

Strain and Lateral Deformation Monitoring of Reinforced Concrete Column using Distributed Fibre Optical Sensor

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Abstract. A reinforced concrete frame structure with a large-span curved beam was designed for a stadium. The finite element analyses show that the stiffness and thus the lateral deformation of the column are critical to the performance of the curved beam. Therefore, distributed fibre optical sensors (DFOS) were used to monitor the strain and lateral deformation. The sensors were installed on the reinforcing rebars close to the interior and exterior sides of the column, and the lateral deformation can be estimated based on the double integration method. Monitoring measurements were taken after demolding and when the roof finish construction. The monitoring results show that the column's stress is less than 200 MPa with lateral deformation less than 0.5 mm at mid height of column. Since the rebars are within elastic range and the lateral deformation is small, it is conclude that there are sufficient lateral restraints for the large-span curved beam at the beam-column joints.

Keywords: Strain monitoring; reinforced column; distributed optical fibre sensor (DFOS).

1. Introduction

Under the dual impetus of accelerated global urbanisation and engineering technology innovation, infrastructure shows a trend of large-scale growth, among which long-span concrete structures are the most representative [1]. These structures have been widely applied in landmark projects, including stadiums, aviation hubs, and transportation terminals [2].

Distributed optical fibre sensor (DFOS) technology is an advanced sensing method that employs optical fibres as sensors to detect the information of physical quantities by analysing changes in optical signals within the fibres [3]. With high sensitivity and resolution, low cost, long distance, and large area monitoring ability, and resistance to electromagnetic interference and harsh environments [4]. Based on the different scattering principles of light in optical fibers, the main optical fiber sensing technologies include Brillouin optical correlation domain, time domain analysis and reflection technology [5], Raman frequency domain and time domain reflection technology [6], as well as Rayleigh frequency domain and time domain reflection technology [7]. Among these, optical frequency domain reflectometry (OFDR) based on Rayleigh scattering has garnered significant academic attention due to its multiparameter measurement capability (temperature, strain, vibration) and millimetre-scale spatial resolution [8]. In recent years, OFDR technology has been increasingly adopted as an alternative to conventional sensor technologies in various fields and civil engineering materials [9].

A 63-meter by 36-meter swimming pool was designed with 15 reinforced concrete frames with a spacing of 4.5 meters, as shown in Fig. 1a). The 30 meter span roof reinforcing beam was designed using reinforced concrete beam with hollow sections and varying sectional heights, as shown in Fig. 1b), in order to avoid the potential corrosion risk if adopting metal structures. The performance of the reinforced curved beam is highly dependent on the structural performance of the supporting columns; thus, its structural monitoring becomes necessary. This paper discusses the monitoring of the column deformation using the distributed optical fibre sensor (DFOS) technology. The results of the two columns labelled in Fig. 1a) were reported in this paper.

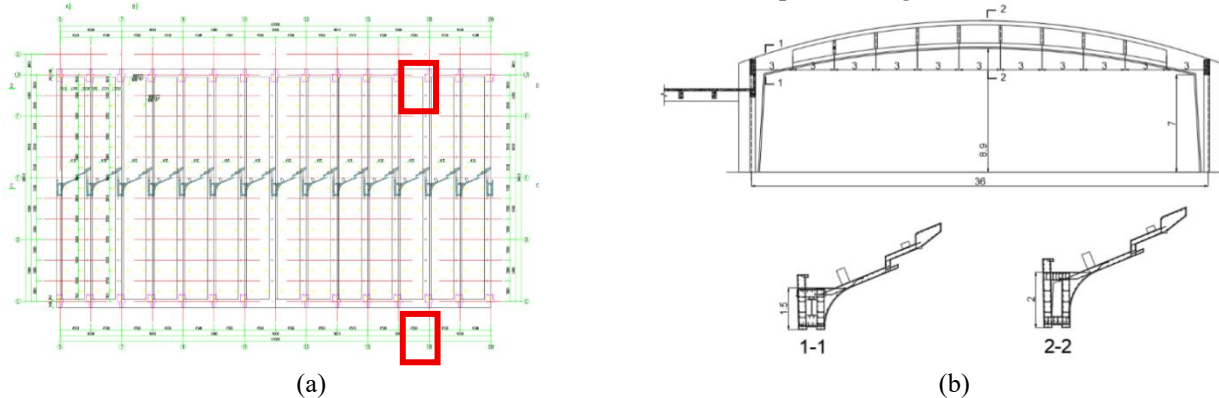


Fig. 1 The project overview: a) Plane view of the frames, b) Side view of the frame.

2. Methodology

2.1 Finite Element Analyses

Finite element analyses based on a simplified beam model were carried out first to explore the performance under different levels of support restraint. C50 concrete was inputted into the programme with the modules of elasticity, axial compressive strength of 34550 MPa and 23.1 MPa, respectively. The cracking and crush stress versus strain curves are shown in Fig. 2a) and b). The stress versus strain of steel material is shown in Fig. 2c), which has a yielding strength of 400 MPa and modulus of elasticity of 205 GPa.

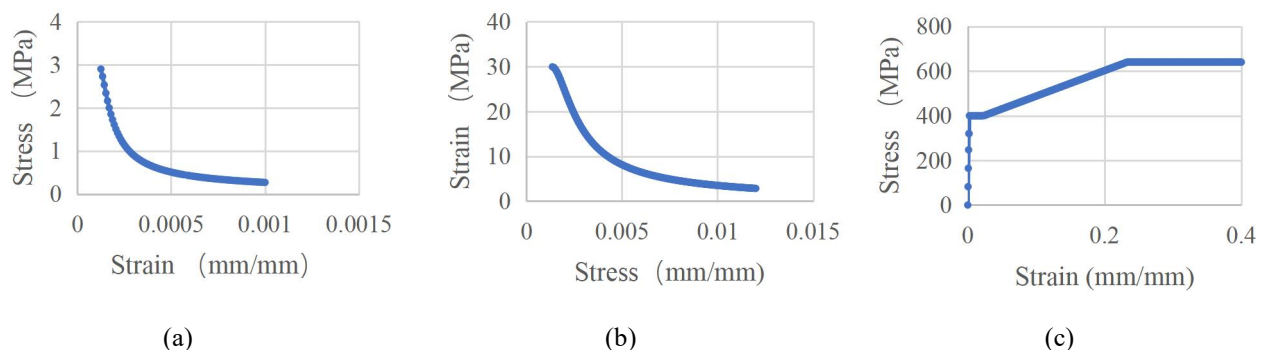


Fig. 2 Material behaviour: a) cracking stress versus strain of concrete, b) crushing stress versus strain of concrete, c) stress versus strain of steel.

Curved beams were modelled in six segments to mimic the curved top surface of the beam. While five of the six segments have hollow sections, the one close to the beam-column joint is solid as specified in the design document. Solid elements were used for concrete while truss elements were used for rebars, as shown in Fig. 3a). The meshed parts were then assembled together by inserting rebar elements into concrete, as shown in Fig. 3b). Self-weight plus a 0.036N/mm² top surface pressure were applied to the model. All other settings using the programme defaults.

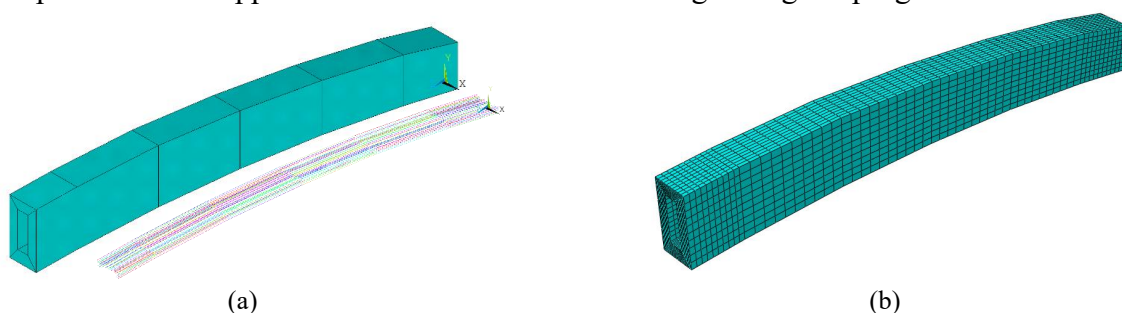


Fig. 3 Finite element model: a) geometric model, b) meshed model.

2.2 Installation of the Distributed Optical Fibre Sensor

Several fibres were attached to the column's reinforcing rebars; their locations and labels are shown in Fig. 4a) and 4b), respectively, for columns Z1 and Z2. The detailed explanations are shown in Table 1. The onsite operation process of glueing the fibre to the rebar is shown in Fig. 4c) and the installed fibres can be seen in Fig. 4d) after placing the steel reinforcing cage before casting.

Table 1. Strain monitoring equipment

Purpose	Coding	Location
For column strain monitoring	Z1/2-ST-1	Strain from the rebar on the interior side of the column, close to the beam-column joint
	Z1/2-ST-2	Strain from the rebar on the interior side of the column, close to the support
	Z1/2-ST-3	Strain from rebar on the exterior side of the column, close to the beam-column joint
	Z1/2-ST-4	Strain from the rebar on the exterior side of the column, close to the support
For column deflection monitoring	Z1/2-DL-1	Strain from rebar at the interior side of the column, crossing the height
	Z1/2-DL-2	Temperature from the rebar at the interior side of the column, across the height
For temperature monitoring	Z1/2-DL-1-T	Strain from the rebar at the exterior side of the column, cross the height
	Z1/2-DL-2-T	Temperature from the rebar at the exterior side of the column, across the height

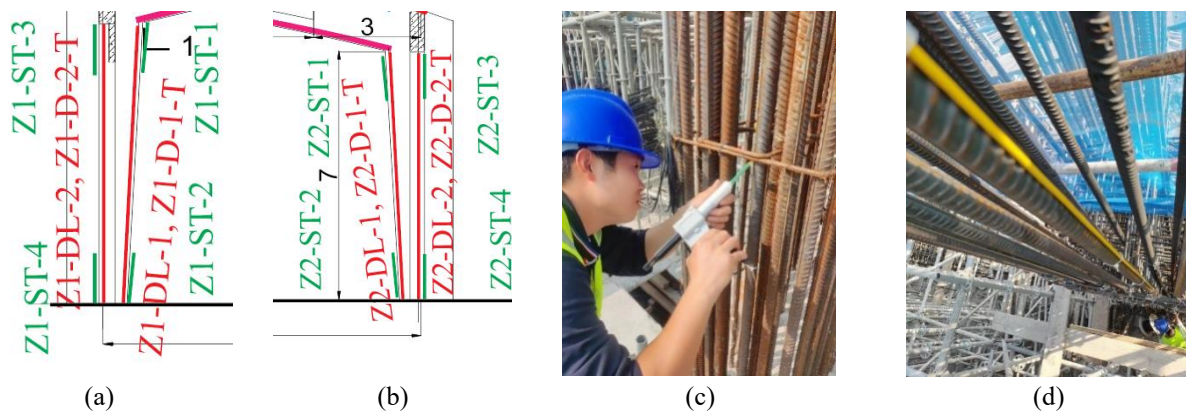


Fig. 4 The project overview: a) Plane view of the frames, b) Side view of the frame.

After installation, three field data collections were carried out as shown in Table 2. Three measurements were conducted. While the first collection served as the baseline, the following two measurements captured the column performance after the demolding of the beams and after finishing the roof construction. The environment temperatures on the measurement days are shown in Table 2.

Table 2. Field data collections

Seq	Conditions	Weather conditions	
		High	Low
S1	One day after casting the beams, set as a baseline	12 °C	7 °C
S2	89 days after casting the beams, after demolding	14 °C	12 °C
S3	288 days after casting the beams, the roof was completed	25 °C	20 °C

2.3 Lateral Deformation Estimation

The lateral deformation of the column can be estimated based on the following equation:

$$v(z) = \sum \sum \frac{\varepsilon_m(z)}{R} \Delta z \Delta z \quad (1)$$

In which, $\varepsilon_m(z)$ is the strain difference of the rebars close to the interior and exterior surfaces of the column section at location z , after the temperature adjustment. R is the distance between the two rebars on the cross-section. Δz is the length of the fibre measurement sampling segment, which was taken as 10 mm in this study. By assuming the fix boundary conditions at the base of the column, the lateral deformation can be estimated by double integration.

3. Finite Element Analyses Results

Besides the boundaries at the symmetric plane, two sets of boundary conditions were applied to the beam-column joint section. Fig 5a) and b), show the beam deflection and strain of concrete when the end of the beam is perfectly fixed. Under this condition, the vertical deflection is only 2.95 mm, and the maximum tensile strain is 82 microstrain on top of the beam near the beam-column joint. Under the other boundary condition, which allowed the lateral movement of the end section but fixed its rotation, leads to different performance. The concrete cracked severely close to the mid-span as shown in Fig. 5d), and the analysis stops when it applies 56% of the total loading. The deflection of the beam exceeded 34 mm at that step, and the corresponding lateral movement of the beam end is 8.9 mm.

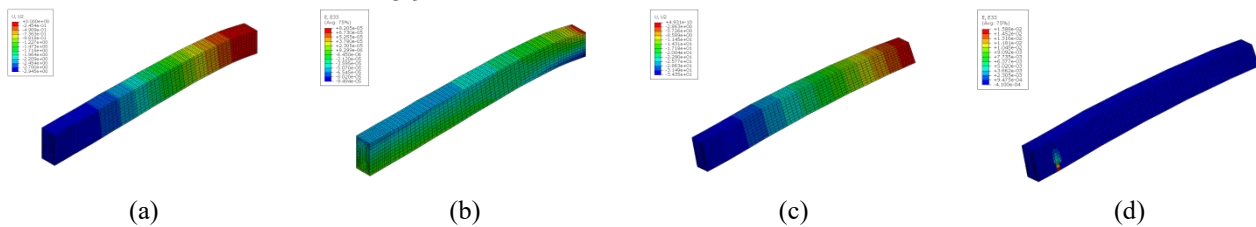


Fig. 5 The project overview: a) Plane view of the frames, b) Side view of the frame.

The finite element results demonstrated that the stiffness and cracking of the concrete in the beam are highly correlated to the lateral stiffness and deformation of the supporting columns. Monitoring the column performance is helpful to examine the performance of the large-span curved beam.

4. Measurement Results

4.1 Results of Temperature

The temperature measurements of the two columns on interior and exterior surfaces are shown in Figs 6a) and b) for columns Z1 and Z2, respectively. It was observed that the temperature is higher after demolding the beam, while lower after roof completion, because the data collection happens at different times during the day. After the completion of the roof, the columns are also shaded from the direct exposure of sunlight. The mode value of temperature recordings, as shown with the dash lines in Fig. 6, were used to revise the strain readings, thus estimating the columns' lateral deflections.

4.2 Results of Lateral Deformation Estimation

The strain recording along the height of the column and after the temperature adjustment is shown in Fig. 7a) and b) for Z1 and Z2, respectively. While the interior strain Z1-1 and Z2-1 show generally positive values, the rebars are in tension. The rebar strain at the exterior column surface varies from positive to negative. By the method introduced in section 2.3. The lateral deformation of the columns can be estimated. The results are shown in Fig. 8a) and b), with and without considering the temperature corrections. Along with the increase of the roof loading, the lateral deformation of the column did not increase significantly as indicated by the measurements, which suffers from the dual impact of the increased vertical loading and the potential rotation at the end of the concrete beam.

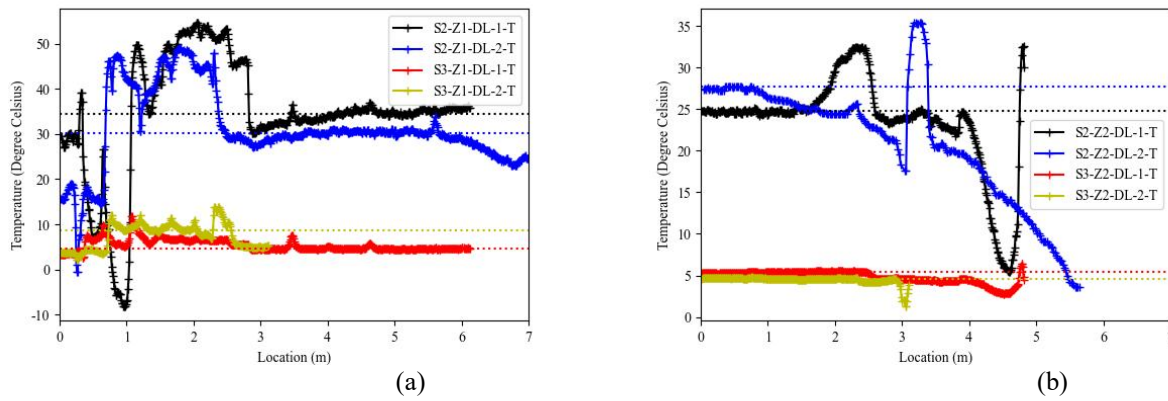


Fig. 6 The temperature measurement: a) Z1, b) Z2.

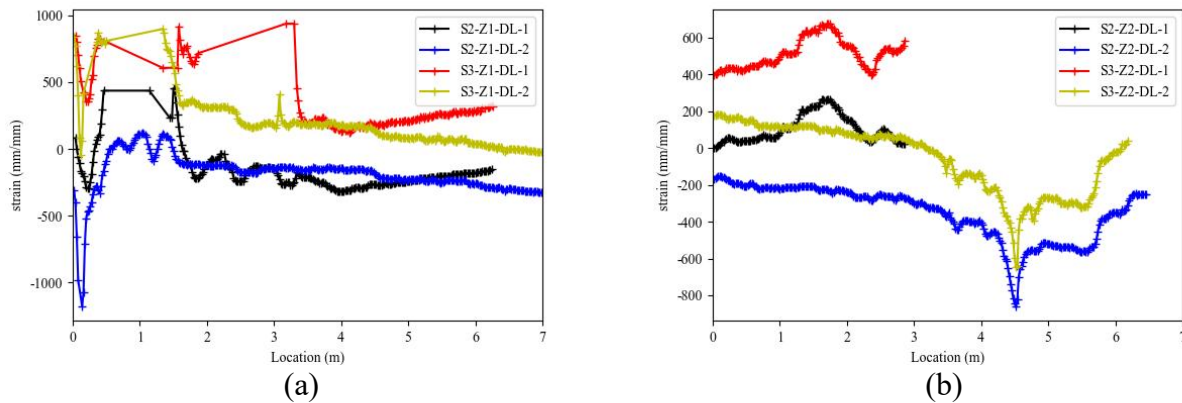


Fig. 7 The strain measurement: a) Z1, b) Z2.

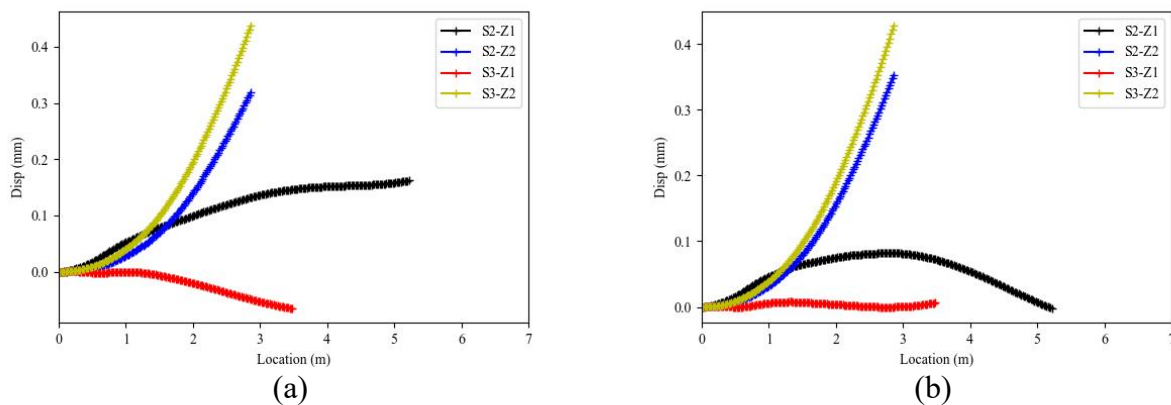


Fig. 8 The lateral deformation of columns: a) Before temperature correction, b) after temperature correction.

4.3 Results of Strain

The strains of rebars in the columns at the support and close to the joint are shown in Fig. 9, at the top and bottom of the columns for Z1 and Z2. Generally speaking, the strain levels in the rebars are low, and the stresses are less than 200 MPa and below the yielding strength. Considering the high stiffness of the column, the large-span reinforced curved beam is predicted to behave as a beam with a fix end support. Due to the technical difficulties, some strain readings are missing, such as Z2-ST-2.

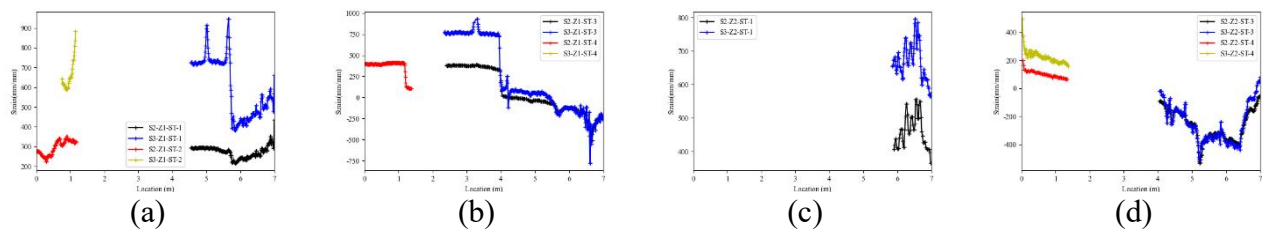


Fig. 9 The rebar strain in column: a) Z1-S1/S2, b) Z1-S3/S4, c) Z2-S1/S2, d) Z2-S3/S4

5. Conclusions and Discussions

This study employed a distributed optical fibre sensor to monitor the columns' performance, thus predicting the behaviour of the large-span reinforced curved beam. The following conclusions can be drawn:

1. Simplified finite element analyses revealed that the performance of the beam is highly correlated to the lateral stiffness of the columns, which justified the necessity of monitoring work.
2. After finishing the roof construction, the maximum rebar stress is less than 200 MPa and still within the elastic range. The estimated lateral deformation of the columns is less than 0.5 mm at the mid-height of the column.
3. Based on the observed performance of the columns, the large-span reinforced curved beam is predicted to behave as a beam with a fix end support.

It shall be noted that data filtering was enforced on the raw collected data to eliminate the unrealistic sparking in the recording, which is commonly found in the DFOS measurements.

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