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Distributed Fiber Optic Sensing for a Full-scale PC Girder Strengthened with Prestressed PBO Sheets

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ABSTRACT: Fiber Reinforcement Polymer(FRP) has been widely accepted as an innovative material for renovation and strengthening of existing infrastructures. Among the FRP materials, the Poly-p-phenylene benzobisoxazole (PBO) fiber sheets attracted great attention in recent years because of the high strength, high Young modulus and high energy absorption capability. In this study, a PBO Prestressing Upgrading Technique (P-PUT) including air bag system and end anchoring system for a full-scale prestressed concrete girder is proposed. For the purpose of evaluating the strengthening efficiency of the PBO sheets and the performance of the strengthened PC girder, specially the compressive and tensional strain distribution of concrete and PBO sheet under different load levels and the bonding performance of the PBO sheet on the concrete surface, a fiber optic sensing system with a strain/loss analyzer based on the Brillouin Optical Time Domain Deflectometry (BOTDR) technique has been employed. Two types of bonding methods for optic fiber installation called Point Fixation(PF) method and Overall Bonding(OB) method are proposed and investigated. A kind of polynomial curve fitting method is presented to processing the field data polluted with noise.

1 INTRODUCTION

In many developed countries, more and more existing reinforced concrete and prestressed concrete infrastructures such as bridges and highways that were constructed in the boom of industrial development are currently not satisfied with the design performance requirement and need strengthening because of the deterioration of construction materials, damage occurrence and the increasing actual load level. Active research activities about application of innovative materials in structural renovation, retrofitting and strengthening have been carried out worldwide in the last two decades.

Fiber Reinforced Polymer (FRP) materials due to their high strengths and ease of constructions have been employed for repair, retrofit and strengthening of reinforced concrete structures. Among these innovative FRP materials, the newly developed Poly-p-phenylene benzobisoxazole(PBO) fiber sheet has attracted great attention because of the high strength, high Young's modulus and high energy absorption capability. Recently, researches and applications on strengthening with FRP sheets for concrete structures have been conducted. In this study, a PBO Prestressing Upgrading Technique(P-PUT) method for the strengthening of a full-scale prestressed concrete girder with PBO fiber sheet is proposed.

With the wide use of different kinds of FRP materials in civil engineering, it has been regarded as a crucial issue to evaluate the strengthening effects, the short-term and long-term performance and behavior of the strengthened structure, specially those structures strengthened with new materials and new construction and strengthening technology. The real behavior of the strengthened structures needs to be testified and compared with the assumption in design procedure. Structural health monitoring with the support of different kinds of advanced sensing technologies for large-scale civil structures plays an important role to meet the needs. The premature peeling or debonding of FRP sheets from the structural elements in the repaired structures with FRP sheets are the major problems, because the premature peeling or debonding of FRP sheets lead to brittle and abrupt failure of the repaired structures. Failure of the retrofitted structure members in a ductile manner is one of the basic requirements. In this study, in order to avoid debonding on the ends of the PBO sheets, a PBO anchorage is designed at each end of the PBO sheet.

On the other hand, distributed fiber optic sensing technology has been treated as an innovative strategy for structural health monitoring, damage assessment and performance evaluation of large-scale civil structures. As one of the most attractive distributed sensing method, Brillouin Optical Time Domain Deflectometry (BOTDR), which is based on the propagation of a train of incident pulses and Brillouin back-scattering that occurs whenever light is transmitted through an optical fiber, has attracted great attention in civil engineering. (Gu et al., 2000, Bao, 1993, 1996, 2001, Horiguchi et al., 1989, Kurashima et al., 1990, 1997, Ishii, et al., 2002 & Wu et al. 2000, 2002a, 2002b, 2003). BOTDR based distributed sensing technique can give strain distribution along the optic fiber and monitor the crack initiation and estimate the cracks width within a local region with specially designed installation methods for reinforced concrete structures(Wu et al. 2000, 2002a).

Experimental study on the loading capacity of a full-scale PC concrete girder strengthened with prestressed PBO sheet is conducted. A strain/loss analyzer AQ8603 (Ando Electric Co. Ltd.) based on the BOTDR technique is employed to measure the strain variation of concrete in compressive and tensional flange and PBO sheets under different load levels and monitor the interfacial bonding performance of the prestressed PC girder strengthened by the proposed P-PUT method. By comparing the measurement of the tensional strain distribution of concrete and tensile strain distribution of PBO sheet on the bottom of the PC girder, the bonding performance of PBO sheet on the bottom of the PC girder can be determined. The experimental study shows that no debonding occurred in the interface between the concrete and PBO sheets of this specimen. This indicates that the mounting method of the anchorage described in the P-PUT methods is efficient to prevent the PBO sheet from debonding. Moreover, for the purpose of comparison, two types of bonding methods for optic fiber installation called as Point Fixation(PF) Bonding method and Overall Bonding(OB) method were proposed and investigated. A polynomial curve fitting method is presented to smooth distribution strain measurement results.

2 Measurement Principle of BOTDR and the Measurement Device

2.1 Measurement principle of BOTDR

Distributed BOTDR sensing technique makes use of optic fibers that are used for both measurement and data transmission purposes. The optic fiber sensing techniques can be employed to determine locations and values of desired parameters along the entire length of fiber. Figure 1 shows a typical scattered light spectrum in an optical fiber. The principle of BOTDR is similar to that of the traditional optical time domain reflectometer (OTDR). In OTDR sensing system, a short light pulse is transmitted along the fiber and the backscattered energy due to Reyleigh scattering is measured at the sending end of the fiber. The time interval between sending the pulse and backscattering light arriving provides the spatial information, whilst the intensity of the backscattered light energy provides a measure of the desired parameters along the fiber. In BOTDR system, the measured is the frequency of the Brillouin backscattering light, which occurs by an interaction between a high-coherence incident light and an acoustic wave generated by the incident light in an optical fiber, rather than the intensity of the Rayleigh backscattering. Figure 2(a) shows the illustrative 3-D Brillouin scattering spectrum describing the Brillouin scattering power(intensity) distribution at different frequencies along the optic fiber. Figure 2(b) shows the frequency shift of back-scattered Brillouin light at a certain location due to the corresponding strain. Figure 2(c) illustrates the Brillouin scattering power (intensity) spectrum at a certain frequency along the optic fiber. The back-scattered Brillouin light frequency determined by the velocity of the acoustic wave is shifted from incident light frequency because of the strain along the optic fiber. The Brillouin frequency shift is determined by the following equation.

$$\nu_B = 2n\nu_A / \lambda \tag{1}$$

where n is refractive index, v_A is the acoustic wave velocity and λ is wavelength of incident light. The frequency shift of Brillouin back-scattering shown in Figure 2 is a function of both temperature and strain in the fiber.

The relationship between the Brillouin frequency shift at a certain location (within the spatial resolution) and its corresponding strain is described by the following equation,

$$v_B(\varepsilon) = v_B(0)(1 + C \cdot \varepsilon) \tag{2}$$

where $v_B(\varepsilon)$ is the Brillouin frequency shift corresponding to the strain ε, $v_B(0)$ is the Brillouin frequency shift without a strain, C is the strain coefficient. Moreover, the temperature change along the optic fiber also has influence on the Brillouin frequency shift. The strain/temperature coefficients of the Brillouin frequency shift at 1.3μm and 1.55μm bands are tabulated in Table 1.

2.2 Measurement device

A strain/loss analyzer AQ8603 (Ando Electric Co. Ltd.) based on the BOTDR technique is utilized to continuously measure the strain distribution along the optic fiber that is used for both sensing and data transmission purposes.

According to the principle of BOTDR, the strain at a certain point of measurement is calculated based on the frequency shift of Brillouin back-scattering pulse within 1m beyond the point. This 1m range is called the spatial resolution of the current strain/loss analyzer AQ8603. Table 2 summarizes the specification of the strain/loss analyzer AQ8603. For a continuous measurement, in this study, the measurement interval of the sampling points (called readout resolution) is 0.1m.

3 Full-scale PC Girder Specimen and P-PUT Method

3.1 Full-scale PC Girder Specimen

As a newly developed fiber reinforced plastics(FRP), Poly-p-phenylene benzobisoxazole (PBO) sheet is employed as an externally bonded reinforcement for the enhancement of a PC girder. The elastic modulus and tensile strength of PBO sheet are fairly higher than the high strength type of carbon sheets. PBO fibers have greater impact-tolerance and energy absorption capacity than other types of FRP materials such as Carbon and Aramid fibers.

The flexural behavior of a PC girder shown in Figure 3, that is prestressed with internal ca steel strands and external PBO sheets reinforcement and with a span of 16.7 meter and a section of 1 meter high, is experimentally investigated. The material properties of concrete, prestressed steel strands, reinforcing bars, and PBO sheets are given in Table 3. In this study, the prestressed level for the PBO sheets is set to be 33% of the assumed effective tensile strength of PBO sheets, and the number of PBO sheets layers is 3. Impregnation of PFRP sheets with the epoxy adhesive is carried out before PBO sheets prestressing.

3.2 P-PUT method

The concept of PBO-Prestressing Upgrading Technique(P-PUT) is illustrated in Figure 4. The basic procedure for prestressing includes 1) pre-tension of PBO sheets, 2) bonding to the tension face of the concrete structures (including curing of adhesive and cutting of the PBO sheets ends), and 3) applying the appropriate end anchorage for PFRP sheets. The flowchart of strengthening method is described in Figure 5. An air bag system shown in Figure 6 is used to ensure a perfect bonding between PBO sheets and concrete surface. As the suction pump sucks up air within the film package, the prestressed PBO sheets is sealed tightly towards the concrete surface because the PBO sheets are pressured against concrete surface by air pressure.

For surface bonded PBO sheets, the end anchoring is the most important issue for effective retrofitting and enhancement. Especially in the case of prestressed PBO updating, prestressing requires the PBO sheets to be effectively anchored at both ends in order to transmit the tensile forces to the concrete beam. In this study, a U-type end anchoring system by the use of extra bonded PBO sheets is proposed as shown in Figure 7. As a countermeasure for relieving shear stress concentration at the prestressed PBO sheets ends, the end of the 3-layer prestressed PBO sheets are wrapped by three U-type end anchoring PBO sheets stage by stage as external confinement reinforcement. Thus, the prestressing forces are transferred into the web of the PC girder. Figure 8 gives the test set-up of the PC specimen strengthened with externally P-PUT technique and subjected to four-point bending.

4 Installation of Distributed Fiber Optic Sensing System

4.1 Bonding methods for BOTDR optic fiber sensing

For the purpose of strain measurement for concrete structures, two kinds of bonding method of the optic fiber sensor to the surface of the concrete specimen are considered here. One called overall bonding (OB) method where the sensing region of fiber optic sensor is bonded completely on the surface of specimen with epoxy resin. Another called as point fixation (BF) method where only the two ends of the sensing region of the fiber optic sensor are bonded to the specimen in order to form a uniform strain distribution within the two bonding points (Figure 9). Therefore, the measured strain value is the average strain value within the measured region.

4.2 Installation of BOTDR fiber optic sensor for PC girder strengthened with externally PBO sheets

In this study, the fiber optic sensors were bonded on the upgraded PC girder after the releasing of the pre-tension of PBO sheets, so the BOTDR fiber optic sensor was used to monitor the strain variation of concrete girder and PBO sheets relative to the state before the optic fiber installation under different load cases. For the simplicity of description, the strain distribution means the strain distribution variation in the following context. The installation of BOTDR fiber optic sensor on the PC girder is described in Figure 10 and 11. For the convenience of description, the whole fiber optic sensor from the connector of BOTDR device is divided into five sensing regions called F1, F2, F3, F4 and F5 successively. The first two sensing regions, F1 and F2, are bonded on the outer surface of the PBO sheets to measure the strain distribution of the PBO sheets under different loading levels. Sensing region F1 is bonded on the outer surface of PBO sheets with the point fixation(PF) method. The interval of fixation points is set to be 1.5 meter, which is longer than the special resolution of the employed BOTDR device. Sensing region F2 is mounted on the outer surface of PBO sheets by overall bonding(OB) method. Sensing regions, F3 and F4, are bonded on the concrete surface of the bottom tensional flange with PF and OB methods, respectively, to measure the tensional strain of concrete under different load cases. Sensing region F5 is pasted on the surface of the compressive flange to monitor the compressive strain distribution of concrete.

Figure 12 gives the installation situation of fiber optic sensor installed on the surface of concrete and PBO sheets. Figure 12(a) shows the fiber optic sensor bonded on the surface of concrete near to the bottom surface of the strengthened PC girder. Figure 12(b) indicates the installation of fiber optic sensor on the surface of PBO sheets. A series of strain gages are also installed on the surface of PBO sheets and concrete for the purpose of comparison.

5 Distributed Sensing Results by Optic Fiber Sensing

5.1 Strain variation measurement results by BOTDR and curve fitting

After the fiber optic sensors are bonded on the surface of PBO sheets and concrete, four-point bending test for the PC girder strengthened with the P-PUT method is carried out. Experimental study shows that the updated PC girder damaged at load case of 606kN in the form of PBO sheets rupture. The fiber optic sensors were broken when the load reached 490kN because of the large local strain induced by the cracks of the concrete flange.

Even though the well-known advantages of fiber optic sensing include electromagnetic noise immunity, electrically passive operation, low weight penalty, high sensitivity, and easy multiplexing capability, the strain measurement results of BOTDR is usually not smooth probably because of the current algorithms to decide the frequency shift of Brillouin backscattering or the limit of hardware of the current optic fiber strain analyzer. It is necessary to fit and smooth the strain distribution measurement reslut.

Here a 10th degree polynomial curve fitting method is adopted to process the strain field data. The fitting curve of the field data is described in the following equation,

$$s_f = p_1 x^{10} + p_2 x^9 + p_3 x^8 + \cdots + p_n x^{11-n} + \cdots + p_{10} x + p_{11} \quad (3)$$

where s_f is the fit strain value at distance x , the coefficients of $p_i, (i = 1,11)$ can be decided from the field strain measurement.

Figure 13(a) and (b) give the field strain measurement on PBO sheets from fiber optic sensors and the corresponding fitting curves with PF bonding method and the OB method, respectively, under load cases of 250kN, 50kN and 490kN. Figure 14 (a) and (b) indicate the field strain measurement on concrete tensile flange from fiber optic sensors and the corresponding fitting curves with the PF bonding method and the OB method, respectively, under load cases of 250kN, 50kN and 490kN. From both Figure 13 and 14, it is clear that the strains of PBO and concrete increased with the increase of load level. But from the results of Figure 13(a) and 14(a), parts of the strain distribution result of FP method are unstable and vary very sharply. For this four-point bending test, the peak value of the strain distribution should appear in the middle span of the PC girder, but the peak values of the fitting curves shown in Figure 13(a) and 14(a) do not appear at the same position. Figure 15 shows an illustrative strain distribution near to and within the fixation point of the optic fiber sensor bonded by PF method. The strain within the center of the fixation point is very small, and the strains along the optic fiber outside the fixation point are constant, there are great strain differences in the small region between the center of the fixation point and the uniformly distributed strain region. The sharp strain variation in the small region, which is extremely shorter than the spatial resolution of the BOTDR instrument, is the probable reason of the unstable performance. The unbelievable data are omitted and two reasonable fitting curves for the PBO sheets and concrete strain distribution by the PF method are obtained. Figure 16(a) and (b) give the comparison of strain measurement results and the fitting curves on PBO sheets and concrete flange, respectively. It is clear that the positions of peak strain on the fitting curve meet with each other.

5.2 Bonding/debonding monitoring by distributed optic fiber sensing

For FRP strengthened concrete structures, the FRP bonding technique is critical to ensure good performance of the adhesive layer, through which stresses can be transmitted from concrete substrate to FRP. Any failure in this stress transmission zone may invalidate the composite action between concrete and FRP and lead to a brittle, catastrophic failure without foreboding prior to achieving the expected strengthening effects, which is often observed in the experiments of FRP-strengthened RC beams, such as premature failure at ends of FRP composites and FRP debonding caused by intermediate flexural cracks or shear cracks. (Niu et al., 2002) In order to achieve effective strengthening by reinforced or prestressed FRP, debonding between concrete and FRP needs to be avoided.

The strain distribution measurement of concrete and PBO sheets by optic fiber provides a way to monitor whether debonding occurs or not in the adhesive layer between the PBO sheets and concrete. Figure 17 (a), (b) and (c) give the comparison of strain distribution on the surface of PBO sheets and tension concrete flange at different load cases. It can be found that the strain distribution on the surface of the PBO sheets is close to that of the concrete. There are not great differences between the strain distribution of PBO sheets and concrete. This means that there are no debonding between PBO sheets and tension concrete surface along the span of the PC girder when load is less than 490KN. The interface between PBO and concrete was perfect and no interfacial shift occurred when load reached 490kN. In other words, the PBO sheets can work with the concrete. Experimental observation also shows that no debonding occurred when load level was less than 490 KN. The strain monitoring results can agree with the experimental results.

Figure 18 (a) and (b) give the comparison of the strain measurement of PBO with OB method and PF method, respectively, and concrete in the middle span under different load levels. It is clear that the strain of PBO sheets can keep close to them of the tension concrete flange in the middle span of the PC girder by both OB and PF installation methods. There is no obvious difference between the strain distribution of PBO sheets and concrete when load is lower than 490kN. Both OB and PF installation methods give reliable bonding and debonding monitoring results.

The field strain measurement results of compressive concrete flange of the upgrated PC girder and its fitting curve are shown in Figure 19. It can be found that the compressive strain of concrete increase with the increase of the load levels and the position of the peak value of each fitting curve appears in the middle of the span.

5.3 Comparison with strain gauge

Tension strain of PBO sheets and concrete

For the purpose of comparison the strain measurement results with the traditional strain gauges, a series of strain gauges are pasted on the surface of PBO sheets and concrete.

Comparison between the strain measurement along the PBO sheets and tension concrete flange by optic fibers with OB and PF installation method and these of strain gauges at the middle span of the PC girder is shown in Figure 20. It can be found that the strain measurement results from BOTDR agree well with the results of strain gauge even though there are some differences in the low load cases. The precision of the BOTDR measurement can increase with the increase of load level.

Compression strain measurement of concrete

The comparison between concrete compression strain measurement from optic fiber with OB installation method and these of strain gauges at the middle span of the PBO strengthened PC girder is shown in Figure 21. It can be found that the difference between the strain measurement from BOTDR and them from strain gauge is large when the load level is low. The maximum difference is about 300 micro-strain. When the load level increases, the difference becomes smaller. As shown in Table 2, the strain measurement accuracy of the used BOTDR system is ±0.01%. But for compression strain measurement, the accuracy of strain measurement from BOTDR may be worse especially when the strain is small.

6 CONCLUAIONS

In this study, a PBO Prestressing Upgrading Technique (P-PUT) is described briefly and employed to update a full-scale PC girder. For the purpose of evaluating the strengthening efficiency of the PBO sheets and the performance of the strengthened PC girder, specially the compressive and tensional strain distribution of concrete and PBO sheet under different load levels and the bonding performance of the PBO sheet on the concrete surface, a fiber optic sensing system with a strain/loss analyzer based on the Brillouin Optical Time Domain Deflectometry (BOTDR) technique has been employed. Two types of bonding methods for optic fiber installation called Point Fixation(PF) method and Overall Bonding(OB) method are proposed and investigated. A kind of polynomial curve fitting method is presented to processing the field data polluted with noise. Based on the experimental results, the following observations can be made:

1. A polynomial curve fitting technology is used to process the field strain measurement results especially in the case of Point Fixation Bonding method. By the polynomial curve fitting technology, smooth strain distribution results can be achieved.

2. Both OB and PF installation methods for optic fiber sensing are capable of tensional strain measurement for concrete and PBO sheets. There are no obvious differences between the strain measurements between OB and PF installation methods. The field measurement from optic fiber with the PF installation method includes more noise, but believable results can be obtained by the proposed polynomial curve fitting method. Compared with the measurement results from strain gauge, the fiber optic sensor give good results for tension strain measurement with both OB and PF installation methods, but the optic fiber for compression strain measurement includes relatively large error, especially when the compression strain is small.

3. As a distributed sensing technique, BOTDR based optic fiber sensing technique measures the strain distribution along the whole structure and provide a useful way to monitor the bonding and debonding performance of the interface between prestressed PBO sheets and concrete by comparing the strain difference between them.

4. The proposed multi-layer end anchoring system for relieving shear stress concentration at the prestressed PBO sheets ends is efficient to avoid the debonding between the concrete surface and the prestressed PBO sheets. And the proposed air bag system for PBO bonding is a useful way to ensure the bonding performance of the interface of the full-scale infrastructure strengthening and retrofit.

Experimental results show that BOTDR based distributed strain monitoring technique provides a useful strain sensing method for structural health monitoring, structural retrofitting performance evaluation, especially for the bonding and debonding monitoring of large-scale infrastructures strengthened by prestressed PBO sheets.

7. ACKNOWLEDGEMENT

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Table 1 The strain/temperature dependence of Brillouin frequency shift (UV coated optic fiber)

Table 2 Specifications of AQ 8603-BOTDR System

Table 3 Summary of material properties

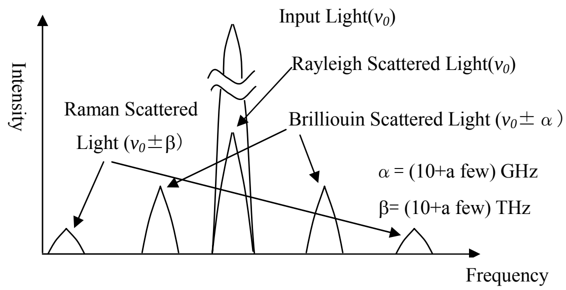


Figure 1 Scattered light spectrum in an optic fiber.

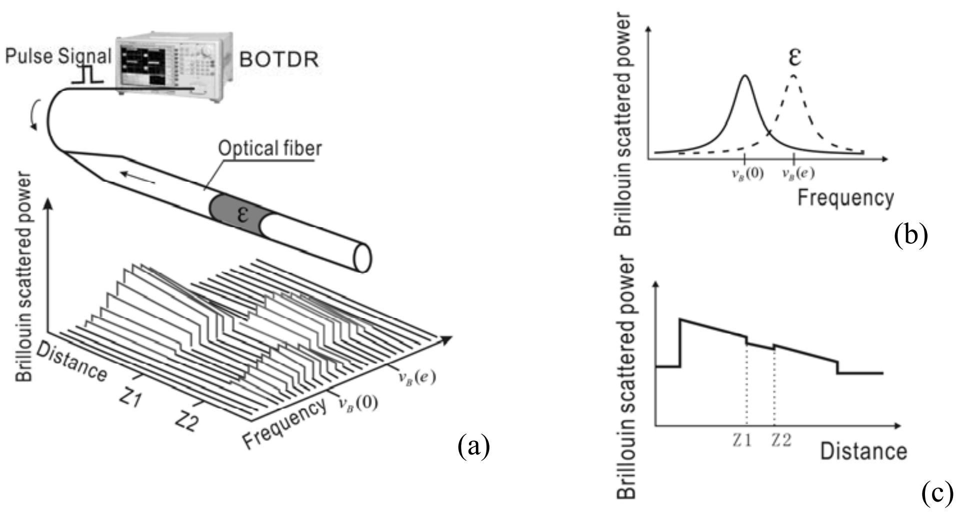


Figure 2 Brillouin back-scattering distribution at difference frequencies along the optic fiber.

Table 1 The strain/temperature dependence of Brillouin frequency shift(UV coated optic fiber)

Wavelength of input light	1.3μm	1.55μm
Temperature (dv_B/dT)	1.22MHz/℃	1MHz/℃
Strain($dv_B/d\varepsilon$)	581MHz/%	493MHz/%

T: Temperature; ε: Strain

Table 2 Specifications of AQ 8603-BOTDR System

Minimum Readout Resolution in Distance	5cm
Minimum Readout Resolution in Strain	0.00001%
Maximum Measurement Range of Strain	± 1.5%
Pulse Width of Light Source	10ns
Dynamic Range	4dB
Maximum Possible Measurement Distance	About 10km
Spatial Resolution	1m
Measurement Strain Accuracy	± 0.01% ± (2.0×10^{-5}) ×Distance

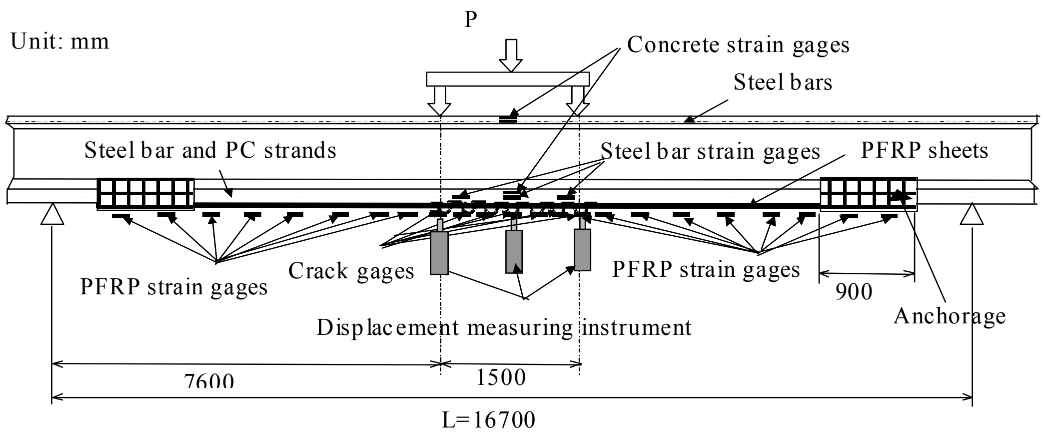


Figure 3. Test set up of the four point bending experiment of the PC girder strengthened by prestressed PBO sheets.

Table 3 Summary of material properties

Concrete	Modulus of elasticity(GPa)	33.9
	Compressive strength(Mpa)	50
PC strand	Modulus of elasticity(GPa)	200
	Tensile strength(GPa)	1.86
	Yielding strength(GPa)	1.57
Steel bar	Modulus of elasticity(GPa)	200
	Tensile strength(GPa)	0.60
	Yielding strength(GPa)	0.30
PBO sheet	Modulus of elasticity(GPa)	240
	Tensile strength(GPa)	4.0
	Width(mm)	300
	Thickness(mm)	0.128

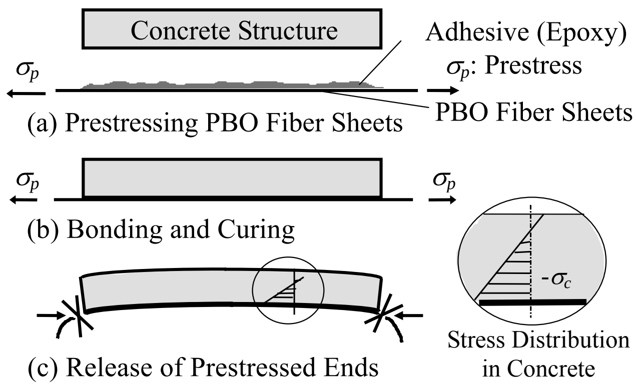


Figure 4. Strengthening of concrete structure with prestressed PBO fiber sheets

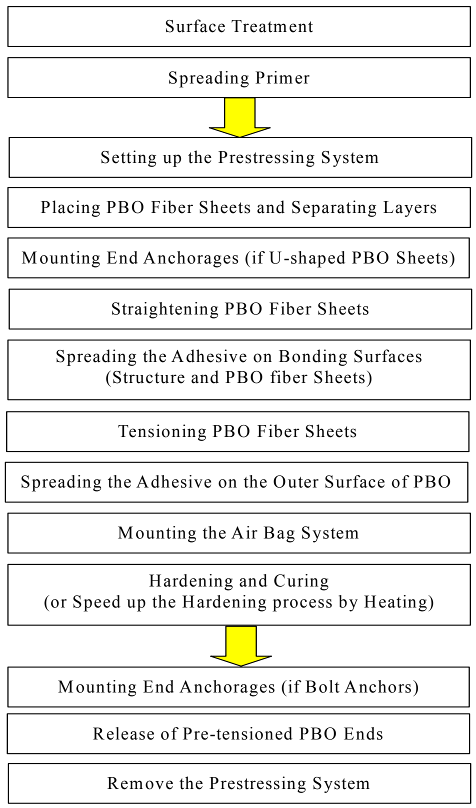


Figure 5. Flowchart of P-PUT strengthening method.

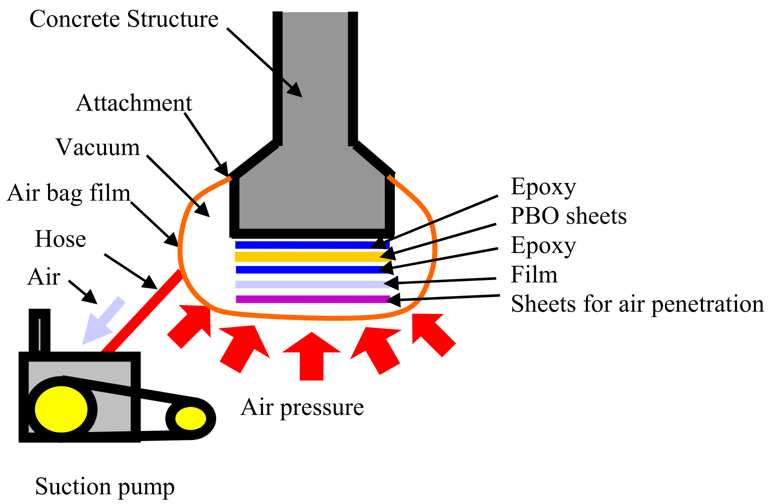


Figure 6. Air bag system for PBO bonding.

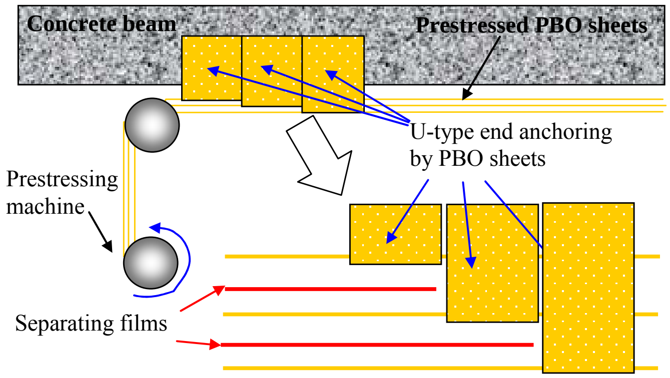


Figure 7. U-type end anchoring system by bonded PBO sheets

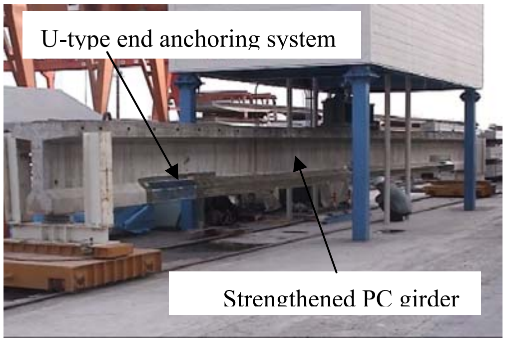


Figure8. The PC specimen strengthened with P-PUT method

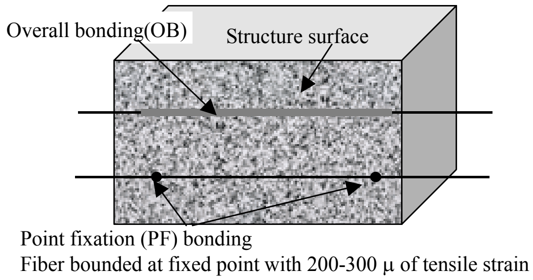


Figure 9. Installation methods of optic fiber sensors.

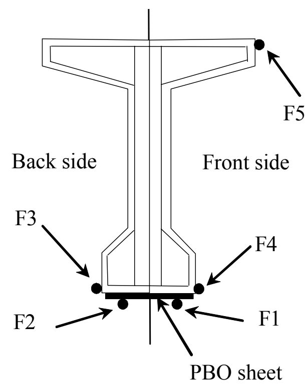


Figure 10. Installation position of fiber optic sensor on the cross section of strengthened PC girder.

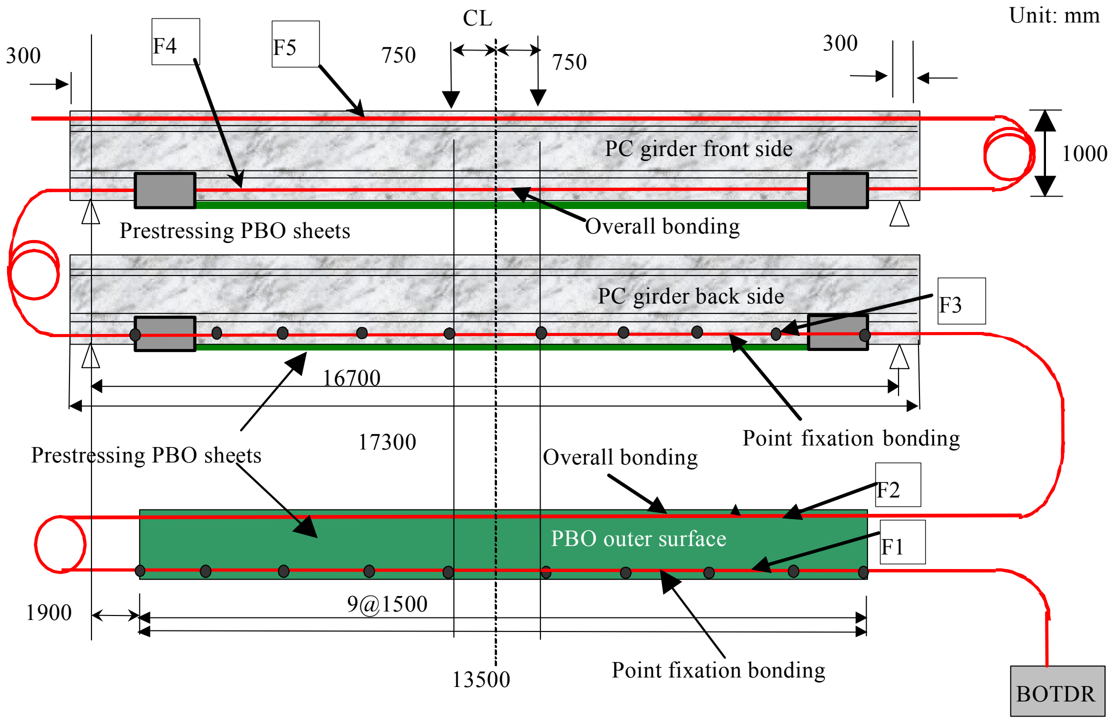
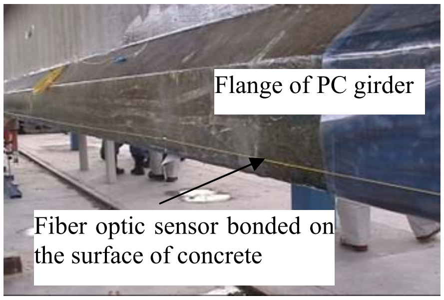
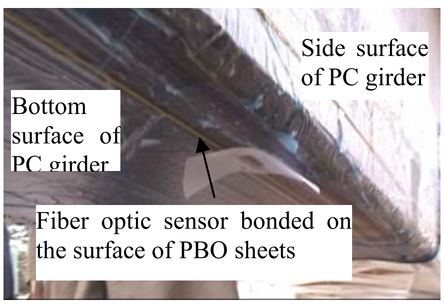


Figure 11. Fiber optic sensor installed on the strengthened PC girder with different bonding methods.

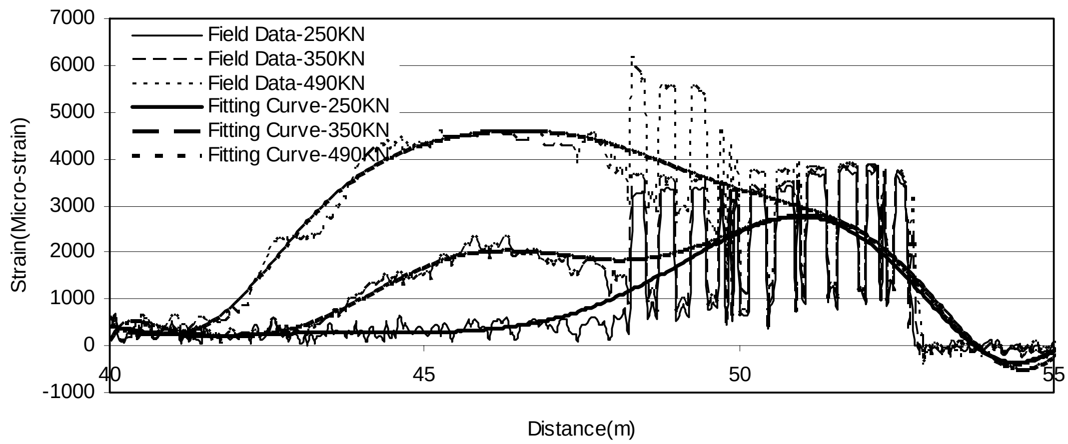


(a) Fiber optic sensor bonded on the surface of concrete

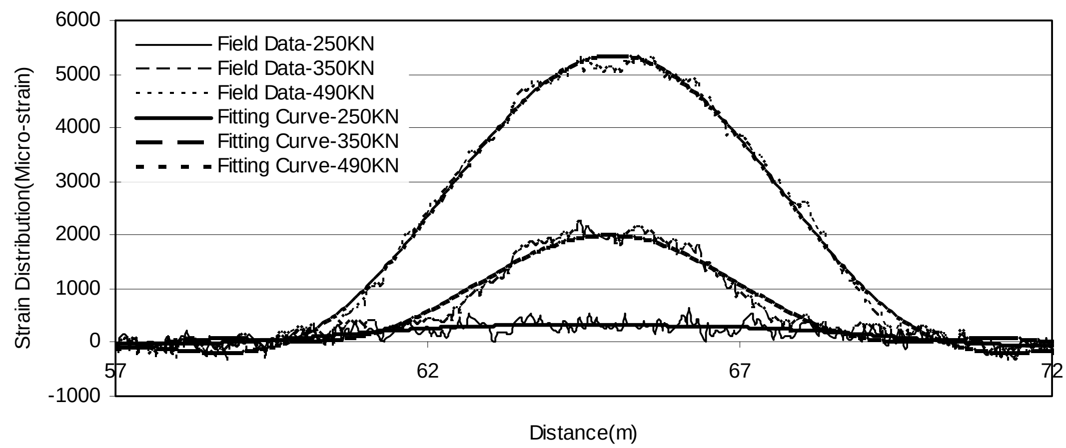


(b) Fiber optic sensor bonded on the surface of PBO sheets

Figure 12. Fiber optic sensor installed on the surface of concrete and PBO sheets.

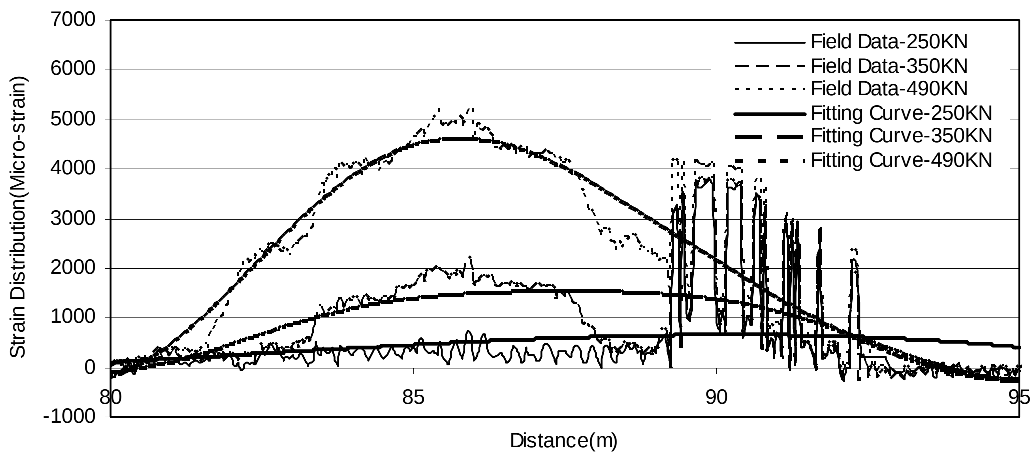


(a) Point fixation installation

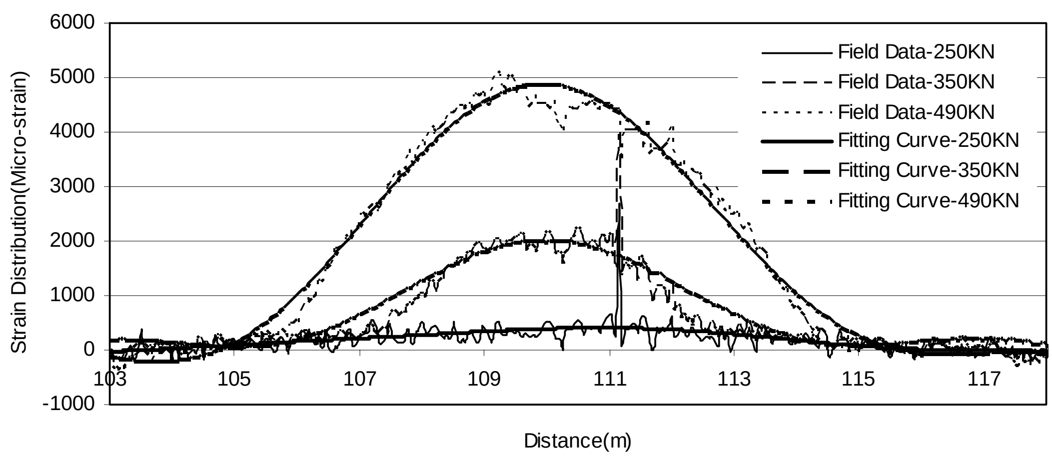


(b) Overall bounding installation

Figure 13. Strain measurement results and fitting curves of PBO sheets.



(a) Point fixation installation



(b) Overall bounding installation

Figure 14. Strain measurement results and fitting curves of concrete of tensional flange.

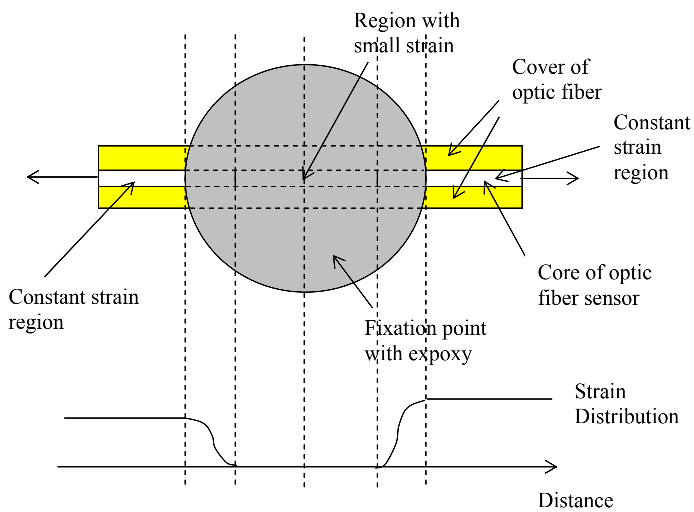
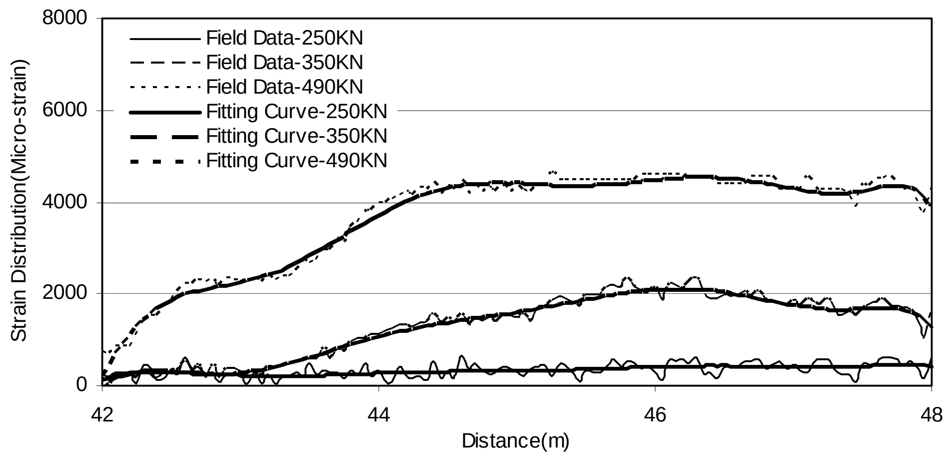
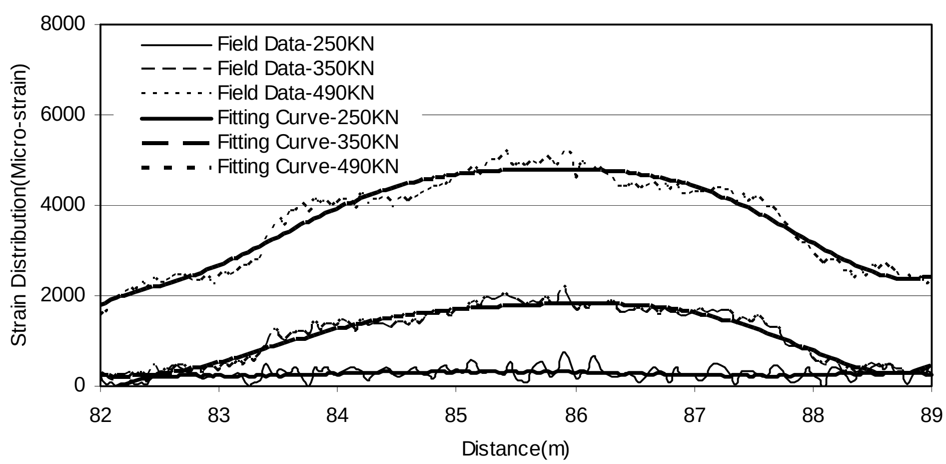


Figure 15. Strain distribution on the fixation point.

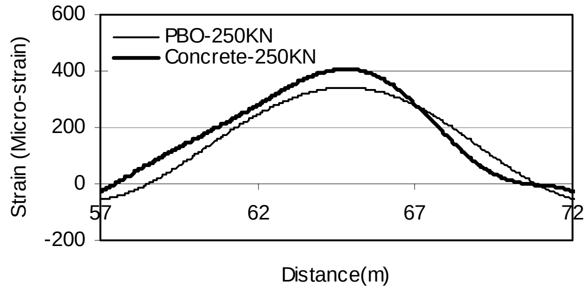


(a) Strain distribution along PBO sheets

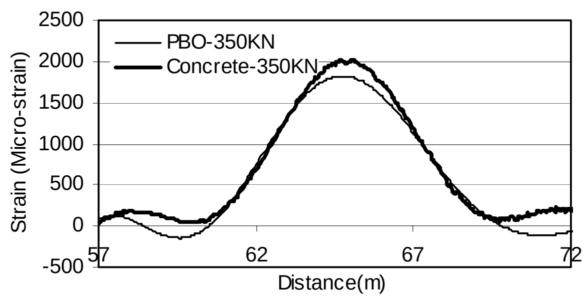


(b) Strain distribution along tension concrete flange

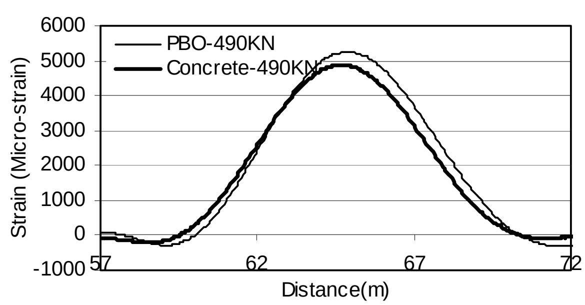
Figure 16. Strain measurement results and fitting curves.



(a) Strain distribution under 250 KN

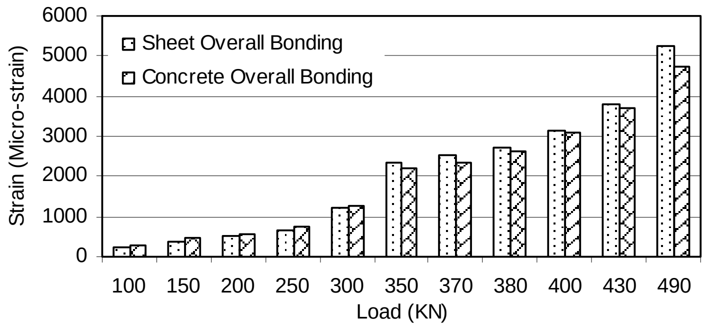


(b) Strain distribution under 350 KN

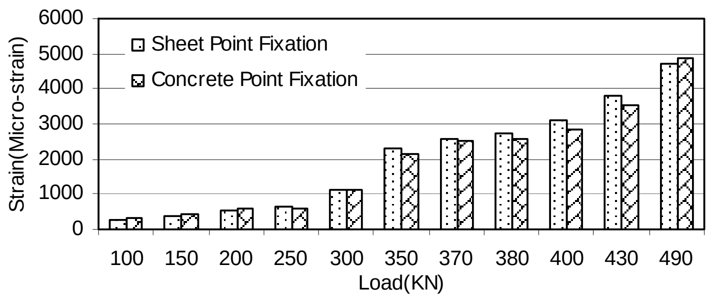


(a) Strain distribution under 490 KN

Figure 17. Comparison of strain distribution along the surface of PBO sheets with them of tension concrete flange under different load levels



(a) Overall bounding installation method



(b) Point fixation installation method

Figure 18. Comparison of strain measurement of PBO sheets and tension concrete flange in the middle span under different load levels.

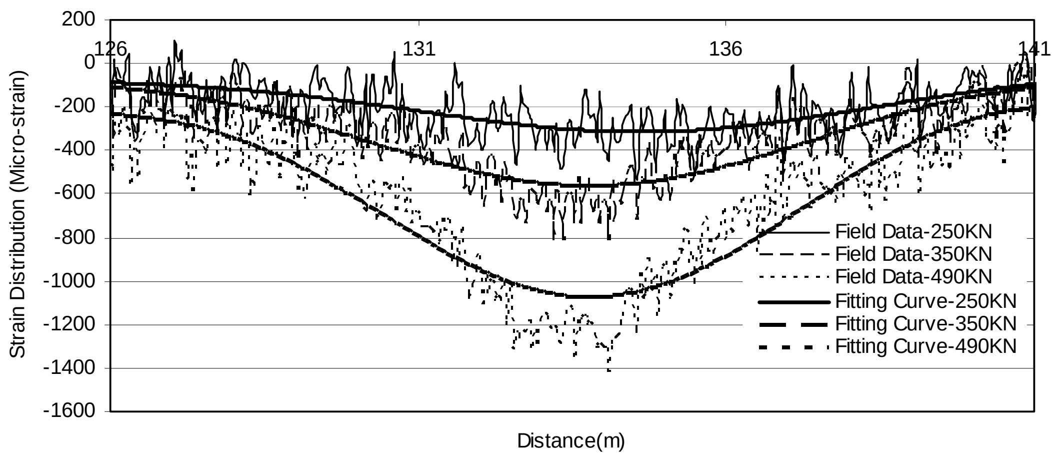


Figure 19. Compression strain measurement along the compression concrete flange.

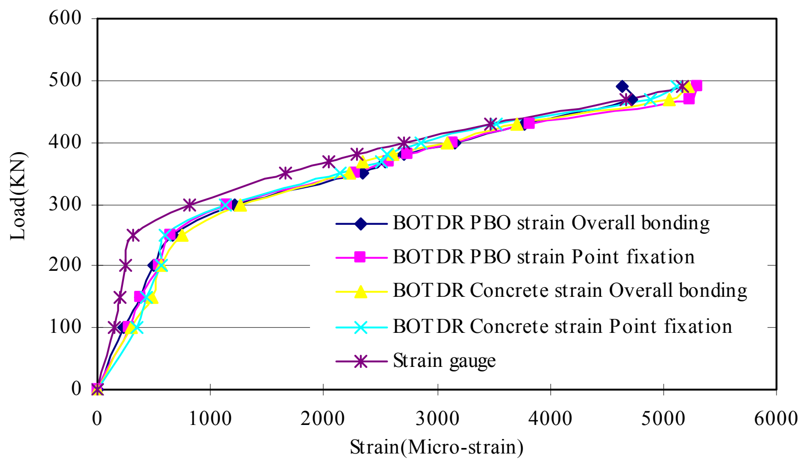


Figure 20. Tension strain measurement of PBO sheets compared with strain gauges in middle span.

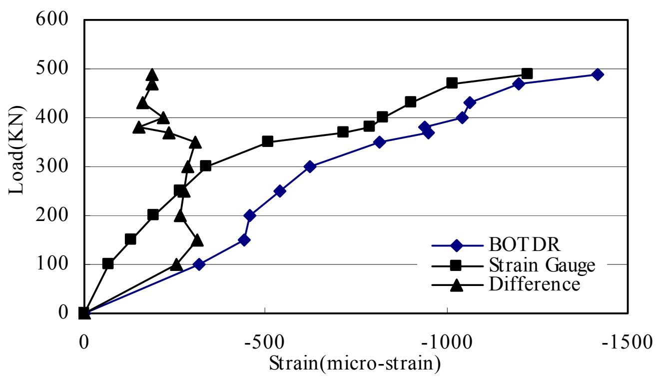


Figure 21. Compressive strain measurement of concrete compared with strain gauges in middle span.