Comprehensive investigation of static and fatigue performance of Fiber Bragg Grating, Digital Image Correlation and strain gages

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Abstract. In contemporary practice, a significant application of strain gauges lies in the experimental stress analysis of structural components, particularly within the aerospace sector. However, over the last two decades, fiber optic sensors, particularly Fiber Bragg Grating (FBG) sensors, have been successfully utilized for strain measurements, gaining recognition for their dependable performance. These sensors deliver strain measurement precision that rivals traditional methods such as strain gauges and extensometers. While traditional tools such as resistive strain gauges are frequently used in testing composite materials, they come with certain challenges. These include bonding and surface preparation difficulties, the need for direct surface contact and providing only single-point data. While DIC provides a broader measurement capability, its precision depends heavily on the quality of the calibration process and the testing conditions. This study investigates the experimental assessment of strain through the application of traditional strain gauges, FBG sensors, and DIC methodologies on glass fiber reinforced composite (GFRC) laminate coupon specimens subjected to quasi-static and constant amplitude fatigue loading. The work aims to comparatively investigate the sensitivity of optical fiber sensors, strain gauges and DIC.

Introduction

Although DIC, FBG sensors, and strain gauges are widely utilized in experimental mechanics, most existing studies primarily emphasize their individual strengths and weaknesses, often neglecting a holistic comparison under diverse and complex loading scenarios. This study seeks to address this shortcoming by conducting a systematic evaluation of these techniques, focusing on their performance, uncertainty quantification, and practical utility. By doing so, it provides valuable insights to inform the selection of the most suitable measurement methods for various engineering applications. Ultimately, this research aims to advance the precision and dependability of deformation measurements within experimental mechanics.

Accurate strain measurement techniques are essential for understanding material behavior under various loading conditions. Among these, DIC has gained significant attention as a non-contact optical method capable of measuring full-field displacements and strains with high spatial resolution. Recent advancements have focused on improving its accuracy by addressing issues related to calibration, noise reduction, and uncertainty quantification by Pan and Sutton et al. [1, 2]. However, despite its advantages, DIC faces challenges under dynamic conditions and with non-uniform strain fields. On the other hand, FBG sensors, known for their high sensitivity, multiplexing capabilities, and ability to withstand harsh conditions, have demonstrated effectiveness in monitoring localized strain and temperature changes, making them invaluable for applications in structural health monitoring by Campanella et al. [3].

Experimental Procedure

In this study, specimens were subjected to testing at ambient temperature (23±2°C) and in a controlled laboratory environment with regulated humidity. The test specimens were mounted to an Instron 8801 servohydraulic testing machine, which has a load capacity of 100 kN, and were subjected to both static and fatigue loading conditions. Prior to the initiation of the tests, one surface of each specimen was prepared for DIC measurement, while the opposite side was instrumented with an FBG sensor and a strain gauge. The FBG sensor was strategically placed at the midpoint of the specimen, with the strain gauge positioned directly above it, aligned along the same axis. Before conducting the static and fatigue tests, a Proportional-Integral-Derivative (PID) settings were established under 1.5 kN alternating loading based on stiffness-based tuning, resulting in a strain of 1000 με on the specimen. At this strain level, all parameters for the strain gauges, FBG sensor, and DIC measurement were fixed. Prior to initiating the testing phase, the camera brightness settings were conducted to enhance illumination, followed by a calibration process aimed at achieving minimal global residuum values. In the static testing phase, the specimen was subjected to a load of 12 kN, implemented in eight distinct steps with a sampling frequency of 2 Hz. Following the completion of the static test, a constant amplitude fatigue loading was introduced to the specimen. This fatigue specimen loading was similarly executed in eight steps, with variations in both the mean and amplitude loads at each stage. The fatigue testing was conducted for 50 cycles at each specified load level and results can be seen Table 1.

Table 1 Measured strain difference between three different techniques under maximum fatigue load

Loading Steps	Step-1	Step-2	Step-3	Step-4	Step-5	Step-6	Step-7	Step-8
Expected Delta-Strain (Theoretical, μm/m)	1,000	2,000	3,000	4,000	5,000	6,000	7,000	8,000
Strain Gage (SG) Delta-Output (μm/m)	982	1,908	2,917	3,981	5,178	6,834	8,826	10,666
FBG Delta-Strain Output (μm/m)	940	1,930	2,909	4,013	5,557	7,509	9,236	11,176
DIC Delta-Strain Output (μm/m)	1,022	1,893	2,936	4,079	5,448	7,225	9,088	10,743
% Difference (SG vs Expected Strain)	2	5	3	0	4	14	26	33
% Difference (FBG vs Expected Strain)	6	4	3	0	11	25	32	40
% Difference (DIC vs Expected Strain)	2	5	2	2	9	20	30	34

Conclusion

This study attempts to address the shortcomings by conducting a systematic evaluation of FBG, DIC and strain gage measurement techniques, focusing on their performance, uncertainty quantification, and practical usability. In doing so, it provides valuable information to guide the selection of the most appropriate measurement methods for different engineering applications. Ultimately, this research is aimed at improving the accuracy and reliability of strain measurements in experimental mechanics. The following conclusions can be reached from this study. The same types of adhesives are applicable for the mounting of both strain gauges and FBG sensors. The DIC measurement exhibit higher level of fluctuation compared to strain gage and FBG sensor under static and fatigue loading. This research indicates that strain gauges, FBG sensors, and DIC show a maximum ten 10 % variation in strain values from theoretical estimates, applicable for strains reaching up to 6000 μm/m under static loading. The results of strain measurement utilizing strain gages, FBG, and DIC techniques exhibit a high degree of comparability when subjected to fatigue loading, specifically up to 4000 μm/m.

References

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