DEVELOPMENT OF A RAIL-STRAIN-PAD USING FBG SENSORS

H. Woschitz
Institute of Engineering Geodesy
and Measurement Systems,
Graz University of Technology, Austria

Railway tracks in alpine regions consist of many curves with small radii of often less than 300 m. There, the elastic pads that are mounted in between the rail and the sleepers are affected by enormous stresses. In the narrow curves, the elastic pads must be replaced every few years which is time consuming and cost intensive. If the deterioration of the elastic pads is not detected in time, the sleepers will be damaged too, and as a consequence the train traffic needs to be shut down during its replacement. Mainly, horizontal forces are assumed to cause the accelerated deterioration of the elastic pads. Consequently, more durable materials are under development currently. However, the forces that are generated by a train passage and subsequently the strain inside the elastic pad are insufficiently known.

In this paper, the development of a fiber-optic rail-strain-pad (RASP) is described. Several fiber Bragg grating (FBG) sensors are embedded into the elastic pad during the production process. Challenges in the development were the very small dimensions of the structure (size of the pad: 150 x 160 x 7 mm^3) and the large strain values of several 1 000 με that are induced by loading the pad. Draw-tower gratings were used, as this sensor type was the only one to withstand the large strains of more than 30 000 με. Several RASP prototypes were developed and tested. Experimental results are shown in order to demonstrate the capabilities of the system to measure large strains. In future, the RASP will be used for weigh-in-motion issues.

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Corresponding author's email: helmut.woschitz@tugraz.at

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1 INTRODUCTION

Elastic pads (fig. 1a) are used in railway engineering to reduce the stress in the roadbed and track components. The vertical forces applied by a passing locomotive are about 70 kN, or even above 100 kN in the case that some neighbouring sleepers do not rest properly on the road-bed. Lateral forces, which are caused by centrifugal forces for example, are usually smaller and may be about 5 - 22 kN in straight rail sections or 10 - 50 kN in narrow curves with 200 m radius (Lichtberger, 2003, p. 40). Due to the applied load, the pad is compressed by about 10% vertically and its horizontal change in size is about 3%.

A current problem is the deterioration of the elastic pads (fig. 1b) and thus the pads need to be replaced after very short time spans. For example, in alpine regions with many narrow curves they are replaced every 2.5 to 4 years (Auer, 2005). If the damage of an elastic pad is not detected, the rail under load is tilted outwards and as a consequence, the track width gets wider (e.g. more than 12 mm, Auer, 2005) which is, of course, a security-relevant aspect. Finally, if the pad is not replaced in time, the sleeper will be damaged, see fig. 1c, and must be replaced within a track lock. This, of course, affects the train traffic.

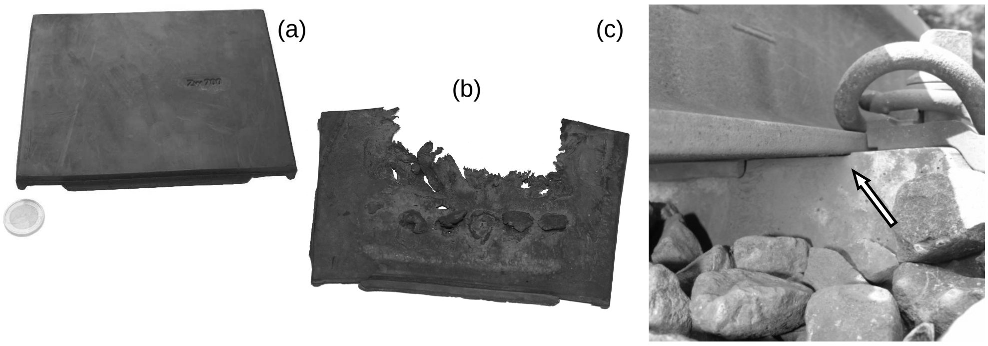

Figure 1: (a) New elastic pad with a 2 EUR coin, (b) an used pad that was removed too late from a regular railway track and (c) starting damage of a sleeper.

The reason for the fast deterioration of the elastic pads is rather unknown. However, it was assumed that horizontal and vertical forces generated by passing trains as well as temperature changes inside the pad are possible causes.

Currently, efforts are made to optimise the whole rail system. Especially, the material performance of the elastic pads should be improved in order to achieve a longer durability of the pads. The performance of the newly developed pads is usually tested in test tracks over several years. But there is no information about the stress behaviour inside the pad. Thus, investigations should be performed with strain measurements inside an elastic pad during the passage of trains as a base for material optimisation. For this purpose, an elastic pad with several integrated sensors (rail-strain-pad, RASP) was developed, tested in the laboratory and used on a railway track under field conditions.

2 FIBER-OPTIC SENSORS

The integration of sensors into a small object - the size of the elastic pad is only 150 x 160 x 7 mm^3 - is rather critical and their proper installation is essential for the representativeness of the measurement results. Fiber-optic sensors (FOS) appeared to be the only suitable sensor type because of their small dimensions (e.g. 0.25 mm fiber diameter) and their potential to transmit the signals of several sensors using one lead-in fiber only which is used instead of many connection cables. When using FBG sensors, several sensors may be integrated into one single fiber and thus the strain distribution inside the elastic pad may be studied. Compared to traditional sensors, another advantage of FOS is their electromagnetic immunity, which is an important issue when measuring close to railway tracks and electric locomotives.

Several types of fiber-optic sensors are available, see Measures (2001) or Peters (2009) for example. FOS were already used in combination with elastic pads (Sensorline, 2009) which are used for the counting of axles for example. However, because of the operating principle (microbending) these sensors cannot be used for the determination of the strain distribution inside the pad.

For the realisation of a RASP, fiber Bragg grating sensors were used as (a) several sensors may be applied to one single fiber and (b) the sensor length may be rather small (some millimetres). Further, (c) the signals of several FBG sensors might be read simultaneously and (d) dynamic measurements are possible.

3 FIBER BRAGG GRATING SENSORS AND THE USED MEASUREMENT SYSTEM

3.1 Fiber Bragg Gratings

The principle FBG sensors is described in Kashyap (2010) or Othonos & Kalli (1999) for example. The FBG reflects one portion of the light which corresponds to

$$\lambda_B = 2n\Lambda_B \tag{1}$$

where n is the refractive index and Λ_B is the grating period. Typical strain and temperature sensitivities of a FBG sensor are (Yu and Yin 2002, p. 127):

$$\begin{aligned} \frac{1}{\lambda_B}\cdot\frac{\Delta\lambda}{\Delta\varepsilon} &= 0.78\cdot 10^{-6}/\mu\varepsilon \\ \frac{1}{\lambda_B}\cdot\frac{\Delta\lambda}{\Delta t} &= 6.678\cdot 10^{-6}/K \end{aligned} \tag{2}$$

3.2 Instrument and FBG sensors used

Within the development of RASP, a Micron Optics sensing interrogator (si425) was used for the reading of the FBGs. The measurement range is 50 nm (1520 - 1570 nm) and the optical resolution is 1 pm. Thus, strain and temperature may be acquired with a resolution of 0.8 με and 0.1 K respectively. On each of the four channels, 32 sensors may be measured simultaneously with a sampling rate of 250 Hz. However, the number of sensors per channel is limited by practical reasons. In order to separate the signals properly, the signal spectra must not overlap which might be a problem in the case of an uneven strain distribution along the fiber.

The maximum strain that may be measured is limited by the breaking limit of the glass fiber and the FBG sensor respectively. This is about 10 N for a standard FBG of the recoating type. There, the coating is replaced before the bare fiber is illuminated with an UV laser for the production of the grating. Afterwards, the section of the bare fiber is recoated, but the strength of the fiber is degraded by this process. One alternative manufacturing method is the illumination of the grating whilst fiber production on a draw-tower prior to the coating process of the fiber, see Chojetzki et al. (2004) for example. The tensile strength of these draw-tower gratings is above 50 N, which almost corresponds to the one of a bare fiber, allowing to measure large strains of about 50 mm/m or more. Because of the large deformation of a RASP (see next chapter), this sensor type was finally used.

Acrylate coatings are widely used. However, acrylate is temperature resistant up to 100°C only, why polyimide coated fibers are often used for applications with higher ambient temperatures. Special coatings with a temperature resistance of up to 800°C are available (see e.g. Chojetzki et al., 2004), but these coatings were not necessary for a RASP (see next chapter). Ormocer which is the common coating of the DTGs provides a temperature stability of up to 200°C and thus it was used for the RASP. Tab. 1 lists the properties of some FBG sensors used during the development of the RASP.

Table 1: Properties of some types of FBG sensors.

FBG type	coating	temperature range [°C]	fiber diameter [µm]	breaking strain [%]
recoating	acrylate	-40 to +100	255	< 1
recoating	polyimide	-40 to +250	155	< 1
draw-tower	ormocer	-180 to +200	195	~ 6

4 PRODUCTION OF A RASP

It was one of the major tasks to integrate the fiber optic sensors into the elastic pad without damaging them. Due to the small size of the pad, the material's quite large coefficient of thermal expansion (CTE; about 150 ppm/K), and in order to get the most reliable results, the bare fiber was integrated into the material matrix of the elastic pad during manufacturing. The material is a closed-cell polyurethane elastomer (PU) with a static stiffness of about 160 kN/mm, see fig. 2. This rather low stiffness was chosen, as there is a trend towards elastic pads with low stiffness in railway engineering.

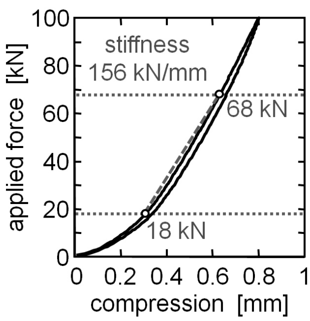

Figure 2: Load deflection curve of an elastic pad of mean stiffness.

Fig. 2 shows the relationship between applied forces and the vertical compression of the pad. At 100 kN, the compression is about 0.8 mm, which is 11% of the 7 mm thick pad. The horizontal deformation was unknown at that time.

Whilst manufacturing, the stiffness of the pad is set by the inclusion of small air bubbles. These bubbles usually have a diameter of less than 0.1 mm and it was experimentally verified that they do not cause the embedded fiber to break when a force is applied. The chemical reaction of the different material components during the production process causes the temperature to increase above 100°C, see fig. 3a. This is one of the reasons, why standard sensors with an acrylate coating could not be used.

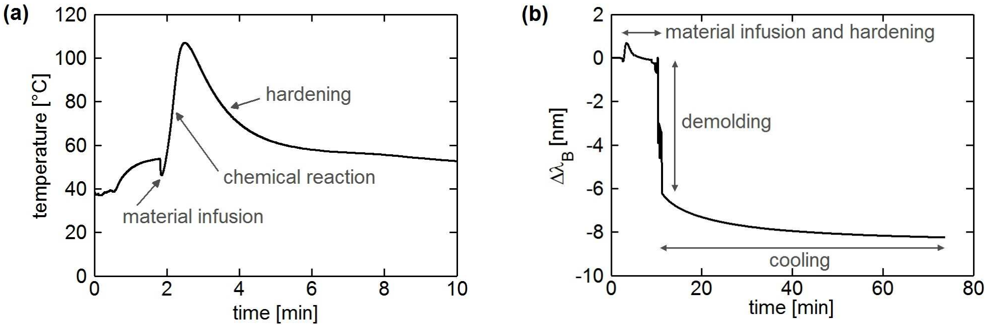

Figure 3: (a) Temperature increase whilst embedding the sensors and (b) wavelength shifts of a FBG sensor whilst the production of a RASP.

The viscous material hardens within several minutes and subsequently the elastic pad can be removed from the mould. Thereby, the pad suddenly changes its size because of the changed pressure ratio, and afterwards it shrinks slowly due to the large CTE. In total, the pad shrinks by about 1 mm (0.7%) which causes the wavelength shift of about 8 nm that can be seen in fig. 3b. As a consequence, draw-tower gratings (manufacturer FBGS, Jena, Germany) were used as the sensing elements. A RASP with these sensors survived tests with applied static loads of up to 200 kN or the whole test of dynamic load changes (> 500 000 load cycles, 55 kN each). Three FBGs (5 mm length, 15% reflectivity) were used on one fiber. In order to separate them correctly in the presence of uneven strain, a rather large wavelength separation of 15 nm was chosen for neighbouring sensors. By using an instrument with several input lines, it was possible to integrate 9 sensors into one RASP. Additionally, a FBG based temperature sensor was integrated into the pad for the temperature compensation of the measured λ_B. In order to protect the lead-in fibers from raised ballast grain on the rail track, armoured hoses of some metres length were used. Fig. 4a shows a schema of a RASP and fig. 4b shows its realisation.

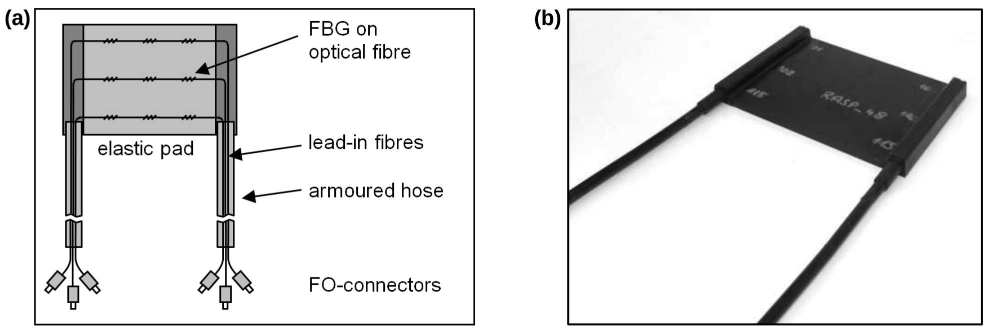

Figure 4: (a) Schema of the rail-strain-pad and (b) its realisation.

5 TESTING A RASP

For testing and calibration purposes, the rail-strain-pad was put on a pressure test facility. The passage of a passenger train (heavy engine, 6 wagons, velocity of 140 km/h) was simulated by loading the pad with the corresponding vertical forces. Fig. 5a shows these forces, which vary in between 18 kN (i.e. the clamping force of the rail clamps which hold the rail at the sleepers) and 65 kN. Exemplarily, the strain measured by the three sensors A to C on the middle fiber (see fig. 5b) is shown in fig. 5c-e. For data conversion, the strain sensitivity given by the sensor's manufacturer was used, which corresponds to the one given in eq.(2). However, for the independent verification of these values we have developed a FOS calibration facility at our institute which is now close to completion.

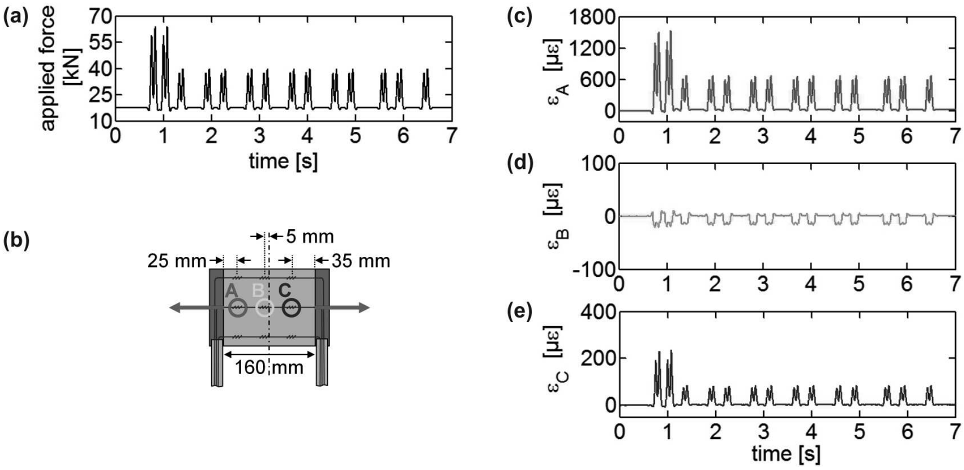

Figure 5: Simulation of a train passage in the laboratory: (a) Vertical forces applied by a test facility, (b) location of the FBG sensors inside the RASP and the strain measured by (c) sensor A, (d) sensor B and (e) sensor C (note the different scales of subplots c, d, e).

Note that the FBG sensors are arranged eccentrically inside this rail-strain-pad. The measured strain values are quite different for the three sensors, indicating that the strain distribution inside the pad is quite nonlinear. Sensor A, which is the outmost of the three sensors, shows the largest strain values (up to 1 500 με). Sensor C, which is 10 mm closer to the pad's centre, provides strain values that are smaller by a factor of 7. In the central region of the pad (sensor B), even negative strain (-20 με) appears, indicating that the pad is compressed in this region. This performance was previously unknown and indicates a non-linear Poisson's ratio for the elastic pad in the position of use.

It is now one of the next goals to compute the forces acting on the RASP by using the FBG signals and individual calibration functions for each sensor. First results were already shown in Woschitz (2010). There, the maxima of the applied vertical forces could be determined with an accuracy of about 2% (laboratory conditions).

6 STRAIN IN THE FIELD ON A RAIL TRACK

In order to get first information about the strain inside an elastic pad under field conditions, several RASPs (14) were manufactured and installed in a mountainous rail track in a narrow curve (R = 290 m), see fig. 6.

Figure 6: Several RASPs installed in a rail track.

During a period of one week, the signals of several trains were measured. Fig. 7a shows the largest signal that was observed in the field, four days after the installation of the RASPs. Shown are the raw signals, as the values for wavelength to strain conversion could be different from the standard values, especially for signals of that magnitude. However, this will be investigated with our calibration facility in future works. In Fig. 7a the vertical axis corresponds to the whole measurement range of the interrogation unit. For comparison, the signal of a corresponding passenger train is shown in fig. 7b; the signal was acquired in the laboratory at the test stand using the same RASP (the sensor positions in this pad differ from the one shown in fig. 5b, why the signals of sensors A and C are almost of the same magnitude here).

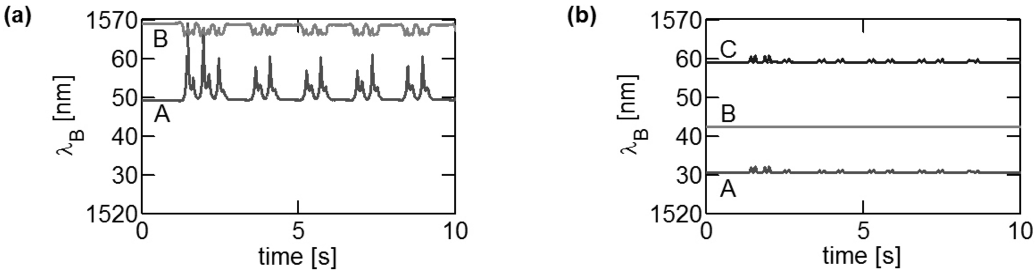

Figure 7: Wavelengths measured with sensors A, B and C (a) in the field during a real train passage and (b) in the laboratory for a simulated train passage with a train of the same type.

At a first glance, the large wavelength difference between the field and the laboratory data can be seen. It is about 19 nm for sensor A and 26 nm for sensor B. In the field, the signal of sensor C (about 1581 nm, measured in a static situation with another reading unit) is even out of the measuring range of the interrogation unit used. Secondly, the signals of the train acquired in the field are about 13 times larger compared to those in the laboratory. Of course, the conditions in the laboratory and the field are different. For example, additional horizontal forces in the field caused a tilting of the rail of 0.5° during the train passage and thus the elastic pad was deformed asymmetrical. But for material optimisation, knowledge about the strain in the pad in real conditions is essential. It is explicitly mentioned that these very large strains cannot be measured using standard sensors; sensor A for example, which provides a nominal wavelength of 1530.0 nm, survived wavelength changes of about 39 nm. Assuming that the standard coefficient for strain conversion is applicable for such large strains, then the corresponding strain might be about 31 000 με! Adversely, all recoated FBG sensors that were used in some early RASP prototypes broke at much smaller strain rates.

One possible reason for the very large signals in the field might be a slip of the elastic pad. The RASP was installed in the track four days before the measurements were performed. Within this time, the pad has moved for approx. 4 mm towards the angled guide plate, see fig. 8.

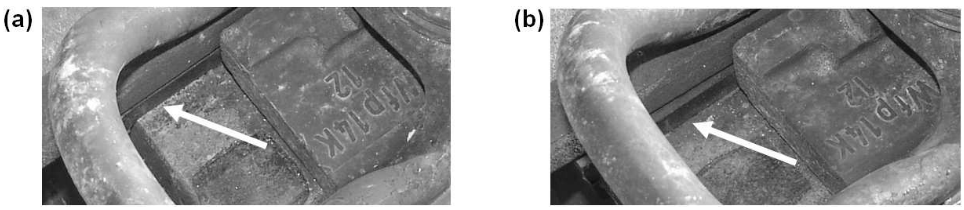

Figure 8: Position of the elastic pad between the rail and the sleeper (a) after its installation and (b) 4 days later.

In order to prove the functionality of the RASP which has shown these large signals, the pad was removed from the rail track after the end of the experiment and again tested in the laboratory. Its correct operation could be demonstrated.

7 CONCLUSIONS AND OUTLOOK

The elastic pads used in railway tracks show large deformation when they are loaded. If installed in narrow curves, the replacement interval of the pads is rather short (some years) and thus their replacement is cost intensive. For the improvement of this situation a better knowledge of the strain variation in a pad is required. For this purpose a rail-strain-pad was developed based on fiber-optic sensors. First, only little information about the material was available and thus standard FBG sensors of the recoating type were used mainly for cost reasons. However, they did not withstand the large strain values that appear inside the small pad during dynamic loading. Draw-tower-gratings were found to be the suitable sensor type for this application. Several RASPs were installed in a narrow curve of an alpine railway track for a period of one week. There, the sensors, which were embedded into the material matrix, survived even strain values of about 31 000 με.

The measurements are the first of this type in the material used and are now the base for the optimisation of the elastic pads by the producer in order to provide pads with a higher durability. A further development of the RASP will be used for the continuous monitoring of loads applied to the railway track. The high elasticity of the elastic pad is a key issue in railway systems, but makes sensing issues a rather sophisticated task. For the investigation of FBG sensors in their limit range, a testing facility was established and the first testing will be done soon. However, for future WIM applications, the RASP will be modified in order to reduce the maximum strain that is induced by the applied loads.

ACKNOWLEDGEMENTS

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