Laboratory Investigation of Sensors Reliability to Allow Their Incorporation in a Real-Time Road Pavement Monitoring System

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Abstract. Unlike other engineering structures, road pavements have a greater monitoring complexity due to their heterogeneous composition and the diverse and increasing loads they are subjected to, hindering the preventive maintenance operations. For that reason, real-time monitoring systems are extremely useful to measure strains/displacements and temperature. Most of the currently applied systems use electric sensors, known as strain gauges, but a new monitoring technology has gained popularity in the last decades. Fibre Bragg grating (FBG) is an optical sensor with great potential that has been introduced on monitoring systems. The attempts to include FBG sensors in pavement monitoring have shown that further investigation is needed. Some factors to be studied are the interaction between the sensor and pavement, the use of coatings, the application method, and the influence of external conditions (e.g., temperature). This article presents preliminary laboratory work on FBG optical sensors vs electric sensors as part of the Rev@Construction project that aims to digitalise the construction industry in Portugal. This work will be essential to assure the reliability of FBG sensors before they are installed in a pavement monitoring system for a highway section. Through a series of controlled strain tests in a four-point bending apparatus, it was possible to conclude that the FBG sensors have a better quality signal than electrical strain gauge (SG) sensors. Furthermore, FBG sensors are not affected by magnetic fields, a clear advantage compared to SG sensors. The importance of temperature calibration on FBG sensors was also demonstrated in this work when analysing the data collected.

Keywords: Pavements · Monitoring · Strain · Sensors · Fiber bragg grating

1 Introduction

Maintaining the condition of the road pavements under the public domain is one of the main challenges governments and road administration face today.

Pavement design is a long-term structural evaluation process aiming to ensure that the traffic loads are efficiently distributed through the multiple layers that compose the road structure. This task must be done with the least resources possible (materials and

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equipment) in the construction phase and throughout the pavement's life cycle. Lately, environmental concerns have also gained an important role in the design process.

In mechanical terms, the design process selects adequate materials/mixtures for the different types of pavement structure layers and their thickness. A series of material related concepts must be considered, especially stiffness.

The thickness of each layer must respond to two design parameters, ensuring enough stiffness (Kara De Maeijer et al. 2019): the tensile strain at the bottom of the lowest asphalt layer and the vertical strain at the top of the subgrade (Fig. 1). These two parameters must be controlled under acceptable limits to ensure the pavement's adequate performance (limiting the cracking and deformation levels) (von Quintus and Hughes, 2019).

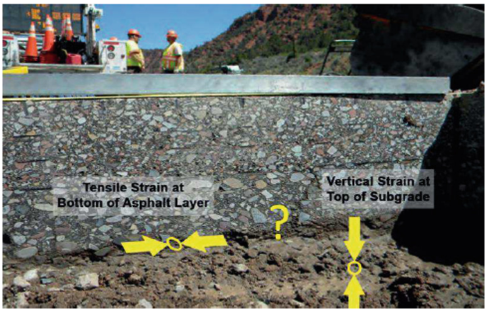

Fig. 1. Common location of critical strains in asphalt pavement (von Quintus & Hughes, 2019)

Assessing the mechanical state of the pavement is crucial to confirm if the design has been done correctly and to maintain surface pavement conditions. Thus, continuous pavement monitoring is a growing trend (Kara De Maeijer et al. 2020).

In situ instrumentation is an intrusive approach for continuous pavement monitoring, essential to understanding the state of life of the structures (Kara De Maeijer et al. 2019) and paving the way to the so-called "smart road" (Sun et al. 2018).

The sensors used in that instrumentation must be as small as possible and compatible with pavement materials' heterogeneous nature and mechanical properties to ensure a correct stress/strain transmission. When applied during the construction process, they must also withstand the high stresses and temperatures experienced and resist corrosion and fatigue to achieve long-term monitoring.

The successful installation of sensors on site is vital for the transfer of outputs to be carried out in the most natural way possible.

Electrical strain gauges, pressure cells, deflectometers, accelerometers, geophones, and thermocouples have been widely used with various applications and proven results about its ability to monitor pavement conditions efficiently.

Nevertheless, as with every technology, electrical strain gauges present disadvantages that, along with advances in fibre optic technology, are fostering a paradigm change, although gradual, in monitoring systems.

Fibre optic sensors are a promising tool in strain and temperature monitoring. They offer numerous advantages compared with conventional sensors, making them the leading candidates for long-time monitoring in harsh environments with high efficiency.

Civil engineering is sometimes treated as an outdated area compared to others at a technological level. The use of advanced sensors in monitoring is an essential and helpful tool in this transition that it is currently being done.

Being part of the mobilising project Rev@Construction, which focuses on the digitisation of the civil engineering industry in Portugal, the work being carried out in the activity "APP PAV 4.0 LC" has the objective of installing an optical fibre pavement monitoring system in a highway section in-service. The data collected (strain, displacements and temperature) by the Fibre Bragg Grating (FBG) sensors will then be used to assess how the structure reacts to heavy vehicles' action and to develop pavement performance models.

Therefore, besides quantifying the loads induced by the vehicles, the system will allow real-time monitoring of the pavement's mechanical condition and provide the road administration with a handy tool to manage their infrastructure's life cycle.

Knowing the constraints that this type of application has in terms of the number and location of sensors, the use of certain joint filings that can jeopardise the correct stress/strain transmission, and the influence of external factors, this paper presents an innovative laboratory approach to the use of FBG optical sensors vs electric sensors.

2 Materials and Methods

This section presents a theoretical framework for the two types of sensors used in this work, emphasising FBG sensors. After that, the laboratory tests performed will be presented.

2.1 Strain Gauge

The strain gauge technology dates back to 1938, when after many developments, a bonded, metallic wire-type strain gauge was presented by Edward E. Simmons and Arthur C. Ruge. The strain gauge is a sensor that produces a difference in the electrical resistance when a force is applied, creating stresses and strains. In order to get these measurements, strain gauges make use of a Wheatstone bridge circuit. When the object experiences deformation, the electrical resistance variation is measured by the Wheatstone circuit and converted to strain with the Gauge Factor (GF). Besides being sensitive to the application of forces, they are also sensitive to temperature variation, which is a determining factor to consider in the measurements (Weiss, 2017).

Strain gauges (Fig. 2) have been widely applied in pavement monitoring over the last decades. In 1992, (Sebaaly, 1992) tested various types of instrumentation for field evaluation under actual truck loading. They were also used to carry out studies on dynamic pavement deflection (Huff et al. 2005) and to develop a self-powered wireless sensor, based on the integration of piezoelectric transduction, capable of detecting strain and temperature simultaneously (Lajnef et al. 2011).

Its use is expected to continue because it is a small, cheap system with a good range of precise measurements. However, it requires permanent calibration and the continuous effect of loads decreases the transmitted signal with time. The fact that the signal is affected by electromagnetic fields is also a critical downgrade (Vanlanduit et al. 2021).

Thus, the paving industry has turned its attention to optical fibre sensors, which presents advantages to some strain gauge problems.

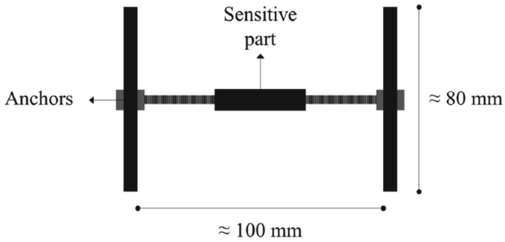

Fig. 2. Schematics of a horizontal strain gauge (H-gauge) (Barriera et al. 2020)

2.2 Fibre Bragg Grating

Fibre grating was first demonstrated by Hill et al. (1978) at the Ottawa Communication Research Center in Canada (Hill et al. 1978; Kawasaki et al. 1978). Later in 1990, the fibre grating sensing principle to strain and temperature was described, boosting its application as a sensing element (Morey et al. 1990). Since then, fibre grating has been widely used in civil, mechanical, aerospace engineering, and medicine.

FBG based sensors present a few advantages compared to traditional sensors used in pavements monitoring, which will make them the trend of the future in this area. Those advantages are small size, flexibility, extreme accuracy, embeddability, high frequency, and immunity to electromagnetic interference (Dong et al. 2012).

Fibre Bragg grating is a small portion of an optical fibre a few millimetres long, created by exposing a single-mode fibre to a periodic pattern of intense ultraviolet (UV) light. This engravement changes the refractive index of the fibre's core, creating a defined index modulation called grating, according to the defined pattern. The change will match the amount of reflected light at each periodic refraction index.

The reflected lights will combine in a particular wavelength when the grating period is similar to half the incident light's wavelength. That singularity is known as the Bragg condition, and the wavelength at which this reflection occurs is known as the Bragg wavelength (Braunfelds et al. 2021).

When light is input into the optical fibre, only the signals within a very narrow spectral width will be back-reflected by the grating (Fig. 3). This engravement causes only the wavelengths that comply with the Bragg condition to be affected and heavily reflected.

The following expression proves that the central wavelength of the reflected signal matches the Bragg condition (Eq. 1):

$$\lambda = 2n_{eff}\Lambda \tag{1}$$

where λ is the Bragg wavelength, n_{eff} is the effective index of refraction, and Λ is the grating period.

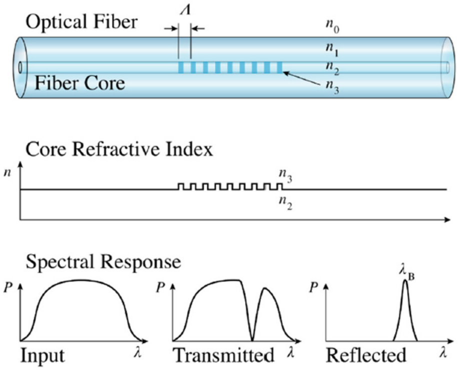

Fig. 3. FBG optical operational principle (Barriera et al. 2020).

Both the parameters n_{eff} and Λ are highly sensitive to external perturbations, like temperature or strain. When there is a change on one of these, the central Bragg wavelength shifts. The expression explains strain variation:

$$\frac{\Delta\lambda_1}{\lambda_1} = \frac{\Delta\lambda_\varepsilon}{\lambda_1} = (1 - P_e)\varepsilon \quad (2)$$

where $\Delta\lambda_\varepsilon$ is the wavelength variation due to the strain, ε is the longitudinal strain and P_e is the effective photo-elastic constant of the fibre core material.

Since this type of sensor does not distinguish the measurement of strain and temperature, it is sometimes necessary to separate the effects to make temperature compensation procedures. Typically, to eliminate the influence of temperature on the measurements, another identical FBG sensor that only detects strain due to the effects of temperature is used (Ansari, 2007; Kim et al. 2013; Wang et al. 2019).

Subtracting the thermal strain effect to the combined effect of load and temperature, obtaining the strain only due to the effect of the external load applied.

Calibrating both sensors is a crucial step to ensure reliable results.

Lately, the reliability of this temperature compensation method has been raised, and new methods, including different technologies like Brillouin Optical Time Domain Analysis (BOTDA), have been tested (Mohamad, 2012).

Studies showed that the temperature effect on the FBG and optical-based sensors, in general, has to be carefully treated, highlighting the need that still exists to understand better and treat this step (Ge et al. 2014).

2.3 FBG Coatings and Fixation Methods

Realising the weaknesses that raw optical fibre presents, many studies have been dedicated to developing sensor coatings and fixation methods before its application.

Monitor Optics Systems, Ltd proposed a glass fibre composite cable with many embedded optical fibres, obtaining a proper transfer of mechanical stress from the structure to the sensor through many kilometres and good compatibility with resin adhesives for a better surface bonding. This solution was applied with good results in a highway pavement in Australia (Nosenzo et al. 2013).

A few authors (Kara De Maeijer et al. 2018; Kolisoja et al. 2019; Skels et al. 2018) have studied the feasibility of embedding FBG sensors on asphalt concrete specimens. The results showed a linear relationship between the wavelength and strain variations.

The most used packaging material for fixing FBG is epoxy adhesive, embedding the sensor directly into the structure or fixing it to the surface. This method might potentially present drawbacks if the FBG presents chirping failures, causing a misleading wavelength value. Besides that, its use in harsh environments should be cautious, and the length and thickness of the adhesive can also affect the accuracy of the measurements (Kuang et al. 2018). For these reasons, metallic-packaged FBG sensors are also used. Due to their stability, durability, resistance to corrosion and high or low temperatures, the metals and metallic compounds can replace adhesive packaging in more aggressive weather conditions, frequently to monitor the temperature. On the other hand, it is also more difficult to directly package the FBG in metallic materials (Kuang et al. 2018).

Besides the necessary care in selecting the adequate coating, the correct installation of sensors in the pavement is another fundamental step to ensure the reliability of the results. (Dong et al. 2012) indicated three key steps that should be completed when installing FBG sensors: (i) the surface where the sensors are applied must be completely levelled to avoid strain distraction; (ii) cables that are part of the system must be bound to prevent them from being pulled, potentially reducing the signal transmission; (iii) the last step is related to the pavement compaction and advises not to use vibration on the first two compactions.

2.4 Laboratory Calibration in the Scope of Rev@Construction Project

The higher initial cost of the FBG alternative, compared to others, requires its development to be done in the most prudent way possible so that, in the end, the results obtained can take advantage of all the potential of the FBG technology that will be used in the "APP PAV 4.0 LC" activity of the Rev@Construction project.

Thus, the work is divided into three phases, and phase one, which is discussed in this paper, is a first laboratory approach to the technology, where it is intended to study some questions such as how to fix the sensors to the structure, which configuration ensures a better transmission of stresses/strains, how do external factors influence the calibration of measurement systems.

Figure 4 presents a few schematic drawings of the various configurations that will be tested in four-point bending tests to analyse variables like the number of sensors applied in series, different types of encapsulations, different filling materials, and the use of glass fibre profiles instrumented with FBG sensors.

In phase two, the data obtained in the laboratory will be validated in a physical model at a pavement trial so that in the last phase, the fully operational system will be installed on a highway in service (phase three).

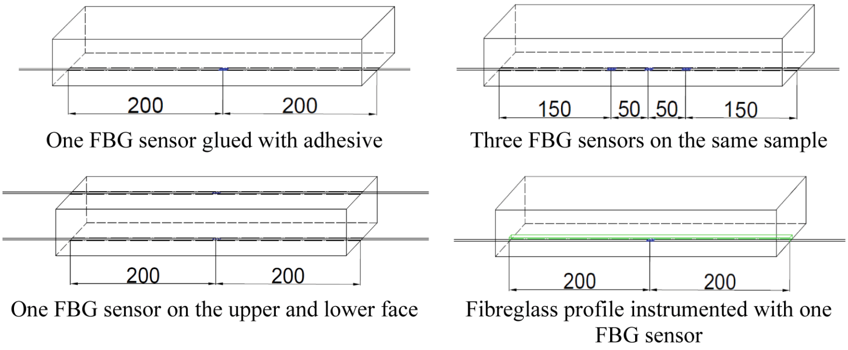

Fig. 4. Different testing configurations to be evaluated in the laboratory.

2.5 Experimental Procedure

A prismatic specimen (beam) of a conventional AC14 asphalt mixture was instrumented on both sides at a preliminary stage of the laboratory work. An FS70FBG strain sensor with a Teflon tube was applied on the beam's lower face (Fig. 5). The optical sensor was made with the raw fibre glued to the structure with an epoxy adhesive recommended by the manufacturer.

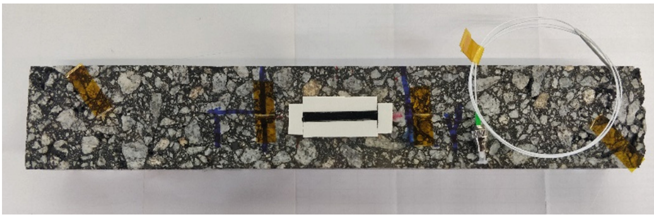

Fig. 5. Specimen face instrumented with FBG sensor.

The application of the FBG sensor is a delicate process, and sharp edges must be avoided due to the shear susceptibility of the optical fibre. The surface must be clean, and the cable slightly tensioned when placing the adhesive. The adhesive must be evenly spread to eliminate potential errors in measuring strains. The bonding length should be enough (40 to 50 mm) to evaluate the actual strain being applied to the specimen surface without the potential interference of any specimen heterogeneity (e.g., coarse aggregates located at the sensor position).

The sensor was then connected to the optical interrogator FS22 Industrial BraggMETER (Fig. 6) that emits the light and receives its response, characterised by changes in its specific wavelength. The response of an FBG sensor is not affected by the light amplitude but only by its wavelength.

A conventional electrical strain gauge (with a GF of 2) was also glued on the beam's upper face (Fig. 7) for comparison with the FBG sensor. This comparison is possible since the beam was subjected to a flexural movement using a sinusoidal loading pattern

Fig. 6. Interrogator FS22 Industrial BraggMETER used in the laboratory work.

(in displacement control), applying the same strain on both faces of the specimen. The strain gauge application also requires cleaning and handling care. It was glued to the specimen with a cyanoacrylate adhesive and connected to a data acquisition system.

Fig. 7. Instrumented sample face with strain gauge

Both optical and electrical sensors were connected to a computer for data display and management using Catman® software (with predefined data analytics) for the FBG sensor and LabView® software with self-developed algorithms for the strain gauge data interpretation. The preliminary test results comparing the quality of signals obtained in both sensors with that of the strain estimated by the testing equipment are presented in Sect. 3. Two other variables were analysed in that section: (i) the influence of a magnetic field on the signals of both sensors; (ii) the influence of the testing temperature on the FBG signal when a calibration temperature sensor is not used to correct the strain values.

3 Results and Analysis

3.1 Quality of the Measured Signals

In the preliminary tests, it is essential to assess the reliability and accuracy of the data collected by the FBG. Thus, the first variable evaluated at this stage was the quality of the signals obtained in each sensor when compared to the strain estimated by the testing equipment. These tests were performed at 30 °C, the reference temperature at which the FBG sensor was calibrated. A sinusoidal loading pattern was used, and Fig. 8 shows a sample of the results obtained for a frequency of 10 Hz.

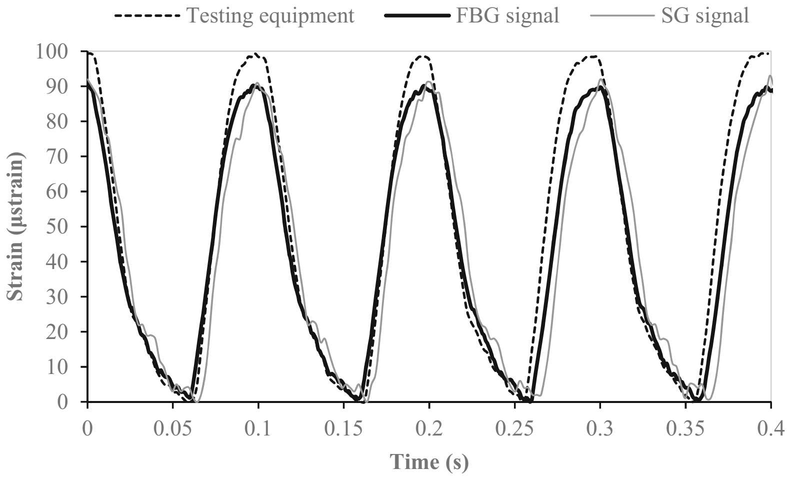

Fig. 8. Comparison between the strain values estimated by the testing equipment and measured by FBG and SG sensors

As can be observed in Fig. 8, the amplitude of both sensors is similar, which shows that the strains measured on both beam faces are approximately the same (90 µstrain). The test was performed in displacement control, aiming at a peak-to-peak strain amplitude of 100 µ strain. The differences obtained may indicate that the sensors may need further calibration or that the estimation of the strain was not correct. The latter may be due to some inaccuracy in the specimen dimensions introduced in the test equipment.

It is also important to note that the sinusoidal curves performed by the test equipment were measured with greater clarity and smoothness by the FBG, without the existence of significant levels of noise. In addition to proving the quality of the sensing system itself, it is also certainly an indication that the sensor location, installation and bonding has been well accomplished.

3.2 Variations due to a Magnetic Field

A magnetic field was created near the sensors without applying any load to the specimen. The objective of this evaluation was to confirm if the FBG sensors are not affected by any electromagnetic interference. For this test, a small magnet was passed near both sensors (at the same distance) to find out the interference of the magnetic field in measured values.

Figure 9 shows the results obtained in this test. The magnetic field was applied approximately between the 2^{nd} and the 7^{th} second presented in that figure.

Analysing the results obtained, the interference that a small magnet causes in the signal collected by the strain gauge is clear. Strain variations of about 4 µstrain were visible in the SG signal, while no variation was observed on the FBG signal due to the presence of the magnet (only marginal variations of less than 1 µstrain was observed as noise, possibly due to the normal air pressure).

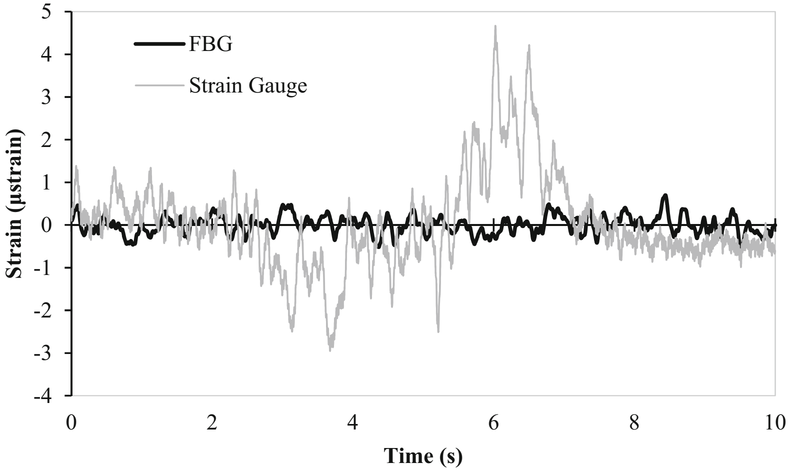

Fig. 9. Magnetic field interference in FBG and SG signals

3.3 Influence of Temperature

In order to assess the influence of temperature calibration on the strain values measured by the FBG, a controlled strain (100 μstrain) test was performed at 20 °C and 30 °C. In the test carried out at 20 °C, the strain values were measured without an additional FBG sensor for temperature calibration. The results are presented in Fig. 10.

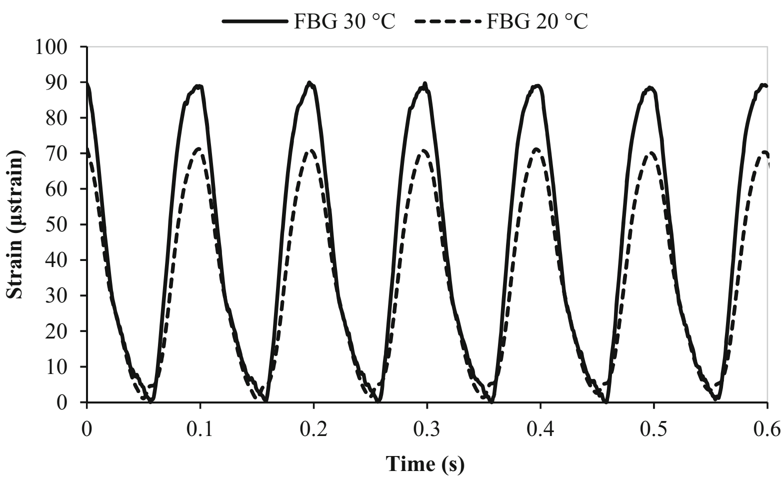

Fig. 10. Influence of temperature on FBG signals without calibration

The results show that FBG sensors must be used together with a temperature calibration sensor. The strain amplitude reduced from the original 90 μstrain to around

70 μstrain, which is a significant reduction. The test was performed in a controlled displacement (strain) mode, so the values obtained should have been the same.

4 Conclusions

This work aimed to present the benefits of FBG sensors compared to SG sensors as a preliminary phase of the "APP PAV 4.0 LC" activity developed under the Rev@Construction project. The results obtained will be used in the subsequent phases of the project, assuring the reliability of the measurements carried out with FBG sensors to be installed in a road pavement section.

The main conclusions that can be drawn from this work are as follows:

- The FBG sensor allows a better signal quality than the SG sensor, which can be important when high-speed traffic is monitored.
- FBG sensors are not affected by magnetic fields, while the presence of even a small magnet influences the signal of SG sensors.
- Temperature calibration in the FBG optical technology is vital for a reliable evaluation of strains occurring at different temperatures since a 10 °C change caused a variation of more than 20% in the strain values obtained.

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