Key Engineering Materials. Vols. 321-323, p. 957-962
online at http://www.scientific.net

Detectability of Bearing Failure of Composite Bolted Joints by Electric Resistance Change Method

Yoshinobu Shimamura[1,a], Keiko Oda[2,b], Akira Todoroki[3,c] and Masahito Ueda[2,d]

[1]Shizuoka University, 3-5-1 Johoku, Hamamatsu, Shizuoka 432-8561, Japan

[2]Graduate student, Tokyo Institute of Technology, Japan

[3]Tokyo Institute of Technology, 2-12-1 O-okayama, Meguro, Tokyo 152-8552, Japan

[a]tysimam@ipc.shizuoka.ac.jp, [b]koda@ginza.mes.titech.ac.jp,

[c]atodorok@ginza.mes.titech.ac.jp, [d]mueda@ginza.mes.titech.ac.jp,

Keywords: Composite materials, Bearing failure, Non-destructive testing, Electric resistance change method, Finite element analysis

Abstract. Bolted joints are widely used for composite structures. As is well known, excessive bearing load gives rise to bearing failure at hole boundaries. Detecting bearing failure is important for assuring integrity of composite structures. Since conventional nondestructive inspection methods are expensive, cumbersome, time-consuming, and not suitable for health monitoring, a simple, low-cost inspection method for bearing failure must be developed. Authors have demonstrated the feasibility of detecting bearing failure by using an electric resistance change method. In this study, more detailed analyses were carried out to investigate the detectability in terms of the damage size and the distance between damage and electrodes. The results show that bearing failure of less than 10mm square causes the electric resistance change of a few hundred ppm and thus can be easily detected, and that the electrodes can be mounted more than 10 mm far from a bolt hole.

Introduction

Bolted joints are widely used for composite structures. As is well known, excessive bearing load gives rise to bearing failure at hole boundaries. Bearing failure has been investigated by many researchers [e.g., 1-5] both experimentally and analytically. Bearing failure of bolted composite joints consists of compressive failure, matrix cracks, delamination, kink band formation, and other phenomena. Detecting bearing failure is important for assuring integrity of composite structures. In general, conventional nondestructive inspection methods, such as C-scan and X-ray inspection, are used to detect bearing failure. The conventional inspection methods are, however, expensive, cumbersome, and time-consuming. In addition, the conventional inspection methods are not suitable for health monitoring because overlaps, insulators, and washers mask bearing failure. A simple, low-cost inspection method for bearing failure must be developed.

Laminae of carbon-fiber-reinforced composites have electric conductivity. Besides having conductivity in the fiber direction, laminae also have conductivities in the transverse and thickness directions, by virtue of fiber contacts in laminae [6]. In other words, laminae have orthogonal anisotropy of electric conductivity. The electric conductivity in the fiber direction is much higher than those in the transverse and thickness directions. Damage within composite materials, such as fiber breakage and delamination, changes the electric resistance of composite materials. Measuring the change in electric resistance allows detection of the internal damage. Many papers have reported the detection of internal damage in composite materials using the electric resistance change method [7-36]. For bolted joints, overlaps, insulators, and washers prevent the use of conventional mountable sensors such as strain gauges. One advantage of the electric resistance change method to detecting bearing failure is that electrodes can be mounted far from bolt holes because of the electric anisotropy. Embedded sensors such as fiber optic sensors are difficult to use because embedding them around the circumference of the bolt holes is impracticable. Another advantage is the low cost of a system for the electric resistance change method. Authors have reported the feasibility of damage detection of composite bolted joints by the electrical resistance change method experimentally [33] and by using FEM analysis [35].

In this study, more detailed analyses were carried out to investigate the detectability in terms of the damage size and the distance between damage and electrodes. The results show that bearing failure of less than 10mm square causes the electric resistance change of a few hundred ppm and thus can be easily detected, and that the electrodes can be mounted more than 10 mm far from a bolt hole.

Electric current path in CFRP laminated plate

Fast of all, electric current paths in CFRP laminated plates were analyzed in order to show the feasibility of the electric resistance change method for remote damage detection.

A plate specimen as shown in Fig.1 was analyzed. The stacking sequences of the specimen were $[45/0/-45/90]_S$, and the ply thickness was 0.2 mm. In this study, 8-node solid elements were adopted for analysis. The size of an element in plane was 3mm×3mm and a ply was divided into 10 elements in the thickness direction. Two point electrodes were mounted on the specimen surface, and direct current of 10 mA was applied. Electrical conductivities used for FEM analysis are shown in Table 1.

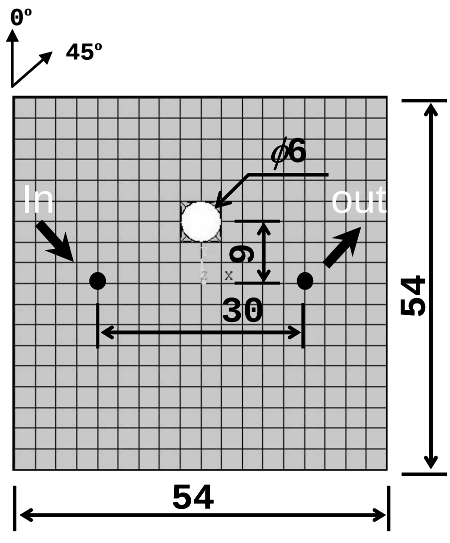


Fig.1 Analytical model of CFRP plate with a bolt hole for FEM analysis

Table 1 Electrical conductivities of CFRP laminates used for analysis

σ_0 [$\Omega^{-1}m^{-1}$]	σ_{90} / σ_0	σ_t / σ_0
5500	3.7×10^{-2}	3.7×10^{-3}

For isotropic materials, electrical current flows across the shortest path between two electrodes. In contrast, electrical current in CFRP laminated plates may detour and the current path depends on the stacking sequence. Fig. 2 shows vector diagrams of the electrical current density in angle plies of a $[45/0/-45/90]_S$ laminate. These figures show that most of the electrical current detours through fibers. If bearing failure cuts the electric current path in a specimen, the electric resistance of the specimen will change. This electric resistance change enables us to detect remote damage, such as bearing failure.

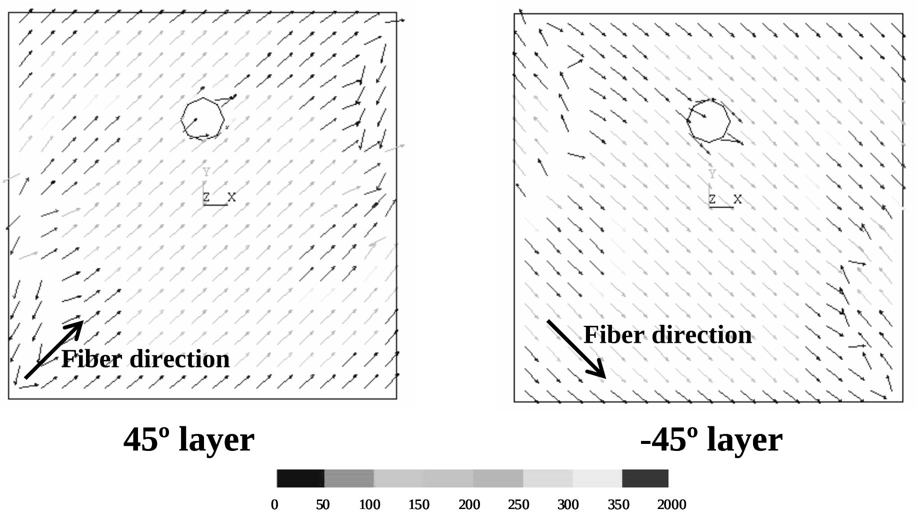


Fig.2 Vector diagrams of electrical current density in 45˚ and –45˚ plies of $[45/0/-45/90]_S$ laminate

Modeling of bearing failure for detectability analysis

In order to investigate the detectability of bearing failure by the electric resistance change method, complex bearing failure of bolt holes has to be modeled into several simple damage modes. Fig.3 shows photographs of a typical bearing failure of a bolt hole for a composite laminate of $[45/0/-45/90]_S$. Three dominant failure modes are the deformation of the bolt hole including fiber breakage and microbuckling at the contact area, surface splitting with delamination, and large delamination.

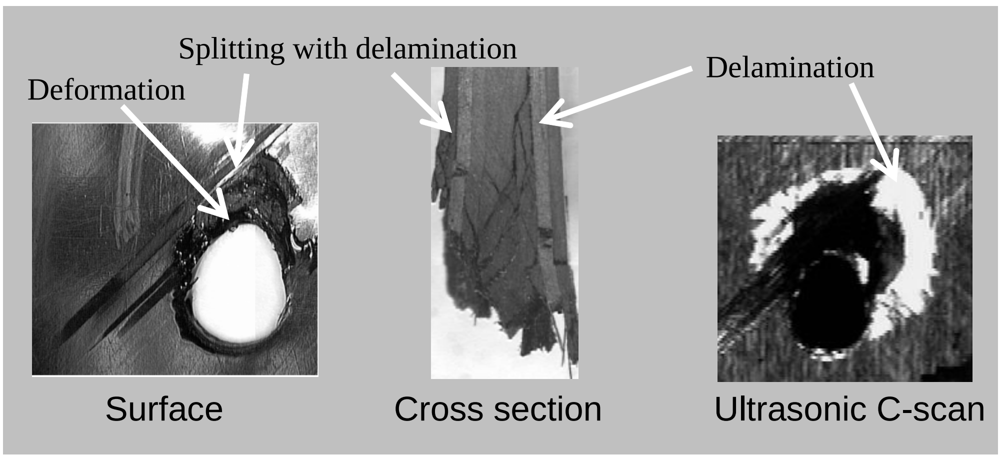
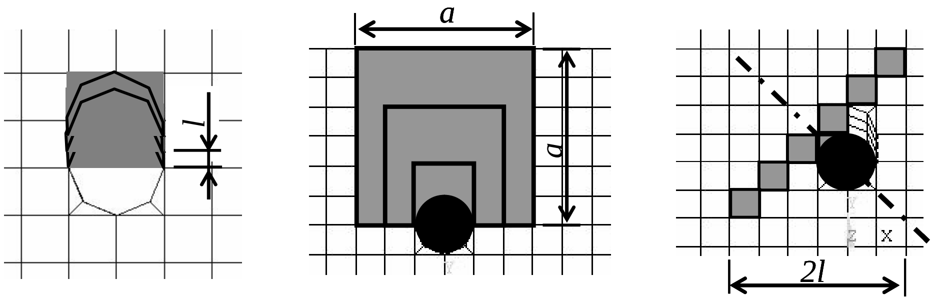


Fig.3 Bearing failure

Fig. 4 shows the damaged elements which correspond to three dominant fracture modes, and the definition of a distance between a bolt hole and electrodes. For deformation of bolt hole, all electric conductivities of the damaged elements are set to zero. For splitting with delamination, the transverse and through-thickness conductivities of elements are set to zero. For delamination, the through-thickness conductivity of elements is set to zero.

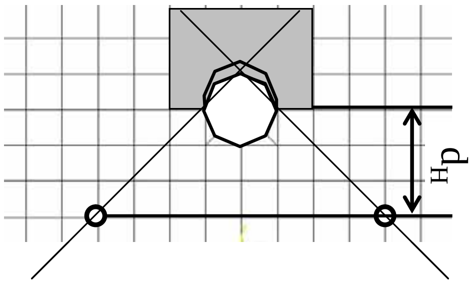


Deformation of bolt hole

Delamination

Splitting with delamination

(a) Damaged area of each fracture mode



(b) Definition of distance between bolt hole and electrodes

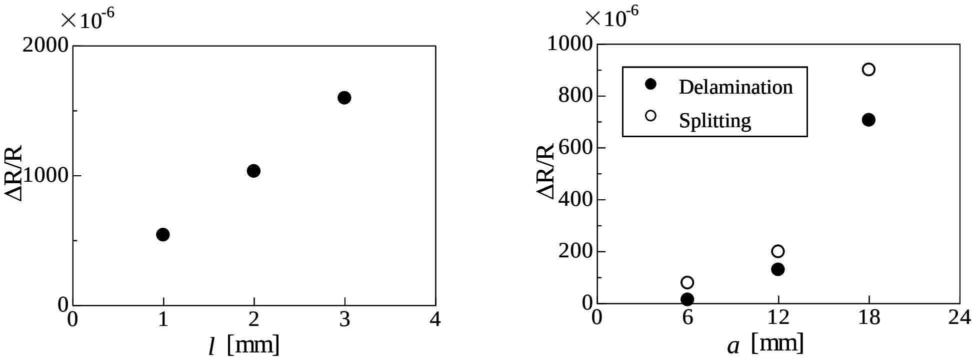
Fig.4 Modeling of bearing failure

Effect of size and distance on electric resistance change

Effect of the size of damage on the electric resistance change for a $[45/0/\text{-}45/90]_S$ laminate is analyzed for each damaged mode and the results are shown in Fig.5. The vertical axis is the electric resistance normalized by the initial electrical resistance, and the horizontal axis is the size of damage. The locations of electrodes are shown in Fig.1. For comparison, experimental resistance changes are shown in Fig.6.

The experimental electric resistance changes are on the order of 0.1% to 1%, and agree with analytical results for CFRP bolted joints. In analysis, the resistance change by delamination increases linearly, and the resistance change induced by delamination and splitting increases exponentially. An electric resistance change of 100μ may result from a deformation of a bolt hole of 0.2mm, a delamination of 100mm^2 or a splitting of 5mm. Since 100μ of electric resistance change can be easily measured using a commercial strain measurement system, we can detect such a small bearing failure by using the proposed method. In addition, actual bearing failure is combinations of these dominant fracture modes and more. This helps the detection of bearing failure because the total electrical resistance change is the sum of those induced by each fracture mode..

Effect of the distance between damage and electrodes on the electric resistance change for a $[45/0/\text{-}45/90]_S$ laminate is analyzed and the results are shown in Fig.7 The vertical axis is the electric resistance normalized by the initial electrical resistance, and the horizontal axis is the distance. Figure 7 shows that the electrical resistance change is inversely proportional to the distance from electrodes. The results indicate that electrodes can be mounted more than 10 mm far from a bolt hole.



(a) Deformation of bolt hole (b) Delamination and splitting

Fig.5 Effect of damage size on electric resistance change

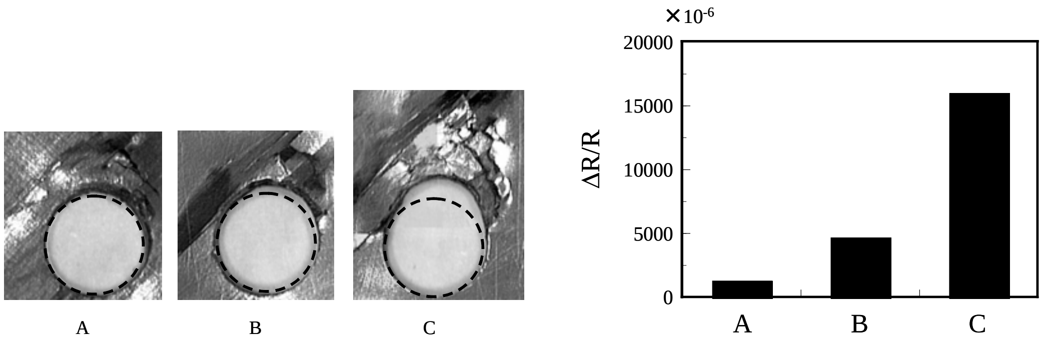
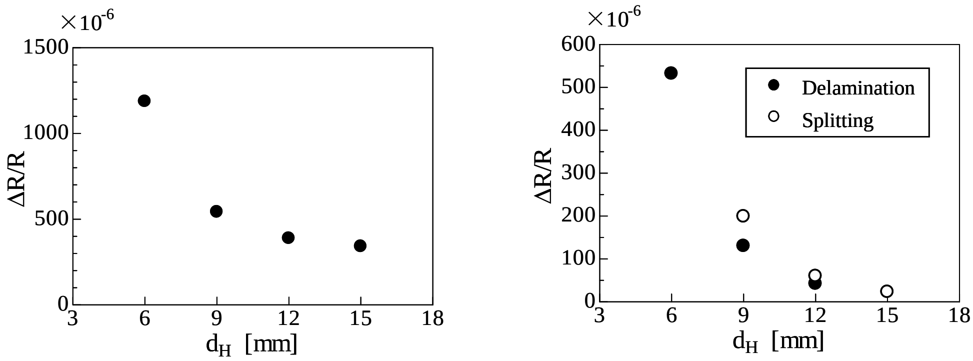


Fig.6 Experimental bearing failure and the electric resistance changes



(a) Deformation of bolt hole (b) Delamination and splitting

Fig.7Effect of distance from electrodes on electric resistance change

Concluding remarks

In this study, the detectablity of bearing failure of CFRP plates using the electrical resistance change method was investigated by conducting finite element analysis. The results show that bearing failure of less than 10mm square causes the electrical resistance change of a few hundred ppm and thus can be easily detected, and that the electrodes can be mounted more than 10 mm far from a bolt hole.

References

[1] T.A. Collings: Composites Vol. 1 (1977), p. 43
[2] W.J. Quinn, F.L. Matthews: J Comp. Mater. Vol. 11 (1977), p. 139
[3] T.A. Collings: Composites Vol. 7 (1982), p. 241
[4] G. Kretsis and F.L.Matthews: Comoisites Vol. 16-2 (1985), p. 92

[5] P.P. Camanho and F.L. Matthews: a review, Composites Vol. 28-A (1997), p. 529
[6] K.J. Lodge: Composites Vol. 7 (1982), p.305
[7] K. Moriya and T. Endo: Aeronautical and Space Japan Vol. 36-410 (1988), p. 139 [in Japanese]
[8] K. Schulte and C. Baron: Comp. Sci. & Tech. Vol. 36 (1989), p. 63
[9] N. Muto, H. Yanagida, M. Miyayama, T. Nakatsuji, M. Sugiya and Y. Ohtsuka: Japan Society Composites Materials Vol.18-4 (1992), p. 144 [in Japanese]
[10] C. Fischer and F.J. Arendts: Comp. Sci. & Tech. Vol. 46 (1993), p. 319
[11] P.W. Chen and D.D.L. Chung: Smart Mater. Struct. Vol. 2 (1993), p. 22
[12] A.S. Kaddoour, F.A. Al-Salehi and S.T.S. Al-Hassani: Comp. Sci. & Tech. Vol. 51 (1994), p. 377
[13] C. Wolfige and K. Drechsier: Advanced Materials for Lightweight Structures, ESTEC (1994), p. 677
[14] P.W. Chen and D.D.L Chung: J Am. Ceram. Soc. Vol. 78-3 (1995), p. 816
[15] X. Wang and D.D.L Chung: Polymer Composites Vol. 18-6 (1997), p. 692
[16] P.E. Irving and C. Smart Mater. & Struct. Vol. 7 (1998), p. 456
[17] J.C. Abry, S. Bochard and A. Chateauminois: Comp. Sci. & Tech. Vol. 59 (1999), p. 925
[18] D.C. Seo and J.J. Lee: Composites Structures Vol. 47 (1999), p. 525
[19] J.C. Abry, Y.K. Choi and A. Chateuminois: Comp. Sci. & Tech. Vol. 61 (2001), p. 855
[20] I. Weber and P. Schwartz: Comp. Sci. & Tech. Vol. 61 (2001),, p. 849
[21]N. Muto, Y. Arai, S.G. Shin and H. Matsubara: Composites: Comp. Sci.& Tech. Vol. 61 (2001),, p. 875
[22] M. Kupke, K. Schulte and R. Schuler: Comp. Sci. & Tech. Vol. 61 (2001),, p. 837
[23] R. Schueler, S.P. Joshi and K. Schulte: Comp. Sci. & Tech. Vol. 61 (2001),, p. 921 [24] S. Kubo, M. Kuchinishi, T. Sakagami and S. Ioka: Applied Electromagnetics and Mechanics, Takagi T, Uesaka M, editor. Proc. of the 10th Int. Symp. (2001), p. 641
[25] X. Luo and D.D.L. Chung: Polym. Eng. Sci. Vol. 20-7 (2000), p. 1505
[26] A. Todoroki, Y. Tanaka and Y. Shimamura: Technomic, Chang FK, editor. Structural health monitoring 2000, Lancaster: (1999),
[27] A. Todoroki, Y. Tanaka and Y.Shimamura: Materials Science Research International, JSMS (2001), p. 139
[28] A. Todoroki, M. Tanaka and Y. Shimamura: Comp. Sci. & Tech. Vol. 62 (2002), p. 619
[29] A. Todoroki, Y. Tanaka and Y. Shimamura: Comp. Sci. & Tech. Vol.62 (2002), p. 1151
[30] A. Todoroki, M. Tanaka, Y. Shimamura and H. Kobayashi: Adv. Comp. Mat. Vol.13-2 (2004), p.107
[31] A. Todoroki: Key Eng. Mat. Vol.270-273 (2004), p.1812
[32] M. Ueda, A. Todoroki and Y. Shimamura: Key Eng. Mat. Vol.270-273 (2004), p.1935
[33] Y. Shimamura, K. Oda, A. Todoroki and H. Kobayashi: Design, Manufacturing and Applications of Composites, 5th Joint Canada-Japan Workshop on Composites (2004), p.416
[34] A. Todoroki, M. Tanaka, Y.Shimamura, Compos. Sci. Technol. Vol.65(1) (2005), p.33
[35] Y. Shimamura, K. Oda, A. Todoroki and H. Kobayashi, T. Inada: Key Eng. Mat. Vol.297-300 (2005), p.653
[36] K. Omagari, A. Todoroki, Y. Shimamura, H.Kobayashi, Key Eng, Mat. Vol.297-300 (2005) p.2096