Localized strain measurements using an integration method to process intensity reflection spectra from a chirped FBG

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ABSTRACT

A chirped fiber Bragg grating was used to measure the non-uniform strain profile of a notched aluminum specimen used to simulate a cracked structure. The specimen was subjected to tensile tests that produced regions of non-uniform strain near the notches. Analysis of power reflectance spectra from the grating, through the use of an integration method, enabled the strain profile near the notches to be determined. Unlike other intragrating sensing methods, this method did not require a disturbance hypothesis to be postulated. The strain profile results from this intragrating sensor were in reasonable agreement with predictions from modeling conducted using the finite element method.

Keywords: Intragrating sensing, chirped fiber Bragg grating, strain measurement

1. INTRODUCTION

Nowadays fiber Bragg gratings (FBGs) [1] are in widespread use as sensors of strain and temperature, or both, in a wide range of application areas. One of the advantages of FBGs is that it is possible to multiplex a significant number of sensors of different wavelengths, on a single fiber, to obtain point readings a number of locations [2]. This is ideal for situations in which information on measurands is required at multiple locations over a large region or distance.

Intragrating sensing, on the other hand, is the process of obtaining a continuous profile of strain or temperature within a single fiber Bragg grating (FBG)[2-4]. This can be accomplished by applying appropriate transforms to complex phase and amplitude spectra through the use of specialized equipment [5-6]. Techniques for intragrating sensing based on conventional FBGs have had varying degree of success [2-4]. One way to overcome problems associated with conventional FBGs is to use chirped fiber Bragg gratings (CFBGs). The chirp rate within the CFBG will affect its performance such as accuracy and spatial resolution [2]. Chirped gratings enable non-monotonic field profiles and peak localised strain and temperature to be measured and also increase the spatial resolution of the measurement [2]. Prior work on determining intragrating temperature profiles using a hypothesis profile and employing transfer matrix or Fourier grating models require the shape of the temperature profile to be conjectured and programmed [7-8]. Recently, we applied an integration method to operate only on reflectance spectra from a chirped fiber Bragg grating (CFBG) without the requirement for prior knowledge of the shape of a hypothesis temperature profile [9]. In the method, which has been used to analyze a temperature hot-spot [9] and a temperature step [10], the known chirp of the grating provides the means to associate each wavelength in the FBG spectrum with a location along the sensor [9].

Much of the interest in intragrating strain sensing relates to applications such as crack detection or identifying conditions within a structure prior to the occurrence of structural failure. The use of strain sensors, particularly those based on fiber Bragg gratings, involves the detection of changes in the strain field, in which sensors have to be arranged carefully within a structure in locations where structural degradation is anticipated.

In this work we have bonded a CFBG sensor to an aluminum test sample containing two thin rectangular notches that was subjected to longitudinal stresses. From the CFBG reflection spectra, the strain distribution was deduced using our integration method [9]. The use of finite element method (FEM) modeling confirms the strain profiles determined.

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2. METHODOLOGY

The CFBG used for this investigation was fabricated in hydrogen-loaded Corning SMF-28 telecommunications fiber with a linear chirped phase mask using a scanning FBG fabrication system. The phase mask had a centre pitch of Λ = 1.0665 μm and chirp rate of 20 nm/cm. A piezo phase mask shaker was used to flatten the average refractive index at the ends of the apodised CFBG, which had a length of 15 mm. The sensor was annealed at 330 °C for 150 s to prevent subsequent shift in the spectra due to out-diffusion of H_2, resulting in a maximum reflectance of 23%, and was calibrated for temperature and strain. Reflected spectra were normalized to 14.6 dB above an average measured reflection spectrum of an FC/PC connector, through a 3-dB, 1550-nm coupler [8].

An aluminum specimen of rectangular cross-section having dimensions of approximately 350 × 12 × 6 mm containing a machined notch at the centre of the specimen was used as shown in Fig. 1(a). The pair of rectangular (with a parabolic tip) notches of dimensions (width 1 mm, depth 3 mm) generated a strain gradient along the axial direction of the specimen. The notch shape was selected to resemble closely a crack in a structure. A shallow slot of 0.5 mm in diameter machined on the surface (along the center of the axial direction) of the specimen was used to embed the sensor at the geometrical centre of the notch using Loctite Fixmaster (97483) epoxy. The epoxy was allowed to cure for 4 days at room temperature, with a small tension applied to the fiber to keep the fiber straight, prior to testing.

Fig. 1(b) shows the schematic of the mechanical and optical arrangements, the latter being similar to that used previously [8-10]. The CFBG sensor was monitored in reflection using an Er^{3+} broadband light source via a 3-dB 1550-nm coupler. The reference and disturbed spectra were measured using an OSA with a resolution of 0.1 nm and saved on a computer. The specimen was subjected to a range of controlled static tensile loads using a materials testing machine. The load was displacement controlled by means of the supporting frame attached to the actuator shaft of the machine, allowing the applied load and the displacement to be measured electronically. As axial tensile forces ranging from 0.5 to 8.0 kN in steps of 0.5 kN were applied, reflection spectra from the CFBG sensor were recorded. Each spectrum presented in Fig. 2 was obtained by averaging 50 OSA measurements at the specified load.

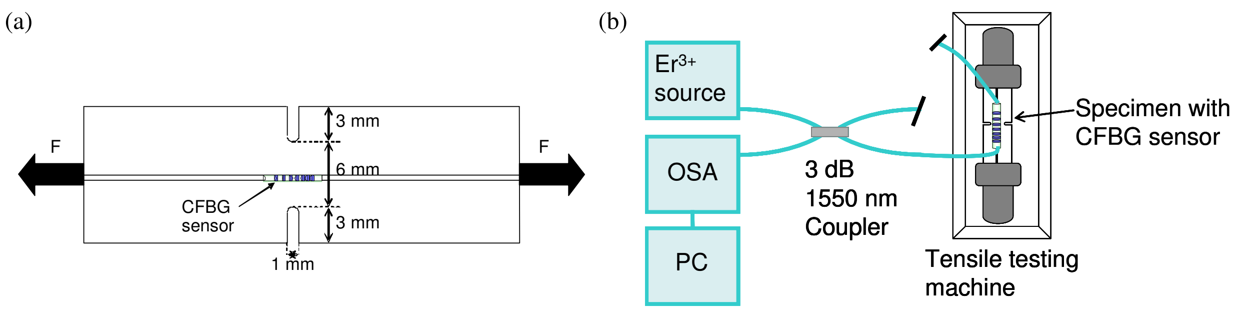

Fig. 1. Schematic diagrams of (a) the aluminum specimen and (b) the experimental system for applying tensile load to the specimen.

The surface strain distribution along the specimen was calculated using the numerical structural finite element method (FEM) based on the linear elasticity theory of solid mechanics, using the FEMAP/NASTRAN software. A 2-D analysis was used since the specimen was subjected to an axial tensile force only. Only one quarter of the specimen was modeled because of its symmetry. The mesh consisted of 6407 grid points (nodes) and 5976 rectangular elements.

3. RESULTS AND DISCUSSION

Fig. 2 shows examples of averaged reflected spectra obtained for the indicated tensile loads. The spectra have characteristic dips and humps around the shape induced strain gradients. As expected, the local Bragg wavelengths around the notch shift to longer wavelengths and the grating chirp becomes nonlinear. The occurrence of two dips and humps suggests that there are two regions of peak strain on either side of the notch centre. The modified peak reflectance is approaching 80%, which justifies the use of a grating with low reflectance for measurements involving large gradients [8].

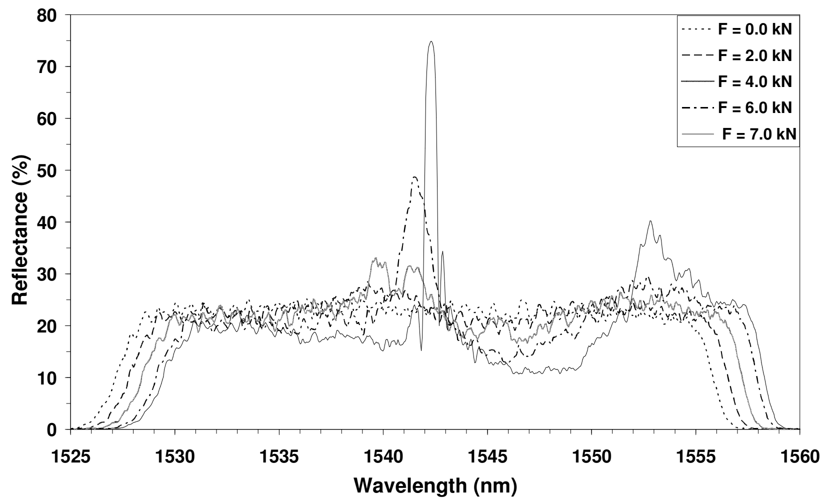

Fig. 2. Reflection spectra from the CFBG sensor subjected to various tensile forces.

Fig. 3 shows the strain profiles, extracted from the averaged CFBG spectra, as a function of position along the grating, obtained using the integration of difference technique [9-10], for various loads. A strain error of approximately 170 $\mu\varepsilon$ has been estimated, due primarily to variations in the applied load. The repeatability of these strain profiles was verified by performing calculations on sub-sets of the 50 measured spectra, and the rms repeatability error was found to be less than 10 $\mu\varepsilon$. All calculations resulted in the two regions of high strain evident in Fig. 3.

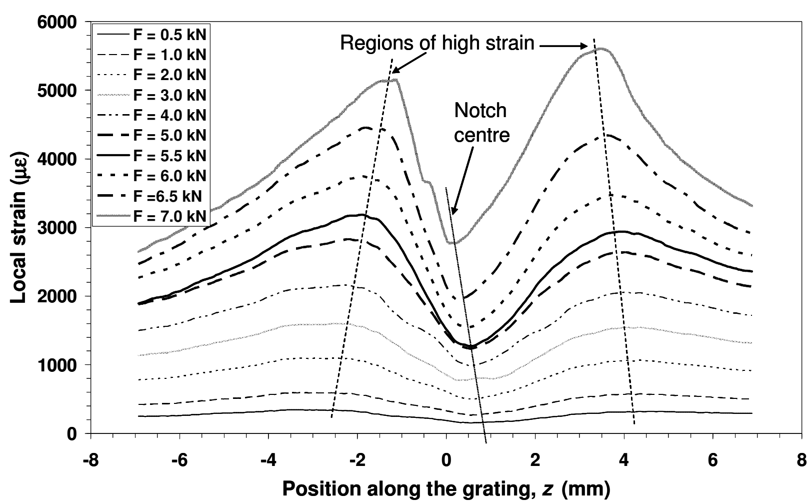

Fig. 3. The deduced strain profile as a function of position along the CFBG sensor during load application.

Fig. 4 shows the extracted and the FEM simulated strain profiles around the notch at an applied force of 1.0 kN. There is good correlation between these curves. However, closer inspection shows that the experimental strain evaluated by the sensor is approximately 100 $\mu\varepsilon$ lower than that predicted by FEM calculations with the deviation being higher at the notch centre. This discrepancy is most likely due to incomplete transfer of surface strain within the specimen through the 3-layers (host/adhesive/stripped-fiber) to the fiber core, and will be the subject of further investigation.

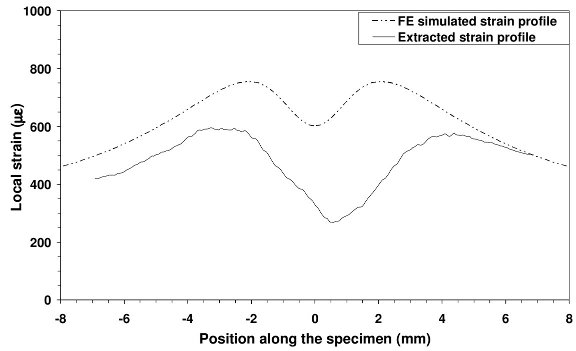

Fig. 4. The extracted and FEM modelled strain profiles around the notch centre for the CFBG at an applied force of 1.0 kN.

4. CONCLUSION

Measurements of localized strain distribution in an aluminum specimen containing a pair of notches using a CFBG, involving processing of power reflection spectra only and without the need for an initial strain distribution hypothesis, have been presented. The results, in particular the occurrence of a pair of strain peaks, compare favorably with FEM simulation, although some discrepancies were noted. An intragrating sensor of this type is expected to find many applications in the area of structural health monitoring.

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REFERENCES

1. A. Othonos and K. Kalli, *Fibre Bragg Gratings: Fundamentals and Applications in Telecommunications and Sensing*, Artech House, Boston, USA, 1999.
2. A. D. Kersey, M. A. Davis, H. J. Patrick, M. LeBlanc, K. P Koo, C. G. Askins, M. A. Putnam and E. J. Friebele, "Fiber grating sensors," *J. Lightwave Technol.* 15, 1442-1463 (1997).
3. M. Volanthen, H. Geiger, M. J. Cole and J. P. Dakin, "Measurement of arbitrary strain profiles within fibre gratings," *Electron. Lett.* 32**,** 1028-1029 (1996).
4. P. C. Won, J. Leng, Y. Lai and J. A. R. Williams, "Distributed temperature sensing using a chirped fibre Bragg grating," *Meas. Sci. Technol.* 15, 1501-1505 (2004).
5. J. Skarr and H. E. Engan, "Distributed intragrating sensing using phase retrieval," *Proc. SPIE* 3746, 588-591 (1999).
6. J. Azana and M. A. Muriel, "Reconstruction of fiber grating period profiles by use of Wigner-Ville distributions and spectrograms," *J. Opt. Soc. Am. A.* 17, 2496-505 (2000).
7. F. Casagrande, P. Crespi, A. M. Grassi, A. Lulli, R. P. Kenny and M. P. Whalen, "From the reflected spectrum to the properties of a fiber Bragg grating: a genetic algorithm approach with application to distributed strain sensing," *Appl. Opt.* 41, 5238-5243 (2002).
8. A. Nand, D. J. Kitcher, S. A. Wade, T. B. Nguyen, G. W. Baxter, R. Jones and S. F. Collins, "Determination of the position of a localised heat source within a chirped fibre Bragg grating using a Fourier transform technique," *Meas. Sci. Tech.* 17, 1436-1445 (2006).
9. D. J. Kitcher, A. Nand, S. A. Wade, J. Elston, R. Jones, G. W. Baxter and S. F. Collins, "Integration method of analysis for intra-grating sensing with a chirped fiber Bragg grating," *Technical Digest of the 18th International Conference on Optical Fiber Sensors*, Cancún México, (OSA, Washington DC), paper TuE46 (2006).
10. D. J. Kitcher, A. Nand, S. A. Wade, R. Jones, G. W. Baxter and S. F. Collins, "Implementation of integration of differences method for extraction of temperature profiles along chirped fibre Bragg gratings," *Proc. 31st Australian Conference on Optical Fibre Technology*, Melbourne, CD-ROM: ISBN 0-9775657-1-8, Oral papers pp. 57-59 (2006).