Static and Dynamic Measurements on a Newly Developed Precast Concrete Track for High Speed Railway Traffic Using Embedded Fiber-Optic Sensors

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ABSTRACT

In a German slab track system ("Feste Fahrbahn" FF, system Bögl) for speeds up to 300 km/h and more different fibre optic sensors have been embedded in several levels and locations of the track system. The track system consists of prestressed precast panels of steel fibre concrete which are supported by a cast-in-situ concrete or asphalt base course. The sensors are to measure the bond behaviour or the stress transfer in the track system. For that, tiny fibre-optic sensors - fibre Fabry-Pérot and Bragg grating sensors - have been embedded very near to the interface of the layers. Measurements were taken on a full scale test sample (slab track panel of 6.45 m length) as well as on a real high speed track. The paper describes the measurement task and discusses aspects with regard to sensor design and prefabrication of the sensor frames as well as the embedding procedure into the concrete track. Results from static and dynamic full scale tests carried out in the testing laboratory of BAM and from measurements on a track are given.

Keywords: railway track system, bonding behaviour, fibre-optic sensor, concrete composites

1. INTRODUCTION

Railway track systems are constructed with concrete since 1909. The Deutsche Bahn AG railway company started their investigations in the sixties of last century. The goal was to replace the maintenance-intensive conventionally ballasted track by a track system which guarantees a continuously high quality and long-term alignment accuracy [1].

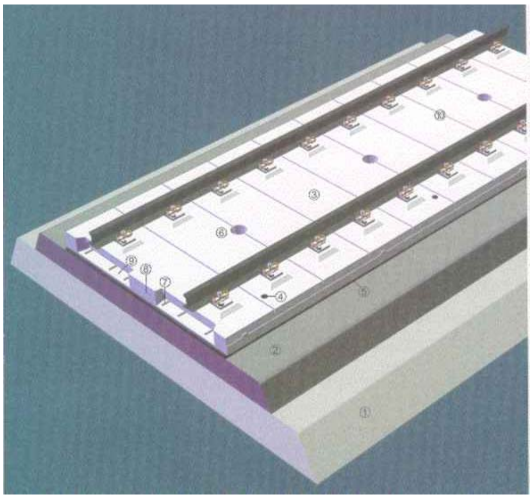

Fig. 1: Slab track system Bögl 2.

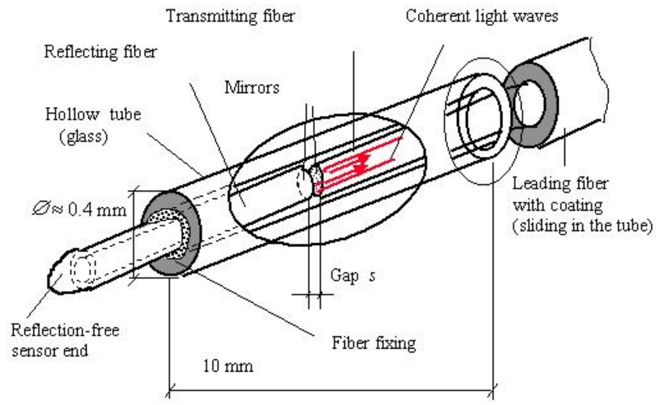

Fig. 2: Fibre Fabry-Pérot interferometer sensor (principle structure)

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The slab track (Feste Fahrbahn-FF) consists of a multi-layer structure. Above the formation and subgrade a cast-in-situ hydraulically stabilized concrete layer or an asphalt base course is located. Above these, a concrete layer which carries the track will be constructed For the investigations described in this paper, the Feste Fahrbahn System Bögl has been chosen. The lower concrete layer is 300 mm thick, the upper precast panel is 6,45 m long and 200 mm thick. The gap between them is filled with a special bitumen-cement grout. This ensures adequate bond of the concrete layers and good performance of the track system under static and dynamic loads during operation. Figure 1 shows the structure of the described track system.

The Deutsche Bahn AG railway company carried out experimental investigations on a full scale - but of only one panel length - test sample as well as on a track in service. In order to evaluate the quality and durability of new railway systems strain at different levels of the bonding area are measured by means of embedded sensors. Because the bitumen-cement grout layer is only 3 cm thick it is necessary to ensure that the measuring zone will not be influenced by any embedded sensors. On the other hand, the embedded sensors must not affect the bonding itself.

2. CHOICE OF THE SENSORS

The following criteria had to be considered for choosing sensors:

- minimum volume for sensors and leading fibres (including coating and covers)
- resolution of strain variations in the order of a few µm/m (µε)
- no reaction to the measuring zone
- long-term stable function of the sensors
- ability of external calibration for the sensors system used.

In order to fulfil these criteria two types of fibre sensors have been chosen: extrinsic fibre-Fabry-Pérot interferometer sensors (EFPI) and fibre Bragg grating sensors (FBG). Both types are very small and do not influence the measuring zone since no voluminous coating is necessary against moisture (as it is necessary for resistive strain gages). On the other hand, these sensors guarantee sufficient strain resolution (EFPI) and the capability of long-term stable work after re-calibration (FBG).

3. DESCRIPTION OF FIBRE-OPTIC SENSORS

The function of EFPI sensors has been described in detail by the authors in previous publications [3]. The tubular sensor element (length around 10 mm, outer diameter 0.5 mm) is connected with the leading optical fibre (diameter 1 mm). This leading fibre links the sensor element to the measuring instrument. Inside the glass tube two smoothly broken fibre ends are positioned face to face; the distance between them is between a few µm and 120 µm at maximum depending on the strain stage of the surrounding material. When strain changes in the material occur, an axial displacement of the fibre end faces produces intensity variations due to interference fringe changes. Intensity variations are transferred into voltage variations and these signal changes are recorded.

In order to minimize the necessary force to shift the fibre in the tube, the connecting fibre is able to slide inside the tube. This flexible form of the classic EFPI sensor makes sure that these sensors work almost without reactions to the surrounding material. The optically active space inside the tube is protected against water ingress. The measuring range of the sensor is about -2000 µε to +2500 µε, the strain resolution in combination with the recording device is in the order of 10^{-7} to 10^{-8}. The temperature dependence is about -5.4 nm/K; from this follows a strain correction factor of 77 nm/m to compensate temperature variations [4]. For the special case of application described here the measuring base has been increased to 70 mm by using special members adjusted to the elastic behaviour of the material to be measured.

The other type of fibre sensors used are FBG sensors. These sensors have frequently been described. They were necessary to obtain reference strain values over a long period of time for instance when the power supply is switched off between measurement events or to recognize drifts which normally occur in other sensors, e. g. in resistive strain gage sensors. In this special case the FBG arrays installed consist of three gratings in series. A specially developed recording device manufactured at the IPHT Jena/Germany has been used. The length of the gratings was 6 mm, two strain grating sensors measure strain in two perpendicular directions; one grating is freely movable and measures only temperature.

The characteristic parameter of these sensors - the Bragg wavelength λ_B - depends on variation of the grating period caused by stain and temperature variations. The recorded data are absolute values and are also available even if the power supply is switched off for a long period of time or if the sensors disconnected. There is a linear relation between strain and temperature dependence:

$$\frac{\Delta\lambda_B(\varepsilon_z)}{\lambda_B} = (1 - p_\varepsilon)\varepsilon_z + (\alpha + \xi)\Delta T$$

ε_z is the strain in axial fibre direction. The coefficient of thermal expansion α is the difference between thermal coefficient of the surrounding matrix and the glass fibre. The term $p_\varepsilon \approx 0.20$ to 0.25 is the effective photo-elastic constant which depends on the manufacturing procedure of the gratings. The gratings used have a strain sensitivity of 0.7 pm per µm/m strain (T = const.) for the wavelength of 820 nm. $\xi = dn/dT$ is the thermo-optic coefficient and describes the temperature dependence of the index of refraction.

4. DESIGN OF THE MEASUREMENT FRAMES

In order to reach the interface area between the intermediate bitumen layer and both concrete courses, bore holes have been drilled into the track system. Measurement cages which contain different fibre sensors at several levels were embedded into these holes. Four measurement levels were chosen: above and below the interface area as well as 5 mm below the upper side of the precast panel and 5 mm above the bottom side of the supporting cast-in-situ concrete base course. In order to test the performance of the measurement frame design, embedding procedure as well as function of the cages were test on a full scale test sample. Figure 3 shows the test arrangement in the large testing facility of BAM.

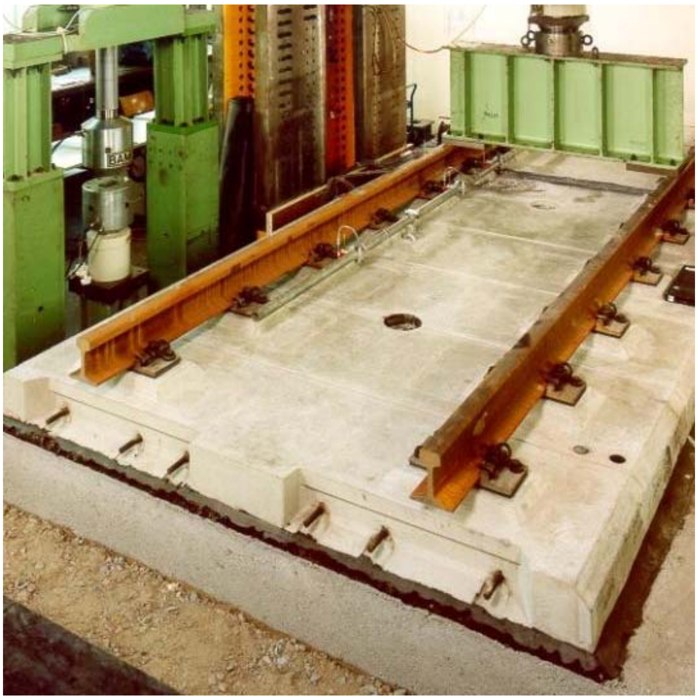

Fig. 3: One precast panel forms the test slab track system in the testing hall

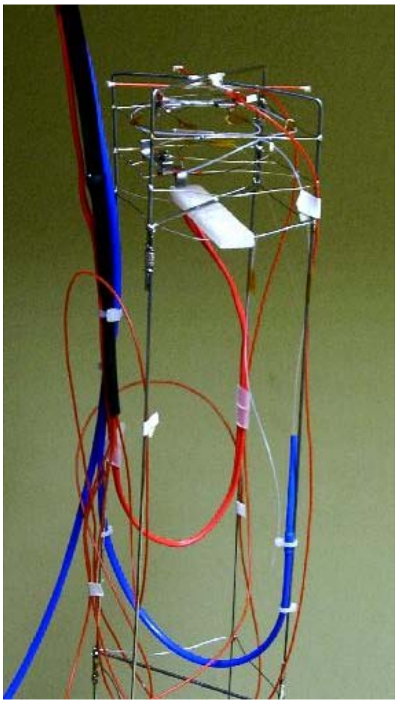

Fig. 4: Side view of one sensor frame (prior to casting)

Figure 4 shows one of the measurement frames. In each of the four measurement levels described above, one couple of strain sensors are orthogonally fixed. This way, the horizontal strain field can be measured in longitudinal (direction of travel) as well as transverse direction. The force-locking fixing was different for both sensor types: the fibre-Fabry-Pérot interferometer sensors (EFPI) were embedded in a cross-shaped supporting element made from modified cement paste; the fibre Bragg grating strain sensors (FBG) were glued to specially designed tiny clips and positioned in the shape of a cross. Additionally temperature sensors are embedded to evaluate the temperature influence. For data recording, special multi-channel devices have been developed at BAM (for EFPI sensors) and at IPHT (for FBG sensors).

After fixing all sensors, the cages were cast in a cylindrical shape using a special grout, the Young's modulus of which was adjusted to the surrounding material. Generally, the measurement cages were divided in two parts. First, the bottom cage was embedded in the base course after shrinkage of the grout had essentially ceased. For the embedding of the cylindrical measuring cage in the lower base course a bitumen-cement grout was brought into the gap between the concrete base course and the cylinder right up to the underside of the prefabricated concrete panel. Second, following the hardening process of the bitumen cement grout, the upper cage was embedded. The leading fibres of the bottom cage were passed through a small hole in the upper cage. Several positions on the track panel have been chosen for testing the cages.

5. EXPERIMENTAL INVESTIGATION

5.1 Laboratory tests

First, the slab was subject to a static load of 325 kN (corresponding to 1.3-times the service load) using a hydraulic loading equipment. In further tests the load was increased to the 1.9-times the expected axle load (250 kN). The load was applied at a nearly central position of the sample (compare Figure 3). Dynamic loading followed the static one. 5,000 load cycles (3 Hz from 175 kN to 325 kN) were carried out several times. Finally, a continuously increasing load up to 725 kN was applied. All recorded data from different measurement levels have been correlated to evaluate the bonding characteristic under static and dynamic loading. In order to verify the data received from the fibre sensors a number of resistive strain gages (including temperature sensors) have been installed additionally.

5.2 Measurements at the Intercity (IC) railway line Husum-Niebuell (North-west Germany)

A short section of the IC line in North Frisia is constructed as slab track (Feste Fahrbahn System Bögl). In one position of the slab track measurement cages are embedded in a very similar way as done in the laboratory. Because the base course layer was constructed with asphalt concrete, the frame for this lower layer was fixed in the bore hole without being previously cast using grout as described above. Thereafter, the hole was filled with asphalt concrete right to the underside of the precast panels. In a further step the upper (already cast) measurement cage was positioned in the bore hole and fixed with special cement grout.

6. TEST RESULTS

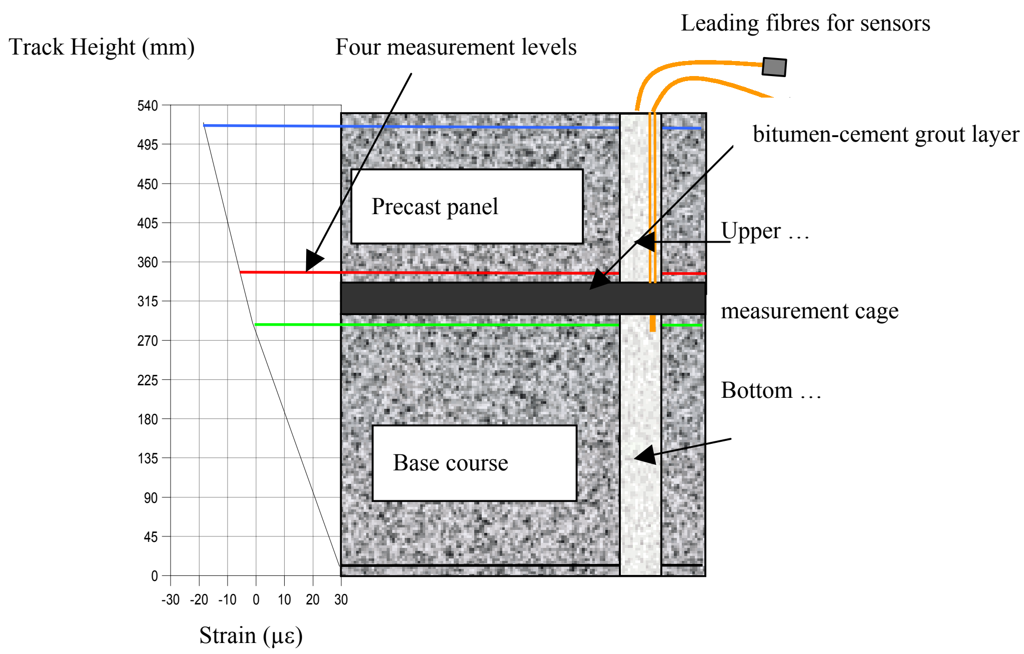

Fig. 5: Strain distribution in the test sample's cross-section

The first test in the laboratory revealed that the strain changes during loading were less then estimated. This may be caused by a relatively stiff bedding of the slab track system on the concrete floor. A 300 mm thick gravel fill and an additional ballasted mat did not simulate satisfactorily a track on embankment. For a load of 400 kN the strain at the bottom side of the bottom base course does not exceed 28 µε. For this reason the measurement basis of the EFPI sensors had to be increased. In this way the resolution could be improved. Figure 5 shows results for a loading of 400 kN achieved by using EFPI sensors with increased sensitivity. The measurement levels shown in the Figure are 10 mm above and below the bitumen-cement grout layer.

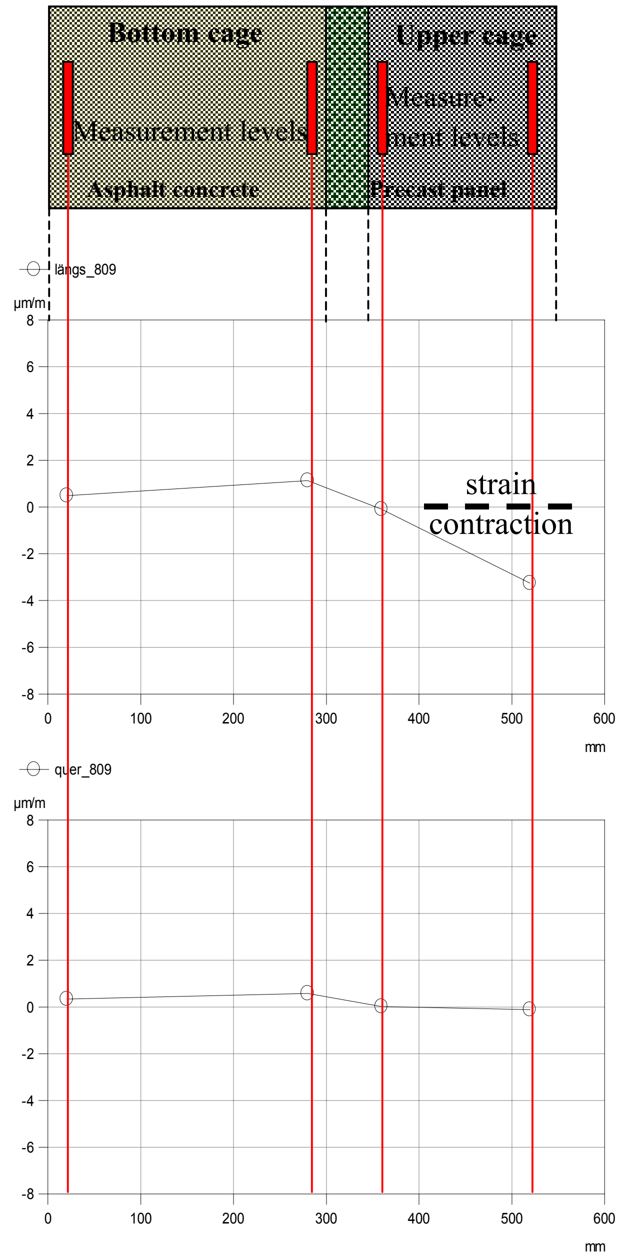

Fig. 6: Second load stage: the first rail couple of the first engine's first leading bogie is exactly above the measuring point (above: strain face to engine, bottom: transverse strain).

Analysis of the result shows a relatively smooth strain distribution over the different concrete layers of the track system. No significant unsteady behaviour in the bonding area was observed around the measuring zone. From these results can be concluded that there is obviously a good bond behaviour of all layers and the loading is virtually transferred to the ground as it occurs in a single layer. The different strain values that occur in the concrete layers having different Young's moduli are not so high that the bond behaviour is lost. This satisfactory behaviour did not change after several thousand load cycles.

In order to evaluate the relation between load and strain distribution, the static load has been increased to 600 kN. Up to this load the load/strain relation is linear. A slight non-linearity could be observed above 600 kN (at maximum 80 µε) at the bottom side of the base course.

Measurements were carried out during train operation at the IC railway line when an express train - drawn by two engines - passed the section where the measurement cage had been installed. Even though the speed of the train was only about 100 km/h at the measurement point, the measurement time was very short. The EFPI sensors were read with a scanning rate of 500 measurement per second. The FBG sensors were used to check remaining deformation in the bonding area after the train had passed. Another important measurement task of FBG sensors is to deliver the reference dimension for long-term evaluation of deformations. When a new measurement will be carried out using EFPI sensors with high strain resolution, the zero-point definition of strain variations can be taken from FBG sensors.

The values measured in the track were again very small, as expected. Maximum bending of the track was observed when the first axle of the first engine's leading bogie was above the measurement point. At this moment, compressive strain in the upper concrete precast panel was -3.7 µε (see Figure 6).

The transverse deformation is smaller; only a few με transverse strain has been measured during train passing. Tensile strains in direction of travel were recorded when the measurement point is located between two bogies of the engines or wagons. In this case, positive strain values on the upper side of the concrete panel could be measured. With regard to the sensor technique it is worthy to note that embedded interferometric micro strain sensors helped to detect already extremely small strain changes in the order of a few ten nm/m.

From the measurements carried out on the IC line it can be concluded that the strain distribution in the track system is non-linear. This is caused by the difference in the Young's moduli of the different concrete layers. Asphalt concrete with a Young's module of 5 GPa (averaged over the year) is definitely more elastic than that of the precast panels made from high quality steel fibre concrete. It can be concluded that there exists good bond behaviour in the real track system because the measurements did not reveal an unsteady strain distribution over the complete system.

Regarding the good resolution of the EFPI sensors it is also worth mentioning that extremely small deformations in the range of a few ten nm/m were measured in the slab track system when a train passed the neighbouring track. Moreover, already the approach of the train could be detected by recording dynamic strain signals in the order of 10^{-8}. This capability, especially the interference-free signal recording next to high electromagnetic influences, offers another measurement possibilities when EFPI sensors will be used in combination with long-term stable absolute FBG sensors. Measurement cycles done using FBG sensors after several trains have passed, showed no permanent deformation in the track system.

7. CONCLUSIONS

Fibre-optic micro strain sensors have been embedded in the bonding area and on selected positions of a German railway track system (Feste Fahrbahn, System Bögl). Strain distribution over the track thickness have been measured under simulated and real loading conditions to evaluate the bond behaviour of the components used in this system. Measurement cages which contain micro strain sensors have been developed during test loading of a full scale test sample in the large testing facility of BAM in Berlin. An optimised measurement cage that can also be quickly installed for measurements on high speed tracks was provided.

Very small strain changes up to two orders better than με values could be reliably detected and noise-free measured in the testing hall in a full scale test as well as on a track under electromagnetic influences during train passages. From the results obtained, a satisfying bond behaviour of the supporting concrete layers could be concluded. The combination of extrinsic fibre-Fabry-Pérot interferometer (EFPI) sensors and fibre Bragg grating (FBG) sensors guarantees the necessary resolution as well as the ability of calibration for separate measurements after long breaks. The small size of the embedded fibre sensors minimizes reactions to the material zone to be measured and it opens new possibilities to obtain information about the lower, inaccessible layers of complicated concrete structures.

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