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Review

On-specimen strain measurement with fiber optic distributed sensing

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ABSTRACT

The paper explores the possibility of the use of high spatial resolution fiber optic distributed sensing technology for on-specimen strain measurements in laboratory element testing. The approach provides the means to evaluate specimen surface deformation through a novel conjuncture helical envelope configuration of a single optical fiber ribbon. Given that this technology has yet to be applied in the area of material characterization, the paper investigates the most basic setup of a uniaxial compression test. It is shown that the approach provides a full-field view of surface strains with a resolution and accuracy level that is comparable with traditional deformation sensors. It enables the evaluation of small-strain mechanical properties as well as visualization and quantification of any indication of non-uniform test conditions. Because of the relative ease and low-cost for instrumentation, the suggested approach has a great potential to be a routine application for element testing.

Contents

1. Introduction

Mechanical material characterization is performed routinely in civil engineering projects as well as in many other engineering disciplines. A typical characterization test

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involves application of force onto a specimen (usually cylindrical) under well-controlled conditions in the laboratory and measuring the resulting strains. In recent years, especially in the geotechnical area [e.g. 1–3], much attention has been placed on characterization under small-strains to better capture the behavior in typical service conditions. It is currently accepted that these deformations can be reliably monitored with local (on-specimen) measurement instrumentations including strain gauges [e.g. 4,5] and Linear Variable Differential Transformers (LVDTs) [e.g. 6–8]. While both sensors are accurate and reliable, in order to ensure the validity of the measurement, complicated and delicate procedures are required such as drilling, gluing and multiple sensor setup [9]. Moreover, they have the disadvantage of offering only a limited view of the deformation field at locations which must be decided prior to the test due to physical size and cost restriction.

Image analysis methods such as Digital Image Correlation (DIC) have been gaining popularity as a viable full-field deformation measurement technique in civil engineering applications [e.g. 10–12]. A problematic aspect of the DIC is that its resolution depends inversely upon the observation window; that is, the imaged field-of-view must be a few millimeters in size for attaining the resolution level equivalent to the aforementioned sensors. Interferometric methods such as Moiré interferometry and electronic speckle pattern interferometry can, on the other hand, provide a high spatial resolution for large observation windows [e.g. 13–15]. However, it imposes stringent experimental requirements such as vibration-free optical platform and sufficient availability of a line-of-sight between the specimen and the imaging equipment. Since mechanical characterization is often performed in closed cells, these requirements may limit the applicability of imaging techniques. The methods also require demanding post-processing computations which are deemed unsuitable for real-time applications.

Throughout the last decade a number of advanced fiber optic sensing technologies have matured and developed into commercial tools for small-strain and temperature measurements in large-scale engineering applications [e.g. 16–24]. In general terms, fiber optic sensing operates through attachment of conventional telecommunication fiber cables (containing one or more bare fibers) to monitored objects. The attachment methods range from continuous gluing, localized point-gluing, to mechanical fixing at a certain interval along the cable. Deformation experienced by the object (or temperature changes) is imposed on the fiber cable and the induced straining alters the optical properties of the bare fiber which are read by a specially designed signal interrogator. It is important to note that the initial fiber strain defines the possible range of the deformation monitoring as the fiber predominantly operates in tension.

Different spatial resolutions, monitoring scales and strain sensitivities are offered depending on underlying technologies: Brillouin scattering based technologies such as Yokogawa's Brillouin Optical Time Domain Refelectormetry (BOTDR) AQ8603; Omnisens' Stimulated BOTDR (named BOTDA, A for analysis) DITEST STA-R; and, more recently, Rayleigh scattering based technology such as Luna's Optical Backscatter Reflectometer (OBR) OBR4600. Currently, BOTDR is capable of long-distance (up to 30 km) distributed sensing with sensitivity of 5 $\mu\varepsilon$, which are suited for large-scale applications of structural and geotechnical monitoring. This technology, however, is limited to a spatial resolution of roughly 1 m and hence not suited for laboratory-scale implementation. It is expected that the spatial resolution of BOTDR/A will be enhanced in near future through advancement in sensing algorithms [e.g. 25,26]. The OBR, on the other hand, has a higher spatial resolution of 1 mm for monitoring distance of 2 km with accuracy of less than 5 $\mu\varepsilon$. Improved resolution can be achieved for shorter distance [27,28].

Based on their reported capabilities, fiber optic distributed sensing can potentially serve as a viable alternative to strain gauges or LVDTs for material characterization in laboratory element testing. Despite this potential, such an application, focusing on routine execution, has not been attempted. Accordingly, this paper explores this possibility wherein the OBR technology is utilized for measuring strains in a cylindrical specimen placed under uniaxial compression. The suggested scheme requires wrapping a single fiber around the specimen. This novel configuration ensures that the fiber elongates while following the deformation of the compressed specimen. It also provides a full-field view of the resulting surface strains.

2. Study of fiber optic sensing related components

In order to utilize fiber optic sensing technology as a deformation measurement tool in a laboratory setting, it is essential to investigate two main components: stiffness properties of the fiber cable and effect of the attaching methods to the specimen. In the current work a Fujikura single-mode fiber cable (SM8) was used. It contains eight bare fibers, each covered by thin colored coating, tied together by a thin flat jacket to form a ribbon. In this study, two fibers were read by splicing the end of the ribbon and thus connecting the two inner fibers. The multiple measurements provided accountability and better accuracy for the readings. Given that the jacket is attached to the deforming object, the tight buffering in the ribbon reduces interface effects. Moreover, the fiber ribbon is both sufficiently flexible and mechanically robust and thus is workable as opposed to fragile bare fibers. The flat surface area of the ribbon is also better suited for gluing.

Prior to any testing, the OBR analyzer coefficient that relates strain and frequency shift needs to be calibrated. For this purpose a 3 m portion of a long ribbon was clamped and elongated under displacement-controlled condition using a caliper. The ribbon was subjected to 32 increments of loading and unloading covering an applied strain range from 100 to 2000 $\mu\varepsilon$. A separately pre-calibrated BOTDA analyzer was also used for cross-validation.

2.1. Fiber ribbon

The stiffness of the ribbon was investigated by a pulling test as illustrated in Fig. 1. An environmentally-controlled single-axis electrodynamic load frame EP10000 by Instron