad to include sensors	Influence of horizontal position	Centre Lateral	Dynamic loading simulating different traffic conditions
	Incorporation of sensor – influence of sensor-holder size	Reference Removable sensor in full-contact Removable sensor in less-contact	
Design of the removable sensor	Influence of sensor thickness	Thin Standard Thick	
	Influence of the material stiffness	R-PP/PE Recycled PE SBS	
Validation	Prove and validation of smart pad	Mechanical characterisation	Static and dynamic stiffness
		Durability	Resistance to water, thermic and freezing and thawing
			Fatigue test under repeated inclined loads
		Functionality	Simulation of train passage

Table 1: Testing plan

2.3 Testing plan

Firstly, in other to define the position of the sensor inside the rail pad area, two possible horizontal position were studied: (a) centre, tested in previous studies [13], [14], being used as a reference in this article; and (b) at the end of the pad under the rail pad area (this was selected because previous studies [21] have seen that this area of the pad is the least damaged during fatigue processes, while greater lateral movements of the pad could be expected, and therefore, increasing the sensitivity).

Secondly, to provide versatility and capacity it was studied the possibility to remove the sensor from its position without the need of lifting the track. This could allow for repairing the sensor without need for replacing the whole pad or using different technologies and type of sensors depending on the objectives of the supervision, which would provide a versatile system with the capacity to adapt to the maintenance requirements of each moment. The removable device was studied in three configurations, the “Full-contact sensor” (when the removable device is in direct contact with the pad), the “less-contact sensor” (leaving a 2 mm space between the sensor-holder and the pad hole) and to compare these results it was employed the reference pad with the embedding sensor.

For the design of the removable sensor, there were two different sensor characteristics studied: a) the influence of the sensor thickness and b) the influence of the material stiffness. The first variable consisted of analysing three distinct thickness of the device: a) a slim 6 mm sensor, establishing an area in which the pad thickness is reduced, potentially leading to more fragile; b) the conventional 8 mm sensor (matching the rail pad thickness); and c) a robust 10 mm sensor, provoking the sensor to be the first part in contact with the load applied. Additionally, to study this variable there were used two types of materials to cover the removable sensor-holder, a medium stiffness material and a soft silicone. Finally, to study the second variable, three removable sensor-holders were made of R-PP/PE, Recycled PE and SBS material to compare the sensitivity in load detecting when evaluating them in the R-PP/PE (study main material Pad).

Therefore, to analyse these characteristics of the sensor the “Dynamic loading simulating different traffic conditions” test was carried out, this test was adapted from the dynamic stiffness of rail pads test according to EN 13146-9. [19] This test included 5 dynamic load steps consisting of applying 1,000 cycles at 5Hz, with stresses of 200, 400, 800, 1600 and 2400 kPa, which were chosen because they represent the range of loads expected for this material during its application on tracks. For the type of material test, it was included 10 dynamic load steps consisting of applying 1,000 cycles at 5 Hz, with stresses of 150, 300, 470, 630, 800, 950, 1200, 1600, 2000 and 2400 kPa, to test the sensitivity of the removable sensor in different materials.

Finally, to validate our findings, it was conducted a three-stage assessment for the most appropriate designs and procedures of including the sensor, according to the previous results. It was carried out the following evaluations: (1) a Mechanical Validation that aimed to examine the potential influence of the sensor design on the alteration of the pad thickness and mechanical characteristics. (2) a Durability Testing focused on assessing the long-term viability and durability of the proposed solution, referring to climate and fatigue resistance. And (3) a Functionality Assessment involving evaluating the solution capacity to measure rail-track interactions when simulating the passage of trains with different level of load per axle.

The stiffness test, carried out for the evaluation of the impact of the sensor on the mechanical performance of the pad, were developed in consonance to the European standard 13146-9 [19]. The climate resistance tests were carried out according to E.T. 03.360.574.2 of ADIF [22] (Railway Infrastructure Manager – Administración de infraestructura ferroviaria de España). After analysing the results of the test, it was expected to compare the device signal before and after executing the study.

The fatigue test carried out when assessing the durability of the smart pad, consisted of simulating repeated loads reproducing the stress transmitted by trains curved sections (considered the most unfavourable testing condition). The test was adapted from Standard EN 13146-4 [23] to focus on determining the durability of the sensor.

3 Results

The results section analyses the influence of key designing factors for the rail pad including the sensor-holder device, while also validating the mechanical and functional properties of this smart pad.

3.1 Study of the influence of the position of the sensor

Figure 2 displays the signal measured by the sensor in different horizontal positions embedded inside the pad when it was subjected to various stress levels. The results confirm that there is a linear response of the signal emitted by the sensor to the gradual variation of the load, which is in line with previous studies [13], [14]. This response holded for the different positions of the sensor and the most noticeable signal was found in the sensor placed at the end of the pad under the rail.

Therefore, it can be said, that under load application the pad tends to expand from the centre to the end and that was the reason that the sensor registers the greatest strain and stresses of the pad. The position of the sensor at the end of the pad under the rail could result in a more durable system, as previous articles [10] have shown that it is one of the least damaged areas of the rail pad during their service life.

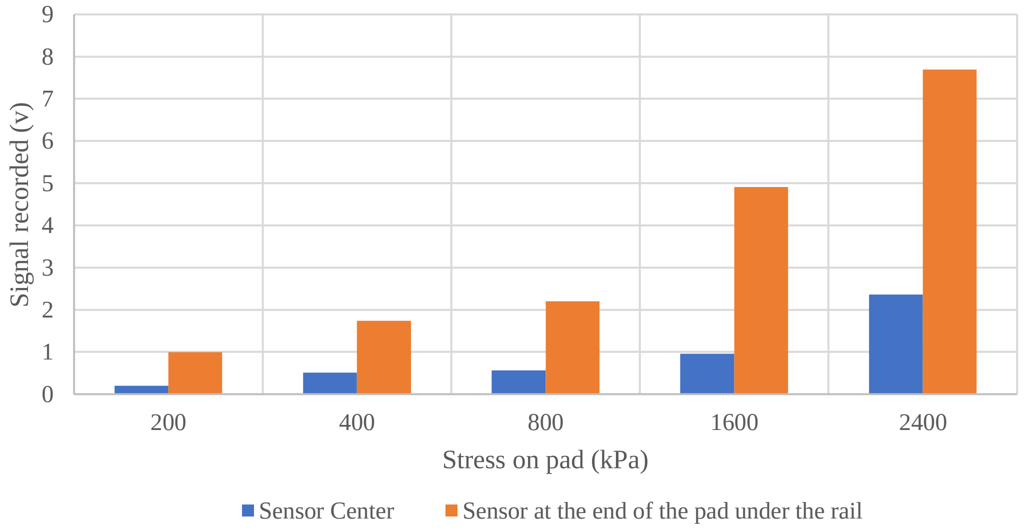

Figure 2: Results of the influence of the horizontal position on the pad by applying a force on the rail

3.2 Study of the design of the procedure for sensor incorporation

Figure 3 displays the evolution of the sensor signal when: 1) the sensor was designed as removable with similar size as the cavity created in the pad; 2) the removable sensor device had a smaller size, leaving 2 mm between sensor edges and pad opening/cavity; 3) sensor embedded on the pad, used as a reference. Despite~~,~~ the embedded sensor signal being superior to such measured for the removable sensors, the Full-size removable sensor also presented enough sensitivity to detect the variations in the conditions of loading, which indicates the viability of using this design for the monitoring of the interaction train-track.

Nonetheless, its important to conserve the contact between the sensing device and the pad to avoid the loss of sensitivity. The less-contact removable sensor also recorded the changes in loading conditions but reducing the level of signal, also implicating a reduction on its reliability. Also, the Full-contact removable sensor solution could be removed from its operating position to both replace the sensor when required or adapting the technology or type of sensor according to future requirements of the railroad monitoring.

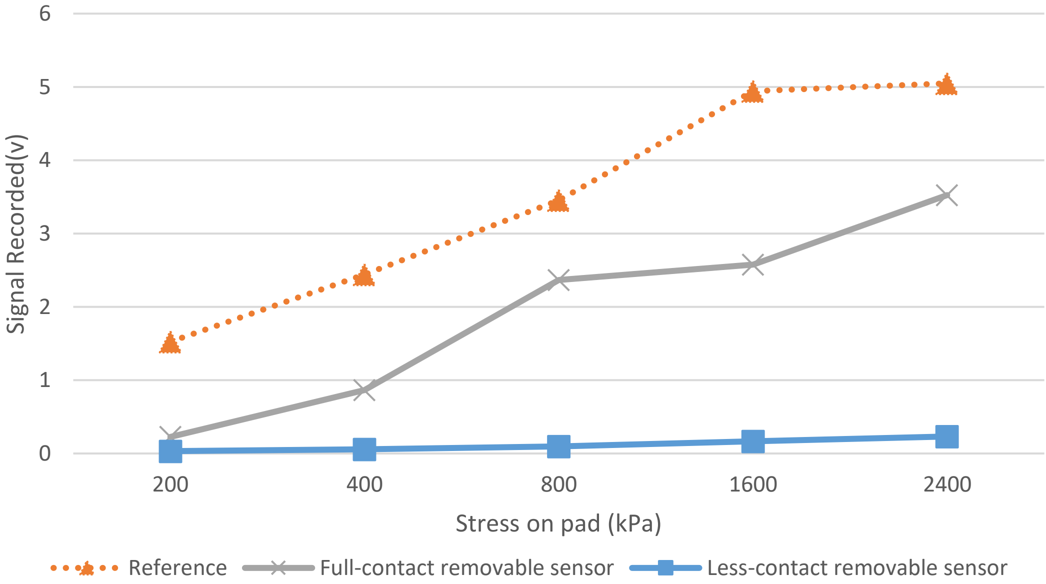

Figure 3: Results of the influence in the pad when removing the sensor for different load applications

3.3 Study of the influence of the sensor thickness

As can be observed in Figure 4, the sensor demonstrated to have a sensitivity to load changes when it was in contact with the rail first than the pad (10 mm thickness). And, as the results show, the soft silicone sensor presented more correlation with the forces applied, capturing the reason for the study, as it was a more flexible material it could be adapted easier to the forces than a more rigid material.

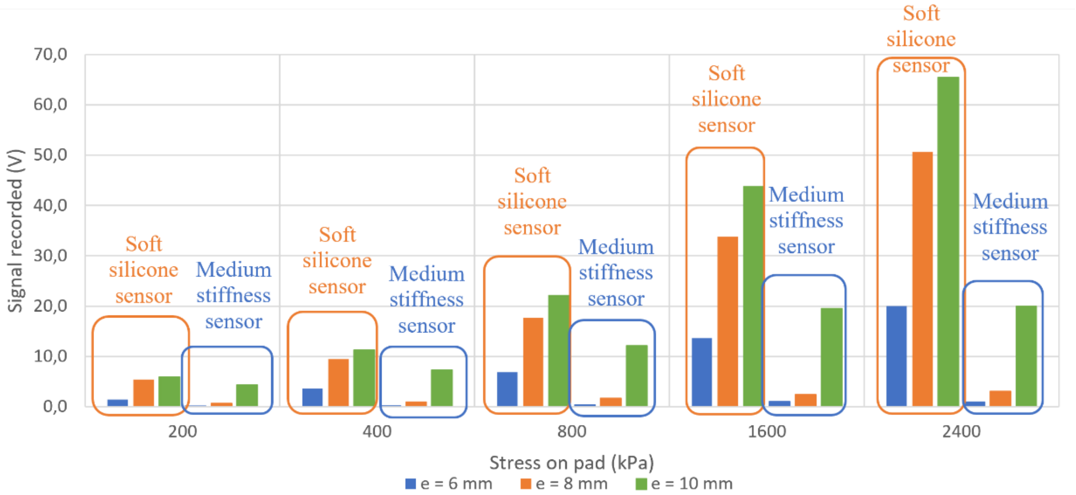

Figure 4: Results of the influence of the thickness of the sensor when applying different loads

3.4 Study of the type of material

Firstly, for the highest loads, the R-PP/PE Removable sensor-holder was found to show a noticeable increase on the signal recorded by the sensor, as it can be seen in Figure 5. This could be due to that the SBS and the Recycled PE removable sensor-holders were the ones with the highest static stiffness values (as indicated in materials section), so the stresses applied on the pad could not be transmitted to the removable device according to the different properties of the material behaviour when applying a load.

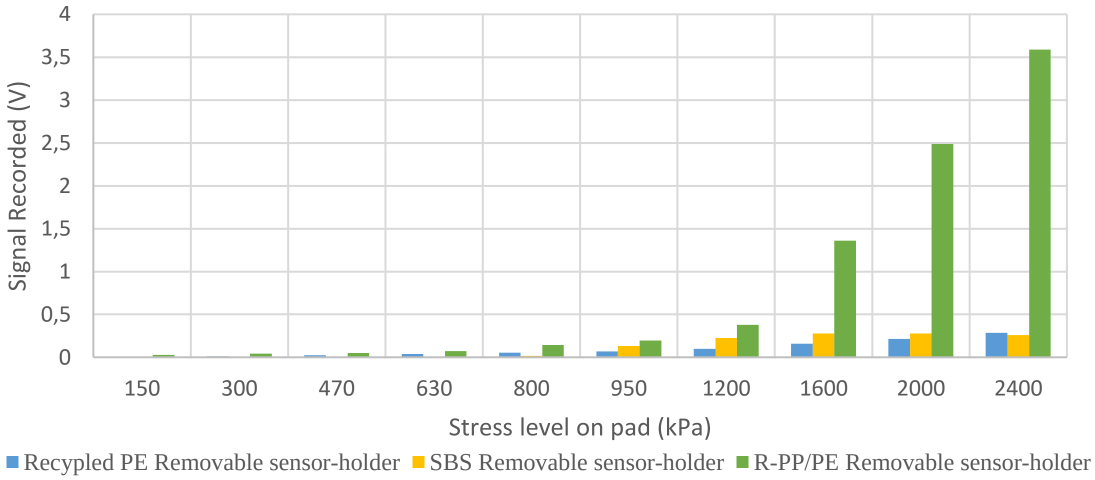

Figure 5: Results of the application of three different Removable sensor-holder materials in the R-PP/PE Pad

3.5 Mechanical and Functional Validation

In order to validate the mechanical and functional characteristics of the smart pad, this section analyses the results of the mechanical laboratory tests.

3.5.1 Static and dynamic stiffness

Figure 6 displays the static and dynamic stiffness of two different type of pads; the reference pad (unmodified shape and without including sensor used as a reference guide); and the pad with a removable sensor. As it can be seen, the inclusion of the sensor produces an increase of a 20% of the stiffness of the pad. On the contrary, the lateral embedded sensor decrease when evaluating the stiffness. These values are mostly associated to the type of material used for manufacturing the study pads, so they will depend on these parameters. Also, in this study, a recycled polymer was used as an example, but the solution could apply to any type of pad.

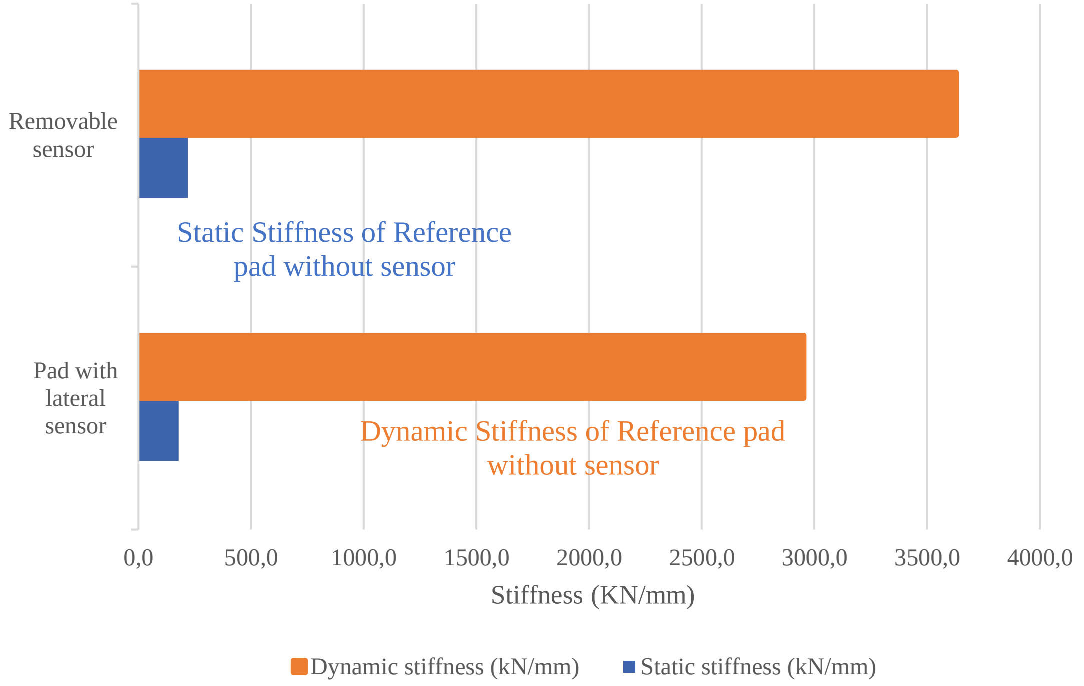

Figure 6: Static and Dynamic stiffness of the reference pad and pad with lateral sensor

3.5.2 Resistance to water, thermic and freezing and thawing.

Figure 7 displays three different tests to analyse the removable sensor performance in case of extreme climate changes. The stages studied were a) BF&TR and AF&TR, meaning “Before and After of Freezing and Thawing Resistance Test”; b) BWR and AWR, meaning “Before and After Water Resistance” and c) BTR and ATR, meaning “Before and After Thermic Resistance”.

As it can be observed, the sensor signal decreases after the Freezing and Thawing and Water resistance tests. This could mean that the sensor could be damaged when water enters through the material pores and reaches the centre of the device where the sensor is located. By contrast, in the Thermic Resistance test, the sensor signal presents an increase after the test. Further studies would be necessary to find a solution for the sensor resistance to water.

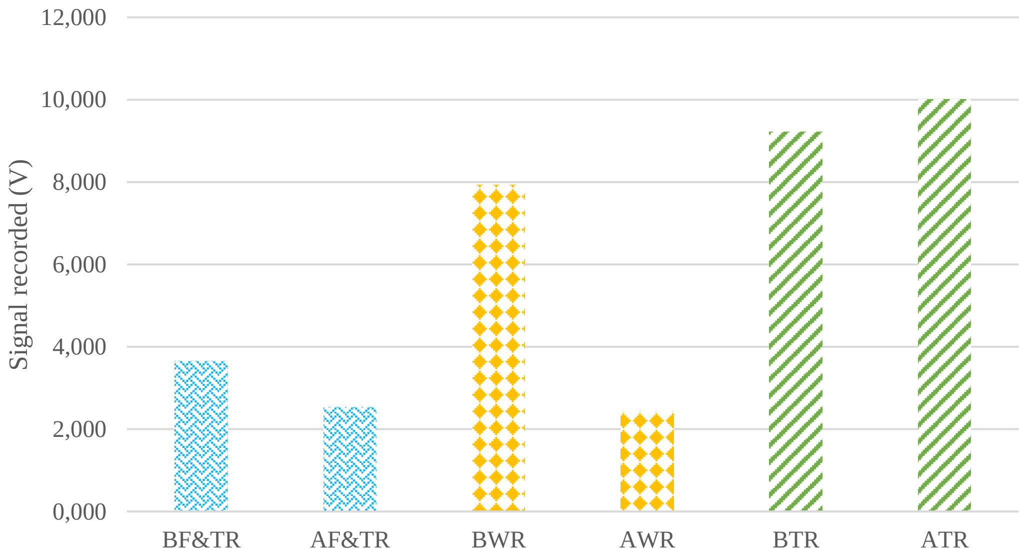

Figure 7: Recorded signal evolution of the sensor when applied water, thermic and freezing and thawing resistance

3.5.3 Fatigue resistance

Figure 8 provides a visual representation of the correlation between the sensor signal and the applied load simulating train passage, after the fatigue process. Consequently, it could be asserted that the sensor demonstrated commendable durability by maintaining its capacity to detect load changes and delivering consistent performance after the fatigue test.

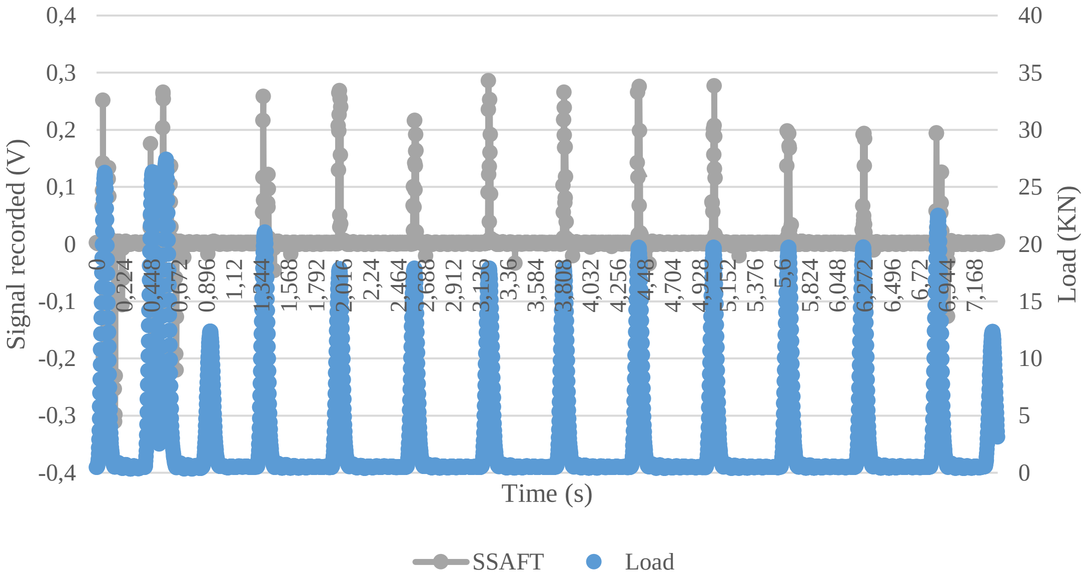

Figure 8: Sensor signal recorded after fatigue test vs Load applied during fatigue test

4 Conclusions and Contributions

The present paper focused on studying the viability of a removable sensor to be included into rail pads, allowing for a versatile system to be adapted depending on monitoring requirements. The paper studies the position where the sensor could be more efficient and effective, both without disrupting the rail pad configuration system, assessing different types of manufacturing material, and finally, proving the device durability under extreme function conditions. From this study, the following conclusions can be drawn:

- Results denoted that the inclusion of the sensor into an extreme of the rail pad (at the edge of the contact rail-sleeper) allowed for a system with capacity to detect changes in traffic-track interaction while providing the ability of designing a removable sensor to be included or extracted from the rail pad.
- To obtain accurate signals from the sensor, it is essential to ensure that the holder device is in full-contact with the rail pad where it is included.
- The stiffness of the rail pad including the removable sensor slightly increases in comparison with other smart pad designs.
- The removable sensor showed an ability to resist diverse thermic conditions, presenting more variation of the signal to cold weather conditions and water degradation. Then, further designs must be carried out to reduce such susceptibility.
- Nonetheless, the smart pad showed resistance to fatigue tests, demonstrating to be capable of conserve the capacity to measure and monitor the interaction between vehicle and track.

Acknowledgements

The present study has been conducted within the framework of the project with acronym "InterActive Pads" and titled "Proof of Smart Pads for Monitoring Vehicle-Track Interaction" (PDC2022-133966-IOO), funded by the Ministry of Science, Innovation and University of Spain.

References

[1] B. Buurman, K. Gkiotsalitis, and E. C. van Berkum, "Railway maintenance reservation scheduling considering detouring delays and maintenance demand," *Journal of Rail Transport Planning & Management*, vol. 25, p. 100359, Mar. 2023, doi: 10.1016/J.JRTPM.2022.100359.

[2] R. Macedo, R. Benmansour, A. Artiba, N. Mladenović, and D. Urošević, "Scheduling preventive railway maintenance activities with resource constraints," *Electron Notes Discrete Math*, vol. 58, pp. 215–222, 2017, doi: https://doi.org/10.1016/j.endm.2017.03.028.

[3] F. Peng, S. Kang, X. Li, Y. Ouyang, K. Somani, and D. Acharya, "A Heuristic Approach to the Railroad Track Maintenance Scheduling Problem," *Computer-Aided Civil and Infrastructure Engineering*, vol. 26, no. 2, pp. 129–145, Feb. 2011, doi: https://doi.org/10.1111/j.1467-8667.2010.00670.x.

[4] K. Odolinski and H. E. Boysen, "Railway line capacity utilisation and its impact on maintenance costs," *Journal of Rail Transport Planning & Management*, vol. 9, pp. 22–33, 2019, doi: https://doi.org/10.1016/j.jrtpm.2018.12.001.

[5] C. Du, S. Dutta, P. Kurup, T. Yu, and X. Wang, "A review of railway infrastructure monitoring using fiber optic sensors," *Sens Actuators A Phys*, vol. 303, p. 111728, 2020, doi: https://doi.org/10.1016/j.sna.2019.111728.

[6] D. Sasi, S. Philip, R. David, and J. Swathi, "A review on structural health monitoring of railroad track structures using fiber optic sensors," *Mater Today Proc*, vol. 33, pp. 3787–3793, Jan. 2020, doi: 10.1016/J.MATPR.2020.06.217.

[7] S. Mishra, P. Sharan, and K. Saara, "Real time implementation of fiber Bragg grating sensor in monitoring flat wheel detection for railways," *Eng Fail Anal*, vol. 138, p. 106376, Aug. 2022, doi: 10.1016/J.ENGFAILANAL.2022.106376.

[8] L. B. Ciampoli, A. Calvi, and E. Oliva, "'Test-site operations for the health monitoring of railway ballast using Ground-Penetrating Radar,'" *Transportation Research Procedia*, vol. 45, pp. 763–770, Jan. 2020, doi: 10.1016/J.TRPRO.2020.02.099.

[9] J. dos Reis, C. Oliveira Costa, and J. Sá da Costa, "Strain gauges debonding fault detection for structural health monitoring," *Struct Control Health Monit*, vol. 25, no. 12, p. e2264, Dec. 2018, doi: https://doi.org/10.1002/stc.2264.

[10] P. Hu, H. Wang, G. Tian, Y. Liu, X. Li, and B. F. Spencer, "Multifunctional flexible sensor array-based damage monitoring for switch rail using passive

and active sensing," *Smart Mater Struct*, vol. 29, no. 9, p. 095013, 2020, doi: 10.1088/1361-665X/ab9e0f.

[12] Y.-J. Lei *et al.*, "A high-precision two-dimensional micro-accelerometer for low-frequency and micro-vibrations," *Precis Eng*, vol. 67, pp. 419–427, 2021, doi: https://doi.org/10.1016/j.precisioneng.2020.10.011.

[13] M. Sol-Sánchez, J. M. Castillo-Mingorance, F. Moreno-Navarro, and M. C. Rubio-Gámez, "Smart rail pads for the continuous monitoring of sensored railway tracks: Sensors analysis," *Autom Constr*, vol. 132, p. 103950, Dec. 2021, doi: 10.1016/J.AUTCON.2021.103950.

[14] M. Sol-Sánchez, J. M. Castillo-Mingorance, F. Moreno-Navarro, T. Mattinzioli, and M. C. Rubio-Gámez, "Piezoelectric-sensored sustainable pads for smart railway traffic and track state monitoring: Full-scale laboratory tests," *Constr Build Mater*, vol. 301, p. 124324, Sep. 2021, doi: 10.1016/J.CONBUILDMAT.2021.124324.

[15] J. Castillo-Mingorance, M. Sol-Sánchez, F. Moreno-Navarro, and M. Gámez, "A Critical Review of Sensors for the Continuous Monitoring of Smart and Sustainable Railway Infrastructures," *Sustainability*, vol. 12, p. 9428, Nov. 2020, doi: 10.3390/su12229428.

[16] S. L. Zhang, C. G. Koh, and K. S. C. Kuang, "Proposed rail pad sensor for wheel-rail contact force monitoring," *Smart Mater Struct*, vol. 27, no. 11, p. 115041, 2018, doi: 10.1088/1361-665X/aadc8d.

[17] G. Jing, M. Siahkouhi, J. Riley Edwards, M. S. Dersch, and N. A. Hoult, "Smart railway sleepers - a review of recent developments, challenges, and future prospects," *Constr Build Mater*, vol. 271, p. 121533, Feb. 2021, doi: 10.1016/J.CONBUILDMAT.2020.121533.

[18] P. Li *et al.*, "A bi-block sleeper dynamic strain monitoring method based on embedded FRP-OF sensor," *Constr Build Mater*, vol. 330, p. 127271, May 2022, doi: 10.1016/J.CONBUILDMAT.2022.127271.

[19] "N0064825-PDF-ES".

[20] M. Sol-Sánchez, F. Moreno-Navarro, and M. C. Rubio-Gámez, "The use of deconstructed tire rail pads in railroad tracks: Impact of pad thickness," *Mater Des*, vol. 58, pp. 198–203, 2014, doi: https://doi.org/10.1016/j.matdes.2014.01.062.

[21] H. Woschitz and H. Woschitz, "DEVELOPMENT OF A RAIL-STRAIN-PAD USING FBG SENSORS," 2011.

[22] "VÍA ESPECIFICACIONES TÉCNICAS SUELAS BAJO TRAVIESA PARA ALTA VELOCIDAD. "N0064824-PDF-ES (1)".