Experimental investigation on the application of distributed long-gage fiber optic sensors in RC structural assessment

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ABSTRACT:

In our resent study, a novel packaged long-gage fiber optic sensor for practical adaptation in civil structural health monitoring has been developed and verified to have the ability to obtain effective macro-strain distributions. This paper discusses the application of the proposed sensor in structural assessment for reinforced concrete (RC) beams. A normal RC beam installed with distributed FBG sensors of different gauge length are utilized for experimental investigations, in which progressing cracks are introduced in successive loading steps and respective measurements from FBG sensors are obtained. Compared with the results from traditional transducers including foil strain gauges and crack gauges, the ability of distributed FBG sensors to detect the location and extent of cracks is verified. Combined with numerical simulations, the structural evaluation on global behavior is implemented as well.

INTRODUCTION

Health monitoring for RC structures often includes two main concerns on local crack condition and global structural behavior. Cracks may lead to structural degradation due to reinforcement corrosion associated with the leakage of water and chloride through cracks. Therefore, detection on the presence, location and significance of cracks is of engineering importance concerning maintenance and reparation. On the other hand, rather than the monitoring on local material behaviors or local stress/strain concentrations, the global behavior evaluation provides the valuable information on the full structural assessment and diagnosis.

Different from visual observation inspection, the real-time monitoring by direct use of measurements has drawn the extensive interests regarding its fewer requirements for labor, more convenience for in-service structural monitoring and the ability to obtain the immediate information. To overcome the difficult in traditional transducers such as the problems of installation, durability, stability and so on, some novel sensing techniques are employed for RC structural health monitoring. In our resent study, a novel packaged long-gage fiber optic sensor for practical adaptation in civil structural health monitoring has been developed and verified to have the ability to obtain effective macro-strain distributions [1]. Meanwhile, the concept of distributed strain sensing techniques is proposed [2], which has been dedicated to utilize the strain distributions throughout the full or some partial areas of structures to detect the arbitrary and unforeseen damage.

In this regards, the application of the developed long-gage FBG sensor in structural assessment for reinforced concrete (RC) beams is discussed. A normal RC beam installed with distributed FBG sensors of different gauge length are utilized for experimental investigations, in which progressing cracks are introduced in successive loading steps and respective measurements from FBG sensors are obtained. Compared with the results from traditional transducers including foil strain gauges and crack gauges, the ability of distributed FBG sensors to detect the location and extent of cracks is verified. Combined with numerical simulations, the structural evaluation on global behavior is implemented as well.

LONG-GAGE FBG SENSORS ARRAY FOR DISTRIBUTED MACRO-STRAIN MEASUREMENTS

A long-gage FBG sensor has been developed recently in our lab [1] for practical adaptation in civil structures. The essential of this sensor (see Figure 1) is the handling of an embedded tube, inside which bare optic fiber with FBG is sleeved and fixed at two ends. Through special packaging by composite materials to extend original Bragg grating with inherent gage lengths on the order of a few millimeters to effective gauge length up to several centimeters or meters, FBG sensor can measure average macro-strain that is less susceptible to local stress/strain concentrations and hence more representative of the deformation of the entire structural member. Furthermore, compared with resistive foil strain gauge and other traditional "point" gauges, this sensor can be easily multiplexed at many locations or distributed throughout the full structure and permit distributed strain measurements of high precision. The image of distributed long-gage FBG sensors array can be seen in Figure 1.

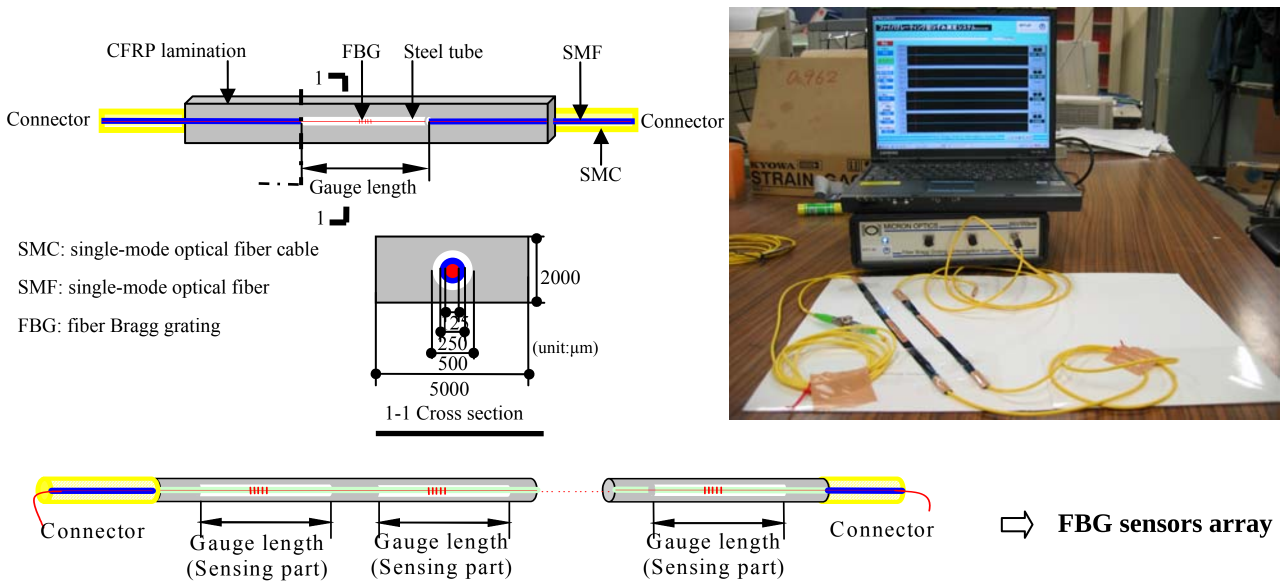


Figure 1. Developed long-gage FBG sensing system

Single-mode optical fiber of Corning SMF-28 was utilized in this study. All the FBGs available for commerce passed 100KPSI proof test and basically could be used to measure strains up to 5000με repeatedly. Meanwhile, an FBG-Interrogation system from NTT-AT with sampling rate of 50Hz was used for data acquisition and signal interpretation.

EXPERIMENTAL INVESTIGATIONS

Test specimen and setup

A RC beam with rollers supported at two points is designed as the test specimen. Details on the beam dimensions and reinforcement configuration are illustrated in Figure 2. The total length of the beam is 2.1m, with a span of 1.8m. The cross section has a rectangular shape with 150mm width and 200mm depth. The compressive strength of concrete is 45.6 N/mm2. Two positive reinforcements of 16mm diameter and two passive ones of 13mm diameter are used for longitudinal bars, with 40 mm distance away from the edges of the beam. Stirrups are also considered throughout the whole length of the specimen, with 10mm diameter and 80mm distance at two adjacent vertical bars. The yield strength of reinforcement is 380 N/mm2. The failure mode of the beam is flexural failure in the design.

Via a transferred steel board, the load applied by loading machine is equivalently split into two parts, landing at two points with a distance of 600mm (corresponding to 1/3 of the span) from each support. The progressively increasing load is applied continuously in a load-controlled mode, up to the failure of beam. To detect the subtle changes before and after the first several cracks, upload is carried out at a very low speed before 30 KN, where 15 KN is supposed to be the cracking load from theoretical calculation.

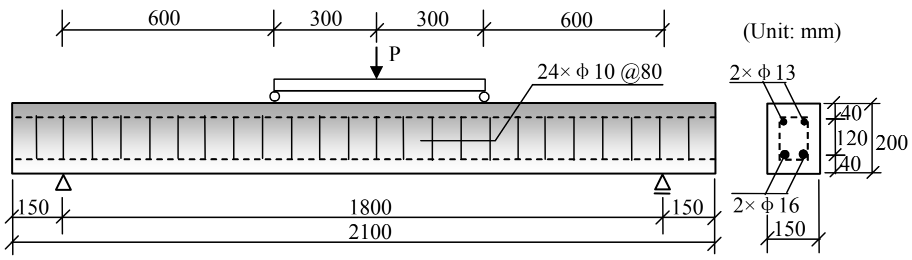


Figure 2. Outline of the RC beam

Sensors placement

To study the performance of long-gage stain sensors on structural assessment for RC beam, four FBG sensors of 200mm gauge length are arranged onto the bottom surface of the specimen to implement a quasi-distributed measurement. The other two kinds of FBG sensors with respective gauge length of 400mm and 800mm are attached in parallel to investigate the influence of different gauge lengths on the sensor behavior. Traditional foil strain gauges of 60mm gauge length are fixed at the top, bottom and side surfaces of the beam. Crack gauges of 200mm gauge length are also used for comparison. A displacement gauge is installed at the center of the specimen to provide an index to verify the structural global behavior. Detailed sensors placement can be found in Figure 3. For the convenience of discussion, the area with sensors installation is artificially divided into four zones, as denoted by Zone1~Zone4.

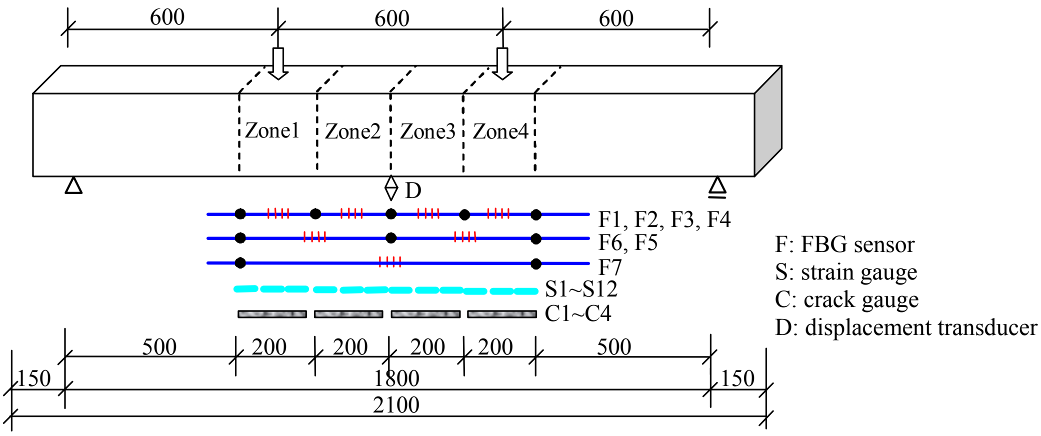


Figure 3. Sensors placement

Experimental results

As mentioned before, upload is applied at a very low speed from the beginning and all of the sensors work in a good condition with graphically linear increases under load. The first abrupt change of the data can be found from S8 in Zone 2 at 13KN, when the initial crack is supposed to occur. With the going-up load, cracks happen and develop in succession at different locations where the spatial space between two cracks is about 100mm. As the load is up to 35KN, six FBG sensors including [F1, F2, F3, F4, F6] fail to work. The accidental reason is still under investigation and likely in that F2 encoded by center wavelength of 1538nm got some problem and incurred the mistaken interrogation of the following [F1, F3, F4, F6] encoded by their respective center wavelengths of [1538nm,1540nm, 1550nm, 1552nm]. Otherwise, F5 (1535nm) and F7 (1532nm) work well until the end of the experiment, when the load is about 75KN. The outline of the specimen after the experiment is shown in Figure 4. For the convenience of the following description, the cracks at the bottom surface of the beam are labeled □~□ from left to right.

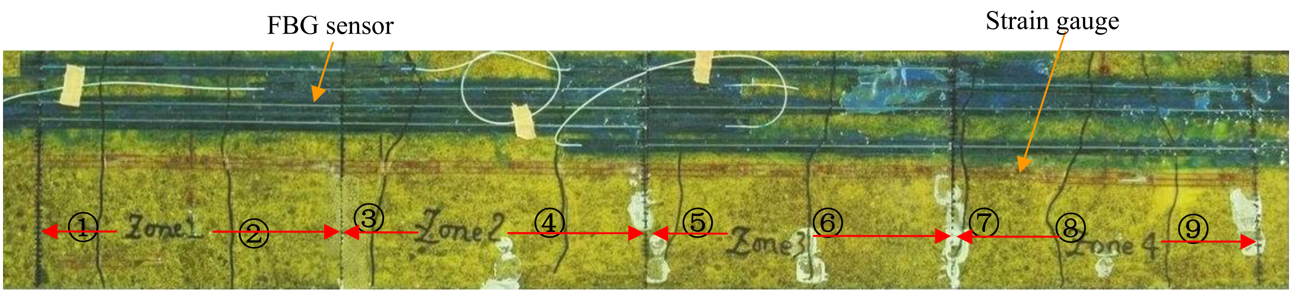


Figure 4. Crack distribution after experiment

NUMERICAL SIMULATIONS

Numerical simulations on the nonlinear finite element analysis of RC beams are carried out by a general FE code (DIANA 9). The analytical model with FE mesh discretization is shown in Figure 5. The 4-node quadrilateral plane stress elements are chosen. For concrete, the linear softening for tension and parabolic softening for compression are supposed to represent the nonlinear constitutive behavior. A smeared crack model based on total strain is adopted in this study. Perfect bond is assumed to reinforcements, simulated by a perfect-plastic Von-Mises model. The same concrete and reinforcement compressive strength as that in experiments for $f_c^{'} = 45.6N/mm^2$ and $f_y = 380N/mm^2$ are taken. The concrete tensile strength for $f_t = 2N/mm^2$ is chosen to match the experimental result.

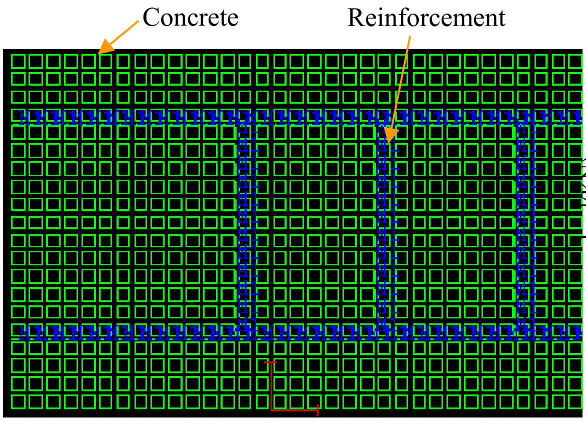


Figure 5. FE model with shrink mesh

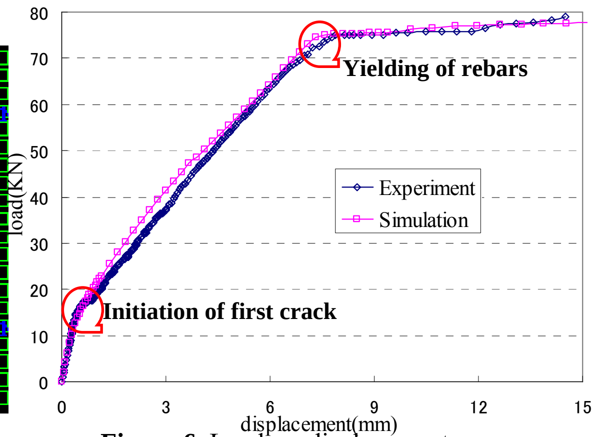


Figure 6. Load vs. displacement curves

Displacement control with Newton-Raphson solution technique is considered for the incremental-iterative solution of equilibrium equations. Figure 7 gives the comparative results on the whole process of load vs. displacement at the center of the beam from the experimental data and FE analysis. It can be found the simulated results have a nice agreement with the experimental ones.

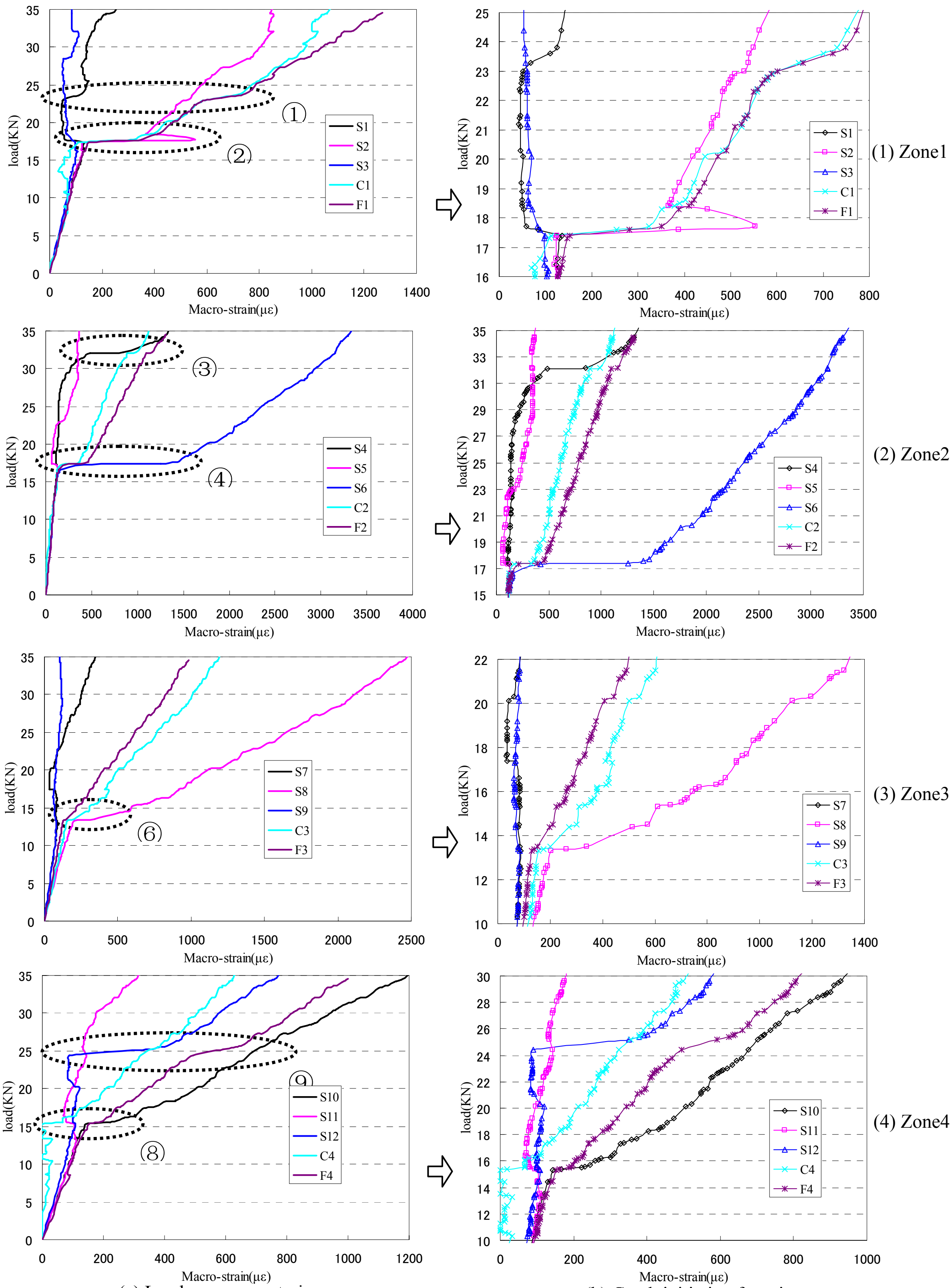
STRUCTURAL ASSESSMENT FOR RC BEAMS

Combined with the experimental data and numerical results, the application of long-gage strain sensors in the structural assessment including local crack monitoring and global behavior evaluation for RC beam are elaborated as follows.

Local crack monitoring

Cracks detection and localization

The strain measurements with loading increase from FBG sensors of 200mm gauge length are shown in Figure 7. The data from crack gauges and strain gauges are also illustrated for comparison. For each zone, the whole process of load vs. macro-strain can be seen on the left. To investigate the more detailed changes, the concerned parts which are supposed to reflect the status pre- and after cracks are magnified on the right. It can be found that the initial crack in every zone (□□□□) can be detected easily by FBG sensors from the inflection points after which the slopes of the curves decrease discontinuously. In the same way, some successive cracks (□□□) can be also discovered although the varying tendency is not so obvious. However, the cracks □□ seem be missed due to the possible reason that the cracks are so small or the crack



(a) Load vs. macro-strain (b) Crack initiation focusing

Figure 7. Local crack monitoring

locations are so near around the ends of sensors that they can't be reflected by the measured data.

Average crack width

The average crack width within a certain region can be regarded as the product of the increase of measured macro-strains and the gauge length of the sensor under the constant load. Considering Zone 1 and Zone 2, the changes of measured data and the corresponding average crack widths obtained by crack gauges and FBG sensors of 200mm gauge length are shown in Figure 8. In most cases (crack□□□) the results from these two different sensors present a good agreement.

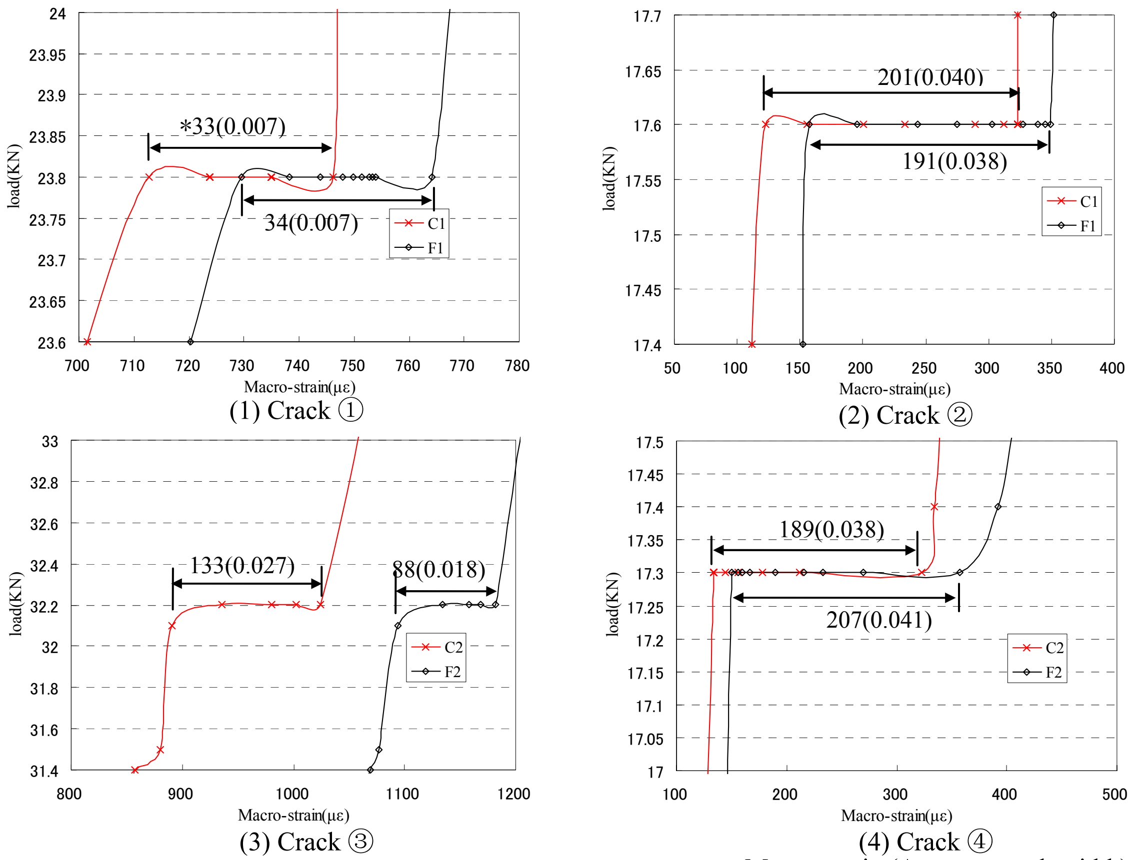
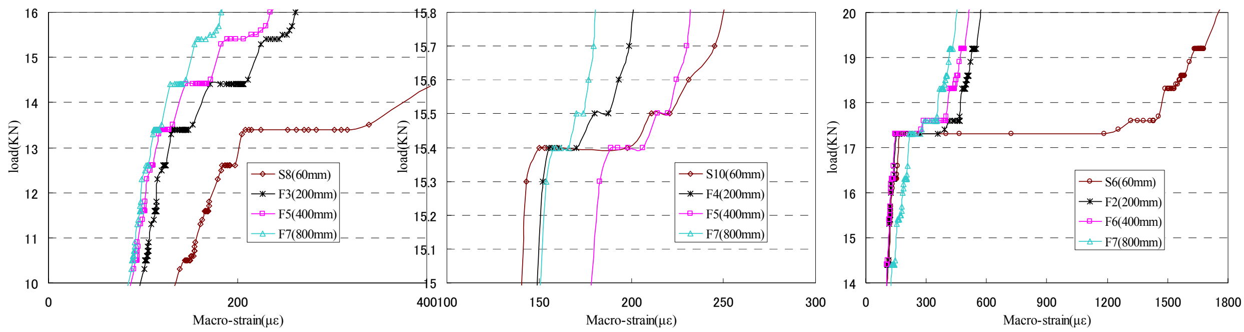


Figure 8. Average crack width

* Macro-strain (Average crack width) unit: με (mm)

Influence of gauge lengths of sensors on crack monitoring

Four kinds of long-gage strain sensors are utilized in this study, including the strain gauge of 60mm gauge length and three FBG sensors of 200mm, 400mm, 800mm gauge lengths. Considering the cracks □□□ which are the first three cracks of the beam in this experiment, the comparative measured results from the above four long-gage sensors can be seen in Figure 9. Obviously with the increase of the gauge length of the sensor, the measured macro-strains change less when the crack occurs, which has proven a very important concept that the average macro-strain is less susceptible to the local stress /strain concentration and more representative of the deformation of the entire structural member. Furthermore, it can be concluded that as long as the extent of crack is small or the gauge length of the sensor is large enough, the aberrant changes in the measured data caused by local crack can be reduced to keep the continuity of the final results.



(1) Crack ⑥ (first crack) (2) Crack ⑧ (second crack) (3) Crack ④ (third crack)

Figure 9. Crack monitoring based on strain sensors of different gauge lengths

Structural evaluation on global behavior

The whole process of macro-strain responses under monotonic loads

The macro-strain responses obtained by F5 and F7 under monotonic loads from FE simulation and experimental data are shown in Figure 10. It can be seen that before the initiation of the first cracks the measurements from FBG sensors have a nice agreement with the analytic results. In general, for such a RC beam with the final crack spatial space of about 100mm, the measurements from the FBG sensor of 400mm or larger gauge length can disregard the influence of local crack and reflect the structural macro-behavior well.

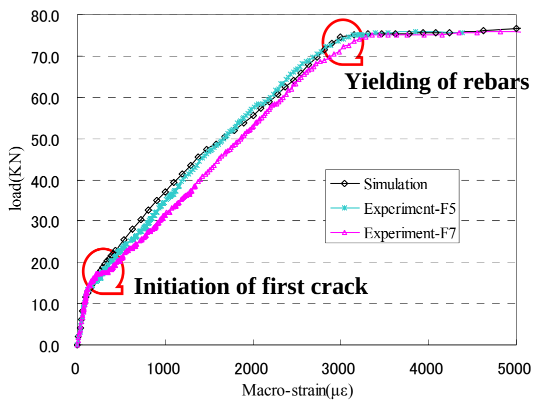


Figure 10. Load vs. macro-strain curves from F5, F7

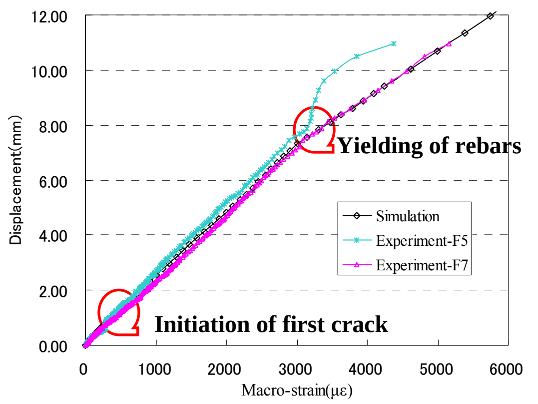


Figure 11. Displacement vs. macro-strain curves from F5, F7

Contrasting Figure 10 with Figure 6 it can be found that with the increase of load the varying tendency of measurements from F5, F7 is similar to that of the displacements at the center of the beam. To study their relations, the macro-strains vs. displacements curves are illustrated in Figure 11, where a perfect linear correlation can be obtained before the yielding of tensile bars. This conclusion is very valuable in that as long as the gauge length and location of the sensors are selected reasonably the long-gage FBG sensor can replace the displacement transducer which is often used for global displacement measurements but difficult to be installed onto the practical civil structures due to the requirement for baseline position. Moreover, it can be seen that the correlation curves maintain the sound accordance before and after cracking, which has again proved the above-mentioned argument that the FBG sensor with enough gauge length can obtain the measurements overlooking the influence of local crack. In addition, compared with those from F5of 400mm gauge length the results from F7 of 800mm gauge length match better with simulation, especially after the yielding of bars.

Influence of gauge lengths of sensors on global behavior evaluation

The experimental and numerical macro-strain responses with loading increase from FBG sensors of different gauge lengths are shown in Figure 12. As the average crack width is less than 0.01mm, the satisfied data can still be obtained from FBG sensors of 200mm gauge length (F3, F4). But the large local cracks (about 0.04mm for □□) will lead to the far-off deviation of responses curves (F1, F2) from the analytical one. However by comparing with the results from F5, F6 and F7 it can be found that this deviation seems to be acceptable. In other words, the FBG sensor of 200mm gauge length is suitable for such RC beam on structural global behavior. It is worth stressing here that with regard to the measurements such as those in Figure 12(4) the distributed strain gauges of 60mm gauge length are not suitable for structural global behavior analysis.

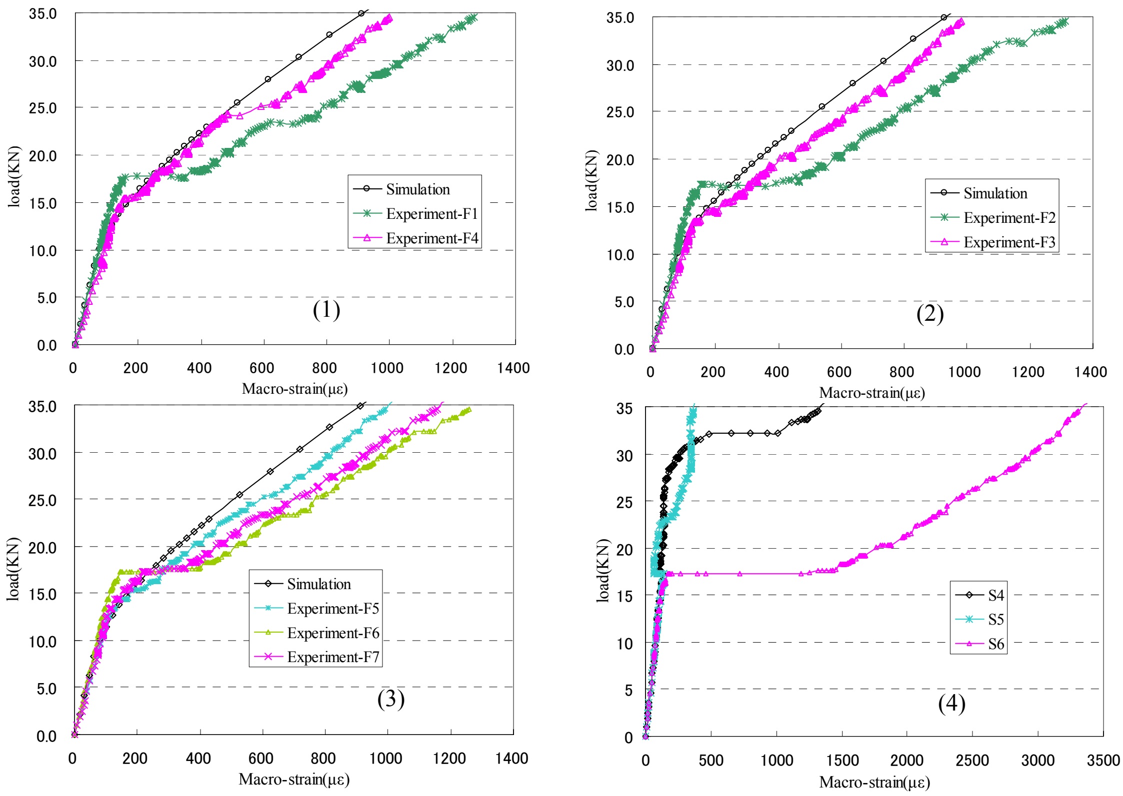


Figure 12. Loads vs. macro-strains from long-gage sensors of different gauge lengths

The average of macro-strain measurements

To investigate the effectiveness of the average of measured macro-strains, the comparative results from different gauge lengths are illustrated in Figure 13. The very satisfied agreements verify the conclusion that regarding RC beam the macro-strain measurements over a certain gauge length can be obtained from the average of those over several sub gauge lengths, i.e. the four distributed FBG sensors of 200mm gauge length are enough for global behavior evaluation on this RC beam. Together with the discussions from local crack monitoring, it can be found that the FBG sensor of 200mm gauge length is a good choice for a RC beam of about 2m span on structural assessment.

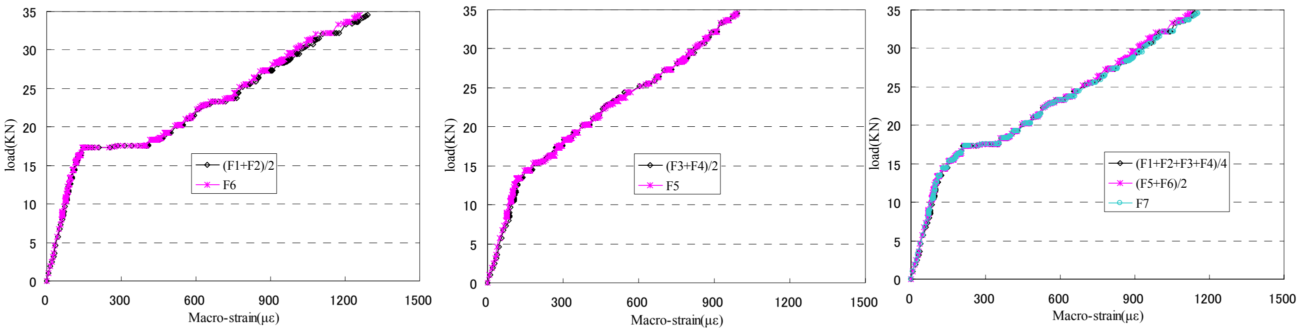


Figure 13. The average of macro-strain measurements

CONCLUSIONS

In this paper, based on the results from experiments and simulations, the application of the recently developed long-gage FBG sensor in structural assessment for reinforced concrete (RC) beams including local crack monitoring and global behavior evaluation is investigated. Some important conclusions can be drawn as follows:

The distributed long-gage FBG sensors can detect the occurrence and extent of cracks effectively. In general, the shorter the sensor gauge length is, the more evident the indication of crack initiation detection is. However, it is crucial to select an appropriate gauge length for practical application of such sensors in local crack monitoring.

The FBG sensor with an adequate gauge length can obtain the measurements overlooking the influence of local cracks and providing the macro-information.

As the gauge length and location of the FBG sensor is selected reasonably the macro-strain vs. displacement curve presents a perfect linear correlation and hence the long-gage sensor may be supposed to replace the displacement transducer which is often used for global displacement measurements but difficult to be installed onto the practical civil structures due to the requirement for a baseline position.

The utilization of the distributed FBG sensors of 200mm gauge length is a good choice for a normal RC beam of about 2m span on both local crack monitoring and global behavior evaluation.

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