Application of Bolt Gauge Concepts to Bearing Damage Monitoring of Bolted Joints

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ABSTRACT:

This study describes a more practical method in developing a complete self-diagnostic technique for damage monitoring in bolted composite or metallic joints. The concept of Bolt Gauge (BG) is proposed by means of bolt itself as a sensory unit, and the information of structural health can be got through monitoring the bolt tension changes by a strain gauge bonded onto the surface of bolt head. Extensive investigations using double lap bolted joint specimens are tested to confirm the damage monitoring capability, including the effects of the bolt clamp-up, material response, joint geometry and loading history. The results have shown that the onset and progress of the bearing damage assessed by BG measurements are agreed well compared with acoustic emission (AE) measurements that used in traditional non-destructive evaluation (NDE) method. Further considerations for the damage monitoring mechanisms including mechanical effects of bolt tension are estimated in both of an axial loading test and a three-dimensional finite element analysis. This study suggests that developing the functionality of smart structures to monitor their own structural integrity bring new potential and opportunity for the exploitation of advanced mechanical fastening techniques.

INTRODUCTION

Joining by mechanical fasteners is the typical procedure for assembling the structural components and has been widely used in the aircraft manufacturing processes for composite or metallic structures. One of the major problems associated with the use of mechanically fastened joints is that it can cause unavoidable stress concentration at the fastener holes. As a result, they are frequent sources of failure in aircraft structures. The general failure mode in fastener joints is the bearing failure. Although such damage is

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barely visible, any growth of this damage can severely degrade the mechanical properties and the load-carrying capability of the structural components [1,2]; hence, early detection of such damages is a key element for preventing catastrophic failure and prolonging the life of aircraft structures.

Current available inspection methods for the joint are employing non-destructive evaluation (NDE) techniques, such as ultrasonic scan, X-ray and eddy current etc., to obtain an image of bearing damage. However, fasteners may have to be disassembled and re-assembled for inspection, which is inconvenient and inefficient for airline because it can cause significant downtime and incurs excessive expense. Therefore, the development in utilizing structural health monitoring (SHM) concepts has attracted significant attention to overcome the issues among the current inspection methods. The primary objective of this study is to address these issues and develop a more practical and convenient method to detect effectively the bearing damage for bolted composite or metallic joints. The efforts should focus on how to utilize the structural functionality that can monitor their own structural integrity.

BOLT GAUGE CONCEPT

The concept of bolt gauge was defined of the bolt itself as a sensory unit, which has been proposed in earlier work [3-5]. It is possible to identify the state of bearing damage through monitoring the bolt strain changes, which can be measured by a strain gauge bonded onto the surface of bolt head. The pivot of detection is to measure the changes of bolt tension due to out-of-plane compressive deformation that is directly related to the bearing damage. Therefore, carrying out the BG measurements would get easily information on the resistances of the lateral constraint in bolted joint, that allow for the detection and quantification of bearing damage. Overview of the BG-based bearing damage identification system is shown in Fig. 1. This unique system doesn't need addition to specific sensors, actuators, signal processors and controllers for damage detection.

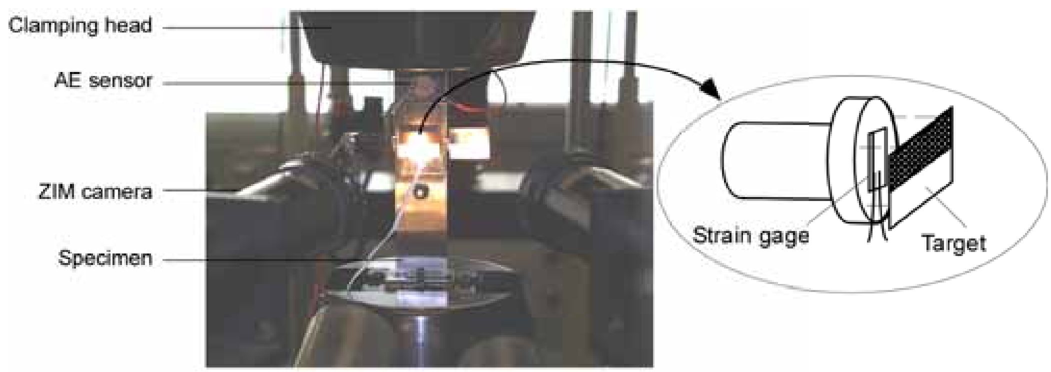


Fig. 1 Schematic of double lap joint specimens with BG system.

EXPERIMENT

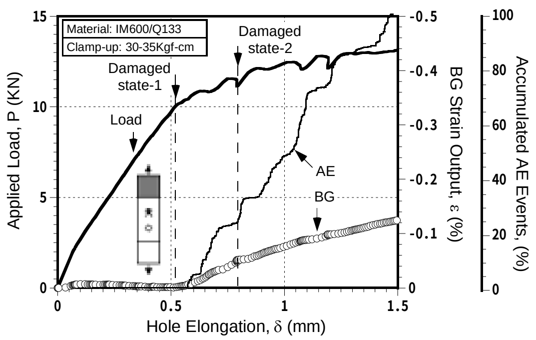
The purpose of the experiment is to verify and examine the concept, reliability and capability of BG for damage monitoring through the different case studies, including the effects of the material response, bolt clamp-up, joint geometry and loading history etc. Three different material systems were selected for investigation of the material response. They are IM600/QC133 carbon/epoxy composite with lay-up $[45/0/-45/90]_{2S}$, 2024-T4 aluminum alloy and chromium molybdenum steel. The double lap joining configuration was adopted for all the tests in this work. All specimens were tested using a servo hydraulic INSTRON-8501 testing machine in tensile mode; crosshead-loading rate was 0.5 mm/min. To measure hole elongation for the bolted joints, a non-contact electro-optical extensometer (product of ZIMMER Co.) was also adopted. The strain gauge employed in BG measurements is a general-purpose type of UFLA-03-11, chosen from product series of Tokyo Sokki Kenkyujo Co., Ltd. It is bonded into the surface of bolt head after joint specimen has been installed.

DAMAGE MONITORING RESULTS

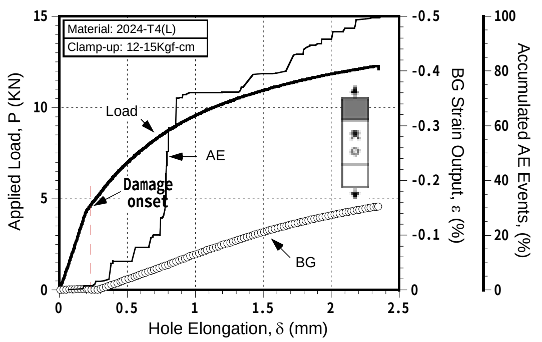
Monotonic Tensile Tests

Fig. 2 shows the bearing damage estimates by BG measurement obtained at the monotonic tensile tests for different material systems, called CFRP specimen and Al specimen. For any case, it can be found clearly that the response of BG output was related directly to the bearing damage and/or deformation. BG output can be obtained in a relatively stable development together with the response of bearing strength (P-δ curve) until the bearing damage occurred, but once the bearing damage occurred, a sharp change in BG output and AE signal was observed. Simultaneously, non-linear behavior appeared in the load-displacement curve. Afterwards, the change of BG output as well as AE signal increased monotonously with hole elongation.

Fig. 3 shows the typical curves of the BG output versus the applied load for the case of CFRP specimen subjected to an initially applied torque of finger tight, 12~15, 30~35 *Kgf-cm*, respectively. Fig. 4 shows the BG output versus the applied load for various joint geometries, since the distinction between the failures is established largely by the



(a) IM600/QC133 laminates



(b) 2024-T4 aluminum

Fig. 2 GB responses for various material systems tested at monotonic tensile loading.

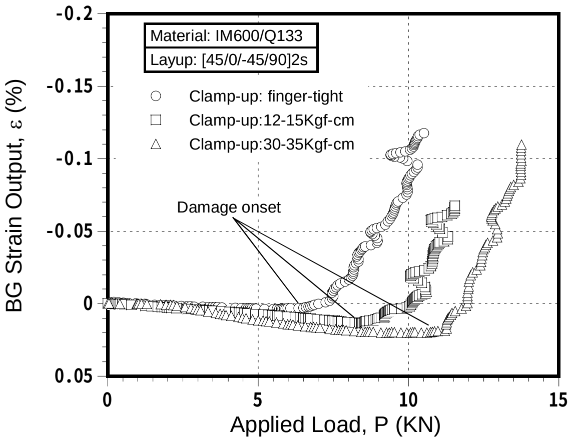


Fig. 3 GB responses plotted as a function of applied load for various clamping forces.

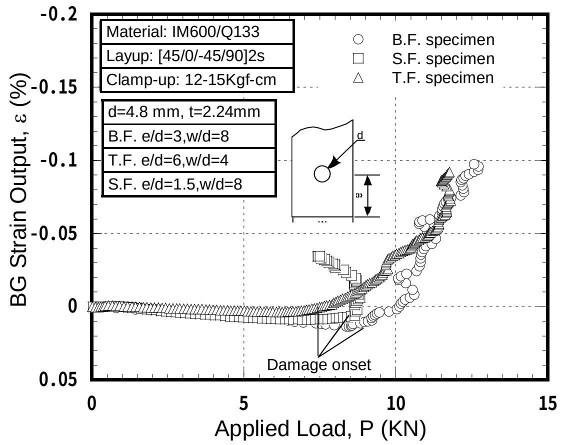


Fig. 4 GB responses plotted as a function of applied load for various joint geometries.

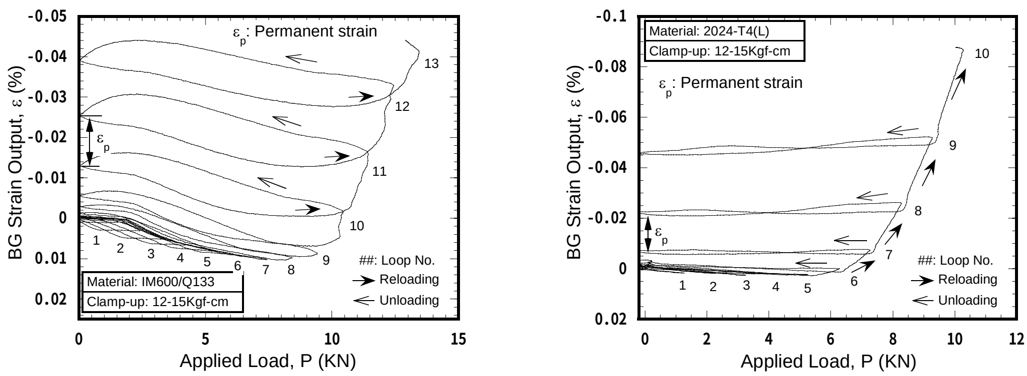
joint geometry, particularly the width-to-diameter ratio, w/d or the edge-to-diameter ratio, e/d. From above, it was evident that the BG output has not been influenced by the change of the initial clamp-up levels or the joint geometry but only has been influenced at the generating time of the initial damage.

Cyclic Loading-Unloading Tests

Fig. 5 shows the BG output versus the applied load for the case of CFRP specimen and Al specimen during the cyclic loading-unloading tests. The enveloping curve shows nearly unchanged in comparison with the monotonic tensile test. The unloading and reloading curves, however, show a somewhat unexpected behavior than the loading, because of the relationship of permanent strain. The results indicate that BG output did not depend on a load history, but can record the permanent strain received in the past.

FINITE ELEMENT ANALYSIS

A finite element analysis was performed to discuss the monitoring mechanisms. The finite element model was established with the commercial finite element package



(a) IM600/QC133 (b) 2024-T4 aluminum

Fig. 5 GB responses plotted as a function of applied load tested at cyclic loading/unloading.

ABAQUS. Because of symmetry, a half of the middle lap in a double shear-lap bolted joint with one-half of the thickness of the aluminum plate was modeled. To predict the bearing damage responses in bolted aluminum plate joint, the progressive failure analysis and material degradation were performed. Because aluminum materials are highly nonlinear, they may also exhibit different yield stresses in tension and compression. Comparison of numerical and experiential for the 2024-T4 aluminum specimens is shown in Fig. 6. The results were found to agree well with the existing experimental data. Fig. 7 presents a series of predicted results for the bolt depression deformation under different loading stages. From the numerical results, the prediction is fairly good if the nonlinear material behavior is included in the model.

CONCLUSIONS

BG diagnostic system presents a more practical technique to the applications of structural health monitoring to bolted joints. Test results have shown that BG method in detecting the bearing damages can respond to change of parameters, such as material,

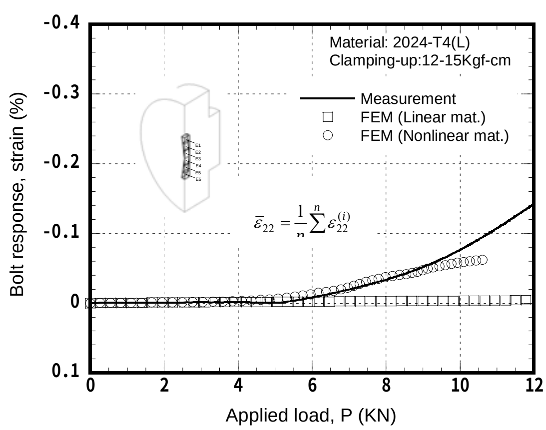


Fig. 6 Comparison between the measured and calculated BG responses.

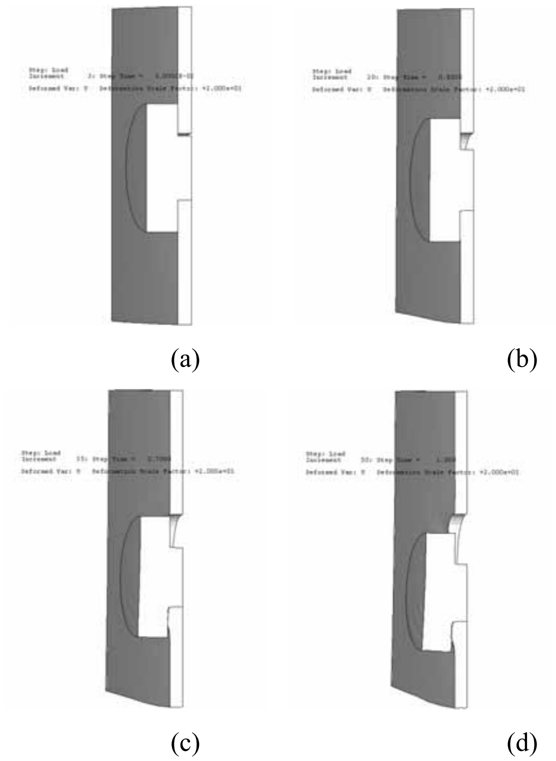


Fig. 7: Predicted bolt depression deformation for (a) P=1.5KN, (b) P=4KN, (c) P=7KN and (d) P=10.5KN.

initial clamping force, joint geometry and loading history.

REFERENCES

[1] Y. Xiao and T. Ishikawa: The Issues for Mechanically Fastened Composite Joints, *in Proceedings of The 28th Symposium of JSCM, 2003, p. 95.*

[2] Y. Xiao and T. Ishikawa: *Compos Sci Technol, 65, 2005, p. 1022.*

[3] Y. Xiao, Y. Kakuta and T. Ishikawa: A Design of Intelligent Bolted Composite Joints with Damage Detection Function, *in Proceedings of Annual Meeting of Japan Society for Composite Materials, 2003, p.63.*

[4] Y. Xiao, Y. Kakuta and T. Ishikawa: A self-diagnostic technique for monitoring the bearing damage in composite and metallic joints, *in Proceedings of The Fifteenth International Conference on Composite Materials, (2005), CD-ROM.*

[5] Y. Xiao, Y. Kakuta and T. Ishikawa: *J. Jpn Soc Compos Mater, 32(4), 2006, p. 171.*