STRENGTHENING AND STRAIN SENSING TECHNIQUES IN RECTANGULAR CONCRETE BEAM USING FIBREGLASS COMPOSITES AND FIBRE BRAGG GRATING SENSORS

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SUMMARY: In this paper, a state-of-art report of an experimental investigation on the responses of the laboratory size rectangular concrete beams with the notch formation on the tension side strengthened by using fibre woven composites is presented. Fibre-optic Bragg grating (FBG) sensors have been embedded at the interface between the externally bonded reinforcement and concrete surface to monitor the internal strain behaviour of the beam, which was subjected to three-point bending load after strengthening. The electrical strain gauges were used to measure the surface strain and compare the results from the internal sensors. The results show that the overall flexural strengths of the strengthened specimens are increased compared with its un-strengthened status. Concrete and bonding failures were observed when the thick reinforcement was used. In addition, the results obtained from the sensor reveal that the stress at the notch tip of concrete was higher than that measured on the surface of the reinforcement.

KEYWORDS: Glass fibre reinforced plastic, Fibre-optic Bragg grating sensor, concrete rehabilitation, strain monitoring, novel system.

INTRODUCTION

In this decade, the rehabilitation and renewal of ageing and deteriorating civil concrete structures represent one of the most significant tasks around the world. The continuing deterioration of the world's civil concrete structures highlight the urgently need for effective rehabilitation technique in terms of low cost and fast processing time with minimising the traffic interruption. Besides, the growing population in some developing countries requires upgrading and retrofitting the original structures because of the increasing the traffic volume, which is beyond the original design capacity.

Fibre reinforced plastics (FRP) have been recognised as a strong material, which can be used to alternate the conventional steel for some structural applications, particularly in the military industry [1]. Its high stiffness and strength to weight ratio, resistance to corrosion and fatigue damages present it benefit for ready applying in all engineering purposes. In recent years, the growing interest of utilising the FRP in civil concrete industry in the forms of rod, plate and jacket has been found increasingly [2-8]. High strength fibres were embedded into the soft matrix to form a composite with high tensile properties with compromising the fatigue and corrosion problems, which are the essential factors that the civil engineers should be concerned. In general, the cracks of the concrete and the corrosion of the embedded reinforced steel bars are the major forms of failure of the concrete structures because of the weak tensile properties of the concrete material. Recent researches focused on the bonding of FRP on the tension surface of the concrete in order to increase the overall tensile strength of the structure [9-12]. The results revealed the remarkable improvement of its flexural strength after bonding by the FRP. However, the mechanical properties of the host structure could not be measured easily by using the conventional non-destructive inspection (NDI) methods such as strain gauge and x-ray radiography due to the existence of the external bonded patches. In Fig. 1, the mechanism of the stress transfer on the surface bonded reinforcement is illustrated. The axial strain on the concrete surface (point A) after strengthening is normally greater than that measured on the surface of the reinforcement (point B) due to the bending effect caused by the shear of an adhesive material. Therefore, the surface mounted strain measuring method cannot be effectively used to measure the mechanical properties of the strengthened structures, particular if the thick reinforcement is used.

Optic-fibre strain sensor is a most attractive technique currently used in the aerospace industry [13-14]. The sensor is embedded into the composite structures to form the novel self-strain-monitoring system, i.e. the system can self-detect the health status of the structure and response the signal to the operator at any marginal situations during service. Fibre-optic Bragg grating (FBG) sensor is one of the most innovative technologies for this purpose, particular for measuring the strain in specified point of the structure. Unfortunately, this technique has not been adapted popularly in the civil engineering application up-to-date.

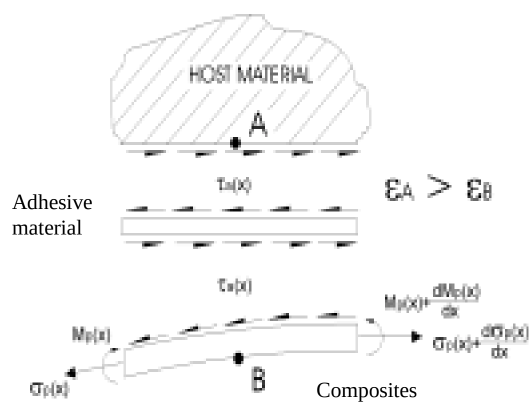

Fig. 1: Stress transfer from the host material to external reinforced patch

In this paper, the experimental investigation of combing the strengthening and strain sensing techniques by using fibreglass composites and FGB sensors, respectively on the rectangular concrete beams with notch formation are presented. The comparisons of the results obtained from the sensor and externally bonded strain gauge are also discussed.

FIBRE-OPTIC BRAGG GRATING SENSOR

The principle of FBG sensor technique has been discovered by *Hill et al* in 1978 [15]. It has been found that the reflective grating could be photorefractively formed in the core of the gramanium doped silicate fibre. FBG technology is defined as the change of the core refractive index of the optic fibre in specified point (grating) and acted as a mirror for reflecting the light signal from the source. The reflective wavelength of the light from the grating depends on the variation of the core refractive index, which is caused by the strain or temperature changes. The amount of the reflective wavelength changes is linear proportional to the straining condition of the grating [16].

For the structural strain monitoring, load is directly transferred from the host material at particular position to the fibre-core section by shear. This causes the length of the grating region to be changed and the resultant refractive index of the core section to vary in due course. The mechanical properties of the structure are simply determined by measuring the reflective wavelength change from the system due to this transformation of the refractive index. The FBG system is illustrated in Fig. 2.

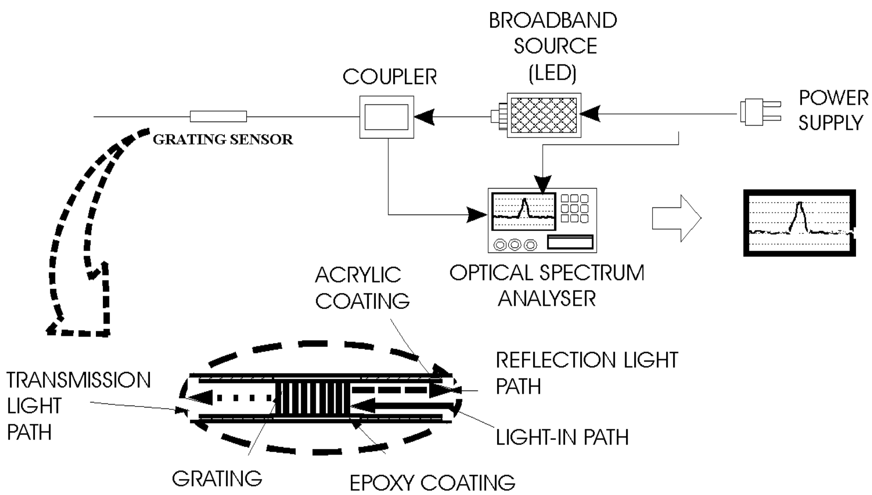

Fig. 2: The FBG system

There is a number of distinguishing advantages of using FBG technology in real life applications. These include: (1) providing an absolute measurement that is sensitive to fluctuations in irradiance of the illuminating source, (2) enabling to measure the strain in particular location in the structure, (3) low manufacturing cost for mass production and (4) the ability to write more than one sensor along the lengthwsie direction of the fibre (multiplexing).

The basic principle of the FBG is expressed as the Bragg's law

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

where the λ_B is the reflected wavelength of the system; n_{eff} is the core refractive and Λ is the spatial period of the index modulation. Any changes of the strain at grating region strain result in the changing of the spatial period and core refractive index. The measurement of the mechanical strain $(\varepsilon=\Delta L/L)$ is determined by the variation of the Bragg wavelength shift $(\Delta\lambda_B)$. From the experimental investigation, it has been proved that the sensors give a linear strain relationship to the reflected wavelength shift from the sensor within the elastic deformation limit of the optical-fibre. The full equation including the effects of the temperature and strain yields

$$\Delta\lambda_B = K_\varepsilon \varepsilon_1 + \lambda_B \xi_o \Delta T \quad (2)$$

The second term in the above equation is expressed as the temperature change of the system, which is normally used in inspecting the manufacturing process of the composite materials [17]. K_ε is called the "Theoretical gauge constant" and can be determined experimentally. In this project, the experiment was performed under the room temperature condition, and therefore the second term of the equation can be neglected.

EXPERIMENTAL INVESTIGATION

Specimen types

Standard laboratory size rectangular concrete specimens for the three-point bending test were made according to the ASTM C293-94. Concrete was mixed by the ratio of 1:1.5:3 and curing for 28 days before the tests were performed. Notches were made in all specimens with notch-to-width ratio of 0.2 and then filled with Epoxy based resin to avoid any environmental attacks on the notch-surfaces. E-glass fibre mats with Epoxy based (Araldite MY 750) resin were used to form composites to strengthen the concrete beams in either bonding on the tension or both a long vertical shear surfaces. Pre-treatment of the concrete surface is essential to ensure that the perfect bond was achieved. Sanding and vacuuming were initially performed on the surface of bond. Cleaning solvent (acetone) was then used to remove the grease and other chemical substances that were attached on the bonding surface.

Fibreglass reinforcements were made by laying-up directly on the surfaces of concrete beam and all specimens were then rest for 24 hours of curing. Strain gauges were attached on the surfaces of reinforcements at the same position of that the sensor was embedded. The schematic diagram of all test specimens is shown in Fig. 3.

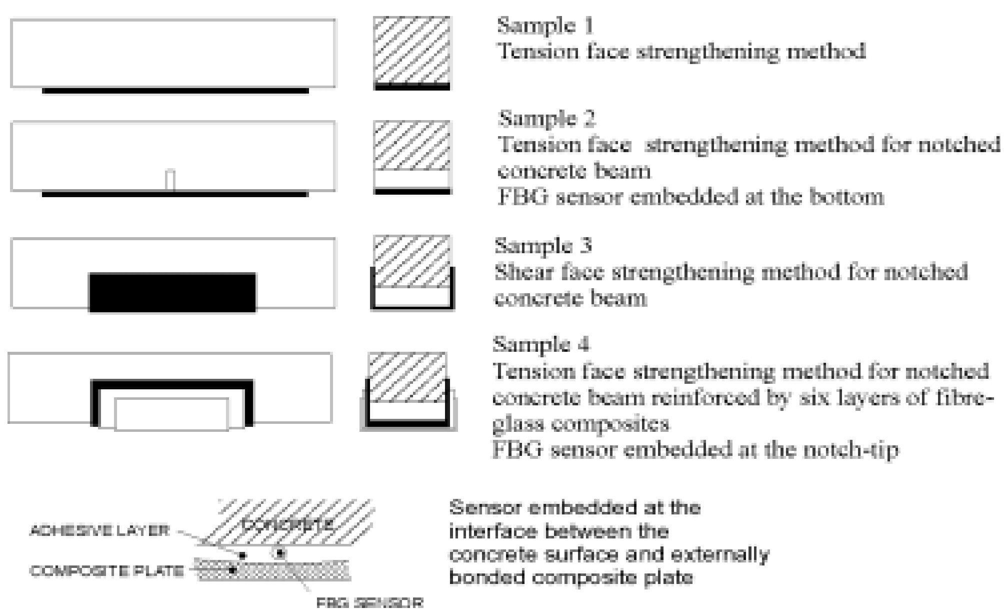

Fig. 3: The schematic diagram of all rectangular concrete specimens

Strain measuring system

The strains were measured by two different systems, which include (1) FBG and (2) strain gauge measuring systems. The FBG sensing system consists of optical spectrum analyser (OSA), coupler, light emission device (LED) and optical fibre with pre-written grating sensor. The reflective light wavelength spectrum is displayed on the screen of OSA and the peak wavelength can be measured directly. The function of the coupler is used to separate the transmitted and reflected wavelength signals, so that the OSA can measure the wavelength shift more accurate. The photography of the test specimen is demonstrated in Fig. 4.

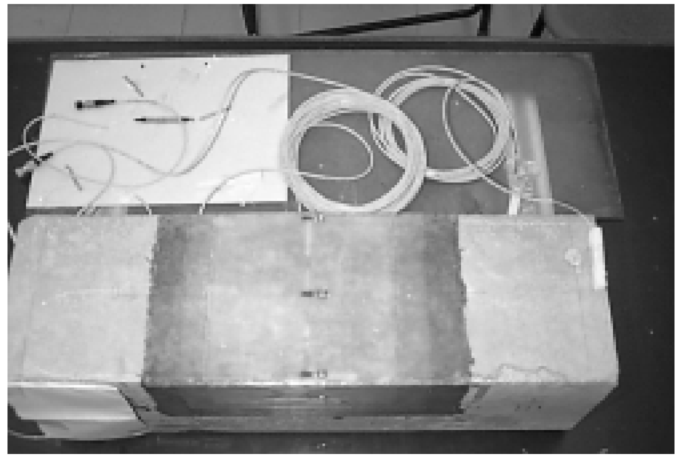

Fig. 4: The test specimen with embedding the FBG sensors

The fibre sensor was bonded on the surface of concrete before laying-up the fibreglass reinforcements. The reflective wavelength from the sensor was recorded simultaneously during the test. The surface mounted strain gauge was used to measure the surface strain condition of the reinforcement after strengthening. All strain and load values were recorded through the computer automatically.

Experiment set-up

All standard beams with the notch formation after strengthening were subjected the three-point bending load to investigate their mechanical behaviours. The test procedure was followed the ASTM standard. The loading displacement rate was set as 0.05mm/min. The experiment set-up of the whole system was illustrated in Fig. 5.

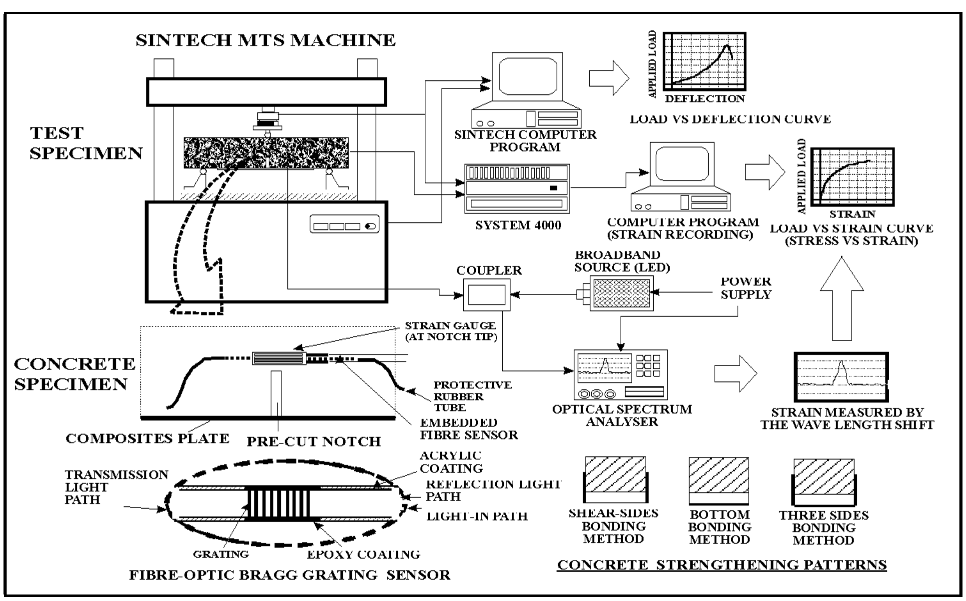

Fig. 5: The experiment set-up of the 3 point bending test

RESULT DISCUSSION

Strengthening technique

The results obtained from the experiment show that using the fibreglass composite as a reinforcement for strengthening the notched rectangular concrete beam can substantially increase the flexural load capacity than the un-strengthened status. Furthermore, the results also indicate that the maximum load capacity of the strengthened beam is not directly proportional to the number of composite layers, which are used to bond on the concrete surface. Concrete and shear failures of the sample 4 was observed at the plate end when the load was applied at 35kN. Debond was initially found at the notch-mouth region when the load was applied up to 33.5kN. It was then expanded rapidly toward the end of the plate. The maximum load and deflection recorded in the experiment are shown in Table 1.

According to the results plotted in Fig. 6a, the maximum strains measured from the bottom surface of the beam (sample 2) show that there is no significant difference between the centre and edge. Also, there is no stress concentration at the notch-tip when the applied load is below 18 kN. Beyond this limit, the strain at the notch-tip increases rapidly compared with that measured at the bottom surface. The strain measured at the notch-tip is four times larger than that from the bottom surface just before failure. Crack was found near the notch-edge of the specimen. Unlike the plain notched concrete specimen (un-strengthened) for which the crack was initiated at the notch-tip and propagated toward the opposite direction of the load applied, the crack was started beside the notch. It is suspected that the filled epoxy resin inside the notch region provides a strong bonding on both inner faces of the notch. Therefore, the crack was started at the adjacent regions near the notch-mouth.

Table 1: Summary of all test samples

Sample	Maximum load (kN)	Maximum deflection (mm)	Failure mode
Plain	21.7	0.61	- failure in concrete
Notched	17.1	0.90	- failure in concrete and the reinforced composites plate + shear failure at the notch-mouth region
1	31.6	0.64	
2	31.5	0.94	
3	35.0	1.12	
4	35.0	1.83	- failure in concrete at the plate end region + shear failure at both notch-mouth and plate end regions

The failure mode of the sample 4 shows that there is no advantageous by using too many reinforced layers to strengthen the beam if the bonding properties are unclear. Strong bonding properties of two different materials are essential in order to allow the load transfer effectively from one material to another without the failure of bond. Otherwise, using the thick reinforced materials become meaningless. The testing result of the sample 4 is shown in Fig. 6b.

FBG sensing technique

The FBG sensors were installed at the interface between the concrete surfaces and the externally bonded composites of the samples 2 and 3. The strain measured from the strain gauge and the FBG sensor are plotted in Fig. 7a and b, respectively. It is obviously shown that the strain at the concrete surface is always higher than that at the surface of the externally bonded composites.

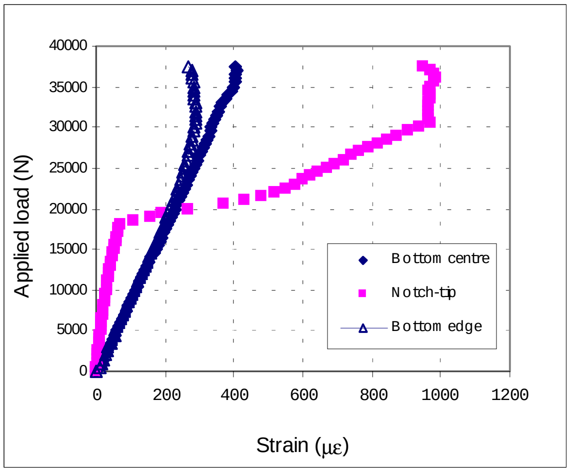

Fig. 6a: The experimental result of the sample 2

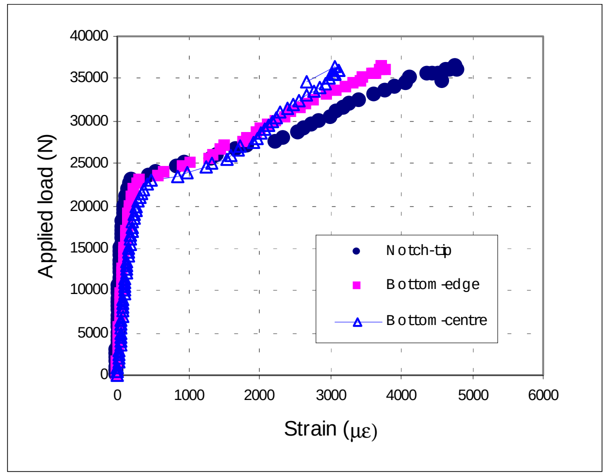

Fig. 6b: The experimental result of the sample 4

FBG sensor can monitor the precise health condition of the concrete and detect the failure earlier than the strain gauge, which is mounted on the surface of the external reinforcement .The results in Fig. 7a also show the rapid change of the strains when the load is applied beyond 20kN. During the experiment, debond was initially found at the notch-mouth region and further expand toward the end of the plate. However, this phenomenon may not influence the outer surface of the reinforcement. Therefore, the strain measured from the FBG sensor is much more sensitive than the surface mounted strain sensing device if the internal debonding occurs at the sensor embedding region.

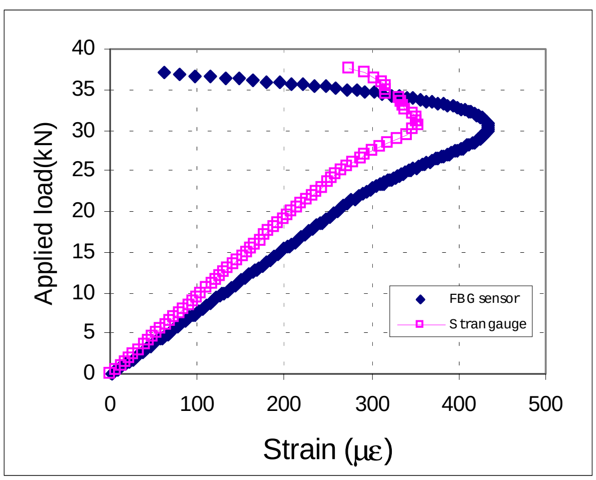

Fig. 7a: The experimental result of sample 2

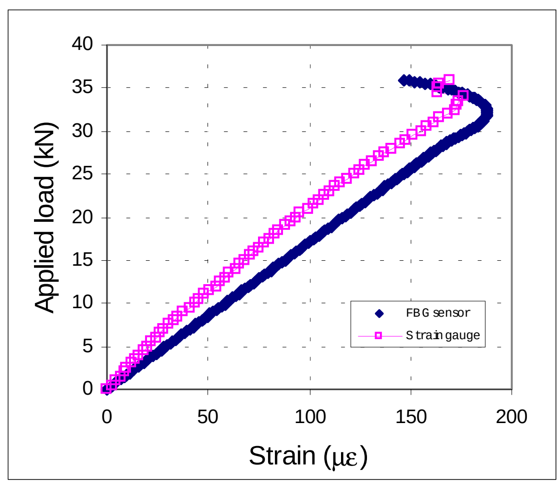

Fig. 7b: The experimental result of sample 3

CONCLUSION

The experimental studies provide a valuable information for strengthening and strain sensing techniques of the civil concrete structures with notch formation. Some conclusions are drawn as follows:

1. Strengthen the rectangular concrete beam by using fibreglass composites does provide a substantial increase of the flexural load capacity as well as the stiffness of the beam.
2. Increase of the number of laminate layers may cause the shear failure of an adhesive material rather than the failure occurred in the composites. Optimisation should be made before applying the thick composite patch on the concrete surface, which is required to be reinforced.
3. The embedded FBG sensor can be effectively used for measuring the internal strain behaviour of the structure, particularly after strengthening by the external bonded reinforcement. The surface mounted strain measuring device cannot be detected accurately.

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