Composite Structures 115 (2014) 69–74

Contents lists available at ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

Finite element analysis for damage monitoring of glass fiber epoxy composites via the piezoelectric method

S.K. Hwang, H.Y. Hwang *

Department of Mechanical Design Engineering, Andong National University, 1375, Gyeongdong-ro, Andong-si, Gyeongsangbuk-do 760-749, Republic of Korea

ARTICLE INFO

Article history:
Available online 9 May 2014

Keywords:
Finite element analysis
Piezoelectric method
Damage monitoring
Glass fiber epoxy composites

ABSTRACT

This study conducted a finite element analysis of the piezoelectric damage monitoring of unidirectional glass fiber epoxy composites to estimate the electric charge signals from the composite materials against the external load or the internal crack length. To verify the results of the finite element analysis, the calculated electric charges were compared with the results of a previous research. In addition, the crack length during Mode I fatigue tests of the DCB specimen was estimated and compared with the measured data. The estimated electric charge signals from the finite element analyses showed tendency similar to that of the measured ones, and could predict the crack propagation.

1. Introduction

Since fiber-reinforced composites have high specific stiffness (stiffness/density), specific strength (strength/density) and damping characteristics, various structures such as precision machine parts, automobiles, aircrafts and leisure goods have been made using composites [1]. In-situ monitoring of cracks and damage in composite materials became very important issues in the improvement of the structural reliability of laminated composites because composite structures have initial defects or inevitable damages. For this reason, various nondestructive techniques were developed and used to detect defects in real composite structures [2–5].

As self-sensor methods use their own materials or structural characteristics and do not require embedded or surface-mounted sensors, they can detect cracks or damages as well as maintain their strength or structural reliability. In-situ damage monitoring methods that use the electric resistance change or the electric potential changes are representative self-sensor-type nondestructive methods. However, they are applied only to electrically conductive composites such as carbon fiber composites and cannot monitor damage in composites reinforced by nonconductive fibers or particles such as glass and ceramic [4,5].

To overcome the limitation of the electric methods, the piezoelectric method, which uses the piezoelectric characteristics of polymer materials for the matrix of composite materials, was suggested recently. Hwang proved the feasibility of the suggested method through static and dynamic tests using unidirectional glass fiber epoxy composites [6]. Subsequently, basic piezoelectric properties of unidirectional glass fiber epoxy composites with respect to the fiber orientation and the strain rate were experimentally investigated using the piezoelectric method [7,8]. Along with researches on material properties, experimental studies on the effects of cracks in polymeric composite materials on the piezoelectric method have been conducted lately [9]. The electrode arrangement or specifications of specimens and cracks are important parameters of experimental studies, but it is impossible to conduct experiments that consider all cases. Therefore, numerical approaches such as finite element analysis should be accompanied by experimental studies.

Most researches on finite element analyses of piezoelectric structures or systems were focused on formulations of the finite element model, the performance of piezoelectric actuators or sensors, and the mechanical behavior of structures with piezoelectric actuators or sensors [10–13]. Although finite element analyses of crack problems in piezoelectric structures were conducted, only the singularities, stress intensity factors and energy release rates were calculated [14–17]. However, the electric signals from the electrodes on the surfaces under external loads can be estimated using finite element analysis of polymeric composites with internal cracks for the application of the piezoelectric method as a self-sensor. Therefore, in this study, finite element analysis of the piezoelectric damage monitoring of unidirectional glass fiber epoxy composites was conducted to estimate the electric charge signals from composite materials against the external load or the internal crack length. To verify the results of the analyses, the calculated electric charges were compared with results of the previous researches on double cantilever beam (DCB) specimens with

---

* Corresponding author. Tel.: +82 54 820 6305; fax: +82 54 820 5167.
E-mail address: hyhwang@andong.ac.kr (H.Y. Hwang).

http://dx.doi.org/10.1016/j.compstruct.2014.04.020
0263-8223/

Table 1
Mechanical and piezoelectric properties of unidirectional glass fiber epoxy composites (UGN150, SK Chemicals, Korea).

Mechanical properties	E_1 (GPa)	43.3
	E_2 (GPa)	14.7
	G_{12} (GPa)	4.4
	ν_{12}	0.3
	ν_{23}	0.4
Dielectric constant	ε_1 (F/m)	4.87×10^{-8}
	ε_2 (F/m)	4.47×10^{-8}
	ε_3 (F/m)	4.54×10^{-8}
Piezoelectric strain constant	e_{13} (C/m^2)	-0.106
	e_{23} (C/m^2)	-0.635
	e_{33} (C/m^2)	0.272
Density (kg/m^3)		1980
Fiber volume fraction		0.6

1 – Fiber direction, 2 – Transverse direction, 3 – Thickness direction.

respect to the crack length. In addition, the crack length during the Mode I fatigue tests of the DCB specimens was estimated and compared with the measured data.

2. Materials and methods

2.1. Materials and specimens

Unidirectional glass fiber epoxy prepregs (UGN150, SK Chemicals, Korea) were used. The mechanical, electrical and piezoelectric properties of the unidirectional glass fiber epoxy composites are listed in Table 1 [8,9].

To investigate the effect of the crack propagation on the piezoelectric damage monitoring of the unidirectional glass fiber epoxy composites, DCB (double cantilever beam) specimens, as shown in Fig. 1, were considered [9]. The overall length and width of the DCB specimens were 150 mm and 10 mm, respectively, and two kinds of specimens with different thicknesses (2.0 mm and 4.0 mm) were used. The considered crack lengths ranged from 50 mm to 130 mm, with 5 mm intervals. To calculate the electric charge signals induced from the specimens under the external loads, two 20-mm-wide electrode pairs were located 60 mm and 100 mm apart from the loading position. All the dimensions and crack lengths of the DCB specimens were selected according to the previous research [9] to compare the measured and calculated results.

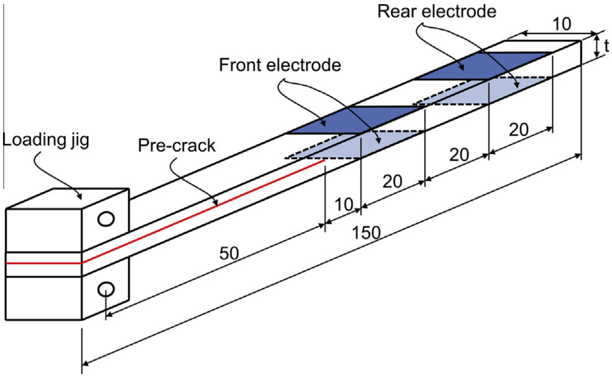

Fig. 1. Dimensions of the DCB specimens of the unidirectional glass fiber epoxy composites.

2.2. Finite element analyses

The finite element analyses were performed to estimate the electric charge signals from the DCB specimens against the external load or the internal crack length by monitoring the piezoelectric damage of the unidirectional glass fiber epoxy composites.

Fig. 2 shows the finite element model of the 2.0-mm-thick DCB specimens. The finite element analyses were conducted using ABAQUS 6.5 (Hibbitt, Karlsson & Sorensen, USA) with a 20-node 3D piezoelectric element (C3D20RE). Twelve thousand elements and 58,597 nodes were used. Transversely isotropic mechanical properties, dielectric and non-zero piezoelectric properties of unidirectional glass fiber epoxy composite are listed in Table 1. To model the crack surface, all the nodes on the potential crack surface were doubly defined. Then only the nodes on the crack surfaces were released together, and the other nodes were tied to maintain the model's coincidence with different crack lengths [9,18,19]. The nodes at the center line of the end surface were fixed to prevent rigid body motion since these nodes ideally do not move. The equal electric voltage boundary conditions were applied to model two upper electrodes, and 0 voltage boundary conditions to model two lower electrodes as the electric grounds. 1 Hz sinusoidal loads of 8 N (for the 2.0-mm-thick specimens) and 15 N (for the 4.0-mm-thick specimens) were applied on the surface for loading jigs. Then the electric flux density (the ratio of the electric charge signals to the electrode areas) of the nodes on the upper electrodes was

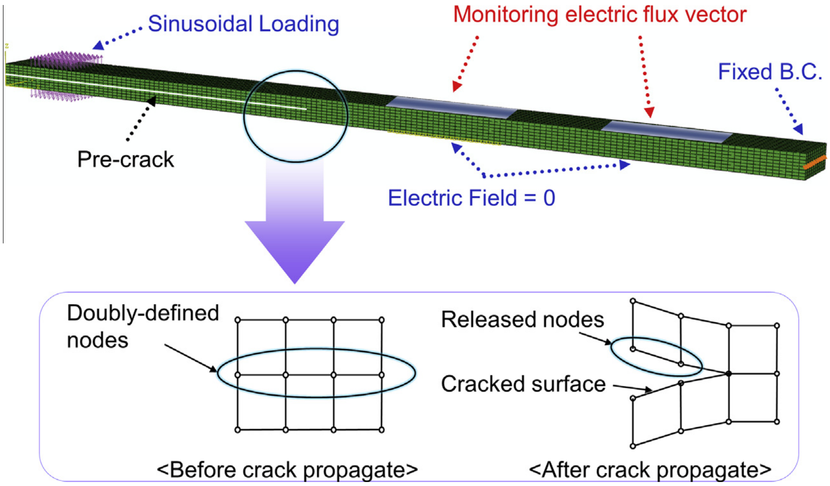

Fig. 2. Finite element model of the DCB specimens and scheme of the crack propagation model.