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MEASUREMENT OF STRESS-STRAIN RESPONSE OF A RAMMED EARTH PRISM IN COMPRESSION USING FIBER BRAGG GRATING SENSORS

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Abstract: A comparative study of strain response and mechanical properties of rammed earth prisms, has been made using Fiber Bragg Grating (FBG) sensors (optical) and clip-on extensometer (electro-mechanical). The aim of this study is to address the merits and demerits of traditional extensometer vis-à-vis FBG sensor; a uni-axial compression test has been performed on a rammed earth prism to validate its structural properties from the stress - strain curves obtained by two different methods of measurement. An array of FBG sensors on a single fiber with varying Bragg wavelengths (λ_B), has been used to spatially resolve the strains along the height of the specimen. It is interesting to note from the obtained stress-strain curves that the initial tangent modulus obtained using the FBG sensor is lower compared to that obtained using clip-on extensometer. The results also indicate that the strains measured by both FBG and extensometer sensor follow the same trend and both the sensors register the maximum strain value at the same time.

Index terms: Fiber Bragg grating sensors, uni axial compression, rammed earth, stress strain response.

I. INTRODUCTION

With increasing infrastructural development across the globe, there is an increasing demand for a variety of construction materials. Further, the climatic changes and the consequent global warming have put a pressing need on using eco-friendly materials in construction. In this context, construction of civil structures using mud / rammed earth has gained relevance [1, 2]. In recent times, to increase the strength and durability of rammed earth structures, cement is used as a stabilizer. It is essential to determine the mechanical properties of such composite materials for design purposes [3].

Generally, the compressive stress-strain response of the material is one of the important parameters for the design of load bearing walls [4]. In strain response studies, the choice of proper sensors plays a vital role in determining the mechanical properties of materials. Several strain measuring devices like demec gauge (mechanical), clip-on extensometers (electro-mechanical) and resistance strain gauges (electrical) have been used for such purposes. However, not all of them have the desirable properties like embeddability, electromagnetic insensitivity, small dimensions, easy installation, ease in reaching inaccessible areas of the specimen, multiplexing capability, etc., which are inherent in Fiber Bragg Grating (FBG) sensors [5,6,7]. FBG sensors are probably the most promising candidates to effectively replace the conventional strain sensors for real time strain monitoring of civil structures [8, 9].

In the present study, experiments have been carried out in the laboratory to test the response & reliability of the FBG sensors and also to validate the material properties of rammed earth specimen by measuring strain under dynamic uni-axial compression. The longitudinal strains measured in rammed earth prisms under uni-axial compression using FBG sensor and extensometer are compared. Assuming that the locations and orientations of the sensors have been suitably chosen, i.e. according to the specific requirement of the analyzing scheme, the measured strains provide valuable information about the behavior of the specimen under test.

II. PRINCIPLE OF FIBER BRAGG GRATING SENSORS

Use of optical fibers as sensors for measurement of various parameters is gaining its importance in recent times [10, 11]. Fiber Bragg Grating (FBG) sensors are one among the popular sensor elements used for a wide range of measurements. A FBG is a periodic modulation of the refractive index of the core of a photo sensitive germania doped silica fiber, which is formed by exposing the core to an intensity modulated, intense UV beam [12,13]. The change of the core refractive index is of the order of 10^{-5} and 10^{-3}.

Over the years, there have been several techniques developed to inscribe Bragg gratings in an optical fiber [14]. The phase mask technique is one of the most effective methods to fabricate FBGs [15,16]. This method, which is used in the present experiments, employs a diffractive optical element (Phase Mask) to spatially modulate an UV beam at 248 nm for fabricating Bragg gratings [17].

When light from a broad band source is launched into a FBG, the constructive interference between the forward and the contra-propagating light waves, leads to a narrow-band back- reflected light [18]. These results in a notch in the transmission spectrum of the fiber while a well-defined peak is seen in the more widely used reflection spectrum which obeys the Bragg's condition (1):

$$\lambda_B = 2\, n_{eff}\, \Lambda \qquad (1)$$

Here, the back reflected Bragg wavelength ($\boldsymbol{\lambda}_B$) is related to the grating period Λ and the effective refractive index of the fiber n_{eff}.

Both the effective refractive index n_{eff}, and the grating period Λ vary with changes in strain ε, temperature T and/or pressure P, acting on the fiber. The response of back reflected wavelength to both strain and temperature is given by

$$\Delta\lambda_B = \Delta\lambda_S + \Delta\lambda_T \qquad (2)$$

Where $\Delta\lambda_B$, is the change in Bragg wavelength; $\Delta\lambda_S$ is the strain effect term and $\Delta\lambda_T$ is the temperature effect term. Temperature affects the Bragg wavelength due to the thermal expansion/contraction through the thermo optic and thermal expansion coefficients. The temperature effects are generally negligible, if the experiment is conducted at room/constant temperature or well understood or when adequately modeled, providing a direct means for measuring strain [19,20,21]. The shift in the Bragg wavelength (λ_B) due to the applied strain or pressure from expansion or contraction of the grating period through photo elastic effect is given by

$$\Delta\lambda_B = \lambda_B\,(1 - P_e)\,\Delta\varepsilon \qquad (3)$$

$$\Delta\lambda_B = \lambda_B K_e \Delta\varepsilon \qquad (4)$$

$$K_e = (1 - P_e) \qquad (5)$$

Here, the photo elastic coefficient of the fiber Pe= 0.22 and strain co-efficientK_e is defined by

$$K_e = \frac{1}{\lambda_B}\frac{d\lambda_B}{d\varepsilon} \qquad (6)$$

III. STRAIN MEASUREMENT IN UNI-AXIAL COMPRESSION TESTS

The compression test performed usually assumes that the load applied on the specimen will only be acting in normal direction and their effects in other directions can be neglected. This is because the frictional forces between the ends of the specimen and the platens exert a state multi axial force [22]. Due to the above mentioned reason, the measured compressive strength of the specimen is found to be slightly higher than its true compressive strength. The determination of strains in uni-axial compression tests is usually carried out to validate the structural properties of the specimens [23]. This phenomenon can be defined by applying Hooke's law for linear elastic solids, given by

$$[\varepsilon] = [s].[\sigma] \qquad (7)$$

Where $[s]$ is the compliance matrix containing elastic constants, $[\sigma]$ is the stress matrix, and $[\varepsilon]$ is the strain matrix.

When a specimen is loaded in uni-axial compression, there will be longitudinal deformation along with transverse deformation (due to Poisson's effect). The presence of friction between the loading platens and the specimen gives rise to multi-axial state of stress in the specimen close to their loading faces which is referred to as "platen effect". The platen effect on compressive strength can be reduced by increasing the height/width ratio of the specimen. The prism test specimen with height to width ratio as 2 is taken as standard for negligible "platen effect". Hence, the middle one-third height of the specimen can be assumed to be free from platen effect and a uniform state of stress exists here [24]. To capture the strain profiles along the height of the specimen, it is essential to measure the strains at various sections along its height.

IV. EXPERIMENTAL SETUP

Figure 1 shows the pictorial representation of the experimental setup, where the specimen to be tested is bonded with a series of three FBG sensors with varying Bragg wavelengths on a single fiber along its height. A clip-on extensometer of 50 mm gauge length is fixed close to the FBG sensor bonded at the centre of the specimen. The single fiber containing three FBG sensors varying in the centre wavelengths of the reflected light is spliced to a patch cord and connected to the FBG interrogation system.

Figure 1. Experimental Setup

a. Specimen Preparation

Materials used in rammed earth construction are soil, sand, cement and water. The soil used in the present work consists of 31.6% clay fraction. From the previous studies, it has been observed that a clay fraction of 14-16% is essential for rammed earth construction from durability consideration [25]. In view of the above, there is a need to reconstitute the soil with sand in the ratio of 1:1. The cement quantity, equal to 8% of soil and sand mix has been added to stabilize the reconstituted mixture. Water (10% by weight of dry mixture) is added to prepare the wet mix.

A 150 mm square rammed earth prism of 300 mm height is prepared by compaction of cement stabilized wet soil mix in three layers of 100 mm each. The wet mix is accurately weighed and poured in the prism mould and compacted with a metal rammer to ensure uniform dry density of 1800 kg/m^3. Dents are made with a special type of rammer, before compacting the next layer, to improve bonding strength between the layers. The three layers are compacted and the surface is leveled. The prism is removed from the mould after 24 hours and is capped with rich cement mortar of 3mm–4mm thickness on the loading faces. This is essential to ensure uniform distribution of load on the specimen while testing.

b. Sensor installation and instrumentation

In materials testing, the proper selection of sensor is important and is primarily determined by the characteristics of the material to be tested. This includes its shape, dimensions, test requirements and the formal standards which must be met. These factors define the gauge length of the sensor, accuracy and test sequence of the experiment.

In order to sense the strain profile along the height of the specimen, a single fiber carrying three FBG sensors, each of 3 mm gauge length with different Bragg wavelengths (1540 nm, 1550 nm, 1555 nm), are bonded axially along the height of the specimen. One of the FBG sensors in the fiber is mounted at the centre of the specimen where it is assumed not have the "platen effect", explained earlier; while the other two sensors are mounted at 75 mm distance from the loading faces of the specimen. This facilitated the measurement of strain in the platen affected portion of the specimen which would not have been possible with traditional clip-on extensometer because of its large physical dimensions interfering with the loading system.

Surface preparation becomes an extremely important task before bonding the fiber with FBG sensors on a non-uniform/rough surface of the specimen, to avoid possible measurement errors induced by strain transfer. A sand and abrasive paper is used to furnish the area of FBG sensor installation. After furnishing, the surface of the specimen is cleaned by cotton immersed in methanol to facilitate the active bonding between the fiber and the surface of the specimen.

Along with the FBG sensors, a clip-on extensometer having a gauge length of 50 mm has also been fixed at the mid height of the specimen. Clip−on extensometers are, as the name implies, mounted directly onto the specimen. The mechanical parts which transfer extension, via knife edges, from the specimen to the internal transducers are short and stiff. One very important consideration on the behavior of the clip-on extensometer is when the specimen fails.

Installation of extensometer becomes extremely infeasible as it will have knifes edge which grips the specimen directly creating epicenters of localized stress. As the test specimen in present case is to be studied till its failure, it becomes extremely difficult to handle the expensive extensometer assembly. High extension or flexible specimens can damage or destroy the knife edges of the extensometer or even the extensometer itself can get damaged due to whiplash, splintering or de-lamination of specimen. On the other hand, the fairly low-cost FBG sensors can be sacrificed during the destructive failure testing of the specimen.

Though the FBG sensors which can be directly bonded on to the surface of the specimen is the best choice, the installation of bare FBG sensors on components of civil structures may result in sensor failure due to the fragile nature of the glass fiber and the harsh environment of the construction industry. However, FBG sensors with suitable packaging are commercially available to overcome this disadvantage.

For recording the change in λ_B of the reflected light from each of the FBG sensors which can l be interpreted to the respective strain, a Micron Optics (SM 130-700) FBG interrogation system has been used which can record data at a rate of 1 kHz with a typical resolution of

2με. This interrogation system allows simultaneous detection of several sensors in a single fiber, in which the maximum number of sensors which can be used, depends on the expected dynamic range of strain on each of the sensor in the experiment.

c. Specimen Testing

A servo hydraulic universal testing machine has been employed for loading the specimen under uni-axial compression in stroke control at a rate of 10 μm/s up-to failure as shown in figure 2. The load and strain histories are recorded through a computer controlled data acquisition system. Figure 2 shows the loading history of the tested specimen. The load on the specimen is gradually increased till failure and a maximum of 124 kN load has been observed for the full scale specimen failure.

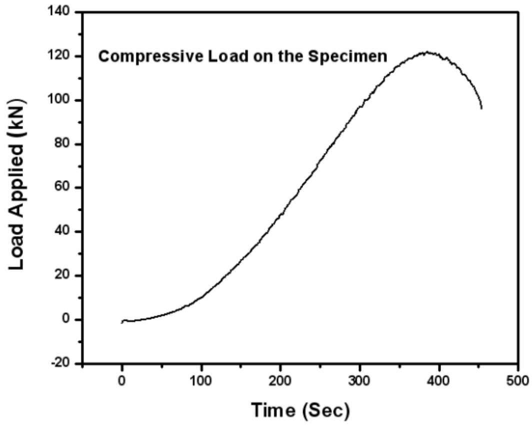

Figure 2. Loading Profile of the Specimen

V. RESULTS AND DISCUSSION

In a typical experiment, a single fiber carrying three FBG sensors each of 3mm gauge length with different wavelengths is bonded axially along the height of the specimen. Among the three sensors, the middle sensor is accompanied by a clip-on extensometer having a gauge-length of 50 mm, fixed to the middle portion of the specimen. A comparative study on performance, accuracy, ease of use and meaningfulness of the data acquired has been carried out on both types of the sensors positioned in the middle of the specimen. Array of three FBG sensors on a single fiber bonded along the height of the specimen facilitates in resolving the strain along the height of the specimen.

Figure 3 shows the failure pattern of the specimen tested with an ultimate compressive load of 124 kN. It is noticeable from figure 3 that the crack generated in the specimen (towards the right side of the specimen in figure 3) has propagated through the centre portion of the specimen where both FBG sensors and extensometer are located.

Figure 3. Specimen at failure

Figure 4 shows the strain history recorded by both FBG sensor positioned in the mid height of the specimen and clip-on extensometer. From the graph it is evident that the strains measured from both the sensors follow the same trend. The nature of loading in the present experiment is compression, which will decrease the central wavelength of the FBG sensor from its initial value. For reader's convenience, the strain in the plot has been shown increasing in the positive direction to compare against the extensometer strain readings. The strains measured from FBG sensor at the mid-height of the specimen is over the gauge-length of 3mm whereas the strain measured using the clip-on gauge was over the gauge length of 50mm. It is also evident from the plot that the both the sensors register the maximum strain value at the same time showing similar response to load applied.

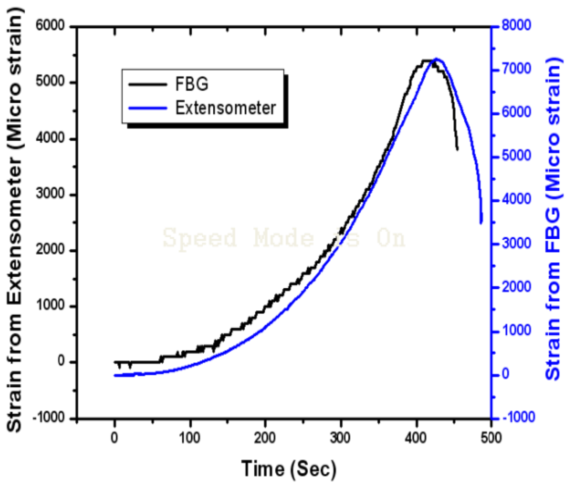

Figure 4. Comparison of FBG sensor and extensometer during the uni-axial compression Test

A comparative study between graphs of both the sensorsof figure 4 reveals that the peak strain recorded by the FBG sensor is more than the value recorded by clip-on extensometer. This can be attributed to the higher gauge-length of clip-on extensometer and possible loss of grip at knife edges; the extensometer senses and averages out the strain over a gauge-length of 50 mm which covers a larger volume of the prism compared to the FBG sensor which senses over the 3 mm gauge-length. This conjecture is also supported by the fact that the strain value is the highest at the centre of the specimen compared at the rear ends.

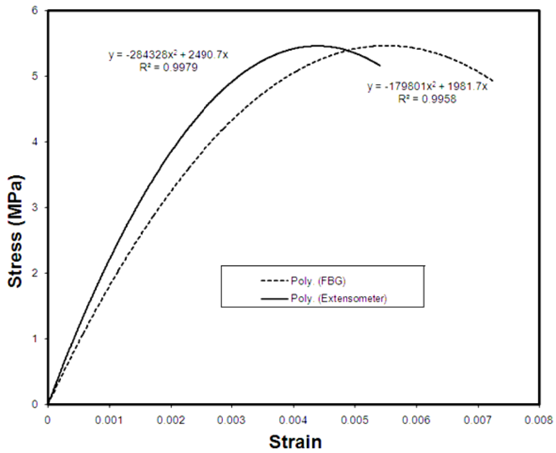

Figure 5. Stress-Strain Curves from FBG Sensor and Extensometer

Figure 5 shows stress-strain curves which are extremely important graphical measures of the material's mechanical properties. In order to calculate the stress response of the specimen, ratio of the load from the loading machine to the area of the specimen is used. It can be seen that the stress-strain response obtained using FBG sensor and clip-on extensometer, are in good agreement. However, the initial tangent modulus (slope of the initial portion of the curve) obtained using FBG sensor is lower compared to that obtained using clip-on extensometer.

Figure 6 shows the graphical representation of the strain along the height of the specimen measured using 3 FBG sensors on a single fiber mounted at different points as discussed earlier. It can be seen from figure 6 that the peak strains recorded in the FBG sensors mounted around the platen affected region of the specimen is lower than that recorded by the FBG sensor mounted at the mid height of the specimen, which is free from platen effect. This also justifies the fact that the strain recorded by the FBG sensor which covers 3 mm from the centre of the specimen is more compared to the clip-on extensometer. The sensors (top and bottom sensors) bonded close to the loading plates experience the platen effect which will negate the longitudinal strain causing lateral strain; Whereas the sensors bonded at the mid height of the specimen (middle sensor) is free from this effect, showing more strain compared to the other two sensors which is evident from figure 6.

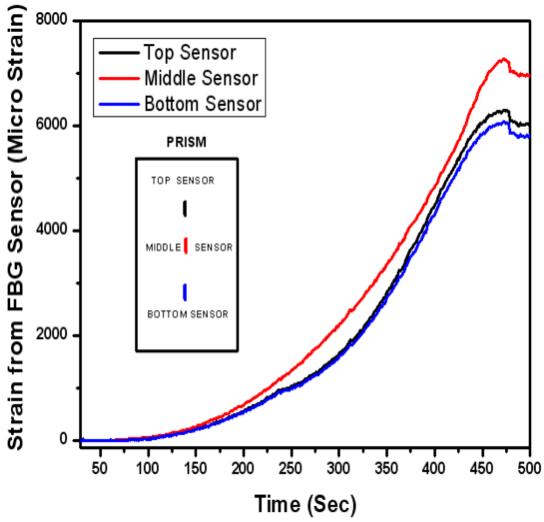

Figure 6. Strain history obtained using series of FBG Sensors

VI. CONCLUSION

The feasibility of strain measurements using an array of FBG sensors along with a commercial clip-on extensometer, for a rammed earth prism, has been investigated. The results obtained indicate that the strains measured by both sensors follow the same trend and also both the sensors register the maximum strain value at the same time. The peak strain recorded by the FBG sensor is more than the value recorded by clip-on extensometer, which can be attributed to the higher gauge length and possible loss of grip at the knife edges of the clip-on extensometer. Further, the strains recorded by FBG sensors mounted near the platen affected region of the specimen is lower than that recorded by the FBG sensors mounted at the mid height of the specimen, which is free from platen effect. It is also noted from the obtained stress-strain curves that the initial tangent modulus obtained using FBG sensor is lower compared to that obtained using clip-on extensometer allowing the data logging till the failure of the specimen.

VII. ACKNOWLEDGEMENTS

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