INTERNAL STRAIN MEASUREMENTS IN CFRP PLATES SUBJECTED TO IMPACT LOAD USING FBG SENSORS

J. Frieden, J. Cugnoni, J. Botsis, Th. Gmür, D. Coric
Laboratoire de Mécanique appliquée et d'Analyse de Fiabilité (LMAF)
École Polytechnique Fédérale de Lausanne (EPFL), CH-1015 Lausanne, Switzerland
jeannot.frieden@epfl.ch

SUMMARY

The local strain response of a composite plate is monitored with embedded fibre Bragg gratings during low velocity impacts. The modal characteristics of the plate, i.e. its eigenfrequencies, coarse mode shapes and modal damping ratios are obtained from the transient response to an impact and are used for damage evaluation after impact.

Keywords: FBG sensor, composite materials, low velocity impact, damage, dynamics

INTRODUCTION

Characterization of the response of polymer composite structures to dynamic and impact loads is at the forefront of experimental mechanics. This is due to an ever increasing interest for long-term monitoring and control of aerospace, naval and civic structures. A first step towards addressing the pertinent problems is the real time strain response of the structure due to the external loads and the associated damage, in particular due to impact [1].

Fibre Bragg gratings (FBG) are extensively used in structural monitoring of fibre reinforced composite structures [2]. While the response of FBG sensors has been well understood under quasi-static loads [3], their use in dynamics and impact loads has not been sufficiently investigated. Recent advances in high rate interrogation systems for short Bragg gratings permit the use of FBG sensors in structural health monitoring. The potential of acquiring internal deformation measurements at rates up to 500 kHz is investigated throughout the present study.

It has been shown that the non-destructive monitoring method based on vibration testing is a suitable tool for damage monitoring in composite structures [4]. Using the most recent interrogation techniques, the utility of FBG sensors in structural health monitoring is extended from sensors for static residual strain measurements to sensors for fast dynamic events due to impact loading or vibration loading.

In the present work, minimally invasive optical FBG sensors are utilised to monitor the transient response of impact loaded plates. The local strain response to non-destructive impact loads is compared to data obtained from numerical models. It is shown that FBG sensors are suited for the acquisition of dynamic events.

FIBRE OPTIC SENSORS

A Bragg grating consists of a spatial modulation of the refractive index along the optical fibre core. A standard optical fibre has a cladding diameter of 125 µm (Fig. 1) and can be integrated into composite materials without considerably changing the material properties and impact resistance when the optical fibre is embedded parallel to the reinforcing fibres and is sufficiently far from the impact location [5]. Once embedded, they can be used to measure the deformation in the host material. If broadband light is coupled into a FBG, a peak with a central Bragg wavelength λ_B is reflected. The Bragg wavelength can shift of an amount $\Delta\lambda_B$ due to a three-dimensional strain state (ε_x, ε_y, ε_z):

$$\frac{\Delta\lambda_{Bx,y}}{\lambda_B} = \varepsilon_z - \frac{n_0^{\ 2}}{2}\left[p_{11}\varepsilon_{x,y} + p_{12}(\varepsilon_z + \varepsilon_{y,x})\right]$$

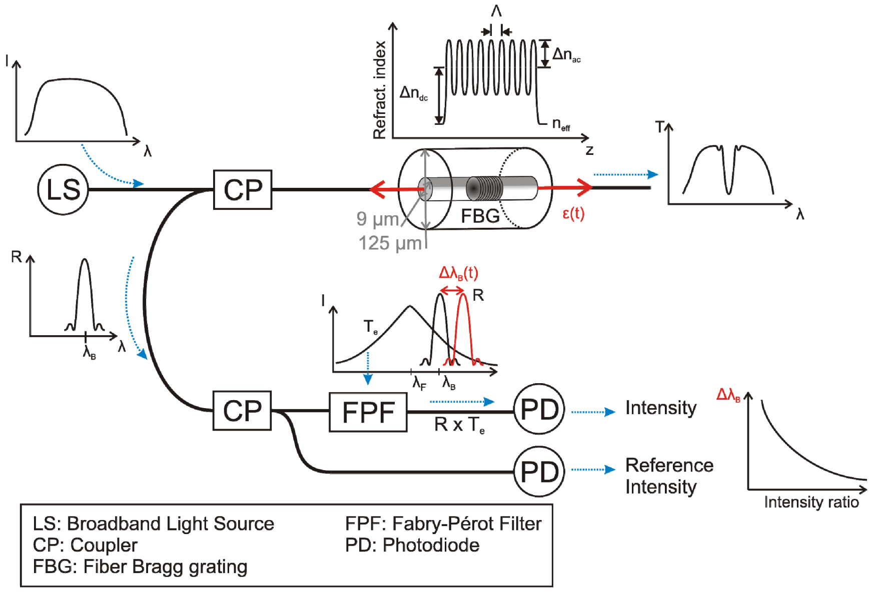

Figure 1: Schematic of a FBG and the fast rate interrogation principle.

The FBG signal is acquired using a fast peak tracking interrogator. By coupling the Bragg reflection peak partially through a Fabry-Pérot (FP) filter with appropriate bandwidth, a Bragg wavelength shift can be modulated into an intensity variation. The intensity is measured using a standard photodiode and the acquisition rate of the interrogator depends on the acquisition rate of the acquisition card. In the present case an acquisition frequency of up to 500 kHz per optical channel is achieved. It is also considered that the Bragg grating measures strain along the fibre and it is assumed that the reflection spectrum shape does not change. In order to compensate for intensity losses or an unstable light source a reference measurement of the total reflected intensity is done.

Knowing the calibration curve (Fig. 2) that depends on the FP filter function and the FBG reflection spectrum, the corresponding wavelength shift and/or strain shift can be calculated as a function of the intensity ratio between the filtered reflection spectrum intensity and the total reflection power. In order to assure that the Bragg wavelength initially is at a predefined offset on the slope of the FP filter, a tuneable filter is used. Adjusting the filter offset on demand with respect to the Bragg wavelength allows the use of FBGs with a different Bragg wavelength and accommodates for temperature drifts or other perturbations if requested. The response of FBG sensors as internal dynamic strain sensors for measurements under steady-state conditions has been validated by means of an experimental-numerical comparison in a previous study [7].

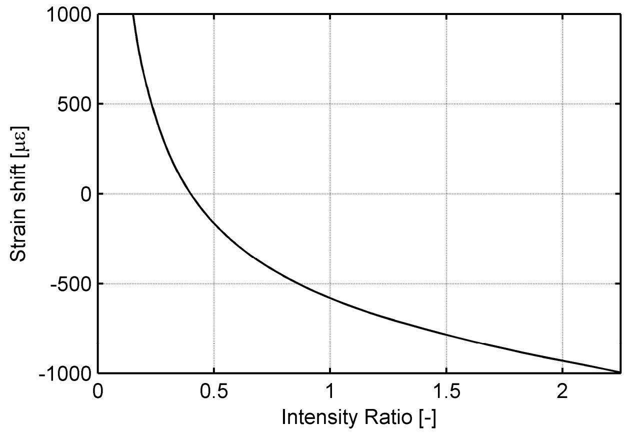

Figure 2: Calibration curve for fast FBG interrogation system.

EXPERIMENTAL PROCEDURE

Cross-ply carbon fibre reinforced (CFRP) plates have been produced with a short FBG sensor (~ 3mm) embedded at a selected location. The laminate has been produced using unidirectional prepreg plies with a stacking sequence of $[(0°_2,90°_2)_3,0°_2]_s$ and have been cured in autoclave for 17 hours at up do 80°C under vacuum with a pressure of 1 bar. The optical fibre has been integrated between the ultimate and penultimate ply parallel to the longitudinal direction of the reinforcing fibres and 30 mm from the centre of the plate. The longitudinal position is chosen to be central and has been determined after curing using optical low coherence reflectometry measurements. The material properties have been determined by inverse mixed numerical-experimental identification [8] using unidirectional and cross-ply specimens. The cross-ply plate has been cut into dimensions 140 mm x 300 mm and has an average thickness of 4.2 mm. Four holes have been drilled along the two short edges of the plate for clamping on an in-house designed and instrumented impact tower (Fig. 3).

The weight of the dropping mass is 860g and can be increased with additional weights and the maximum drop height is 2 m. The impactor is equipped with a force transducer mounted close to the impact point in order to acquire accurately the contact force. A Doppler laser vibrometer head is pointed on the plate for measuring a local velocity response. Accelerometers on the plate and the support are used for validation of the experimental setup and the numerical model. The local strain response can be monitored in different locations of the embedded fibres using the fast interrogator. The acquisitions of the signals are triggered via a light barrier for synchronisation.

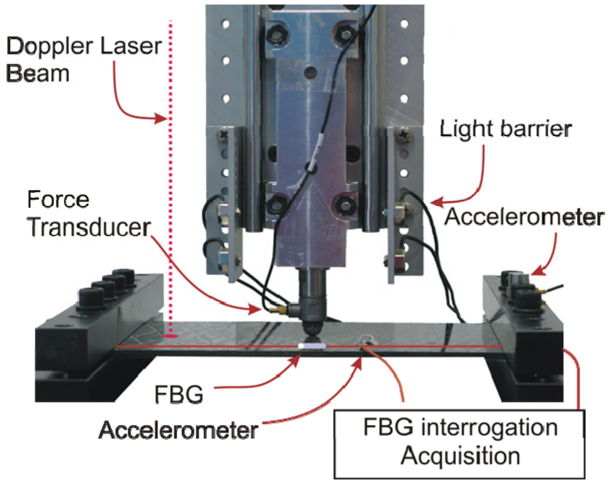

Figure 3: CFRP plate mounted on the instrumented impact tower.

A set of plates is impacted at the central location with impact heights varying between 0.2 and 1.2 m. The influence of the impact damage on the global stiffness and hence on the natural frequencies is studied. The modal parameters of the intact plates are experimentally determined under free boundary conditions using acoustic excitation and under clamped boundary conditions using hammer excitation. A post impact modal analysis under free and clamped boundary condition reveals any change in the global stiffness that is due to damage. For highest accuracy, the dynamic response measurements are done in both cases using a Doppler laser vibrometer. The eigenfrequencies are obtained using modal fitting algorithm using the commercial software Me'scope.

Micrographic images are produced in order to reveal the damage modes and quantify the effective extend of the damage. Furthermore C-scan images are produced in order to characterize the shape of the damage. Due to the relatively high dispersion and absorption of acoustic waves in the composite material, it was not possible to identify the shape of each delaminated interface. Nevertheless the global shape of several delaminations in a volume of finite thickness inclosing multiple plies could be observed.

NUMERICAL SIMULATION OF IMPACT

In order to validate the response from the FBG to an impact event, a numerical simulation of non-destructive impact is performed using the commercial software Abaqus 6.8 Explicit. An impact velocity of 2.4 m/s has been used and corresponds to a drop height of 0.3 m during experiments. This velocity has been chosen because such an impact creates no, or low damage in the given composite plate. First the results of a numerical modal analysis of the clamped plate are compared to experimental modal analysis in order to build a valid model for the boundary conditions. The material properties obtained through inverse numerical-experimental identification based on free non-contact modal analysis have been used.

A non-destructive impact is simulated by integrating the linear dynamics equations using the explicit solver. A solid finite element model of the impactor and of the plate is created using through-the-thickness homogenised material properties for the cross-ply laminate. The numerical results are validated by comparing the contact force, the local acceleration and velocity results to experimental measurements and the spectral content of the numerically obtained plate response to experimental modal analysis results. Furthermore the contact stiffness parameter is adjusted in order to allow for a good convergence of the solver and to fit the experimentally determined contact duration. The damping of the transient response of the plate has been obtained by adjusting the Rayleigh damping coefficients even though it is difficult to fulfil a correct attenuation for all frequencies.

The strain response of an element integration point at the location of the Bragg grating could be compared to the measured FBG response. Using sub modelling technique it could be shown that the longitudinal strain field in the direction of the reinforcement fibres is very well transmitted to the optical fibre, whereas the optical fibre is not very sensitive to the transverse strain field. This is due to the fact that the optical fibre's Young modulus of 71 GPa is more the 8 times higher than the surrounding material in the transverse direction. Hence it has been supposed that the reflection spectrum of the FBG does not depend on a transverse strain field.

RESULTS

The unidirectional (UD) material properties have been determined using specimens with a $[0°_{28}]$ stacking sequence and through-the-thickness homogenised material properties have been determined using $[(0°_2,90°_2)_3,0°_2]_s$ cross-ply specimens. Specimen geometries with different sizes and aspect ratios have been tested and a mean standard deviation of less than 0.6% has been obtained for longitudinal and transverse Young modulus and in-plane shear modulus of the UD properties. A longitudinal and transverse Young modulus of 96 GPa (65.9 GPa) and 8.67 GPa (44.9 GPa) respectively and an in-plane shear modulus of 4.07 GPa (4.23GPa) has been identified for the UD (cross-ply) laminate.

The contact stiffness parameter and the boundary conditions model adjustment allowed for a good agreement of the contact force, contact duration and the eigenfrequencies of the numerical model with experimental results. It can be seen on figure 4 that the acquired FBG signal corresponds well to the numerical strain response. Analysing the response spectrum of the FBG signal, the natural frequencies of the plate can be identified. In the experimental response however asymmetric modes are excited during the impact because of asymmetries in the non-uniform thickness of the plate. Moreover the longitudinal position of the FBG is not exactly centrally located.

The FBG strain sensor allows monitoring the maximum deformation during an impact as well as the transient response of the plate after the impact. The high sampling rate of up to 500 kHz permits the acquisition of fast events without aliasing. The deformation range depends on the FP filter that is used in the measurement arm. Hence, the same sensor can be used to perform acquisitions with high deformation amplitude and to do measurements with high resolution.

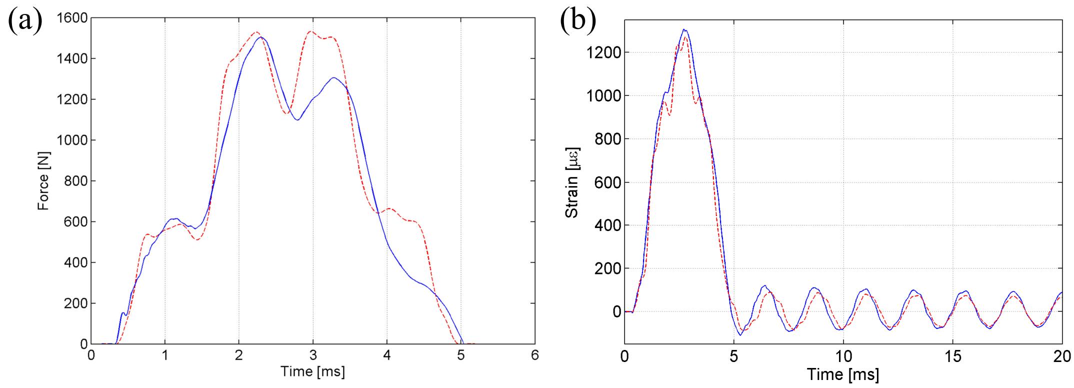

Figure 4: (a) Experimental (blue) and numerical (red dotted) impact force signal, (b) and local numerical (red dotted) strain response compared to FBG sensor response (blue) during an impact with an incident kinetic energy of 2.6 J.

Experimental modal analyses with free and clamped boundary conditions reveal that some modes are influenced by the impact damage. Figure 5 shows that the eigenfrequencies of the corresponding modes systematically change with increasing impact energy. Relative changes of up to 1.5%, that are considerably higher than the measurement accuracy, can be observed for an impact height of 1.2 m. An equivalent accuracy of the natural frequencies can be obtained using FBGs as dynamic sensors. The modal damping coefficients also exhibit relative changes of up to 50 %. However no systematic increase of the damping is measured with increasing impact energy or the measured relative change of damping is small compared to the measurement accuracy. Moreover the measurement accuracy drops with increasing damage. In the case of more severe damage, the frequency response function presents a phase change different from 180° at eigenmodes, which may be explained by the non-linear effects introduced by the damage, e.g. opening and closing from delaminated interfaces.

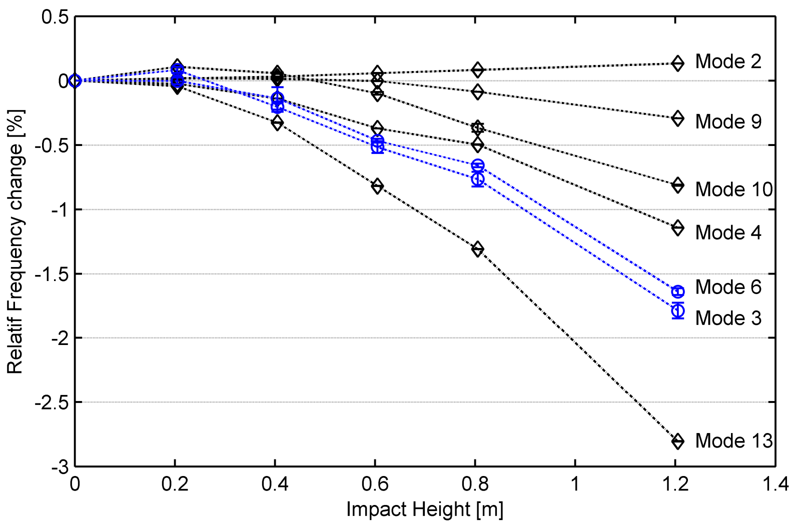

Figure 5: Relative change in eigenfrequencies due to impact damage for selected modes under free (black diamonds) and clamped (blue circles) boundary conditions. Error bars indicate the standard deviation obtained during repeated measurements.

The mode shapes of the plate are determined along the longitudinal centre line and adjacent parallel lines of the plate using a scanning laser Doppler vibrometer under free boundary conditions. The mode shape measurements are done on the intact and damage specimens for comparison. The plate is excited acoustically at a selected natural frequency determined during modal analysis and the deflection shape is measured along the longitudinal direction on approximately 500 points per line. After applying a spline smoothing function and a second derivative, the surface curvature shape is obtained along these lines. Figure 6 shows the influence of the damage zone on the local stiffness and hence on the measured curvature shape. The presence and the extent of the damage can be clearly identified. Thus FBG sensors can be embedded into selected plies for measuring directly local deformation and reconstruct the strain mode shape.

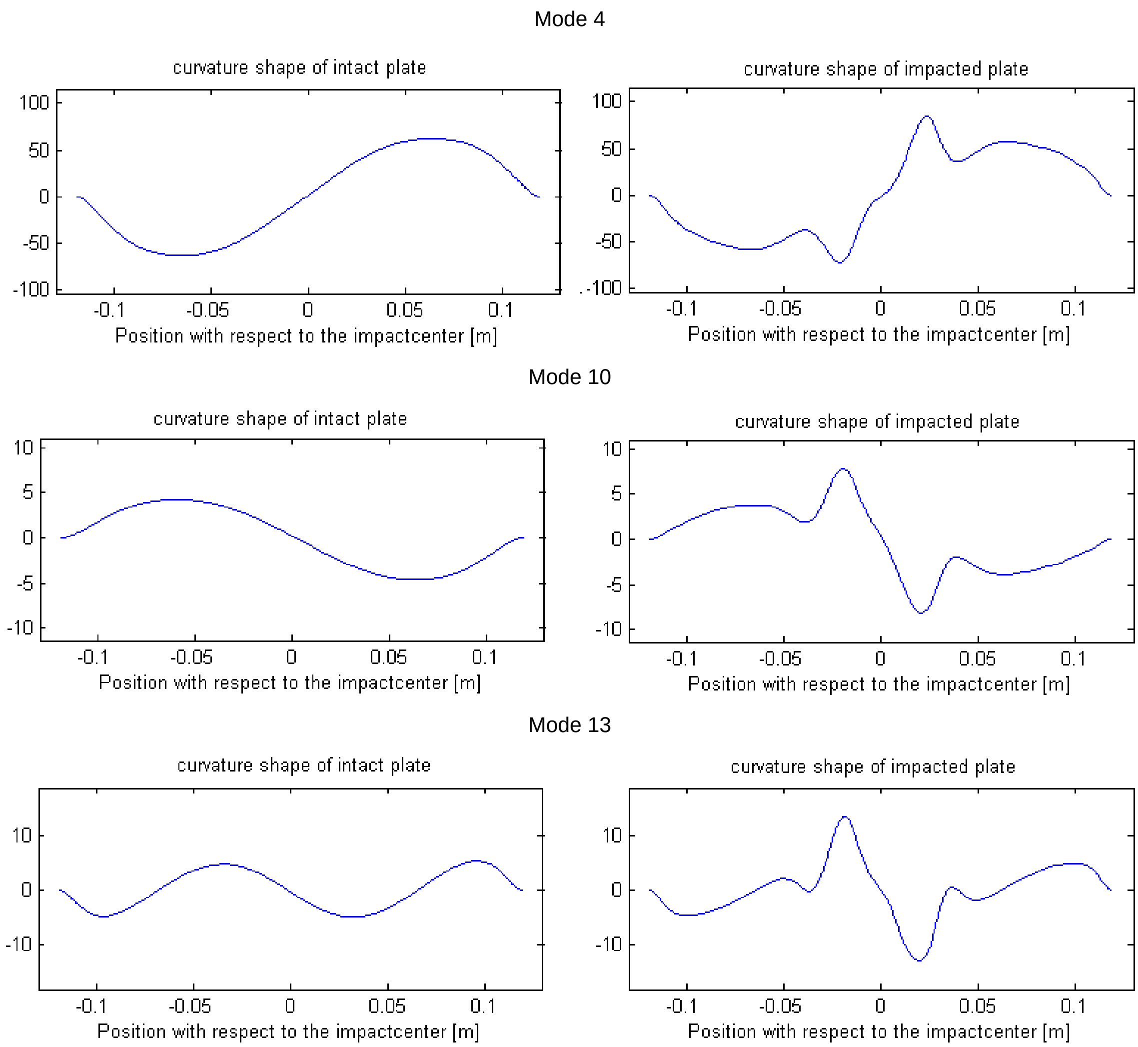

Figure 6: Curvature mode shape of modes 4, 10 and 13 along the longitudinal centre line of a damaged plate under free boundary conditions. The damage is due to an impact with energy of 10.1 J corresponding to a drop height of 1.2 m.

A set of images has been produced to identify the damage modes and to quantify its amount. As shown in figure 7 the plates have been sectioned in the transverse direction and multiple delaminations and intralaminar cracks can be observed. The delaminated areas spread either in the longitudinal or the transverse direction depending on the interface in the layup, having an increasing area towards the opposite surface of the impact location.

Figure 7: Optical microscopy image of a plate impacted with an energy of 10.1 J.

CONCLUSION

The dynamic sensing capabilities of FBG sensors are confirmed by means of numerical and experimental comparisons. A good agreement between numerical explicit impact simulation and experimental non destructive impact tests has been observed. FBG sensors are reliable gauges for deformation monitoring in impact loaded structures. Hence the local deformation response to an impact load can be monitored via FBG sensors and the signal can be analysed in time and frequency domains. The peak deformation value of the instant response during impact can be monitored and the transient response after impact can be characterised from the response frequencies, deformation amplitudes, mode shapes and damping factors. In addition it has been shown that impact damage in CFRP materials can have a significant influence on the natural frequencies of a structure. Furthermore changes in residual strains can be monitored via the same sensors. The most recent advances in FBG interrogation systems and the tested and mature sensing capabilities under static conditions pave the way for health monitoring systems combining both insights in micromechanics and vibration mechanics.

ACKNOWLEDGEMENTS

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