FIBER OPTIC SENSORS FOR HEALTH MONITORING OF CIVIL ENGINEERING STRUCTURES

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ABSTRACT

Civil engineering structures are generally the most luxurious reserves/assets in any country and these structures are deteriorating at distressing rate. The increased effect of aging, overloading and extreme environmental conditions on the civil infrastructure has necessitated the requirement of advanced structural health monitoring and damage detection tools in the current era. Structural Health Monitoring (SHM) proves to be promising in determining the condition and predicting the performance of the structure during its life cycle.

This growing interest is developing appropriate sensors and techniques for structural health monitoring in the field of civil engineering that would be highly reliable and effective. Even though many sensors and measurement techniques are available, fiber optic sensing technique has been identified as the most appropriate for health monitoring of civil engineering structures. This paper aims to investigate the feasibility of adopting smart sensors, particularly Fiber Bragg grating sensors, in the application of automated, real-time and online structural health monitoring systems, which can provide an alternative to conventional monitoring systems, such as electrical resistant strain gages etc.

The advantages of FBG over conventional sensors such as high sensitivity, immunity to electromagnetic interference, ease of multiplexing, long-term stability of their strain readings, simple monitoring architecture and durability. Performance of Fiber Bragg Grating sensors are evaluated by conducting experimental studies by testing under compression, tension and Bending loading in laboratory specimens of steel and concrete members. Experimental results are compared with both theoretical and numerical analysis (ABAQUS).

Keywords: Structural Health Monitoring, Fiber Bragg Grating Sensor, Strain Measurement, Electrical Resistant Strain Gage, Concrete and Steel Elements.

I INTRODUCTION

1.0 GENERAL

The research of Structural Health Monitoring (SHM) and damage detection has recently become an area of interest for a large number of academic and commercial laboratories. This kind of technique allows systems and structures to monitor their own structural integrity while in operation and throughout their life, and are useful not only to improve reliability but also to reduce maintenance and inspection cost of systems and structures. It is a system devised to allow the testing for structural damage without interfering directly with the structure itself. Various sensor systems have been used in SHM like Extensometer, Accelerometer, Pressure transducers, and Temperature sensors. But each of these is attributed to certain drawbacks, most of them highly susceptible to ambient noise frequency, inaccessibility to remote areas, fragile nature, or is equipped with only manual and visual readouts. The large size and complex nature of the civil structural system render the conventional visual inspection very tedious, expensive, and sometimes unreliable. The aim of this paper is to study the feasibility of using Fiber optic sensors for load and health monitoring of steel and concrete structures.

Conventional instrumentation techniques for monitoring the performance of existing and new structures are mainly limited to the application of electric and magnetic principles using electrical resistance strain gages, linear differential transducers etc. while these can serve well for short term measurements ,they have major limitations in evaluating long term behaviour of structural members ,especially in concrete structural systems. The main problems associated with these conventional instrumentation techniques, stem from their response to ambient electrical noise and potential for degradation with age. Optical fiber sensors are adaptive and self-calibrating and have found use as strain sensors for monitoring civil engineering structures. Over the past few decades, optical fiber sensors have seen an increased acceptance as well as a wide spread use for structural sensing and monitoring applications in civil engineering, aerospace, marine, oil & gas, composites and smart structures. Recent developments in fiber sensor systems have the potential to offer advantages that essentially eliminate conventional sensors deficiencies and permit long term reliable quantitative monitoring. the advantages of fiber optic sensors over conventional sensors are small physical size and weight, flexibility, immunity to EMI, resistance to corrosion, high resolution , large band width of signal, practically no noise and high sensitivity .

Fiber optic sensors are designed to monitor a number of physical parameters (measurands) including temperature, pressure, strain, displacement, vibration, rotation, PH values, chemical concentration of materials and electrical current. In India, efforts made in this direction are still in the infancy, though some R&D groups are working in the area of fiber optic sensor for different application. The type and characteristics of fiber optic system is primarily a function of intended application, and the environment in which it will function. Fiber optic sensor systems are commercially available and they are reported to be useful for application in civil engineering field. This paper brings out the potential and current status of technology of fiber optic sensor for civil engineering application.

II FIBER OPTIC SENSOR

Fiber optic sensors can be classified under different categories. Localized, distributed and multiplexed sensors are based on sensing methods [2]. Intensity, interferometric, polarimetric and spectrometric based sensorsis classified according to the transduction mechanism. Fiber optic sensors are often categorized as being either extrinsic or intrinsic. Extrinsic or Hybrid fiber optic sensors have an optic fiber which carries a light beam to and from a “light modulator”, which in response to an environment effect modulates the light beam. Intrinsic fiber optic sensors measure the modulation of light due to an environmental effect, within the fiber.

2.1 Fiber Bragg Grating

Fiber Bragg Grating (FBG) sensors are the most promising optical fiber sensors based on the state-of-the-art technologies. FBGs have initially begun to be used extensively in the telecommunication industry for dense wavelength division de-multiplexing, laser stabilization and erbium amplifier gain flattening at 1550nm wavelength range. In addition, the characteristics that an FBG reflects a specific wavelength that shifts slightly depending on the strain applied are ideal for mechanical sensing.

2.2 Principle of Fiber Bragg Grating Sensors

Hill and coworkers first observed fiber photosensitivity in germanium-doped silica fiber in 1978 [3]. Since then and entire class of in-fiber components, called the Fiber Bragg Grating (FBG), have been introduced. Fiber Bragg Gratings are periodic structures that are imprinted directly into the core of glass optical fiber by powerful ultraviolet radiation. Such structure consists of a periodically varying refractive index over typically several millimeters of the fiber core. The specific characteristic of FBG for sensing applications is that their periodicity causes them to act as wavelength sensitive reflectors.

During imprinting process, the intensity of the ultraviolet illumination is made to occur in a periodic fashion along the fiber core. At a sufficiently high power level, local defects are created within the core, which then give rise to a periodic change in the local refractive index. Fig.1. shows the refractive index profile on FBG. This change in refractive index (RI) created are permanent and sensitive to a number of physical parameters, such as pressure, temperature, strain and vibration. Thus by monitoring the resultant changes in reflected wavelength FBG can be used of sensing applications to measure various physical quantities.

In a single mode optical fiber, light is guided along the axis of the core in the fundamental mode. When light passes through an FBG, Fresnel reflection takes place due to the variation in refractive index. Fiber optic Bragg grating sensor response arises from two sources (Fig.1), namely the induced change in pitch length (Λ) of the grating and the p_e. The wavelength of the reflected spectrum band is defined by the Bragg condition

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

Where, n_{eff}= effective core refractive index

Λ = induced change in pitch length/ grating period

λ_B = Bragg wavelength

When an FBG is strained, the Bragg wavelength (λ_B) changes due to change in grating spacing (Λ) and the change in refractive index (n_{eff}). Thus the Bragg wavelength changes due to applied strain. The theoretical relationship between change in wavelength and strain has been established as perturbation of the effective core refractive index (n_{eff}).

$$\frac{\Delta\lambda_B}{\lambda_B} = (1 - p_e)\varepsilon \qquad (2)$$

Where, $\Delta\lambda_B$ = change in Bragg wavelength (λ-λ_B)

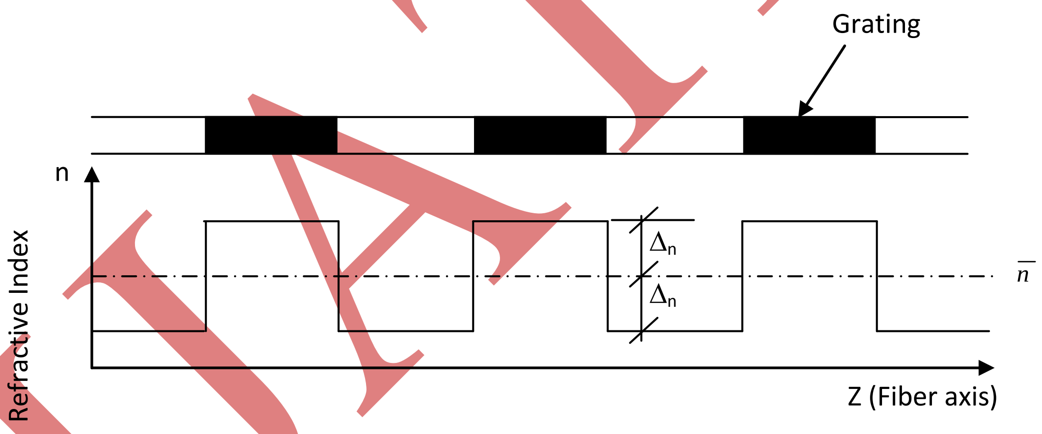
λ_B = initial Bragg wave length

λ= Bragg length after straining/loading

p_e = effective photo elastic constant for the fiber (~0.22)

From Eq.(2) ε= strain

$$\varepsilon = \frac{\Delta\lambda_B / \lambda_B}{(1 - p_e)} \qquad (3)$$



Where, Δ_n = depth of refractive index modulation

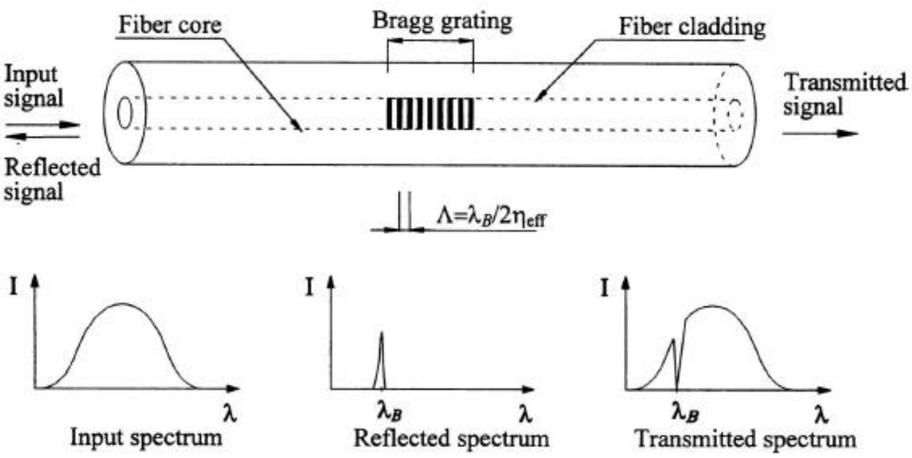
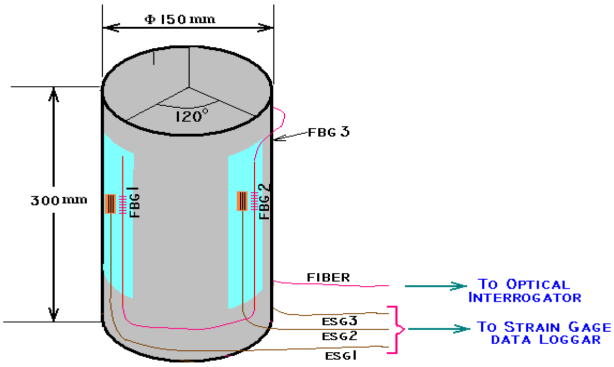


Fig.1 Typical refractive index profile on FBG

III EXPERIMENTAL INVESTIGATION

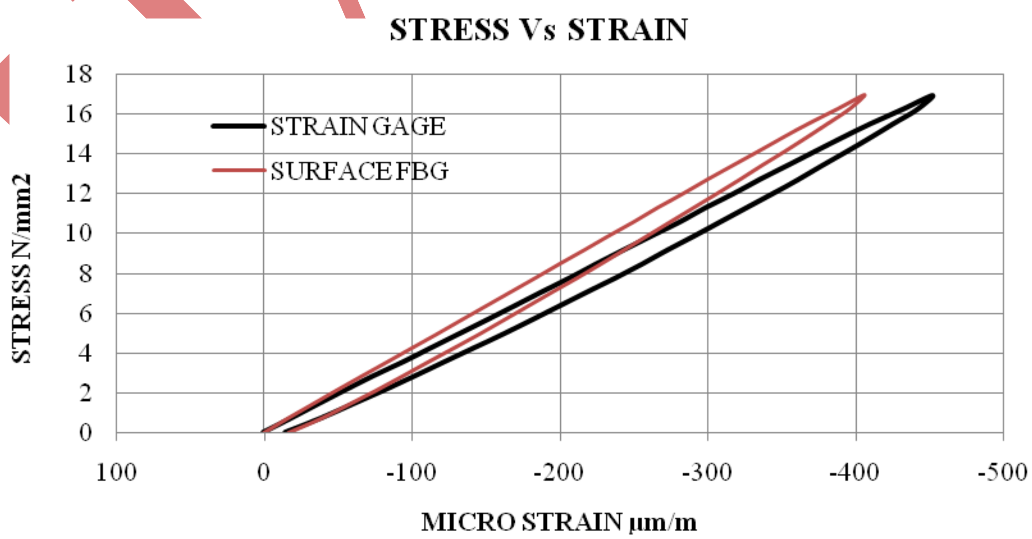
3.1 Pure Compression

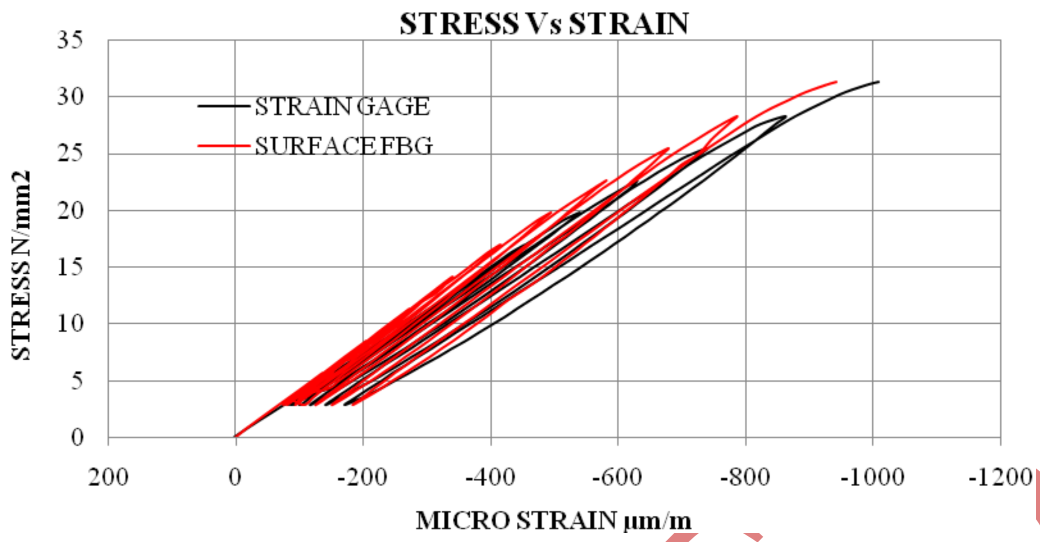


Experiments are conducted to assess the behaviour of fiber optic sensors, when fixed to surfaces and also embedded into the concrete. In this experiment a FBG sensor with three gratings of 10 mm (FBG1, FBG2 and FBG3), interspacing of 300 mm, nominal wavelengths of 1540.49 nm, 1539.722nm and 1539.585 nm respectively were bonded on the surface of the concrete cylinder as shown in Fig. A fiber optic strain sensor of 10mm size was fixed on the 130 mm of fiber optic packaging and it was embedded into the standard concrete cylinder of 150mm dia and 300mm long cylinder. Three conventional Electrical resistance strain gages of size 60 mm (SG1, SG2 and SG3) was bonded near each FBG grating on surface to compare the responses from FBG sensor.

The instrumented concrete cylinder was tested under compression in UTM. The cylinder was subjected to a compressive load and the load was applied in steps of 0 KN to 300 KN for static loading. For each step loading output from fiber optic sensor and conventional strain gage were recorded. Few cyclic load trials were conducted in steps of 0 KN to 553 KN (table). The responses from FBG sensors and electrical resistance strain gages were recorded. The average value of strain measured from three FBG sensors and electrical resistance strain gages were compared. To discover the consistency of measurement the test was conducted twice. Fig. shows the typical load Vs average strain measured from FBG sensor and electrical resistance stain gage for concrete cylinder under compression with 4% variation.

STATIC LOAD & CYCLIC LOAD TEST RESULTS FOR COMPRESSION





3.2 Pure Tension

In order to weigh up the deeds of FBG sensors, experiments were conducted on standard uniaxial tension specimens. For this study, two mild steel tension specimens were prepared as per ASTM E 8M-04 for conducting tension test. For this experiment, one mild steel tensile specimen was instrumented with surface mounted Fiber Bragg Grating sensor of 10mm and electrical resistance strain gage of 5mm, kept one on each surface of the specimen.

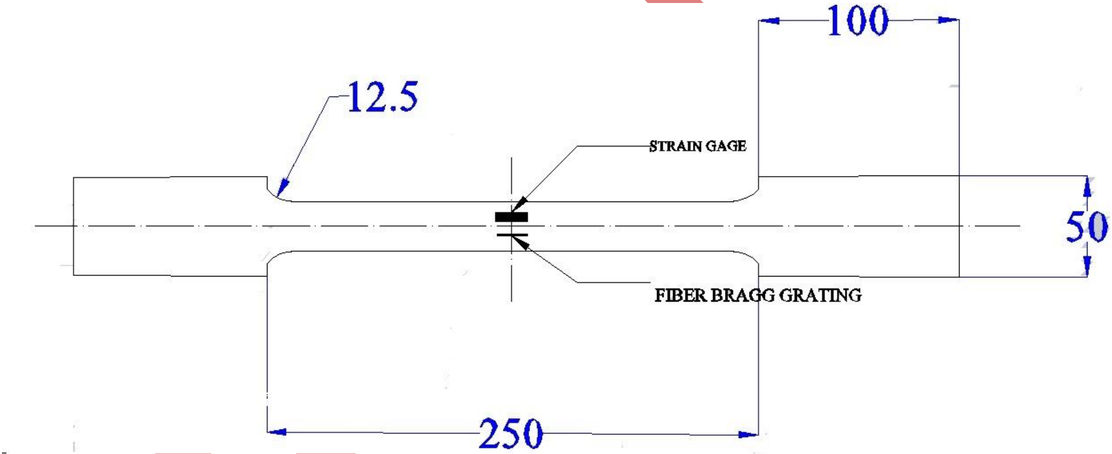
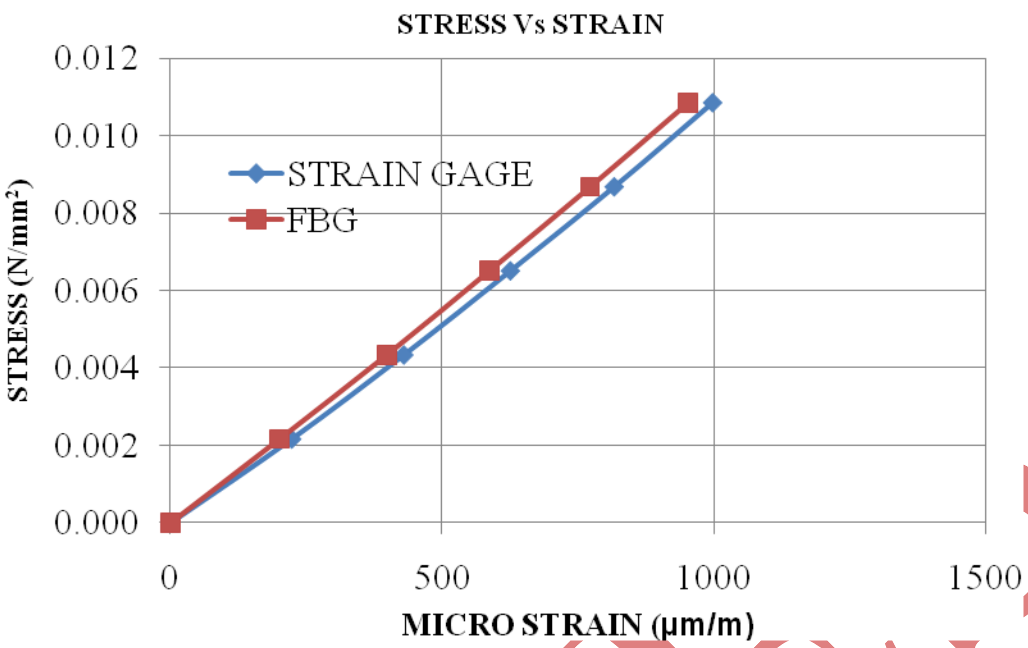


Fig 1 Steel plate as per ASTM E 8M-04

The specimen was subjected to axial tension in an UTM. The load was developed in steps of 200kg, up to a maximum of 1000kg and strain responses from fiber optic sensor and conventional strain gages were recorded. Three cycles of loading and unloading were carried out (table). Load Vs strain graph were prepared to evaluate the comparative performance of Fiber Optic Sensors. The concurrence of values between the Fiber Bragg Grating sensor and conventional strain gage is fairly good.



3.3 Pure Bending

In order to judge the behavior of fiber optic sensors under flexural loading, a two-point bending load test was conducted. One mild steel I-beam was prepared for bending test. The steel I-beam specimen was instrumented with one surface mounted FBG fiber optic sensor (kept at top flange) and one conventional electrical resistance strain gages, one each kept at top and bottom flanges, adjacent to fiber optic sensor

The test set-up was designed to create a constant bending zone at the instrumented locations of the I-beam. The beam was subjected to two-point bending load and the load was applied in steps. Strain responses from fiber optic sensors and conventional strain gages were recorded for all loading steps. The I-beam specimen was then kept upside down and bending load was again applied to the beam. The above technique helped to collect tensile as well as compressive strain responses of fiber optic strain sensor. Table shows the comparison of fiber optic and electrical resistance strain gage for steel beam under bending test. Load Vs strain plotswere prepared to evaluate the sensitivity of fiber optic strain sensor

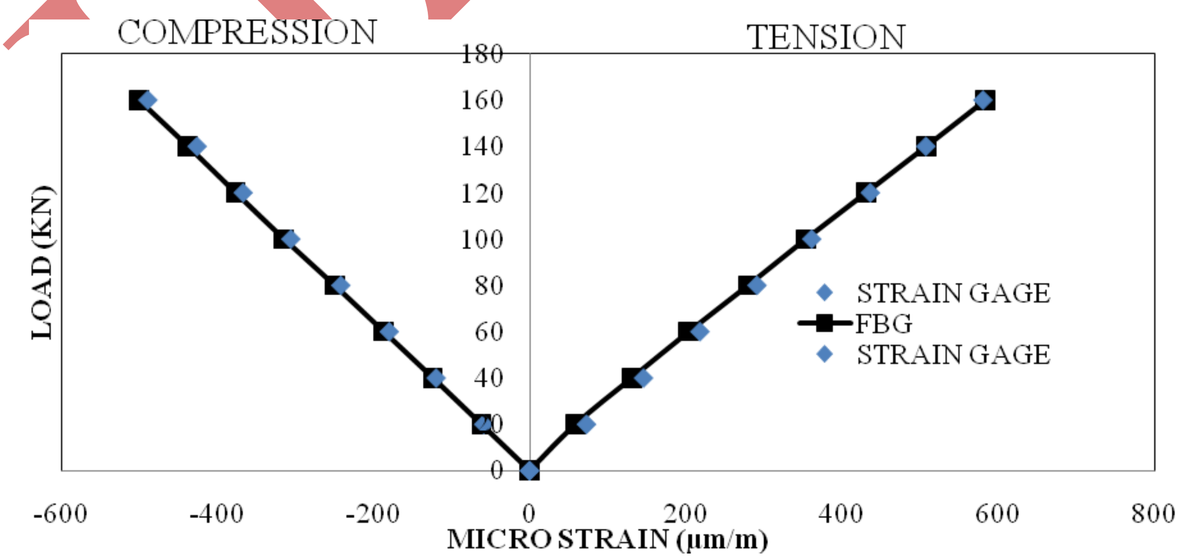
TABLE FOR BENDING TENSION

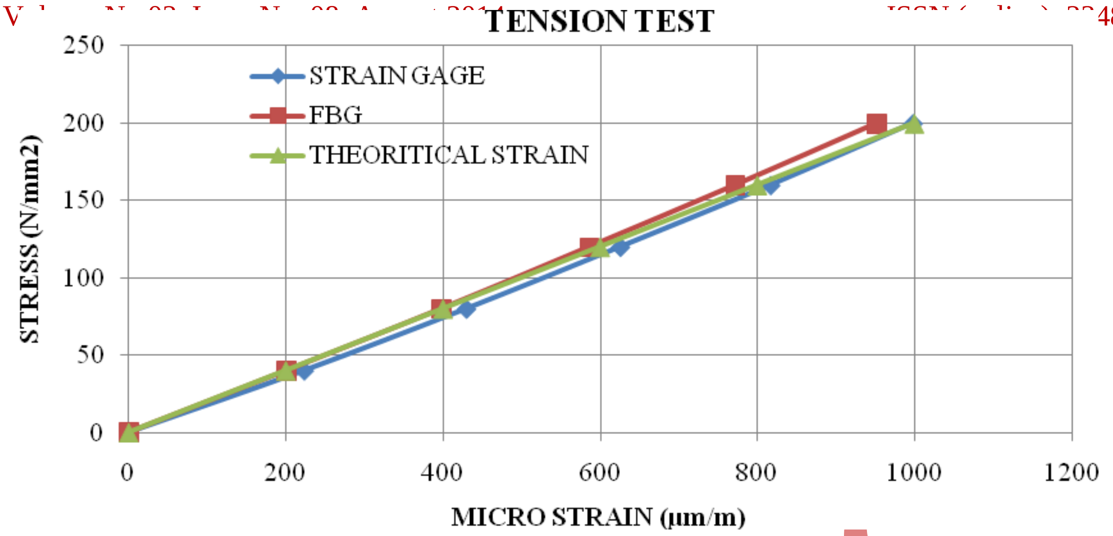
	Micro-strain					
Load	Trial 1		Trial 2		Trial 3	
	SG	FBG	SG	FBG	SG	FBG
0	0	0	0	0	0	0
20	73	59	76	61	75	61
40	146	131	146	133	147	133
60	218	204	217	208	217	208
80	291	280	290	283	291	283
100	361	354	364	358	362	357
120	436	431	436	434	437	434

140	507	508	509	509	511	512
160	580	584	584	587	585	587
140	499	504	504	509	505	510
120	422	424	425	427	426	429
100	343	343	349	348	349	349
80	267	265	270	268	271	269
60	196	191	196	191	197	191
40	129	121	129	121	130	121
20	65	56	65	55	67	56
0	-3	-1	0	0	0	-1

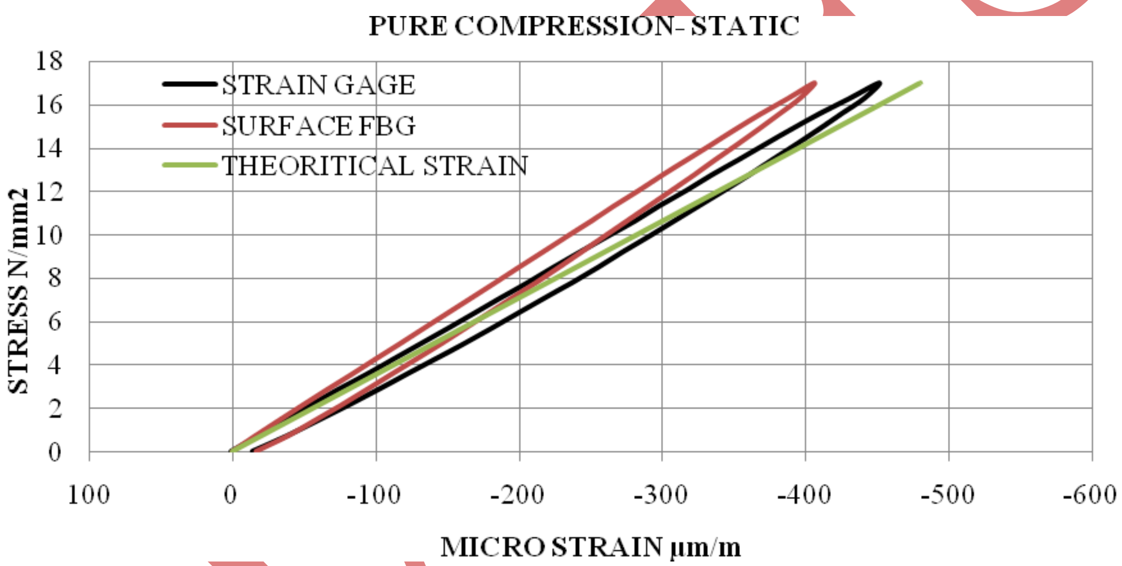
TABLE FOR BENDING COMPRESSION

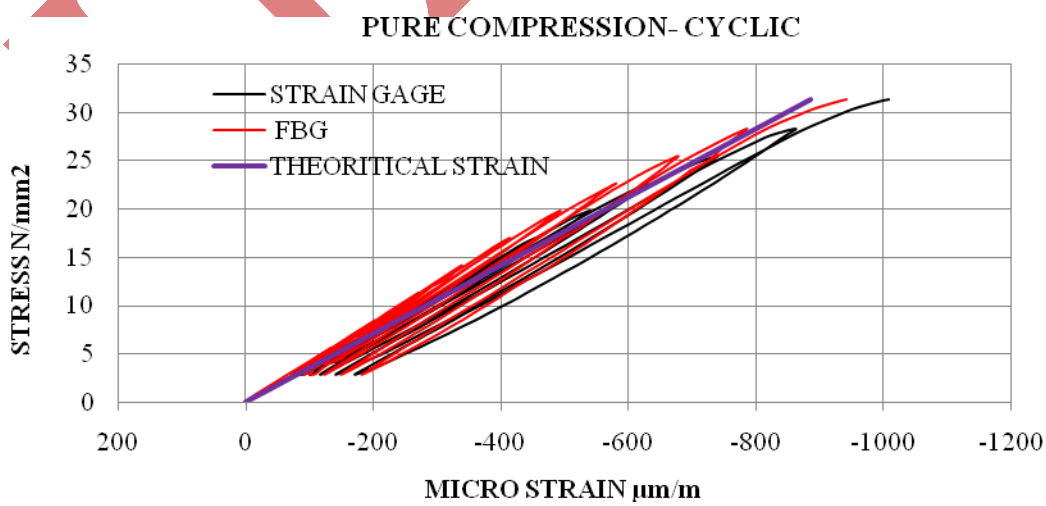
	Micro-strain					
Load in	Trial 1		Trial 2		Trial 3	
	SG	FBG	SG	FBG	SG	FBG
0	0	0	0	0	0	0
20	-59	-62	-60	-67	-61	-69
40	-120	-124	-123	-130	-125	-134
60	-180	-187	-186	-194	-187	-197
80	-242	-250	-247	-256	-248	-257
100	-306	-315	-307	-317	-307	-318
120	-367	-377	-368	-377	-367	-378
140	-426	-438	-428	-437	-427	-437
160	-489	-501	-489	-498	-488	-499
140	-428	-444	-427	-441	-428	-442
120	-368	-384	-368	-382	-368	-384
100	-307	-323	-309	-323	-308	-323
80	-242	-259	-246	-260	-245	-261
60	-182	-198	-184	-198	-185	-199
40	-122	-136	-122	-134	-123	-136
20	-58	-72	-60	-71	-61	-73
0	0	-3	0	0	0	-2

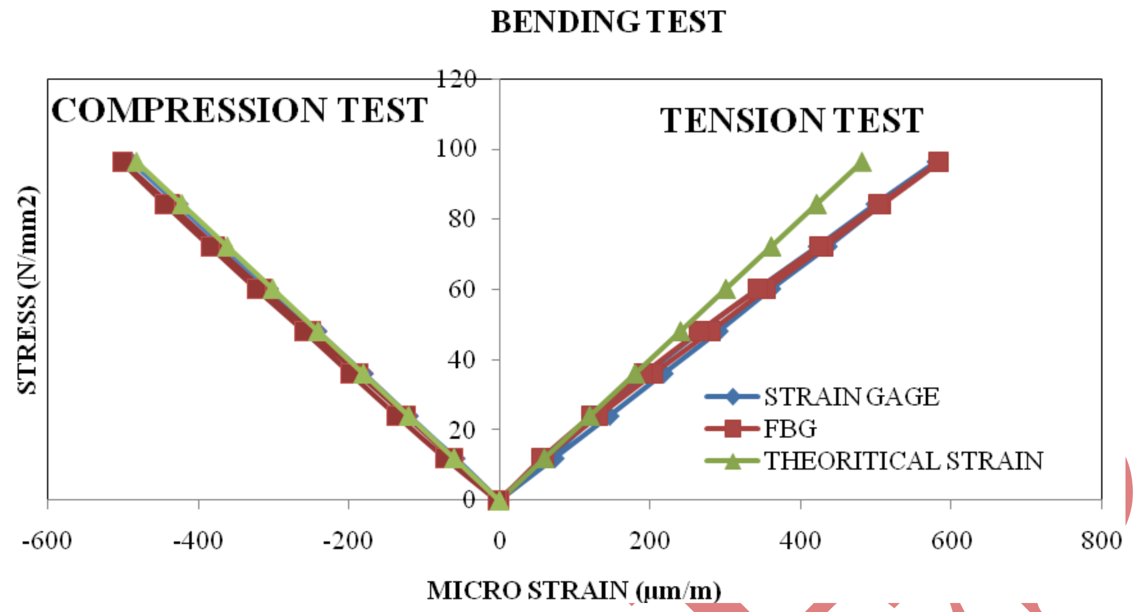




THEORITICAL STRAIN







IV NUMERICAL STUDY

A numerical study was carried out using ABAQUS finite element software in order to validate the experimental results. In this analysis concrete cylinder were modeled as 3D – Deformable elements and the concrete cylinder has been modeled as HOMOGENEOUS SOLID section.The parts were created as independent instances.After that the load was applied in terms of pressure in increments at the top of the cylinder. And pinned boundary condition is applied at the bottom of the cylinder {fig}. The above procedure is followed to create steel plate tensile specimen. After that the load was applied in terms of pressure in increments at the bottom of the steel plate. And pinned boundary condition is applied at the top of the plate. {fig}.The bending specimen was created and the two point concentrated load was applied at the top of the I-beam. The pinned boundary condition was applied at bottom of the beam to carry out bending compression analysis. In bending tension analysis the load was applied at bottom and the pinned boundary condition was applied at the top of the beam.

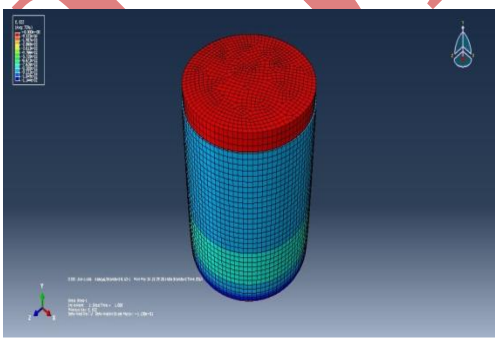


Fig-4 Deformed Compression Specimen

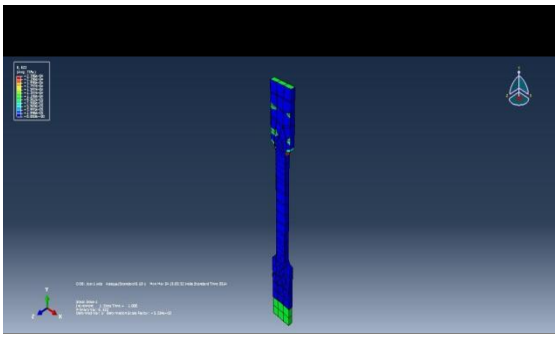


fig-5. Deformed Tension Specimen

Meshing was done individually for both the elements [fig]. After this job model was submitted for analysis. Results were taken from post processing. Strain along the length of the web was obtained from the results in the post processing mode. The results obtained from numerical studies were compared with the results from experimental studies.

V SUMMARY

Experimental studies were carried out to evaluate the performance of FBG sensors under static and dynamic loads and evaluated their suitability for short-term loading conditions. Performance of the fiber optic sensor mounted on steel specimen under axial tension, concrete cylinder under axial compression and bending tension and compression of the steel beam were carried out.

A concrete cylinder of 150x300 mm has been cast with this package sensor at the centre of cylinder and 3 FBG sensors were mounted at the surface of the cylinder with electrical resistant strain gage was compared. The cylinder was tested for compressive load. The response from FBG sensors and surface mounted ERS are compared well.

A mild steel tension specimens were prepared as per ASTM E 8M-04 for conducting tension test. Three cycles of loading and unloading were carried out. Load Vs strain and stress Vs strain graph were prepared to evaluate the comparative performance of FBG with ERS. The concurrence of values between the Fiber Bragg Grating sensor and conventional strain gage is fairly good.

One mild steel I-beam was prepared for bending test. The beam was subjected to two-point bending load and the load was applied in steps. Strain responses from fiber optic sensors and conventional strain gages were recorded for all loading steps. Load Vs strain and stress Vs strain plots were prepared to evaluate the sensitivity of fiber optic strain sensor.

Relative performance of FBG sensor with conventional electrical resistant strain gages was carried out and the strain responses between the two types of sensors are found to be matching well. The theoretical studiesof strain measurement in the specimens are also compared with the two kinds of sensors.

The numerical study was carried out using finite element software ABAQUS. And strain responses from experimental results are also compared with numerical results. The two types of results are found to be good.

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REFERENCES

1) P.Cappa, G.De Rita, K.G McConnell, L.W. Zachary, "Using Strain Gages To Measure Both Strain & Temperature", Experimental Mechanics –vol - 32/1992
2) Raymond, M.Measures. (2001). "Structural Monitoring with Fiber Optic Technology", Academic Press, California.
3) Parivallal.S; et.al, "Fiber Optic Sensors for Health Monitoring of Civil engineering", Journal of Structural Engineering vol-31/2004.

4) Hong-Nan Li, Dong-sheng Li, Gang-Bing song, "Recent Application Of Fiber Optic Sensor To Health Monitoring In Civil Engineering, Engineering Structures –Vol-26/2004.
5) K.Kesavan, K.Ravisankar, S.Parivallal, "Application Of Fiber Optic Sensors For Structural Health Monitoring , Smart Structures And Systems – Vol– 1/2005
6) Deng;Lu, Application Of Fiber Optic Sensors, Structural Engineering & Mechanics – Vol – 25/2007
7) Rossi, p. And LeMaou. F., "New Method for Detecting Cracks in Concrete using Fiber Optics", RILEM Material and Structures, Vol.22, 1989
8) Ting-Hua Yi, Hong-Nan Li and Xiang Wang "Smart structures and systems" – vol– 12/2013
9) Maaskant, R., Alavie, T., Measures, R.M., Tadors, G., Rizkalla, S.H. and GuhaThakurta, A., "Fiber Optic Bragg Grating Sensors for Bridge Monitoring", Cement & Concrete Composites", vol.19, No.1, 1997
10) Tennyson, R. C., Mufti, A. A. And Neale, K. (2001). "Fiber Optic Sensing for Civil Infrastructure", Proceedings of SIPE on "Health Monitoring and Management of Civil Infrastructure Systems", Newport Beach, USA, Vol.4337, pp 203-211.
11) Moreman, W., Wacle, W. De. Coppens, C., Taerwe, L., Degrieck, J., Baets, R. and Callens, M. (2001). " Monitoring of a Prestressed Concrete Girder Bridge with Fiber Optical Bragg Grating Sensors" Journal of Strain, Vol 37, No 4, pp.151-153
12) Tennyson, R. C., Mufti, A. A.Rizkalla, S., Tadors, G. And Benmokrane, B. (2001). " Structural Health Monitoring of Innovative Bridges in Canada with Fiber Optic Sensors", Smart Materials and Structures, Vol 10, pp 560-573