

Monitoring Masonry Wall Performance Using Strain Gauge and Distributed Fiber Optical Sensor

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Abstract. Current, a substantial number of masonry structures remain in existence, and it is of great significance to monitor their safety. This study employs quasi-static testing of masonry walls as the research objective to monitor masonry wall performance using both strain gauge and distributed fiber optical sensor (DFOS). This study revealed the failure patterns of masonry wall under the quasi-static condition. By comparing the results from single-point optical fiber strain measurement with those from strain gauge, the feasibility and precision of DFOS for strain monitoring in masonry structure were validated.

Keywords: Strain monitoring; masonry wall; strain gauge; distributed optical fiber sensor (DFOS).

1. Introduction

Masonry structures have a long history in the field of civil engineering. To this day, numerous renowned masonry buildings are preserved worldwide, and masonry structures remain a predominant form of residential construction in both urban and rural areas [1]. However, during their service life, masonry structures are subjected to multiple factors, including limitations of early construction techniques, seismic activities, corrosion, and material degradation, leading to varying degrees of damage and deterioration. Many masonry structures have gradually lost their original appearance and integrity, raising increasing concerns about their safety [2]. Strain measurement, as an effective means of structural safety assessment, can capture the stress amplification phenomena prior to sudden structural failures, making it crucial for monitoring the safety of masonry structures.

In recent years, the integration of emerging sensing technologies and computer vision has driven the evolution of strain measurement from traditional discrete point-based methods to continuous full-field monitoring. Current strain measurement techniques primarily include resistive strain gauges [3], distributed fiber optic sensing (DFOS) [4, 5], and digital image correlation (DIC) [6]. While strain gauge remains the dominant method due to its well-established theoretical framework and ease of implementation, it has limitations in practical applications: local strain measurements at single points fail to reflect the overall structural strain, and poor adhesion or high-strain environments can reduce the survival rate. Advances in technology have introduced innovative solutions, such as DFOS based on the optical frequency domain reflectometer (OFDR), which enables continuous strain monitoring at a millimeter-level spatial resolution, offering a new approach for structural health monitoring. Wu, et al. [4] validated the effectiveness of OFDR technology in reinforced concrete beams through four-point loading tests with surface-mounted and embedded fiber optic sensors. Their findings demonstrated that OFDR technology can detect micro-cracks invisible to the naked eye, with strain peaks accurately indicating crack locations, achieving a positioning error of less than 1 cm. Tan, et al. [7] further explored the application of OFDR technology in high-performance fibre-reinforced concrete (HPFRC) beams, particularly in crack width measurement and visualization. They developed a crack width calculation method based on the integration of strain distribution, eliminating the assumption of linear strain distribution in traditional method and achieving a spatial resolution of 0.65 mm. Experimental results indicated that DFOS can detect micro-cracks at an early stage and visualize cracks through

strain distribution maps. The measured crack widths showed high consistency with those obtained from crack microscopes, confirming the reliability of the sensors.

In previous retrofitting tests of masonry walls, it was observed that overly strong strengthen materials could result in no apparent damage to the surface after pseudo-static test, while internal damage had already occurred within the masonry walls. Therefore, this study employs pseudo-static test to monitor the strain of masonry walls using OFDR technology and compares the results with those from traditional strain gauges. The aim is to verify the feasibility and accuracy of OFDR technology for strain monitoring in masonry structure. The findings of this research will provide significant theoretical and experimental support for the health monitoring of masonry structure.

2. Methodology

2.1 Strain Gauge

As the earliest applied sensing technology in structural health monitoring, resistance strain gauges consist of four primary components: a sensitive grid, substrate, protective coating, and lead wires. These devices operate on the principle of piezoresistive effect in metallic sensing grids. During experimental implementation, the gauge is securely bonded to the specimen surface, enabling synchronized deformation between the sensitive grid and test specimen. The resulting resistance variation is captured by a strain gauge reader and subsequently converted to strain values through established electromechanical relationships [3].

2.2 DFOS Based on OFDR

DFOS based on OFDR represents a fully distributed sensing technology capable of simultaneous temperature and strain measurement through analysis of backward Rayleigh scattering variations. The system configuration employs a frequency-swept laser source that generates linear frequency-modulated optical waves. Through an optical coupler, the laser output splits into two paths: reference light (reflected by a fixed mirror) and probe light (launched into the sensing fiber). Environmental perturbations (temperature, pressure, or strain) along the fiber length induce localized changes in Rayleigh scattering characteristics. The interference between returning scattered light and reference light produces beat frequency signals detected by a photodiode array. Subsequent fast Fourier transform (FFT) analysis of these signals enables spatial resolution of scattering profiles, from which distributed strain/temperature measurements are derived through established optomechanical relationships [4].

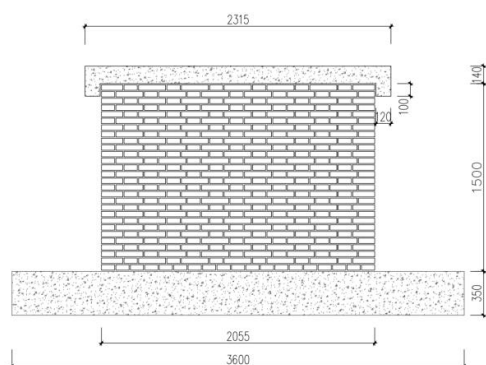
3. Masonry wall monitoring experiment

3.1 Specimen Design

The experimental investigation employed an unreinforced masonry wall specimen (Fig. 1) comprising three structural components: a reinforced concrete top beam, a brick masonry wall, and a reinforced concrete bottom beam. The top and bottom beams served dual functions of load transfer and specimen fixation. To prevent interfacial failure at beam-wall junctions, both connection zones were reinforced with 10 mm thick cement mortar (mix ratio: cement: medium sand is 1:3). Additionally, the top beam featured specially designed “cat ear” protrusions to enhance interlocking with the wall and prevent detachment during loading. The dimensions of the masonry wall are shown in Fig. 1 a), yielding a height-to-width ratio of 0.73. Constructed using a running-bond pattern with MU10-grade non-standard bricks (dimensions: 216 mm × 105 mm × 43 mm), the mortar was assembled using M1-grade cement mortar (mix ratio: cement: medium sand is 1:11). The compressive strength of brick, mortar, C40, and C50 concrete are 9.3 MPa, 0.63 MPa, 45.9 MPa, and 53.9 MPa, respectively.

3.2 Masonry Wall Test Setup and Loading Scheme

The test was conducted in the Structural Engineering Laboratory of Xi'an Jiao Tong-Liverpool University. The loading setup is shown in Fig. 1 b). The vertical load was applied using the 500T hydraulic jack through a horizontal loading beam, while the horizontal load was introduced via a steel reaction beam connected to a 100T servo-controlled actuator. The quasi-static cyclic loading protocol followed the Standard (JGJ 101—2015). Prior to testing, the specimen was securely anchored to the reaction floor using high-strength bolts, and the bottom beam was laterally restrained by hydraulic jacks to prevent sliding during loading.



Dimensions of the specimen



Test Setup

Figure 1. The unreinforced masonry wall and test setup

The loading procedure consisted of four stages:

1) Preloading (10 kN): A preliminary load was applied to verify the stability of the test setup and ensure proper instrumentation function.

2) Vertical Loading (5 kN/min): The axial load was gradually increased until reaching a compressive stress of 0.3 MPa (237 kN), which was then kept constant.

3) Horizontal Cyclic Loading (Displacement Control): The specimen was subjected to reversed cyclic loading, with push (positive) and pull (negative) displacements applied symmetrically. The target displacements are 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 12, 14, 18, and 22 mm. Each displacement target was repeated once.

4) Termination Criteria & Unloading: The test was terminated when either the horizontal load dropped below 80% of the peak resistance or severe damage prevented further loading. Finally, the horizontal load was removed first, followed by the vertical load.

3.3 Strain Monitoring Equipment and Monitoring Scheme

Multiple strain monitoring techniques were employed in this study, with the instrumentation details summarised in Table 1. The layout of strain gauges and optical fiber was illustrated in Fig. 2.

Table 1. Strain monitoring equipment

Strain monitoring	Parameter	Manufacturer
Strain gauge	Gauge length: 50 mm; Resistance: 120Ω.	Chengdu Electric Measurement & Sensing Co., Ltd. (China)
DFOS	Optical fiber: Tight-buffered strain sensing fiber (2 mm diameter); Interrogator model: OSI-S (Maximum measurement distance: 100 m; Spatial resolution: 1 mm; Strain measurement accuracy: 1 microstrain).	Suzhou Nansee Sensing Technology Co., Ltd. (China)

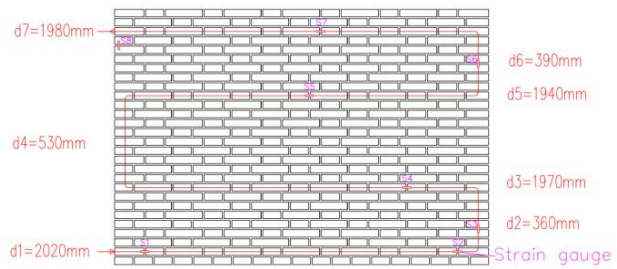
4. Results and discussion

4.1 Pseudo-Static Test

Following the completion of preloading, a vertical load of 237 kN was first applied to the specimen at a loading rate of 5 kN/min. During the application of the vertical load, the wall remained in the elastic stage. Subsequently, periodic horizontal loads were applied to the wall under displacement control. The results of the quasi-static tests on the specimen were presented in Fig. 3.



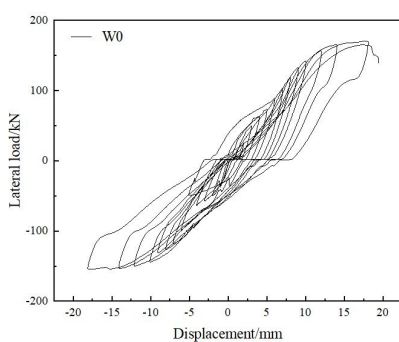
a) Photo of the optical fibre layout



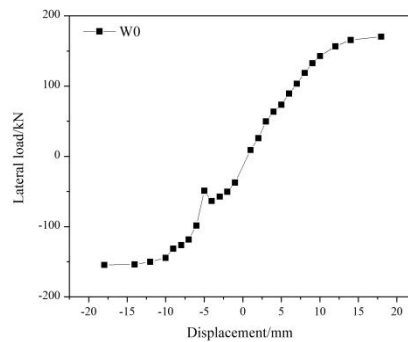
b) Location and length of optical fiber

Figure 2. The layout of strain gauges and optical fiber

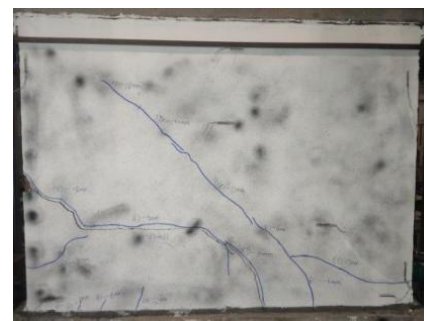
Initially, the force-displacement curve of the wall exhibited a linear relationship, indicating that the wall remained in the elastic stage without significant damage. As the load increased, cracks developed at the locations of early damage. When the displacement reached 6 mm, diagonal cracks appeared in the lower-middle portion of the wall. With continued loading, the crack propagation exhibited three distinct stages: stable propagation (6-8 mm), accelerated propagation (8-18 mm), and unstable propagation (>18 mm). Eventually, when the displacement reached 22 mm, the wall experienced severe damage, and the load rapidly dropped below 85% of the ultimate load. The test was terminated. Overall, the wall exhibited shear-type failure characteristics. Besides, the results revealed that the hysteresis curves showed peak loads of 170 kN (the displacement is 18 mm) and 160 kN (the displacement is 14 mm) in positive and negative loading directions, respectively, with significant nonlinear behaviour and strength degradation. The skeleton curve confirmed the bipolar characteristics of load-displacement relationships, demonstrating higher stiffness in the positive direction.



a) Hysteretic curve



b) Skeleton curve



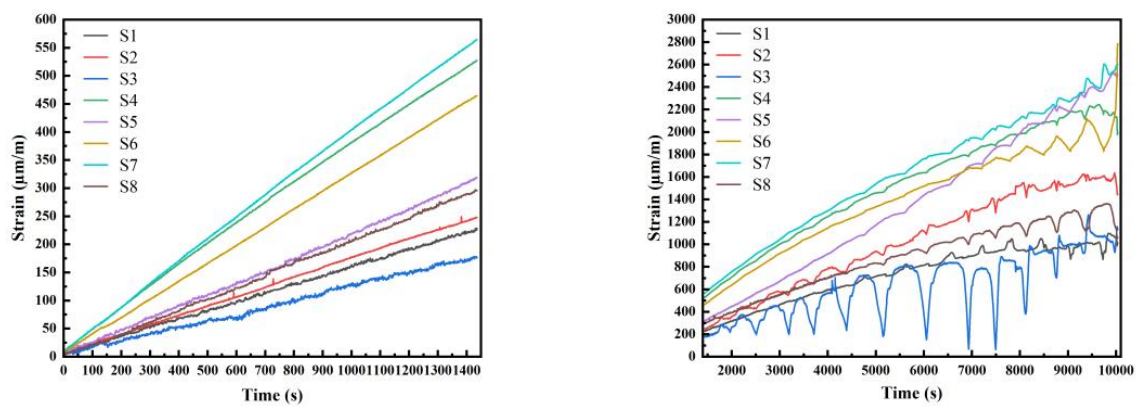
c) Crack development

Figure 3. The results of pseudo-static test

4.2 Strain Gauge Measurement

The results from strain gauges at different stages of the quasi-static test are presented in Fig.4. During the vertical loading phase, the strain gradually increased, indicating that the wall remained in the elastic stage with relatively uniform stress distribution. However, strain gauges S6 and S7 showed a slightly higher strain growth rate than other regions, suggesting localised stress concentration, which may be attributed to local defects or material property variations. During the initial stage of horizontal loading (1437–5000s), the strain continued to increase linearly, indicating

that the wall remained in the elastic stage. Subsequently, the strain growth rate significantly increased, marking the transition of the wall into the plastic stage, which may be associated with localised yielding or damage accumulation. Significant fluctuations were observed in the strain measurements in the later loading stage (after approximately 8000s), indicating the onset of localised instability, likely related to crack propagation or localised failure. The experimental results align with the aforementioned failure mechanisms of the wall. Horizontal loading was identified as the primary driver of damage development, and the failure process of the wall can be divided into three stages: elastic uniform deformation, plastic accumulation, and localised instability. Further analysis revealed a significant spatial correlation between the stress concentration regions (S6/S7) and the final failure regions (S2/S3). Strain gauges S2 and S3, located in the crack development zones, recorded significant strain fluctuations, which correspond to the opening and closing behaviour of cracks. This observation further validates the correlation between strain gauge measurements and the damage development of the wall.



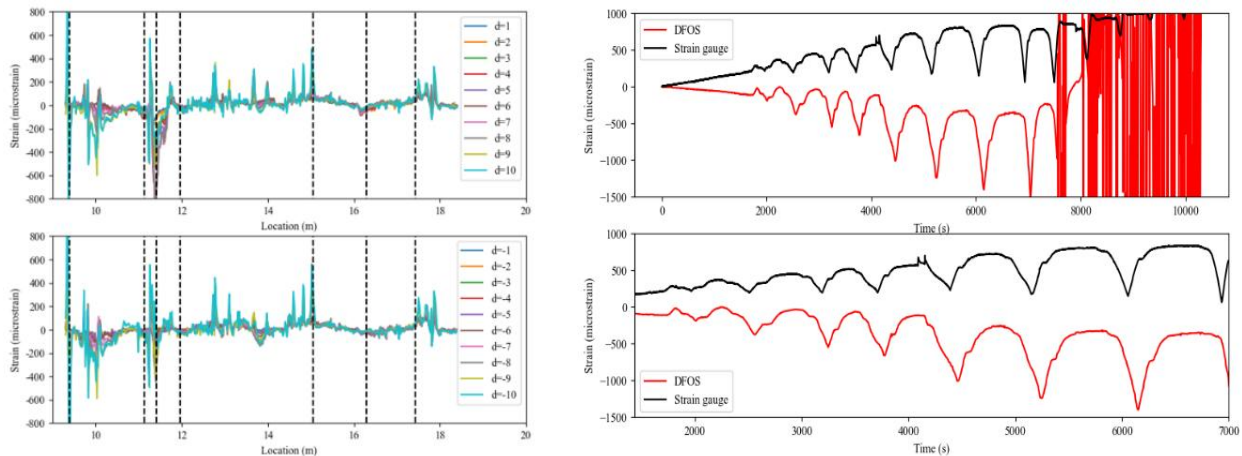
a) The vertical loading phase

b) The horizontal loading phase

Figure 4. The strain results from strain gauges

4.3 DFOS Based on OFDR Measurement

Strain results from DFOS can be found in Fig. 5a). The optical fiber was damaged under excessive deformation, as shown in Fig. 5b). When the loading time exceeds 7900 seconds, the readings from DFOS show significant fluctuation and thus are unreliable. Fig. 5a) shows the history of DFOS in the overall range of fibre location between 9.385 and 17.425 meter, which covers the location for strain gauge S1-S7. The values at target displacement from 1 mm to 10 mm were plotted for both the positive and negative peaks, respectively. When comparing those results to strain readings from Fig. 4, it is clear that some discrepancies exist because the optical fibre was attached to the surface of the bricks while the strain gauges were attached to the surface of the surface layer, but it is clear that the optical fiber is still very accurate in catching cracks. Records from strain gauge S3 were compared to those from DFOS, as shown in Fig. 5b). Although the absolute values are different due to the different loading history under the vertical loading stage, the readings from strain gauges and DFOS show similar cyclic trends in the horizontal loading stage with comparable variation of the strain readings.



a) Strain records of all region

b) Strain records for S3 location

Figure 5. The stain results from DFOS

Conclusions

This study employed DFOS based on OFDR and strain gauges as strain measurement sensors for monitoring masonry wall performance. The conclusions of the study can be summarised as follows:

1. The masonry wall exhibited distinct shear failure characteristics under quasi-static loading, with the damage development process being divided into three stages: elastic uniform deformation, plastic accumulation, and local damage instability.

2. Strain gauges mounted on the plaster mortar layer of the masonry wall could accurately capture the strain response at the gauge locations but failed to reflect the overall strain response of the entire wall. Moreover, the measured data from the strain gauges exhibited pronounced jumps due to cyclic loading and unloading, particularly under high-strain conditions, where the measurement results were more unstable.

3. DFOS based on OFDR enabled high-precision, continuous full-field strain monitoring of the masonry wall, effectively capturing the development and propagation of micro-cracks within the wall. Compared to the strain results from strain gauges, the single-point strain measurements from DFOS exhibited better continuity and linearity with loading and unloading cycles, providing a more accurate reflection of the strain characteristics and damage development of the masonry wall at different loading stages.

4. The strain fluctuations recorded by both the strain gauges and DFOS showed significant spatial correlation with the opening and closing behavior of wall cracks, thereby validating the correlation between strain measurement results and wall damage development.

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