Composite Structures 207 (2019) 255–263

Contents lists available at ScienceDirect

Composite Structures

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

# Real-time electrical impedance monitoring of carbon fiber-reinforced polymer laminates undergoing quasi-static indentation

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A R T I C L E I N F O

*Keywords:*
CFRP
Electrical properties
Non-destructive testing
Structural health monitoring
Electrical impedance tomography
Quasi-static indentation

A B S T R A C T

Laminated composites are vulnerable to damage from out-of-plane loading, particularly impact loading, and the incurred damage is often only detected by evaluating the post-impact condition of the composites. Real-time monitoring techniques are desirable for early detection of damage. Utilizing changes in the electrical properties of composites to track incurred damage is promising, but the interpretation of such measurements is still challenging. Here, an electro-mechanical system is introduced to understand how well we could detect mechanical degradation in carbon-fiber-reinforced polymer (CFRP) plates undergoing a quasi-static indentation (QSI) test, which is representative of an impact load. The system measures the in situ, real-time changes in impedance and phase angle along the specified conductivity paths. Two different electrode configurations are proposed and tested. In all studied cases, the system effectively detected severe damage, characterized by an immediate reduction in strength, in CFRP. Using our proposed electrode configurations, we discovered that the early detection of barely visible damage strongly depends on two factors: (i) the location of the injection-measurement points with respect to the damage, and (ii) the orientation of the measurement paths with respect to the fibers orientation in the laminated CFRP surface.

## 1. Introduction

Laminated composites are used to make large structures in the aerospace, automotive, oil and gas, and civil construction industries, as well as other fields. These composite structures are inevitably subjected to impact loading. Depending on the energy level of the impact, the resulting degradation may be visible (such as penetration or perforation damage) or almost undetectable (barely-visible impact damage, BVID). In all cases, the degradation is immediately detrimental to the compressive strength and, eventually, the overall structural integrity [1]. For this reason, a structural health monitoring (SHM) method that determines the real-time damage level to the composites in situ is highly desirable. Monitoring methods such as an ultrasonic C-scan [2–4], X-radiography, or micro-computed tomography [5–9] are commonly used to support SHM schemes for measuring impact damage in composites. However, these methods incur additional costs and time because they require the structures to be offline (system shut-down) and highly skilled personnel to physically inspect the structures and systems. Therefore, a user-friendly SHM method for monitoring the composite structures is still required to improve maintenance and repair procedures and to avoid unexpected catastrophic failure due to undetected degradation.

Electrical-based SHM methods have received great attention and are promising for use in composites (e.g., carbon fiber–reinforced polymer, CFRP) [10–14]. Since the carbon fibers in CFRP are naturally conductive and act as sensors, the change in impedance or conductivity that occurs in CFRP can be measured to monitor the material state [10]. To this end, electrical impedance tomography (EIT) systems have been proposed to reconstruct the induced damage in CFRP by monitoring changes in conductivity using electrodes attached to a specimen [11,15]. An EIT system was also proposed for detecting impact damage, although the signal reception was strongly influenced by the sensor location [16]. Thus far, the use of EIT systems has been limited to determining the existence or location of damage in CFRP post-mortem and invasive electrode attachment (i.e., drilling the specimen is required) [11,12,15,17,18]. In light of these limitations, there is still a need for an effective EIT system that is capable of detecting real-time damage progression, as well as operational on real structure and non-invasive for CFRP (e.g., utilizing surface electrodes, which do not require drilling of the CFRP plate).

In this work, we first developed an electro-mechanical system capable of observing changes in the electrical properties of CFRP laminate

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https://doi.org/10.1016/j.compstruct.2018.09.030
Received 30 July 2018; Received in revised form 9 September 2018; Accepted 17 September 2018
Available online 19 September 2018

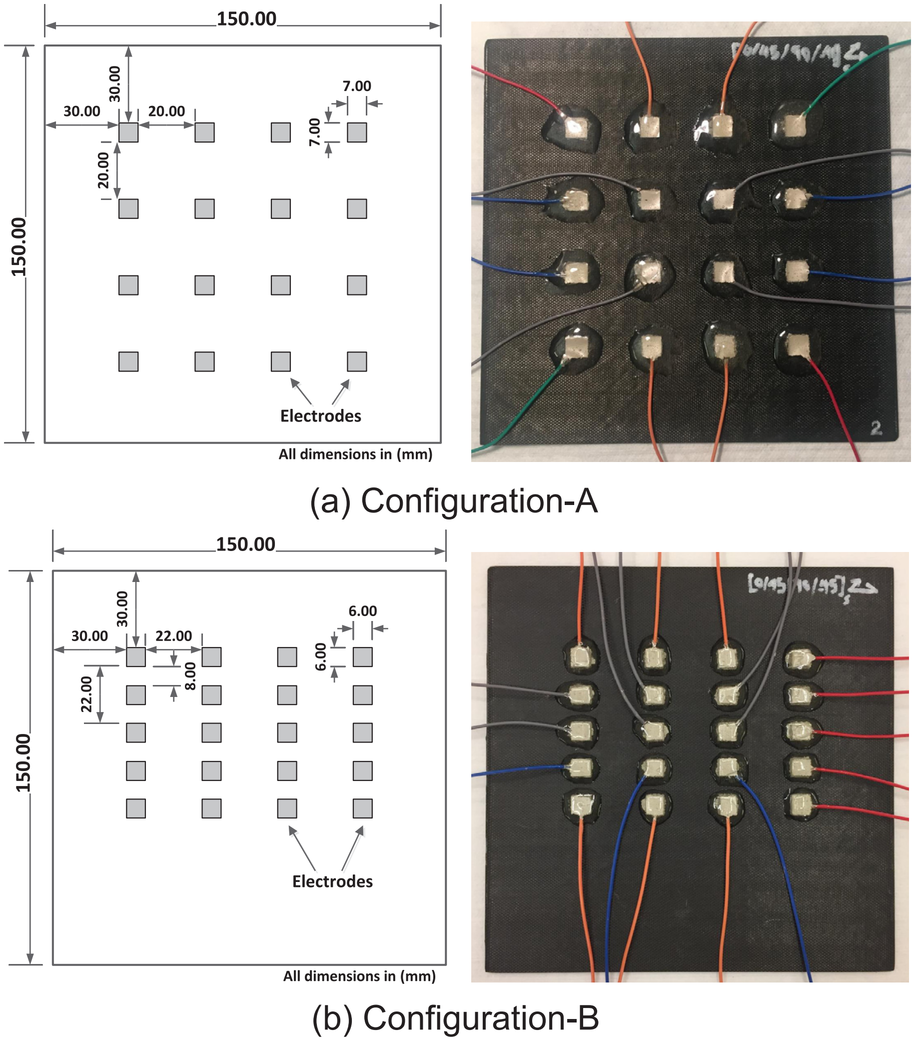


**Fig. 1.** Schematics of the electrode arrangements and actual CFRP plates for (a) Configuration-A with four-by-four electrodes, and (b) the optimized Configuration-B with five-by-four electrodes.

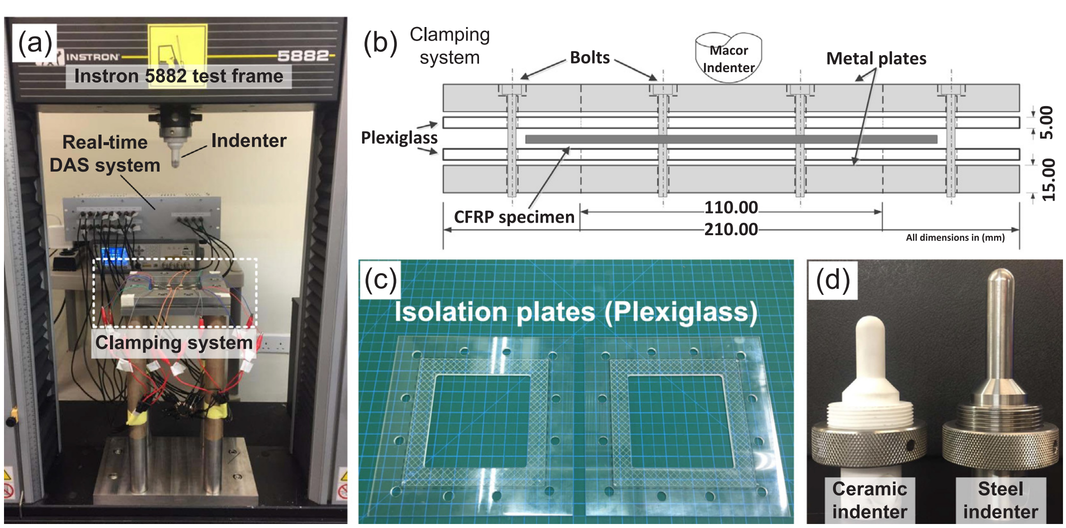


**Fig. 2.** (a) Quasi-static indentation setup, (b) schematic of clamping system with metal and isolation plates (dimension in mm), (c) non-conductive, isolation plates made of plexiglass to electrically insulate the specimen from the fixture during the QSI test, and (d) ceramic (Macor) and steel indenters.