Submillimeter Crack Detection With Brillouin-Based Fiber-Optic Sensors

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***Abstract*—Submillimeter crack is detected with a dedicated fiber-optic strain cable, a 1-m-spatial-resolution (w) distributed Brillouin sensor and an advanced signal processing technique. The signal processing approach consists in spectrum shape analysis and multiple peaks detection.**

***Index Terms*—Brillouin optical time domain analysis, Brillouin optical time domain reflectometer, crack detection, distributed Brillouin sensor (DBS), fiber-optic strain sensing cable, signal processing, spatial resolution, structural health monitoring, strain measurement.**

I. INTRODUCTION

STRUCTURAL HEALTH MONITORING (SHM) is an important development of the civil engineering field [1]. Recent events remind us that the cost of a bridge collapse is much more than economical; it touches people's life, as dramatically demonstrated by the collapses of the Laval's La Concorde overpass, in fall 2006, and, the Minneapolis bridge, in summer 2007. The implementation of comprehensive SHM in civil infrastructure is made possible by the use of optical fiber sensors and can substantially improve the safety of civil structures and help to manage them more efficiently. More specifically, distributed Brillouin-based sensing systems (DBS) are capable of measuring strain everywhere along a dedicated optical fiber cable attached to the structure to be monitored [2]. Measurement readings can be taken every tenth of cm, which is a clear advantage when localized faults, such as cracks, need to be detected, but their position is not known beforehand.

Among the principal aims of SHM, the detection and localization of cracks appear as an essential task as crack can lead to lethal faults for the structure's life. There are, however, challenges associated with crack detection. In fact, cracks need to be detected at an early stage of their development, when they are still shorter than a 1 mm. Such small dimension imposes constrains to the interrogator and to the fiber-optic cable. First, it implies that the interrogator has the ability to resolve submillimeter faults. DBS-based systems suffer a strong limitation as the strain resolution degrades when spatial resolution is reduced [3]. This degradation is caused by Brillouin spectrum broadening and SNR drop. Academic researches are still being conducted to overcome such limitation. Centimeter spatial resolution was achieved with setups, using correlation based [4] or coherent probe-pump interaction [5] with little compromise on the strain resolution. For instance, the coherent probe-pump interaction successfully detected and measured cm-size faults such buckling induced on small diameter distribution pipe [6]. These instruments are certainly promising and would be helpful when submeter spatial resolution is needed. Nevertheless, the other issue associated with crack detection lies with the ability of the fiber-optic sensor to handle very large strains. Crack generates concentrated strain and stress in the optical fiber sensor at the location of its occurrence over distances lower than a millimeter. Strain concentration is so high that it would provoke a rupture of the sensor interrupting the monitoring. Using a high spatial resolution interrogator would then be pointless as the sensing channel is disrupted.

The present work addresses that issue by introducing an approach based on a stress transfer mechanism from the crack to the sensor. Such approach would avoid any risk of sensor breakage. The idea consists in bonding the dedicated fiber-optic sensor cable in a way that creates delamination over about 10 cm or more when a 0.5-mm crack occurs. The increase of stress on the sensor is now distributed more than tens of cm and no longer enough to lead to the sensor rupture. The strain is very high but distributed over a short length, shorter than spatial resolution of commercial Brillouin interrogator (0.5 m). Here, comes into play a unique feature of Brillouin interrogators. These instruments can measure faults smaller than the sensor spatial resolution as these events generate additional peaks in the measured spectrum. Such crack detection approach can be applied to Brillouin optical time domain analyzers and reflectometers [7].

II. METHOD

In the DBS-based applications, the sensing medium is a standard single-mode optical fiber. The sensing mechanism relies on the stimulated Brillouin scattering (SBS) effect in which a counterpropagating lightwave (probe) is amplified at the expense of a pump lightwave (Fig. 1). The interaction between the pump and the probe reaches the maximum when the frequency difference between the two lightwaves equals the acoustic mode frequency of the fiber, known as the Brillouin frequency ν_B. Typically, the Brillouin frequency of International Telecommunication Union (ITU) G.652 fibers is about 10.85 GHz at 1.55 μm. The Brillouin

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Fig. 1. Schematic of the interaction between probe and pump signals in an SBS-based fiber-optic sensor.

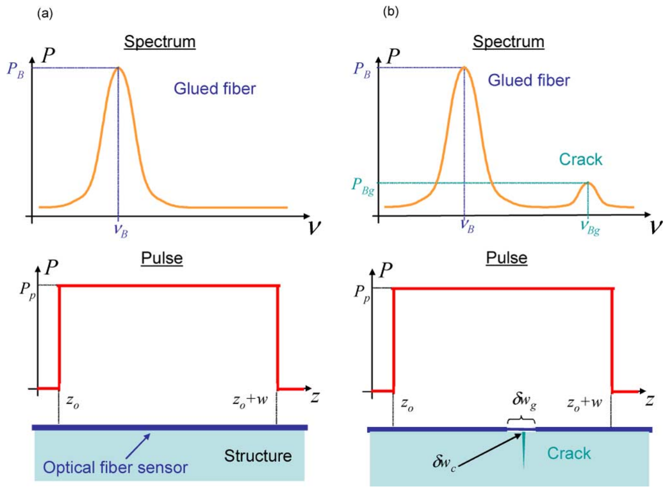

Fig. 2. (a) Optical fiber sensor is bonded at the surface of a substrate. A pump pulse of peak power P_p and spatial resolution w propagates down the sensor and interacts with the cw probe. The result of the interaction is a Brillouin spectrum that is characteristic of unstressed fiber as schematized. (b) Crack occurs and delaminates the sensor over a length of δw_g, crack size length at surface is $\delta w_c < \delta w_g$. At the crack location, pump-probe interaction leads to the measurement of a new spectrum, experiencing an additional peak, which is a signature of the fault formation.

frequency is proportional to strain and temperature variation, turning the approach into a method of choice for the sensing of mechanical and thermal effects. As an example, strain and temperature coefficients are 0.05 MHz/$\mu\varepsilon$ and 1 MHz/°C at 1.55 μm [9], [10], respectively, noted C_e and C_T. Distributed properties are accessed by time modulating the pump lightwave, the probe signal remaining a continuous wave (Fig. 1). For more details, please consult [8]. The spatial resolution of the sensor is related to the pulsewidth $(\Delta\tau)$ and is mathematically defined as $w = c\Delta\tau/2n$, where n is the fiber refractive index. More rigorously, the sensor spatial resolution can be defined as the smallest event, whose strain can be measured with define or target accuracy [11].

For the time being, let us consider only the strain measurement capability of the DBS. In practical applications, a second fiber is used to compensate for temperature variation. The DBS can be viewed as a spectroscopic technique in which spectra is measured all along the fiber. Once a spectrum is acquired, the next step consists in measuring the peak frequency and comparing its value with a reference measurement. Any deviation from the reference measurement is a signature of change in the body monitored. As long as the strain induced by the fault is uniform over w, the strain can be measured accurately as only one peak is present in the spectrum [Fig. 2(a)]. If the strain distribution over w is nonuniform, the spectrum becomes distorted [12] or contains additional peaks [13] [spectrum of Fig. 2(b)], characterized by unstrained and strained peak frequencies, noted ν_B and ν_{Bg}, respectively. In both cases, the spectrum shape can be analyzed and the strain information extracted. The problem consists in finding the peak frequency and gain of the spectrum components. That is done using a peak search and/or multiple distribution fitting algorithm in which the initial conditions are carefully set such as the unstressed fiber Brillouin frequency and Brillouin spectrum linewidth at each location [13], [14].

In crack detection, several issues can be identified. First of all, such faults have a very small width (δw_c), usually $\delta w_c < 1$ mm, which means that a large strain concentration is induced leading quickly to the fiber sensor break. Second, should the sensor survive, the peak would be buried in the noise of the measurement as the spectrum peak powers are roughly proportional to the length of the events [14]. One efficient way to detect a crack consists in transferring the stress to a longer section of the sensor, defined as the delaminated length (δw_g), such that there is no risk of breakage and the peak height is high enough to be measured. That approach is illustrated in Fig. 2(b). Nevertheless, there are limits to large δw_g. In fact, the debonding can be so long that the induced strain is small. A small strain has the consequence to hide the crack information in the main peak, making the fault detection more difficult. Moreover, there is also another upper limit to δw_g. In fact, we want to keep it as short as possible so that deformation monitoring and crack detection capabilities elsewhere in the structure are not jeopardized. From all what precedes, there is clearly the need for the estimation of an optimum delaminating length δw_g.

In order to estimate the optimum δw_g, we propose to consider the length-stress (LS) diagram introduced and extensively discussed in [12]–[14]. This diagram is a graphical representation of the normalized relationship between measured strain and the length of strained section (δw) when that length is smaller than the spatial resolution (w). The diagram relates the strained section length and the amplitude of the strain to spectrum shape. Normalization is done for both strain and length information. Strain, or more exactly the induced Brillouin frequency shift $\Delta\nu = \nu_{Bg} - \nu_B$, is normalized relatively to the Brillouin gain linewidth Γ while strained length (δw) is normalized to the spatial resolution. Such LS diagram has various uses. In particular, it allows the drawing of a borderline between single and multiple peaks spectra, which are typical features of nonuniformly strained sections over w, as illustrated in Fig. 3 [12]–[14]. As shown in Fig. 3, the borderline curve (dashed) is a unique combination of couples $(\delta w_g/w, \Delta\nu/\Gamma)$. Any other couple would fall in the single peak or in the two peaks region.

It is interesting to note that the strain-induced Brillouin frequency shift is a simple function of the delaminated length δw_g. It is expressed as $\Delta\nu = (\delta w_c C_\varepsilon)/\delta w_g$ when it is remembered that the strain induced by the crack is given by $\varepsilon = \delta w_c/\delta w_g$. When drawing this function on the LS diagram (plain curve), after normalization, it is obvious that the strain induced decreases with the increasing delaminated length. Fig. 3 shows that the curve crosses the border for $\delta w/w \approx 0.2$. We then conclude that the delaminating approach can be used for $\delta w_g/w < 0.2$. According to [14], when $\delta w_g/w \approx 0.1$, the peak associated with the crack is about a fifth of the main peak. Such signal level

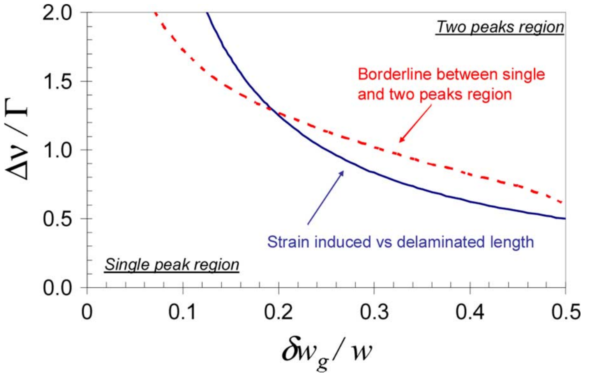

Fig. 3. LS diagram showing the borderline between single peak and two peaks region (dashed curve), and the curve representing the induced strain as a function of the delaminated section length (plain curve).

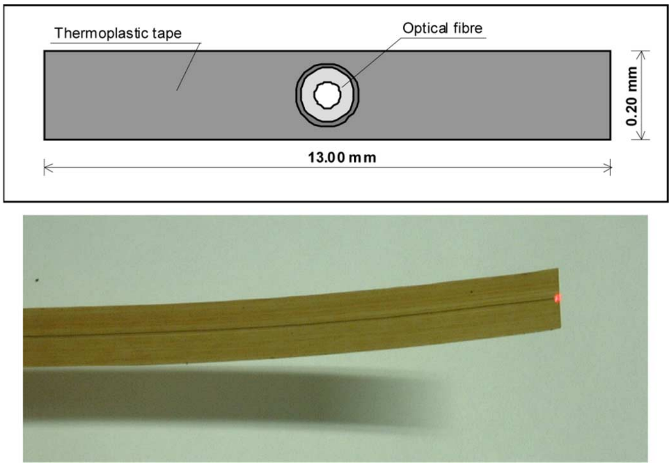

Fig. 4. Fiber-optic sensing cable characteristics (SMARTape).

guarantees a crack detection capability for most of the practical cases.

The fiber sensor packaging and bonding procedure must then be carefully selected to delaminate over an optimum delaminating length that is about one tenth of the spatial resolution, typically 10 cm when $w = 1$ m.

In poor optical budget measurement conditions, borderline and hence optimum delaminated length determination would be affected by the interrogator measurement noise. These conditions also degrade strain measurement resolution (defined as twice the standard deviation on repetitive measurements [11]), which is unacceptable for SHM applications. The use of SBS-based interrogator makes possible the compensation for fiber loss increase and strain resolution degradation. An optical budget of 20 dB can be accommodated, while strain resolution better than 10 $\mu\varepsilon$ can be maintained. Such performance implies that the relative peak power sensitivity remains smaller than 0.5%.

III. Practical Case

The approach is validated by using specialty optical fiber sensor cable, the SMARTape [15] dedicated to the measurement of strain, with a Brillouin optical time domain analysis-based interrogator unit, the Omnisens DITEST. Both components have proven track of uninterrupted and reliable field operations [16]–[19].

The SMARTape was developed because strain measurement on a structure requires an excellent bonding between the sensor and the substrate surface. Optimum strain transfer occurs when the fiber-optic is embedded in a thermoplastic tape in the similar manner as the reinforcing fibers are integrated in composite materials. To produce such a tape, a glass fiber reinforced thermoplastic with polyphenylene sulfide matrix is used. This material has excellent mechanical and chemical resistance properties. Since its production involves heating to high temperatures, (in order to melt the matrix of the composite material) it is necessary for the fiber to withstand this temperature without damage. In addition, the bonding between the optical fiber coating and the matrix has to be guaranteed. Polyimide-coated optical fibers fit these requirements and were therefore selected for this design. The typical cross-sectional width of the thermoplastic composite tape that is used for manufacturing composite structures is in the range of 10–20 mm. As a consequence, it is not critical for optical fiber integration. The thickness of the tape can be as low as 0.2 mm, and this dimension is more critical since the external diameter of polyimide-coated optical fiber is of 0.145 mm approximately. Hence, only less than 0.03 mm of tape material remains on top or bottom of the optical fiber, with the risk that the optical fiber will emerge from the tape. The scheme of the sensing tape cross section, with typical dimensions, is presented in Fig. 4. The use of the SMARTape is twofold: it can be used externally, attached to the structure, or embedded between the composite laminates, having also a structural role.

Important optical losses, ranging between 25 and 30 dB/km, are generated in optical fibers during the production of the SMARTape. These losses are induced by microbending and matrix shrinkage, which limit maximal length of a single sensor to 200–250 m approximately. Functionality of sensors with such losses is guaranteed by extraordinary high power budget of the reading unit (20 dB). Several laboratory and on-site tests were performed in order to assess the performance of the SMARTape [18]. Axial Young modulus was determined to be approximately 31 GPa, while the rupture strain was higher than 3%. Such high Young modulus and strength provide the necessary stiffness to ensure safe installation of long sensors and delamination of sensor in area surrounding the crack. Comparisons of strain measurement obtained by SMARTape with those obtained by traditional micrometer had linearity error of 0.3% and correlation coefficient square $R^2 = 0.99992$.

The glue used to install the SMARTape is carefully selected in order to both ensure good transfer of strain from the structure to the sensor and make possible delamination in case of crack opening. The selection was made after consulting several suppliers and testing different types of glue. The tests included shear strength and peel tests and exposure to extremely low temperatures, down to $-30°$C. Once the glue selected, the installation procedure was fully developed and tested in laboratory and on-site.

The field test is performed on rails loaded by wagon, where the SMARTape is compared with other interferometric optical

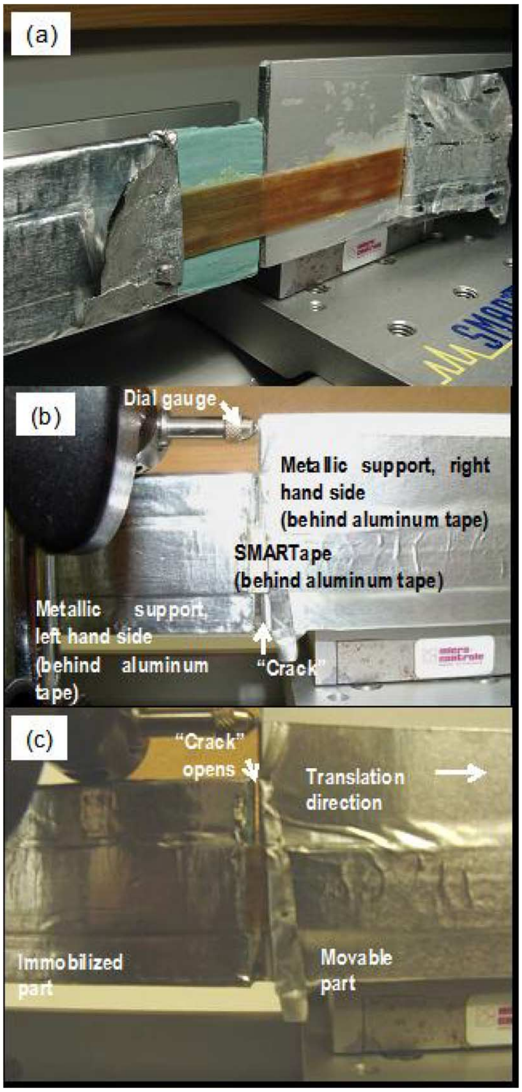

Fig. 5. (a) SMARTape glued on the metallic supports. (b) Test setup before the "crack" is formed. (c) Test setup after the "crack" is formed.

fiber sensors [type Surveillance d'Ouvrages par Fibres Optiques–Structural Minitoring Using Optical Fibers (SOFO)]. Installation is performed following the preestablished installation procedures, and the differences between two types of sensors were in range of resolution of interferometric interrogator ($2\mu\varepsilon = 2 \times 10^{-6}$ m/m), confirming applicability and good field measurement performance of the SMARTape. The installed SMARTapes were left on the rails in order to assess the performance in long-term and after nearly five years were still in a good condition.

Finally, several tests in laboratory and on-site were performed for the purposes of real application on a bridge [19]. These tests included verification of installation procedures, midterm performance, comparison with mechanical gages, crack detection, and parameterization and temperature compensation.

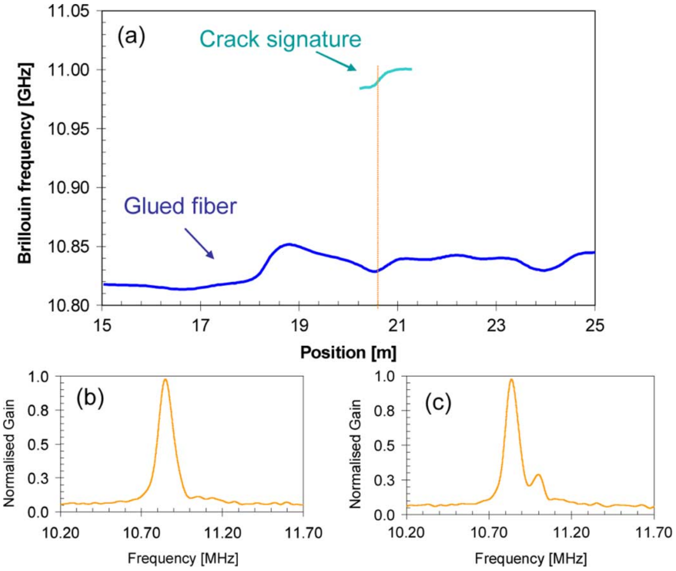

Fig. 6. (a) Brillouin frequency distribution near the crack location derived from the measured spectra. (b) Brillouin spectrum at 20.5 m, off the "crack" region. (c) Brillouin spectrum at 20.6 m, in the "crack" region.

The DiTeSt Brillouin interrogator system is an innovative high-dynamic range laser-based monitoring system based on SBS [8]. The inherent stability of the system comes from the use of a single laser source and a high-speed electrooptic modulator for the generation of both pump and probe signals. The intensity of both optical signals can be controlled in order to have the highest possible signal-to-noise ratio and reduce the acquisition time. The frequency difference between pump and probe signal is precisely controlled by the modulation frequency applied to the electrooptic modulator, leading to 10^{-5} precision on the frequency determination. Typically, the DiTeSt system performs strain profile measurement with a 10 $\mu\varepsilon$ resolution and a spatial resolution better than 1 m over the first 10 km. For SHM applications, the interrogator is designed to handle short distance and large, optical budget (over 20 dB). Fifty thousand distance points can be measured with a minimum sampling interval of 0.1 m. The acquisition time (time to get one complete profile) may vary from a second to 10 min, depending on the application requirements.

Validation of our approach requires a test setup in which cracks are produced in a controlled manner. In order to achieve that goal, we built a special setup. Two flat and smooth metallic supports were assembled. One of them is fixed while the other can be moved. As an initial step, the two supports were joined and the SMARTape was glued on their surface (Fig. 3). The metallic supports were then exposed to a relative translation movement simulating crack opening. The relative translation movement was ensured by special metallic holders that prevented relative rotations and forced the metallic supports to slide over straight lines. The translation motion was imposed by a micrometric screw. The relative displacement between the two metallic supports is strictly monitored by using a dial gauge (Fig. 5).

The crack opening was also monitored by measuring the SMARTape behavior with the DiTeSt. Fig. 6(a) shows the Brillouin frequency distribution once a 0.56 mm "crack" was formed. As it appears in Fig. 6(b), the spectrum off the "crack" region is typical of a fiber not subjected to a localized stress, i.e., the Brillouin frequency is uniform over the w. When we examine Fig. 6(c), it is obvious that in the "crack" region the spectrum presents a composite structure. Two peaks are observed, the highest being related to the unstressed part of the fiber while the tiniest is a signature of the "crack." It is not a surprise that the detected crack section seems to extend roughly over a distance $w/2 > \delta w_g$. The measurement interval is a fraction of w such that there is much more than one digitized position in which the crack appears. In other words, the event has an apparent length of about w. Nevertheless, crack actual location can be estimated more accurately because of the following reasoning. According to Fig. 6(a), delaminated section is composed between 20.2 and 21.2 m, which is the crack signature interval. That interval can be sampled into 10 cm segments due to the instrument sampling resolution. Moreover, delaminated section is centered on the middle of the crack signature interval that is to say at 20.80 m. As crack is located within the delaminated section, it is estimated to be localized between 20.75 and 20.85 m as the instrument sampling resolution is 0.1 m.

IV. CONCLUSION

In the present work, we demonstrated that the combination of the DiTeSt interrogator with the SMARTape sensing cable successfully detects the opening of submillimeter cracks. The proposed method guarantees the sensor uninterrupted operation and allows the detection of the crack with a 1-m spatial resolution because of the careful analysis of the Brillouin spectrum shape. It also reveals the advantage of the DBS method over other distributed techniques such as optical time domain Rayleigh and Raman reflectometers: the DBS has an event detection capability smaller than its spatial resolution, making the DBS the monitoring tool of choice when high-spatial detection capability is required.

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