SMART APPROACH TO DETERMINE DAMAGE GROWTH IN MECHANICALLY FASTENED JOINTS

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Abstract

This study provides a practical method regarding the development of a smart approach to determine the bearing damage growth in bolted composite or metallic joints. The basic concept is based on making BG (Bolt Gauge) measurements that has been proposed in earlier work [1,2]. That is, bonding a strain gauge onto the surface of bolt head to monitor the bolt strain changes that would identify bearing damage. Extensive tests using double lap bolted joint specimens are performed to verify the health monitoring technique, including the effects of the bolt clamp-up, material response, joint geometry and loading history. The results have shown that the bearing damage detected by BG measurements agreed well with acoustic emission measurements. Finite element analysis is also performed to discuss the monitoring mechanisms.

1 Introduction

Joining by mechanical fasteners is the typical technique for assembling the structural components and has been widely used in the aircraft manufacturing processes for composite or metallic structures. However, 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 [3-4]. As a result, they are frequent sources of failure in aircraft structures. The general failure mode in fastener joints is the bearing damage what is often called to as *oversize* in engineering. Although such damage is barely visible, any growth of this damage can severely degrade the mechanical properties and the load-carrying capability of the structural components [5-6]; 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 joint inspection employ 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.

In the past few years, the development in utilizing structural health monitoring (SHM) concepts has attracted significant attention to solve the issues among the current inspection methods [7]. In the efforts to utilize SHM techniques concepts for damage detection of joints, attention has focused on the use of surface mounted sensors and actuators, embedded sensors and actuators and a combination of both [8, 9]. Little work to apply the self-sensing concepts in the damage detection of bolted joints has been done. For example, to develop an electric-resistance change method to detect the bearing failure for CFRP composite bolted joints [10]. It is insufficient and impractical to apply the SHM techniques available in aircraft structures today. Self-sensing is valuable for structural materials, especially those for smart structures. It does not involve the use of embedded or attached sensors, as the structural material is itself the sensor. In any case the use of embedded or attached sensors, may lead to the problem of structural degradation of the host structure on the mechanical strength.

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 [11-13].

2 Smart Approach

In order to successfully achieve the goal of self-sensing mentioned in the previous section, an initial approach that utilized a concept of bolt gauge (BG) by means of the bolt itself as a sensory unit for damage detection, has been proposed in author's earlier work [1-2]. A general view of the diagnosis system by the BG method is shown in Fig. 1. It is possible to identify the state of bearing damage by bonding a strain gauge onto the surface of bolt head to monitor the bolt strain changes. 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 can get easily information on the resistances of the lateral constraint in bolted joint, that allow for the detection and quantification of the bearing damage.

The proposed BG method has the following features: It not only can maintain the basic functions but also can provide the new possibility for smart structure. Since the bolt itself is a sensory unit, it does not need specific sensors, actuators, signal processors and controllers for damage detection. And, it would be easy to integrate a network of sensors onto the practical multi-fastener structures. It also offers a special potential in development of new measurement system, which is able to replace the existent strain gauge.

3 Experimental Procedures

The purpose of the experiment is to verify and examine the concept, reliability and capability of BG system for damage monitoring through the different case studies, including the effects of the material response, bolt clamp-up, joint geometry and loading history etc.

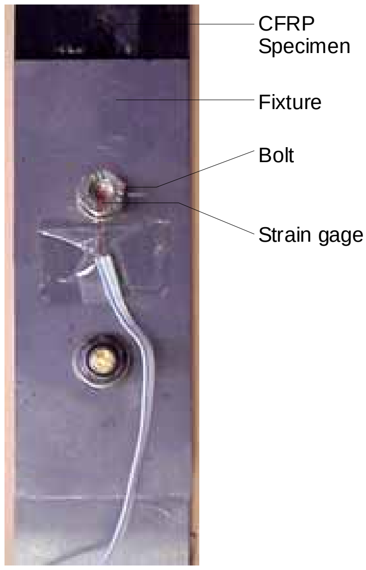


Fig. 1. Schematic of double lap joint specimens with BG system

Three different material systems were selected for investigation of the material response. They are IM600/Q133 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 (see Fig. 1); the design patterns were used based on the findings of earlier authors (e.g. [6]). The specimen for different material systems was used as central laps of joints while steel plates with chromium molybdenum steel were used as outer laps. The values of the geometrical parameters for the double lap joint specimens are listed in Table 1. In examining the effect of joint geometry, the associated specimens were made with the different geometrical ratios *W/d* and *e/d*, corresponding to different failure modes, net-tension, shearing-out, and bearing, respectively. For the initial clamping forces, various levels of tightening torque (finger-tight, 12-15 *kgf-cm*, and 30-35 *kgf-cm*) were carried

Table 1. Geometrical parameters for joint specimen

Specimen	Length *L (mm)*	Hole diameter *d (mm)*	Thickness *t (mm)*	Width-to-diameter ratio, *W/d*	Edge-distance-to-diameter ratio, *e/d*
TM (Tension mode)	110	4.8	2.24	4	6
SM (Shearing-out mode)	110	4.8	2.24	8	1.5
BM (Bearing mode)	110	4.8	2.24	8	3

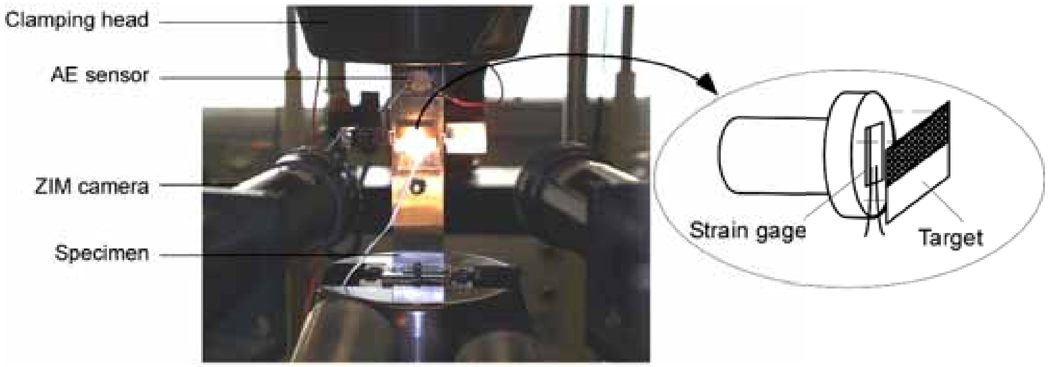


Fig. 2. Schematic of damage monitoring test setup

out, and all specimens were adjusted finally by means of a mini-torque wrench.

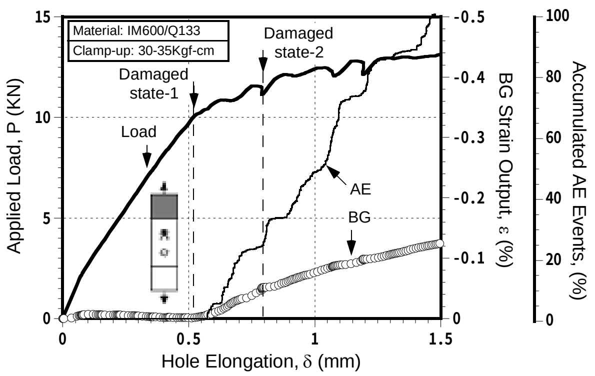
All specimens were tested using a servo hydraulic INSTRON-8501 testing machine in tensile mode, at room temperature. Crosshead-loading rate was 0.5 *mm/min*. To measure hole elongation for the bolted joint specimen, a highly functional measurement system based on a non-contact electro-optical extensometer (product of ZIMMER Co., MODEL-100B) was also adopted, additional details on this system are fount in [13-14]. Schematic of bearing damage detection test can be seen in Fig. 2. Moreover, during the damage monitoring tests, a conventional NDT (Non-destructive testing) method by AE (acoustic emission) measurement was also used to compare the proposed BG method. Two-channel MISTRAS 2001 system (Physical and Acoustic Co.) was used in the AE measurement. The strain gauge employed in BG measurements is a general-purpose type of UFLA-03-11, with 3mm gauge length, 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. Also, as shown in Fig. 1, the vertical location of strain gauge was adjusted so that it might be in agreement with the loading direction. It should be noted that the influence of bolt residual stress caused by the initial clamping forces could not be considered in this study because zero balance was performed in data loggers before recording the strain output.

4 Damage Monitoring Results

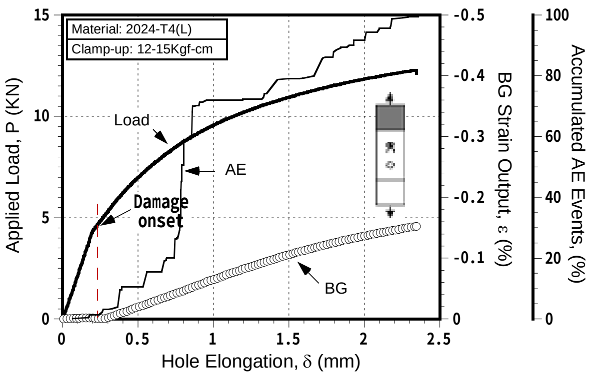
4.1 Effect of Various Materials

Fig. 3 shows the bearing damage estimates by BG measurement obtained at the monotonic tensile tests for three different material systems, called CFRP specimen, Al specimen and Steel specimen, respectively. There was a common behavior both in the CFRP specimen and Al specimen; 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. A more interesting result can be shown that the BG output characteristic would reflect the failure mechanism in different materials. For example, compare the BG output of CFRP specimen and Al specimen as shown in Fig. 3 (a) and (b). While BG output in CFRP specimen appears a sudden type resulting from an unstable development of internal compressive failure, e.g. micro bucking or delamination (so-called brittle fracture), BG output in the case of Al specimen appears a rather smooth type resulting from plastic deformation. It turns out that both differences appear more clearly.

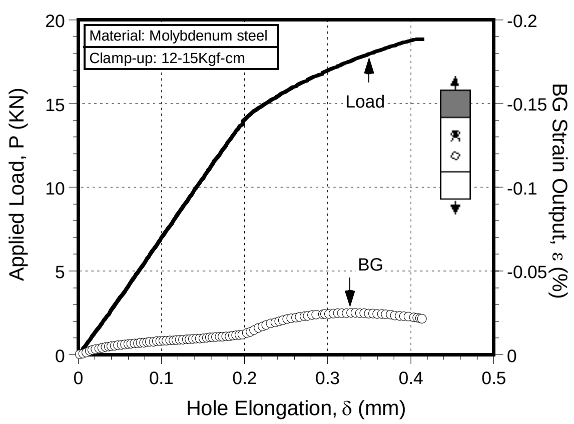
On the other hand, a peculiar behavior for the Steel specimen unlike with CFRP specimen and Al specimen was observed, as shown in Fig. 3 (c) when the applied load was increased to 15*KN* (about 0.2*mm* in hole elongation). That is, after BG output has changed suddenly, it decreased gradually with increased load. That can be understood from stiff rate for the different material properties in joints. From the observation after experiment, it is evident that the bearing damage occurred in both hole and bolt shank. Therefore, it can be assured that damage monitoring by the BG method has gotten more or less of the information relative to a damage situation enough even when the shearing or bending failure was caused in bolt.



(a) IM600/Q133 laminates



(b) 2024-T4 aluminum



(c) Chromium molybdenum steel

Fig. 3. BG responses for various material systems tested at monotonic tensile loading

4.2 Effect of Various Clamping Forces

Fig. 4 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. Evidently, there existed a significant feature on the BG output at point where the BG response stops decreasing and starts increasing, i.e. the initial bearing failure occurred. The results also showed that the generated time against feature point was just proportional to the initial clamp-up levels. Thus, the stronger bolt clamp-up not only increases the bearing strength but also play an important role in delaying the generated time of the initial damage.

4.3 Effect of Joint Geometry

There are various modes of failure for single fastener joints and the most frequently occurring ones are called bearing failure, tension failure and shear-out failure. The distinction between the failures is established largely by the joint geometry,

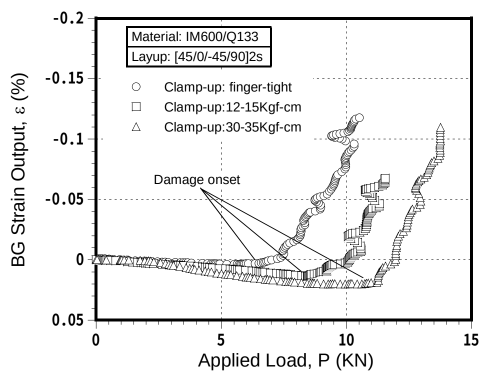


Fig. 4. BG responses plotted as a function of applied load for various clamping forces

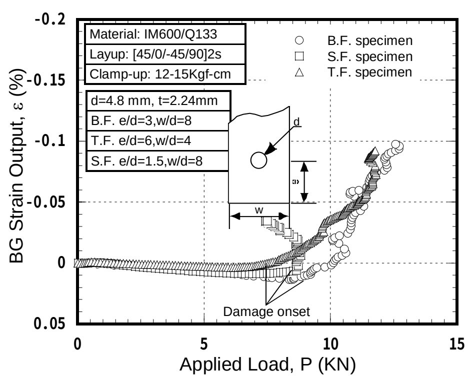
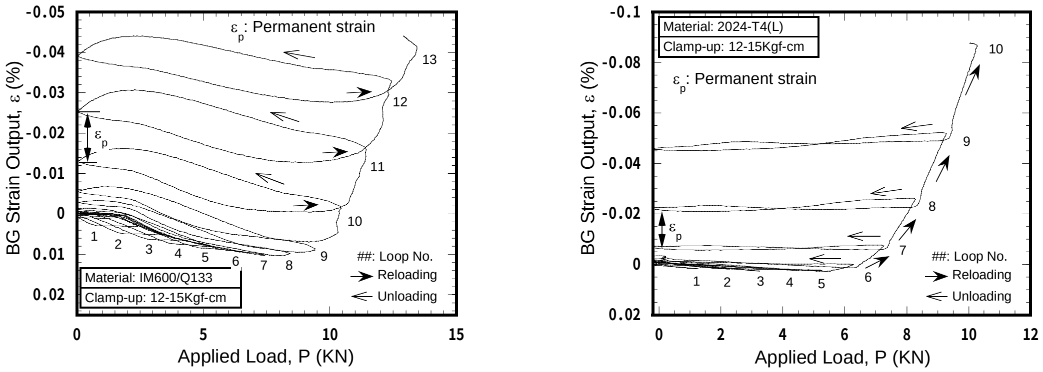


Fig. 5. BG responses plotted as a function of applied load for various joint geometries



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

Fig. 6. BG responses plotted as a function of applied load tested at cyclic loading/unloading

particularly the width-to-diameter ratio, *w/d* or the edge-to-diameter ratio, *e/d* (see Table 1). Fig. 5 gives an example of the effect of joint geometry in the composite specimen. It is evident that the BG output characterization can respond sensitively to various geometrical parameters, and identify the generated time of initial damage and the degree of damage progress.

4.4 Effect of Loading History

The cyclic loading-unloading test was performed to examine the BG output characterization during loading-unloading. Test was conducted using displacement-controlled mode. For all the load cycles, increments of 1*KN* were used in loading and unloading until the maximum load (13*KN*). The load-displacement curves and hysteresis loops were recorded to observe the behavior in BG output. Fig. 6 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.

5 Damage Monitoring Mechanisms

In these investigations above, referring to Fig. 4, evidently, there existed a significant relationship between BG output and applied load, which the BG output was decreasing first and then was increasing. This is attributed to the change in bolt preload, i.e. the bolt's initial clamping forces were canceled. This

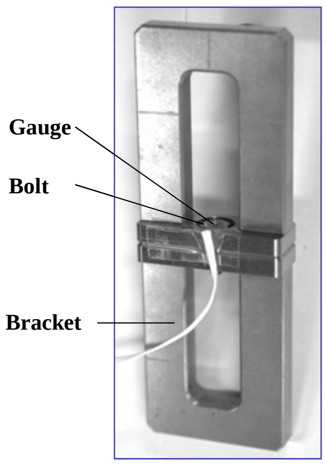


Fig. 7. Tension bolted joints test

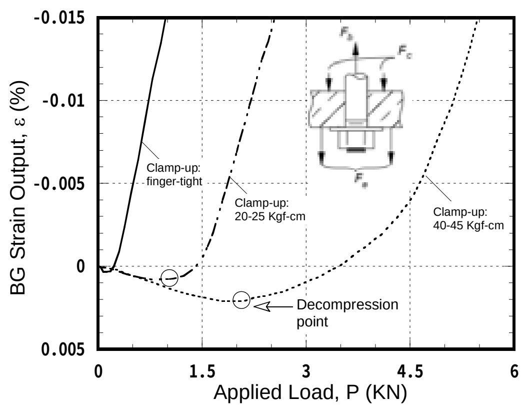


Fig. 8. Bolt load vs. applied load at tension bolt test

mechanism can be illustrated in the following test.

5.1 Tension Bolted Joints Test

Tension bolted joints test was used to examine the change of bolt preload when applied load is increased. Fig. 7 illustrates schematically the tension bolted joints test configuration considered in this study. It involves a set of bracket that was jointed with bolt and nut. Tensile loading is applied to the bracket end. The bolt preload versus the applied load with different clamping forces is shown in Fig. 8, where F_b is the total bolt load, which is preloaded with initial clamping load F_c, before the external load F_e is applied. It was clear and distinctive that the bolt load does decrease significantly until F_e exceeds F_c. Referring to Fig. 8, note that once the decompression point is reached, joint, or bolt, failure usually occurs.

5.2 Finite Element Analysis

To investigate the bearing damage behavior, and validate the BG sensor readings, the bolted joint was modeled using finite element (FE) analysis, which is the commercial finite element package ABAQUS. Using the symmetry of the joint, it was only necessary to model half of the middle lap in a double shear-lap bolted joint, see Fig. 9. To assess the bearing damage responses in bolted aluminum plate joint, the FE analysis were performed, including the progressive failure analysis and material degradation. Due to aluminum materials are highly nonlinear, they may also exhibit different yield stresses in tension and compression.

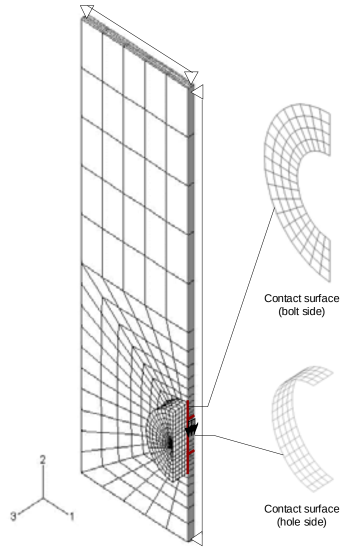


Fig. 9. FE model and boundary conditions

Fig. 10 shows the bearing behavior plots obtained from the finite element analysis. It was found that the bolt-depressed responses depend strongly on the failure sequence in joint materials, as follows: yielding, damage initiation and growth,

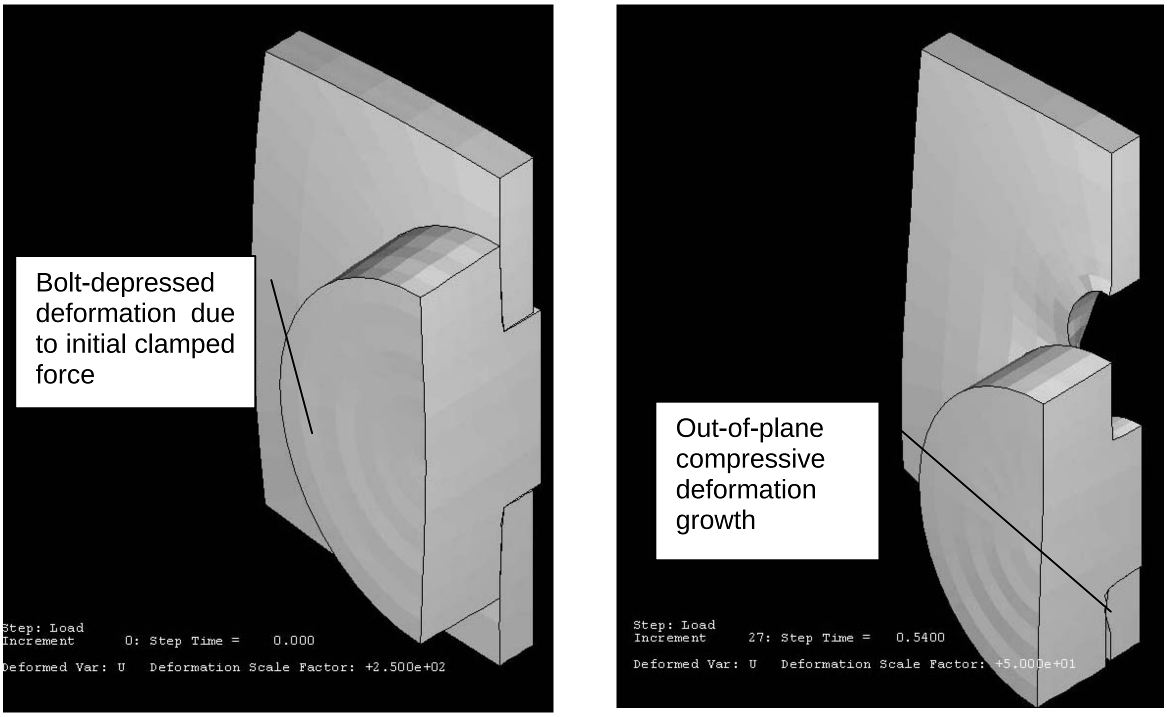


Fig. 10. Bearing deformation behavior obtained from the finite element analysis

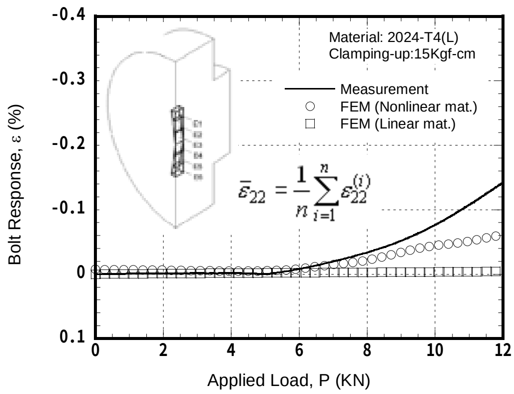


Fig. 11. Comparison of numerical and experiential for the 2024-T4 aluminum specimens

followed by final fracture. Comparison of numerical and experiential for the 2024-T4 aluminum specimens is shown in Fig. 11. The results were found to agree well with the existing experimental data. From the numerical results, the prediction is fairly good if the nonlinear material behavior is included in the model.

6 Conclusions

BG diagnostic system presents a more practical technique on the applications of structural health monitoring in bolted joints. Test results have shown that BG approach in detecting the bearing damages can respond to changes in parameters, such as material, initial clamping force, joint geometry and loading history.

References

[1] Xiao Y., Kakuta Y. and Ishikawa T. “A Design of Intelligent Bolted Composite Joints with Damage Detection Function”. *Proceedings of Annual Meeting of Japan Society for Composite Materials*, pp.63, 2003.

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

[3] AGARD Conference Proceedings CP-427. *“Behaviour and analysis of mechanically fastened joints in composite structures”*. North Atlantic Treaty Organization, 1988.

[4] AGARD Conference Proceedings CP-590. *“Bolted/bonded joints in polymeric composites”*. North Atlantic Treaty Organization, 1998.

[5] Xiao Y. and Ishikawa T. “The Issues for Mechanically Fastened Composite Joints”. *Proceedings of The 28th Symposium of JSCM*, pp 95, 2003.

[6] Xiao, Y. and Ishikawa, T. **“**Bearing Strength and Failure Behavior in Bolted Composite Joints (Part I&II)” *Composites Science and Technology*, Vol. 65(7-8), pp 1022-1043, 2005.

[7] Staszewski W.J., Boller C. and Tomlinson G. R. (Editor) *“Health Monitoring of Aerospace Structures: Smart Sensor Technologies and Signal Processing”*. John Wiley & Sons, Inc. March 2004.

[8] Ihn J.B. and Chang F.K. “Detection and monitoring of hidden fatigue crack growth using a built-in piezoelectric sensor/actuator network: II. Validation using riveted joints and repair patches”. *Smart Mater. Struct.* Vol. 13, pp 621-630, 2004.

[9] Peairs D.M., Park G.H. and Inman D.J. “Practical issues of activating self-repairing bolted joints”. *Smart Mater. Struct.* Vol. 13 pp 1414-1423, 2004.

[10] Shimamura Y., Mukai S., Todoroki A. and Kobayashi H. “Damage Detection of CFRP Bolted Joints by Electric Resistance Change Method”. *Proc. Tenth U.S.-Japan Conference on Composite Materials,* pp.215-220, 2002.

[11] Xiao Y., Kakuta Y. and Ishikawa T. “Innovative Design of Mechanically Fastened Joints with Damage Diagnostic Function”. *J. Jpn Soc Compos Mater,* 32(4), pp 171, 2006.

[12] Xiao Y., Kakuta Y. and Ishikawa T. “A New Concept for Structural Health Monitoring of Bolted Composite Joints”. *Key Engineering Materials,* Vols. 334-335, pp.465-468, 2007.

[13] Xiao Y., Kakuta Y. and Ishikawa T. “Application of Bolt Gauge Concepts to Bearing Damage Monitoring of Bolted Joints”. *2006 Asia-Pacific Workshop on SHM*, Yokohama, Japan. ID 008 in CD-ROM, 2006.