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FBG-based smart composite bogies for railway applications

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ABSTRACT: FBGs are used as *in-situ* transducers for mechanical reliability assessment of new composite-based bogies. A 16 million cycles fatigue test was carried out. Asynchronous undersampled FBG measurements are in agreement with modeling.

KEYWORDS: Fiber Bragg Grating (FBG), Optical Fiber Sensor (OFS), structure monitoring, smart structure, composite material, smart bogies, railway rolling stock, asynchronous undersampling, fatigue testing, modeling.

INTRODUCTION

Mobility is an important factor for the economic growth. Enhancing train transportation will become a key issue, as competing transportation means, like road and air, are gradually becoming saturated in capacity. The European Union tries to promote this by developing initiatives and enhancing the competitiveness of the rail grid by means of deregulation and interoperability, supporting this process with a planned upgrade to the existing rail network, the 'Trans-European Net' [1]. This will require the upgrade of 40,000 km of existing rail tracks for use at speeds up to 200 km/h instead of 160 km/h today and the development of 20,000 km of new rail tracks for use at speeds greater than 230 km/h. In this framework, some companies in Europe aim to develop new functionalities for trains.



Fig. 1: *Alstom® train*

In France, *Alstom Transport S.A.*, the railway division of *Alstom®* company, has been leading a new project for 3 years with *DDL Consultants* and the *CEA-List*, involving composite materials in a new bogie. It has been presented to the media at the latest JEC'2001 composite show in Paris, France [2].

1. FIBER BRAGG GRATING SENSORS FOR COMPOSITE MONITORING

For about ten years [3], many R&D laboratories and some companies have shown that Fiber Bragg Gratings are temperature, strain and pressure sensitive, and could be used as intrinsic sensors, mainly for structure monitoring applications [4]. It is now well known that the Bragg wavelength λ_B shifts linearly when the grating is submitted to at least one of the above mentioned parameters. So, for instance within the 1.55 µm telecom window, the spectral sensitivities are respectively: a ~ 12 pm/K, b ~ 1.2 pm/(µm/m) and c ~ - 5 pm/MPa, depending on the intrinsic fiber properties, and on the exact Bragg wavelength.

In a recent past, many research topics were dedicated to the use of OFS, and FBGs, in the purpose of continuous manufacturing process improvement and 'structure monitoring'. Today, concerning manufacturing process, more and more composite material manufacturers are willing to consider such Non-Destructive Techniques first to shorten the qualification time for new structures, and secondly to improve the quality of manufacturing and to reduce the number of rejected parts [5]. More specifically, during conception and depending on process, their needs may include temperature, pressure, void content estimation, glassy temperature, resin front progression, and/or shrinkage and residual stress evaluation, as well as in-line cure monitoring (Degree-of-Cure, and even cure rate). On the contrary, in this study, both optical fibers and FBGs are used to validate the structural design of bogie composite blades, and further, for their future Health Monitoring during railway rolling stock operation.

2. A NEW CONCEPT OF BOGIES BASED ON COMPOSITE MATERIAL



Fig. 2: *Traditional metallic bogie for railway rolling stock*

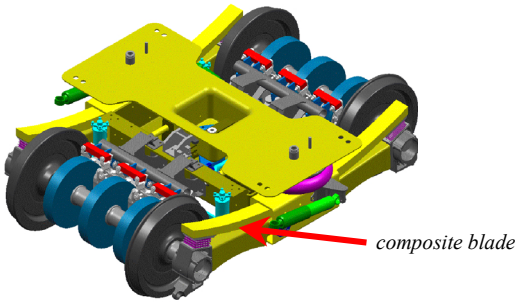


Fig. 3: *New Alstom® composite bogie*

Glass Reinforced Plastic materials present many advantages: lower density and higher strength than metals, but they are new for such a use in the railway industry whose bogies were, up to now, made with metal (fig. 2) [6].

Composite materials with polymeric matrix (Carbon Fibre Reinforced Plastic: CFRP, Glass Reinforced Plastic: GRP, ...) are extremely useful for many applications of high technology (aeronautical, space, marine, railway rolling stock, ...) because of their exceptional stiffness and resistance associated to a light weight. This makes possible the design of stiff structures dedicated to a particular use, presenting excellent mechanical behaviour, often unrivalled by bulk materials, mainly thanks to the choice of the type of laminated, the number of plies and to the specific proportion of reinforcement fibres. However, the large exploitation of the potential of these « new » materials is slowed by the difficulty to predict internal defects. Traditionally, this led the designers to oversize the structural parts, which reduces consequently the profits awaited in their use.

Alstom® has decided to go further for the security of the railway networks, in embedding FBGs to overcome this situation and improve both their mechanical behaviour's knowledge and their ability of predicting internal defects evolution, by the use of high performance optical strain measurement methods and corresponding validation facilities.

Consequently, one important part of this development consisted of validating both design and mechanical behaviour of the bogie (fig. 3). The bogie engineering work (architecture, tools specifications and tests) was done by *Alstom®*. *DDL Consultants* (an expert company in composite structure design and modeling) led the mechanical modeling with *SAMCEF®* finite element analysis software. The static and dynamic validation tests were carried out with the monitoring technology of the *Optical Measurements Laboratory* of the *CEA/List*, based on embedded Optical FBGs.

2.1 The composite bogie

The main structure of this new bogie is made of several GRP parts, each of them, like spring blades, being bolted and glued (Fig. 3).

To check initial design of such parts, a 16 million cycles fatigue test was carried out on the blade (see § 2.3), but other tests including more cycles were also carried out on other parts and on the whole structure. For instance, the ultimate load before the first failure appeared to be greater than 350 kN.

Finite element analysis was a tool of choice in modeling the composite blade mechanical behaviour (fig. 4: *SAMCEF®* modeling) but such models are also very useful to predict strains in order to find optimal positions of FBGs into the composite material.

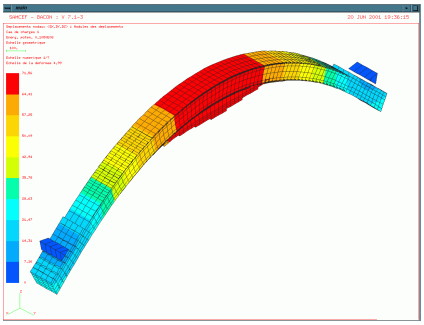


Fig. 4: *Static test – FEM – deflection under 150 kN (measured value during test: 72.6 mm)*

2.2 Blade manufacturing and related testing method

Such massive composite structures are manufactured with a specific *Alstom®* proprietary process. In comparison with traditional metallic bogies, the composite ones are strongly anisotropic with a mechanical resistance close to the glass fiber strength in the direction of the reinforcement fibers, with a theoretical maximum elongation strain close to 3.5 %, and a Young's modulus about 43 GPa. Since this structure is strongly anisotropic, the testing procedure has to be able to evaluate the strain level in each critical direction, in order to guarantee that the destructive load is never reached in normal use.

FBGs are well-suited for such measurements because they are easily embeddable, which guarantees the accuracy of the measurements, also free from (electronic and optoelectronic) components ageing, since they are related to a spectral -electromagnetic immune- measurement. Moreover, FBGs can measure strains along a specific direction which allows separate measurements of transverse and longitudinal strains into the composite blade [7].

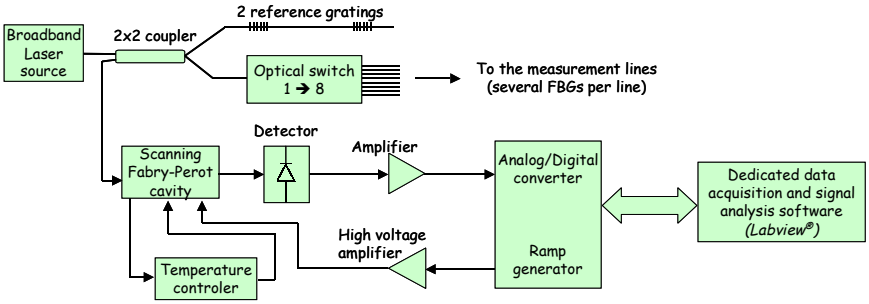


Fig. 5: *CEA FBG measurement system architecture*

The *CEA* measurement system consists of a broadband laser source and a scanning Fabry-Perot interferometer, connected *via* an optical switch, to the FBG measurement lines (fig. 5). Two reference gratings are included inside the system to provide spectral references [8].

Measurements can be performed up to 100 Hz on a single line, with real-time digital signal processing. The strain accuracy is close to 10^{-6} (µm/m level), depending on the averaging and the embedment of the gratings.

2.3 Qualification testing: impacts and dynamic fatigue testing

The first tests consisted of impacting a separate plane sample with 2 kinds of projectile at different angles, with a normalized impact energy equal to 120 J. Trials at 200 J, 250 J and 300 J were also carried out. Several classical fibers were embedded inside this sample, close to the surface below the impact locations, to evaluate damages.

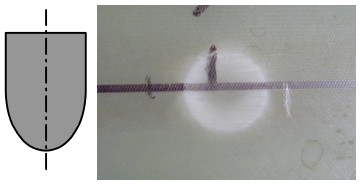


Fig. 6: *Hemispherical projectile test and related impact*

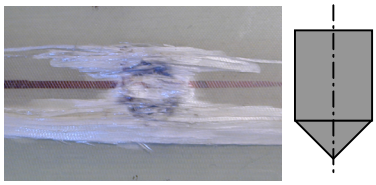


Fig. 7: *Cylindrical projectile test and related impact*

Tests made with the hemispherical projectile showed embedded fiber breaks, in contradiction to other tests where only few surface reinforcement fibers were broken. It seems that the hemispherical impact have spread its energy deeper into the sample, which left surface unchanged, except for its color which turned from pale green to white (fig. 6 and fig. 7).

In such a case, the embedded fibers let us to point out the internal damages of the composite material after some specific impacts, which justifies the usefulness of embedded optical fibers.

In a second phase, dynamic fatigue tests were carried out at *f=7 Hz* according to the *UIC 515-4* standard[1] on the blade itself (fig. 8).

The stress levels were induced according to three cycles of dynamic loading added to a static one [27 kN ± (8 kN @ 7 Hz); 32 kN ± (10 kN @ 7 Hz); 38 kN ± (11 kN @ 7 Hz)]. Corresponding strain was about 2500 µm/m up to 3500 µm/m in static and 700 µm/m to 1000 µm/m in dynamic mode. Such tests also include temperature and humidity cycling in the same time.

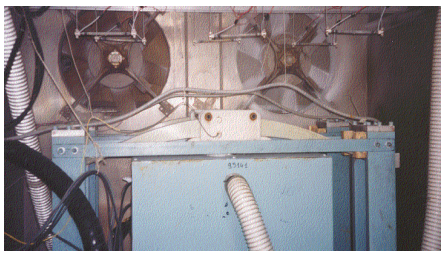


Fig. 8: *Experimental set up for fatigue testing*

To perform *in situ* measurements, an optical fiber with 4 FBGs was embedded in a composite blade during the manufacturing process; 3 of them were dedicated to strain measurements, and the last one to temperature compensation (fig. 9).

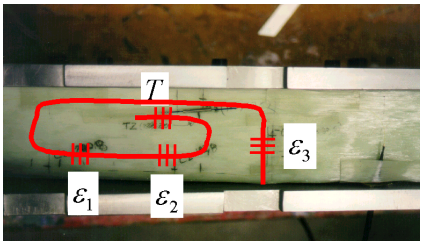


Fig. 9: *FBG location inside the composite blade*

Due to test duration (about 26 days), acquisition rate was set 7 times lower than the load frequency in order to reduce the volume of data. In spite of this undersampling, both average and amplitude of strains were accurately estimated for any sensor, since the medium's behaviour remained elastic during the experiments, with volumic acceleration and internal forces negligible in comparison with the external applied loads.

A basic statistical analysis shows that if the blade's behaviour is supposed to be adiabatic during one sinusoidal excitation cycle, each strain amplitude[2] $\Delta\varepsilon$ can be correlated to its corresponding standard deviation σ_N of averaged sets of N randomly sampled measurements according to the following relationship: $\Delta\varepsilon = \sigma_N\sqrt{2N}$. Since asynchronous measurements were performed, strain levels were simply calculated from standard deviation of recorded data. With 16 hours per thermal cycle, the blade underwent more than 16×10^6 cycles during 26 days of experiments, including 6×10^6 cycles at 38 kN exceptional load, which is, to our knowledge, the most severe test ever done with FBGs. In comparison, electrical strain gages glued on surface failed after 10^6 cycles.

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[1] *UIC: Union Internationale des Chemins de Fer* (International Union of Railways).

[2] $\varepsilon(t) = \bar{\varepsilon} + \Delta\varepsilon.\sin(2\pi ft - \varphi)$, where φ is the initial reference phase, and $\bar{\varepsilon}$ the average strain.

2.4 Results

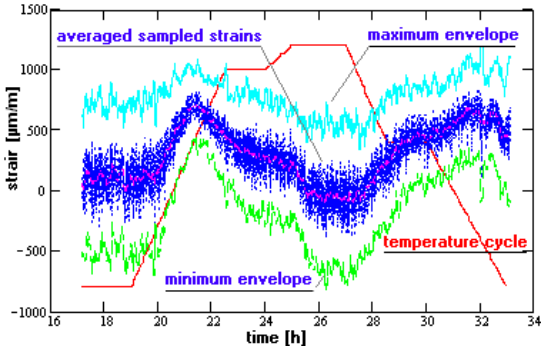


Fig 10: *Dynamic fatigue test results (sensor ε_1)*

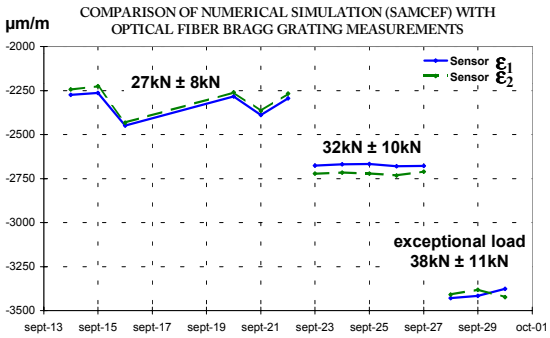


Fig. 11: *Strain measurement versus time*

Fig. 10 shows measurement data recorded during one thermal cycle (~ ½ day). For embedded FBGs, maximum and minimum envelopes are determined on the basis of recorded data standard deviations (see § 2.3).

Such FBG measurements made it possible to find strain levels in good agreement with those estimated by modeling. Little differences with modeling can be explained by a shift of the fiber during the manufacturing process (fig. 11 and fig. 12), *i.e.* a non accurate positioning of the grating in the material.

Moreover, both average and amplitude of strains remained stable at any load level during the experiments, which demonstrates the mechanical integrity of the composite blade.

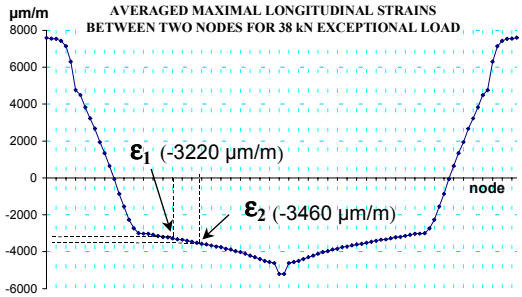


Fig. 12: *SAMCEF® longitudinal strains modeling*

CONCLUSION

Fiber Bragg Gratings are well known to be suited for *in-situ* strain measurements. This work shows that they are also well-suited for long term and extremely severe experiments, where traditional strain gages fail. With the help of optical fibers and *CEA* FBG-based measurement system, *Alstom®* has succeeded in demonstrating the mechanical integrity and the constant stiffness of its new bogie composite blade.

Today, performances reached with this new composite bogie are better than those obtained with a traditional steel bogie. Moreover, thanks to FBGs, the reliability of this highly modular bogie is enhanced.

As FBGs can now be embedded in such smart composite blades, they could be used for health monitoring purposes as well as predictive maintenance. Several strategies could be considered: on-board real-time measurements or periodic checking, depending on the objectives of the railway companies.

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