J Opt (October–December 2015) 44(4):346–352
DOI 10.1007/s12596-015-0308-z

RESEARCH ARTICLE

FIBER Bragg Grating (FBG) sensor for estimation of Crack Mouth Opening Displacement (CMOD) in concrete

K. Samrajyam[1] · R. L. N. Sai Prasad[1] · T. D. Gunneswara Rao[2] · B. Sobha[1]

Received: 24 June 2014 / Accepted: 16 October 2015 / Published online: 2 November 2015

Abstract Crack mouth opening displacement (CMOD) is one of the important parameters for characterizing the fracture properties in concrete. Amongst various optical fiber senors, Fiber Bragg gratings are (FBG) being used for structural health monitoring in the recent times. Very few reports exist in literature for use of CMOD estimation using FBG sensors. We report here, the use of FBG based sensor for the estimation of CMOD in plain concrete beams prepared as per recommendations of Reunion Internationale des Laboratoires et Experts des Materiaux, Systems de Construction et Ouvrages (RILEM) and subjected to three point bend test in a digitally controlled Universal Testing Machine (UTM). The results are compared with Linear Variable Differential Transformer (LVDT) and a good agreement is found. The FBG sensor's resolution is better than LVDT beyond the peak stress.

Keywords Crack mouth opening displacement (CMOD) · Fiber Bragg grating (FBG) · Plain concrete · Three point bend test · Linear variable differential transformer (LVDT)

Introduction

Optical fiber sensors in particular Fiber Bragg Gratings (FBG) have seen an increased acceptance as well as widespread use for structural sensing and monitoring applications in various fields such as civil engineering, aerospace, marine, oil and gas, composites, and smart structures. FBGs, show advantages like immunity to electromagnetic interference and power fluctuation along the optical path, high precision, durability, compact size, ease of multiplexing a large number of sensors along a single fiber, resistance to corrosion, and more therefore have become prominent sensors as they are particularly suitable to perform measurements under harsh environment areas such as in the presence of electrical noise, electromagnetic interference and mechanical vibrations, where conventional sensors cannot readily operate [1, 2].

Concrete is a type of multiphase composite material, which consists of a mixture of cement, coarse and fine aggregates, water, air and chemical admixtures. Many factors such as natural hazards, aging earthquakes, thermal contraction upon drying, shrinkage due to water unbalance, the loads applied can be responsible for cracks in concrete structures. Depending on the extent and location of cracks, the severity of damage to the structure can be different. For instance, a crack width of 0.3 mm is sufficient to result in corrosion. In this connection crack monitoring and detection plays an important role in the structural health assessment and monitoring. The fracture behavior of quasi-brittle materials such as concrete is characterized by a Fracture Process Zone (FPZ) ahead of the main crack where mechanisms such as micro-cracking, crack deflection, aggregate bridging and crack branching, determine the fracture behavior of concrete.[3—4]. The Crack Mouth Opening Displacement (CMOD) is known to be a good indicator of fracture properties that characterize the concrete materials. Several methods do exist for estimation of CMOD in concrete beams subject to three point bend tests especially the ones based on optical fibers [5]. In recent times DIC based studies have also been adopted for estimation of CMOD (COD)/Crack Tip Opening Displacement (CTOD) [6]. Recently Ref. [7] have reported measurement of CTOD in

✉ B. Sobha
rangas2007@gmail.com

1 Department of Physics, National Institute of Technology, Warangal 506004, India

2 Department of Civil Engineering, National Institute of Technology, Warangal, India

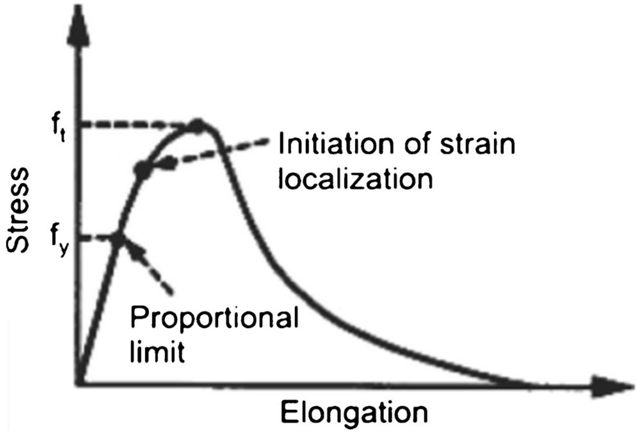

Fig. 1 The load elongation curve of Concrete [8]

concrete beams with compressive strengths ranging from 30 to 150 MPa. Their Ref. [7] measurements were reported forCTODc/Crack Opening Displacement (COD) using FBG (Fiber Bragg Grating) in three point bend tests. In this paper we report in detail the method for obtaining CMOD on M20 grade concrete mix beams (subjected to three point bend testing) using an FBG sensor and Linear Variable Differential Transformer (LVDT). It is not our objective to evaluate CMOD using the models of Linear Elastic fracture Mechanics.

Theoretical background

The fracture process zone in concrete and CMOD, CTOD

The load deformation curve of a quasi brittle material like concrete exhibits a substantial non-linearity before the maximum stress and also exhibits softening of strain beyond the maximum stress point f_t as shown in Fig. 1 below.

When loaded externally a tension zone forms near the crack tip. The fracture process zone plays an important role in influencing the fracture behaviour of concrete. It is the zone where the material undergoes tearing or softening damage. The region of non linearity at the crack tip is largely surrounded by the FPZ. as indicated by 'N" in Fig. 2a. The fracture process zone can be roughly divided into two zones viz., bridging zone and a microcracking zone. The processes at the crack tip fracture include microcracking, crack deflection, crack branching, crack coalescence, and debonding of the aggregate from the matrix These features are shown in Fig. 2b. The processes mentioned above constitute a group of inelastic toughening mechanisms. These mechanisms coexist with a crack during its propagation and thus determine the fracturebehaviour of concrete [3–5, 8]. When the material is tested under closed loop displacement controlled testing condition, the displacement beyond the peak stress results due to major crack opening. This process is accompanied by unloading of the rest of the specimen.

For purposes of computation in fracture mechanics the FPZ is represented by a damage band or a band of crack-closing pressure. The closing pressure in turn depends on Crack Tip Opening Displacement (CTOD) of concrete Critical fracture occurs when the value of the CTOD exceeds a critical value. It is often difficult to determine CTOD as it is linked to the details of constitution of the micro cracked zone. However CTOD is related to the crack mouth opening displacement (CMOD), The interrelationship between CMOD and CTOD is complex mainly due to the considerable extent of the micro cracked zone in front of the crack tip.

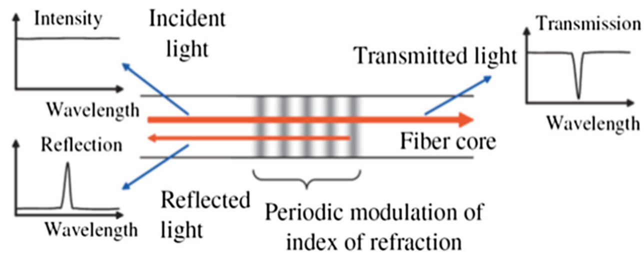

Fig. 3 The working principle of the Fiber Bragg grating (FBG) [9]

Fig. 2 **a** Fracture Process Zone (FPZ) in concrete and **b** Schematic of the constituents of FPZ that can be roughly divided into a bridging zone and a microcracking zone, [3–5, 8]

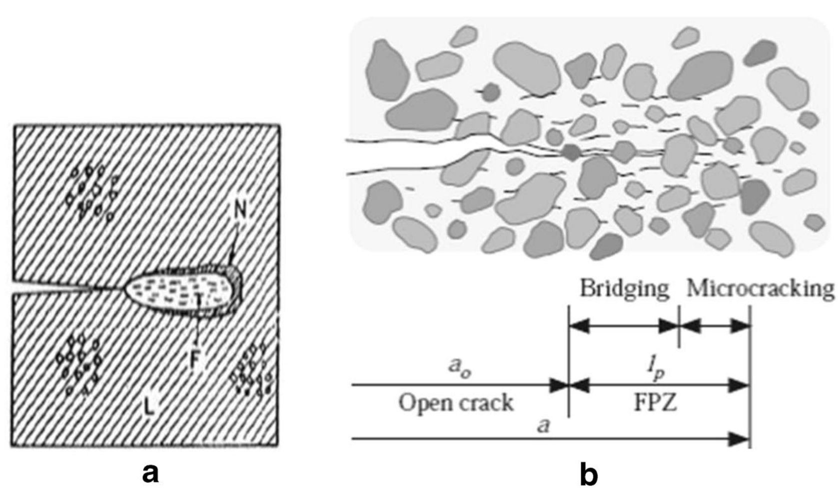

Table 1 Specific gravity of materials used for M20 concrete mix

Property	Cement (IS 12269-1983)	AturalRiver Sand (fine aggregate)	Crushed Coarse aggregate
Specific Gravity	3.16	2.60	2.78

The fiber Bragg grating

The FBG consists of periodic changes of the refractive index that is formed in the core of a single mode optical fiber from exposure to an intense UV interference pattern. The working principle of the FBG is illustrated in Fig. 3 When light from a broad band optical source is coupled into the FBG, this grating structure results in the reflection of light at a specific narrow-band wavelength [9]. The center wavelength of this narrow light spectrum is referred to as Bragg wavelength λ_B. Thus the Bragg grating is transparent for the incident light at wavelengths other than the Bragg wavelength where phase matching of the incident and reflected beams occur. The Bragg condition for the wavelength of reflected light is expressed as

$$\lambda_B = 2neff\Lambda \tag{1}$$

where λ_B is the Bragg wavelength of FBG, n_{eff} is the effective index of the fiber core, and Λ is the grating period. The refractive index of the fiber core is affected by mechanical and thermal changes.

A shift in the Bragg wavelength peak occurs when the grating is exposed to strain and temperature changes. As observed in Eq. (1) above, the reflected wavelength satisfying the Bragg condition is dependent on the effective core refractive index and grating period. This implies that the changes in the strain and temperature will affect the refractive index of the core and the grating period if the fiber is compressed/stretched or exposed to temperature variations. Accordingly the wavelength shift from its central value due to changes in strain and temperature is given by the Eq. (2) below [9, 10]:

Fig. 4 Photograph of the casted specimens

Table 2 Composition of the concrete members and the achieved compressive strength for M20 Concrete

Beam Dimensions (L×B×D) (mms)	Compressive Strength (MPa) of concrete measured	Cement	Fine aggregate	Coarse aggregate	Water/ cement ratio
400 × 100 × 100	28.56	1	1.58	3.17	0.5

$$\Delta\lambda_B = 2\left(\Lambda\frac{\partial n}{\partial l} + n\frac{\partial \Lambda}{\partial l}\right)\Delta l + 2\left(\Lambda\frac{\partial n}{\partial T} + n\frac{\partial \Lambda}{\partial T}\right)\Delta T \tag{2}$$

The first term in the equation above represents the strain effect term while the second represents the temperature effect on the Bragg wavelength shift. 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 It can be observed that this corresponds to a change in the grating spacing and the strain-optic induced change in the refractive index. The linear relation between shift in wavelength and strain can be expressed as

$$\Delta\lambda_B = \lambda_B(1-P_e)\varepsilon_z \tag{3}$$

Where, P_e is the effective strain-optic constant and ε_Z is the applied strain. The effective strain optic coefficient is given by Eq. (4) below as

$$P_e = \frac{n^2}{2}[P_{12}-\upsilon(P_{12}+P_{11})] \tag{4}$$

In the above υ, is the poisson's ratio, p_{11} and p_{12} are components of the strain-optic tensor, n is the refractive index of the core. For a typical optical fiber, the values of p_{11} = 0.113, p_{12} = 0.252, υ = 0.16, and n = 1.0.482 [9]. Using these

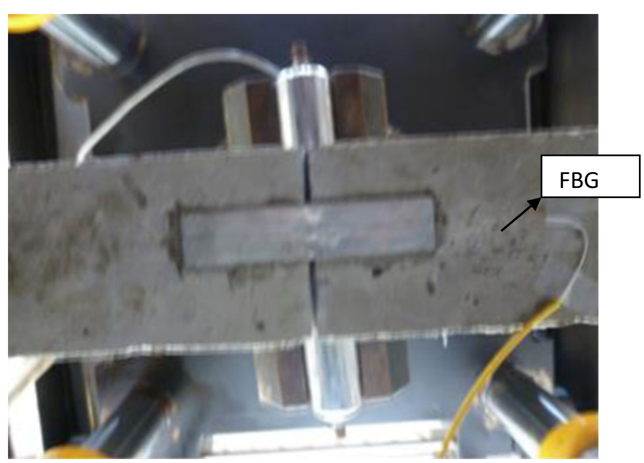

Fig. 5 Photograph showing the FBG mounted across the prenotch

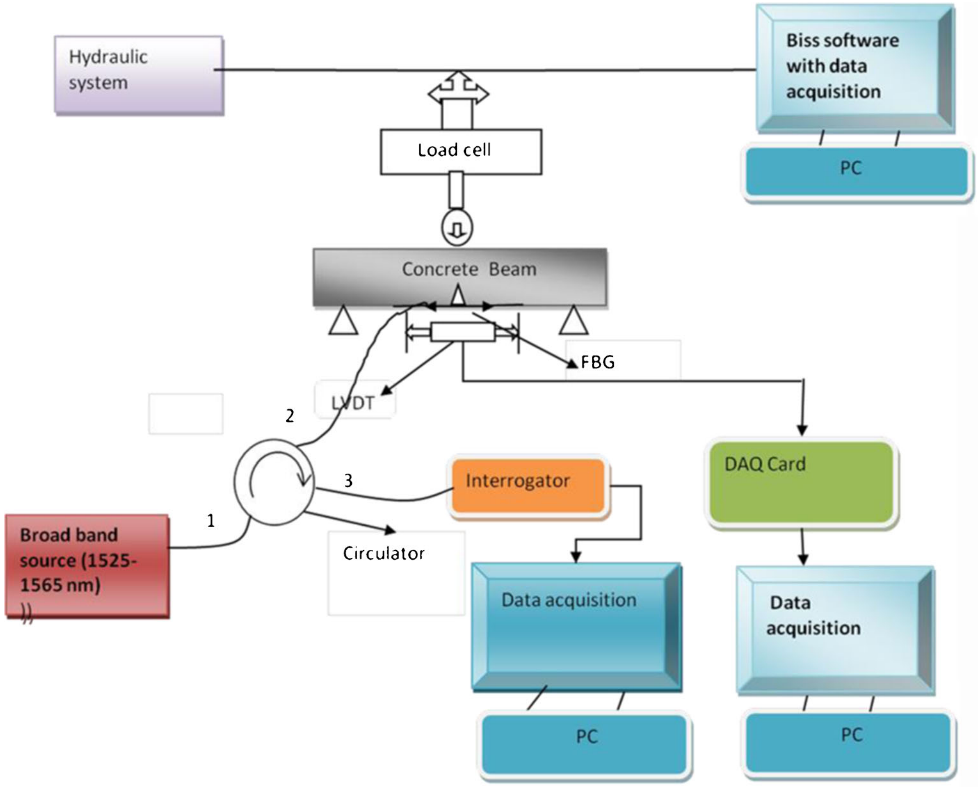

Fig. 6 Schematic of the experimental setup used for determining CMOD

parameters and the above equations, the expected strain sensitivity at 1550 nm is found to be 1.2 pm/με [10–12]. Under an applied load, this wavelength shifts linearly with strain due to change in the period of the grating unit. By measuring the shift in the wavelength, the strain due to the applied stress can be measured accurately Therefore, the strain in the present study is calculated by using the Eq. (3). The CMOD (in mms) can be evaluated from Eq. (5) below,

$$\text{CMOD} = \text{strain*notch width} \tag{5}$$

For the concrete beams used in our experiments a notch width of 4mms was adopted.

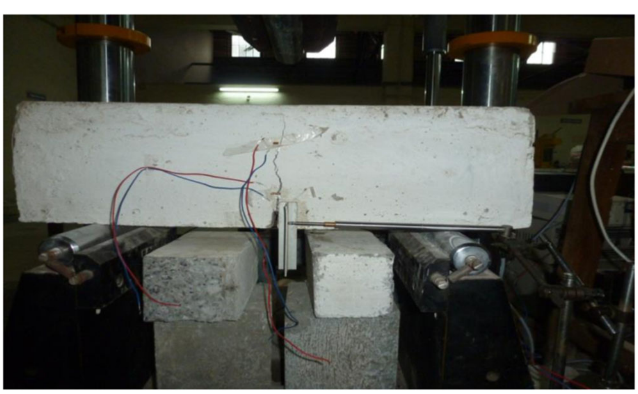

Fig. 7 Photograph showing a LVDT mounted close to the concrete beam at the prenotch

Experimental details

The concrete MixM20

Cement conforming to IS 12269 – 1983 with specific gravity 3.15, Natural river sand with specific gravity 2.60, crushed coarse aggregate of size 20 mm (60 %) and 10 mm size (40 %) with specific gravity 2.78 as fine and coarse aggregate respectively were used in preparing the concrete mix. The details of materials are tabulated in Table 1. M20 grade concrete mix design was used for the casting and the mix ratio adopted was 1:1.58:3.17 for the preparation of concrete samples [13, 14].

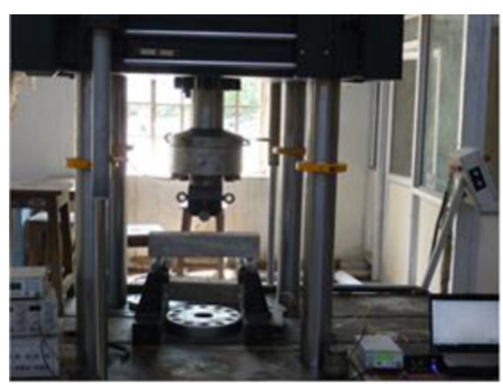

Fig. 8 Photograph of the Experimental Setup for the Three point bend test of Concrete Beam on 1000KN Digital controlled UTM at Materials Laboratory, Civil Engineering Laboratory NIT, Warangal

Fig. 9 Photograph of the data acquisition system in detail

Casting of M20 concrete

Concrete prisms having dimensions of 400 mm x100mm × 100 mm (L x B x D), were cast for the purpose of three point bend tests using a needle vibrator for compaction. The photograph of the casted specimens is shown in Fig. 4 below. The specimens were cured for a period ranging from 28 to 40 days in a curing tank. The measured compressive strength and the mix proportions of the concrete members are given in Table 2. After separation from the curing tank, a notch was made in the specimens using a notch cutter. The notch depth *a* used for prisms and beams of width *b* was taken in the ratio of a/d = 0.2, 0.3 where *d* stands for the depth of the beam.

The measuring system

FBGs fabricated by phase mask technique with central wavelength of 1551.732 nm (spacing of 10 mm, length of 3 mm) and provided by Indian Institute of Technology, Chennai have been used in the present investigation. The surface of the concrete beam was scrubbed with a grit size paper no. 900

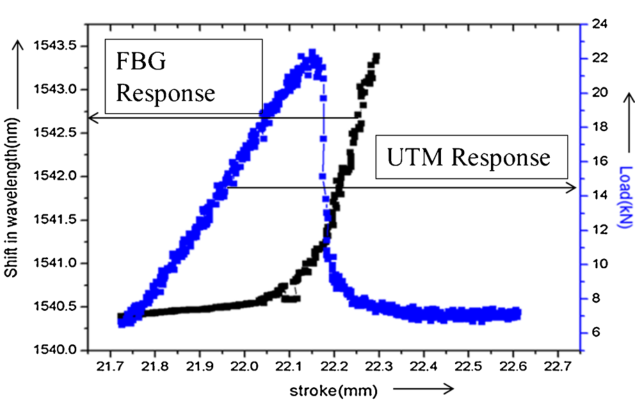

Fig. 10 Experimental plot showing the increase of Bragg wavelength shift (mm)/Load (kN) with stroke (mm)

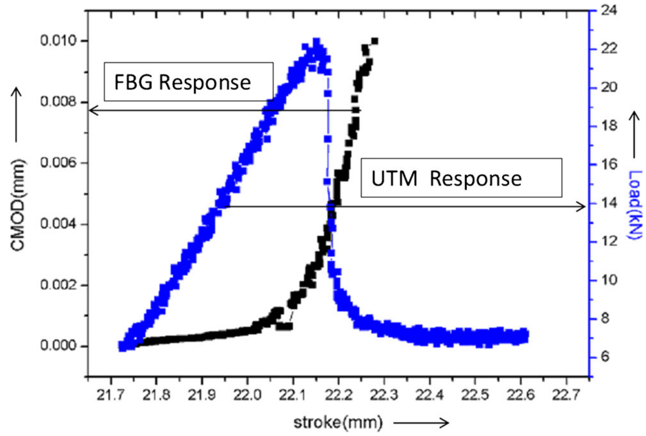

Fig. 11 The plot of stroke (mm) vs Load (kN)/CMOD (mm) for first FBG (FBG1)

and then a thin steel plate having thickness 0.5 mm was attached using cyanoacrylate adhesive across the notch of the concrete beam. The FBG is then glued to the steel plate exactly at the place of the notch as shown in Fig. 3 below. The mounting is carried out carefully to ensure that the center point of the FBG coincides with the center point of the prenotch of the concrete beam (of notch width 4 mm) (Fig. 5).

The schematic of the experimental arrangement for the determination of CMOD using FBG as sensor is shown in Fig. 6. The Port 1 of the three port fiber optic circulator (ThorLabs bearing model No 6015–3-FC) has been used to couple the light from the broad band light source to the FBG which is connected to the Port 2. The reflected Bragg wavelength peak from the FBG is routed to the Interrogator (JPFBG-3000) via Port 3of the circulator. The signal from the interrogator is finally fed to the data acquisition card in the lap-top. A Linear Variabale Differential Transformer (LVDT) is also fitted to the concrete beam close to the prenotch for recording the CMOD data simultaeneously. This is illustrated in the photograph of Fig. 7.

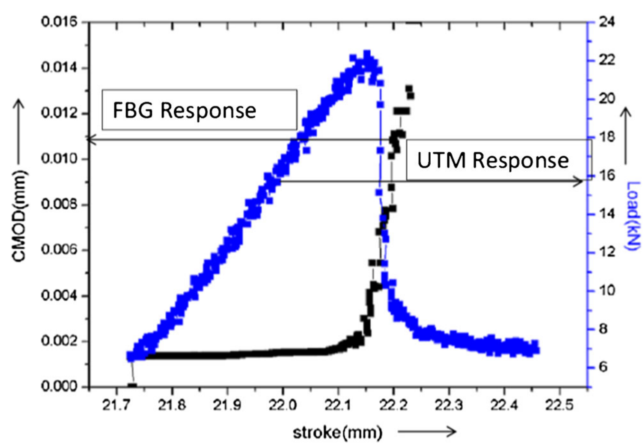

Fig. 12 The plot of stroke (mm) vs Load (kN)/CMOD (mm) with second FBG (FBG 2)

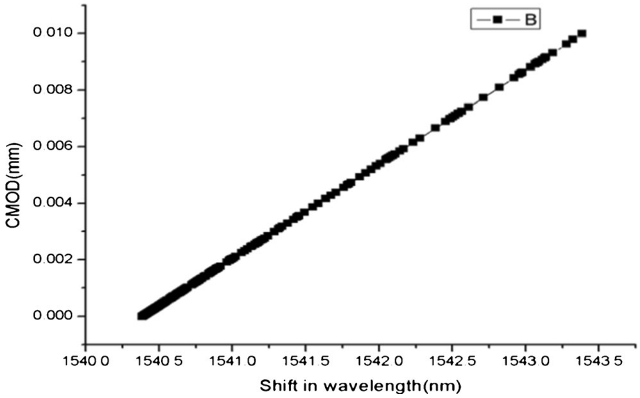

Fig. 13 Plot showing the Bragg wavelength (mm) shift vs CMOD (mm) for FBG1

Experimentation and results

The photograph of the experimental setup for the three point bend tests carried out using a 1000 kN digitally controlled Universal Testing Machine (UTM) in the Materials Laboratory, Department of Civil Engineering, NIT, Warangal. is shown un Fig. 8. The details of the data acquisition system are presented in the photogragh of Fig. 9.

A slow rate of loading 0.005 mm/s was applied to the concrete beams in all the experimental runs. The response of the FBG sensor was obtained in terms of wavelength shift with load using the data acquisition system. Initially there is no observable shift of wavelength of FBG. However, when the applied load approaches the point of peak stress, the rate of shift in the Bragg wavelength is seen to increase and continues beyond the point of peak stress.

This is attributed to the initiation of cracking in the concrete beam, at the peak stress followed by crack propagation. The applied stress on the FBG in the direction of the fiber axis results in the extension of its physical dimensions and in the change of effective period of the FBG viz.Λ. The effective period of the grating Λ increases with crack initiation and propagation beyond peak stress point. The shift in the Bragg

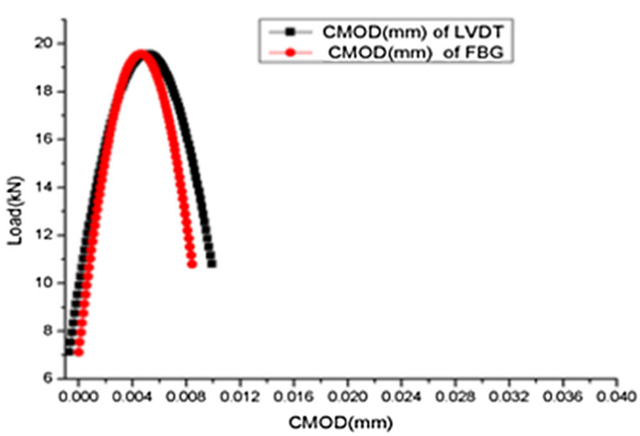

Fig. 14 The comparison plot of the data obtained with FBG1 sensor and LVDT

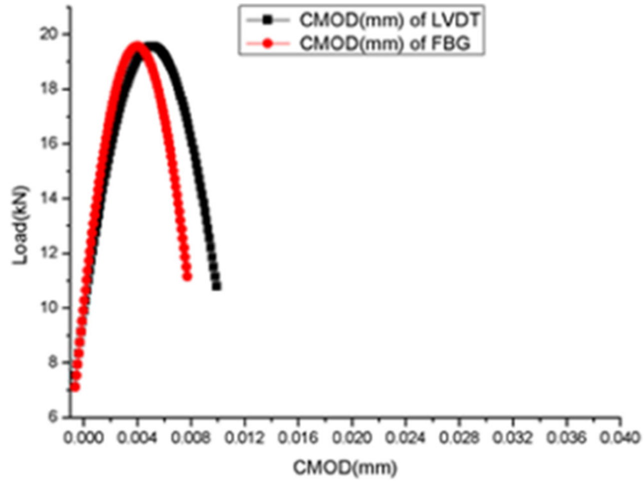

Fig. 15 The comparison plot of the data obtained with FBG2 sensor and LVDT

wavelength increases till the unloading point. These features can be clearly understood from the experimental data plot of Fig. 10.

From the knowledge of the acquired wavelength shift after the peak stressthe corresponding strain developed was calculated (in to micro strain) by using Eq. (3). The variation of cmod (mms) estimatedfrom Eq. (5) and plotted as a function of stroke (mm) with increasing load (in kN) is shown in Fig. 11. From this plot it can be inferred that the crack mouth opening displacement (CMOD) increases rather slowly till the peak stress. Beyond the peak stress the value of CMOD increases at a faster rate due to the opening of the crack in the concrete beam at the prenotch region. The nature of the results was repeated with all FBG sensors tested. This is illustrated in the plot shown in Fig. 12 for another FBG sensor (FBG2).

The nature of linear variation between the shift in the Bragg wavelength and the estimated crack mouth opening displacement (CMOD) is plotted in Fig. 13, below. From Eq. (1) it is

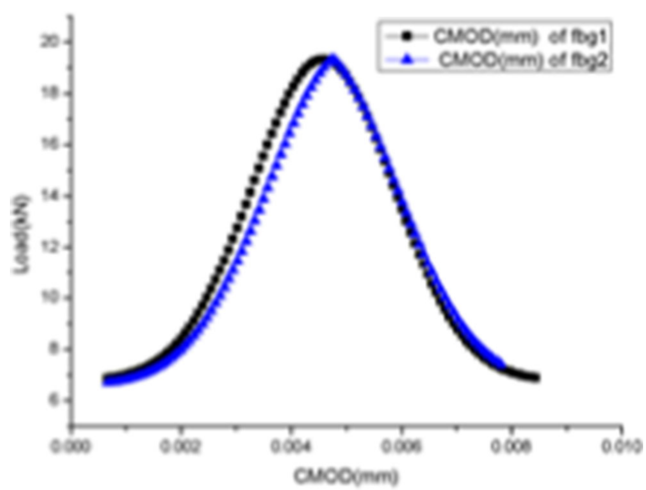

Fig. 16 Plot showing the repeatability of the data obtained using different FBGs

observed that the Bragg wavelength is directly related to the effective grating periodΛ. As the load is applied starting from the minimum value there is an increase in the strain experienced by the FBG. This leads to theincrease of effective grating period Λ and hence the increase in Bragg wavelength shift. The strain thus measured is used to estimate the CMOD from Eq. (5). Thus this plot serves as a validity for the theory outlined in previous sections.

The CMOD obtained from the FBG sensor was also compared with the CMOD acquired by using an LVDT which was fitted to the concrete beam close to the prenotch. The agreement obtained is seen in Figs 14 and 15 for the two FBGs respectively. The FBG sensor exhibits better sensitivity than the LVDT on strain softening side beyond the peak stress (refer Fig. 1).

The repeatability of the measured CMOD has also been found to be very good even when the FBG is changed,. This is shown in Fig. 16. This was always true with all FBGs tested. Furthur the average value of CMOD measured at peak stress is 0.005 mm.

Conclusions

The method to obtain the value of crack mouth opening displacement (CMOD) in case of M20 grade concrete specimens under three point bend test making use of Fiber Bragg Gratings (FBG) as sensor is presented. The results are compared with conventional method of making use of LVDT and are found in good agreement. It was also found that FBG sensor provide greater sensitivity and good reliability.

Acknowledgments The authors gratefully acknowledge Department of Electrical Engineering, Indian Institute of Technology, Chennai, India for having provided the Fiber Brag Gratings (FBG). The authors also like to acknowledge the cooperation and help offered by the Photonics Group, Department of Physics, NIT, Warangal in making the measurement.

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