Title: Improved Active Tagging Non-Destructive Evaluation Techniques for Full-Scale Structural Composite Elements

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ABSTRACT[1]

An on-site particle tagging non-destructive evaluation (NDE) technique has been developed for health monitoring of a full-scale structural element of glass-fiber reinforced plastics (GFRP) composites in which conventional NDE approaches are not very effective. Unlike conventional passive tagging NDE inspection, the technique uses an electromagnet exciter to interrogate tagged composites. A laser Doppler vibrometer is used for high-speed and non-contact surface vibration detection. An accept-reject criteria based on the signature pattern difference of a healthy and a damaged structure is then applied to extract an index of the health of the structural elements. The experimental results of the active particle tagging inspection shows a variation in the dynamic response of the specimens when defects and/or damage are presents. The variation could be used to diagnose and to monitor the integrity of materials.

INTRODUCTION

In high volume civil engineering constructions and industrial applications, the use of advanced reinforced composite materials can provide elegant solutions to difficult engineering problems. Unfortunately, the physical attributes of the composite materials present problems for the accurate detection and evaluation of internal flaws. This is especially true for the GFRP composites, which are electrical insulators and, hence, non-conductive. These difficulties have created a need for new NDE techniques optimized specifically for GFRP composites materials since conventional NDE methods are not very effective. A new NDE technique, dynamic characteristics evaluation using magnetic interrogation (DCEUMI), was shown to be non-intrusive, capable of fast data acquisition, and

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sensitive to a wide range of common composite flaws (Rogers, *et al*., 1995; Zhou, *et al*., 1995).

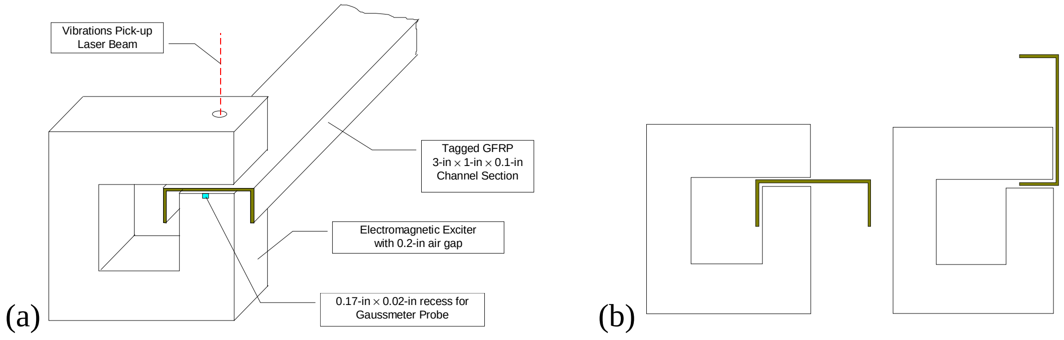

Figure 1. Layout of the active tagging interrogation of C-channel section using an 1.5-in × 1.5-in working section electromagnetic exciter and a laser beam for vibrations pick-up: (a) general layout; (b) placement options for the C-channel section.

The authors (Giurgiutiu, *et al.*, 1996) found that, with GFRP composites, a presence of damage could be detected by signature-pattern identification of the frequency response and natural frequency peaks. In this paper, the DCEUMI technique, which utilizes a powerful electromagnetic exciter and a laser Doppler vibrometer is developed for detection of internal defects and/or damage for full-scale GFRP composite-elements inspection.

PROPOSED CONCEPT AND METHOD FOR FULL-SCALE NDE INSPECTION EQUIPMENT

The proposed concept is presented schematically in Figure 1. A 3-in × 1-in × 0.1-in C-channel tagged-composite section is passed through the narrow air gap of an electromagnetic exciter. Under the influence of the electromagnetic field, the tagged composite material is locally excited at high-frequency. The resulting vibrations response is picked up by a laser beam. The processing of the vibration response in correlation with the high frequency magnetic excitation yields meaningful information regarding the integrity of the composite material, possible delamination, cracks, and other defects.

The method of performing NDE on the full-scale GFRP composite C-channels is straight forward and consists of passing the channels through the interrogation window of the equipment. Since the method is non-contact, several passes may be applied without affecting the part being inspected.

EXPERIMENTAL TECHNIQUES

The principal improvements of this technique over that previously reported by Giurgiutiu, *et al*. (1996) are the replacement of the piezoelectric force gage fixed to the tagged composite specimen with a laser Doppler vibrometer for the non-contact sensing and the development of a powerful custom-made electromagnetic exciter. The advantages of the new system are as follow:

1. The external impact on the tested specimens in successive evaluation is minimized. Since the laser detection is on non-contact, no extra mass is attached to the composite part being inspected.

2. Because the scanning laser head is remote from the composite elements being inspected , the new inspection method can be applied to on-site and in-field quality control, e.g. while the composites parts are in the fabrication process, or while they are on the construction site.

3. Since exciting the structure and monitoring the response are done at the same position, the method can be used to simultaneously detect the presence of defects and to determine their location and size. In addition, the effect of boundary conditions on the evaluation process is minimized high-order frequencies and modal parameters are used.

The technique consists of the excitation of the vibration modes with an electromagnetic exciter. The response is sensed by the laser Doppler vibrometer. Input and response signals are fed into an FFT analyzer, and the frequency response function over the desired frequency span is displayed, in real time, on the oscilloscope and stored in the computer memory. Subsequent processing of the signal and of the frequency response curves yields the inherent characteristics of the specimen (natural frequencies, modal parameters, etc.)

SPECIMENS AND INSTRUMENTATION

Tagged and untagged GFRP composite specimens containing 4% by weight of resin lignosite powder were produced by Creative Pultrusions, Inc. as 3-in × 1-in × 0.1-in C-channels section ladder rails. In some specimens, delaminations were created using 1.5-in diameter, 4-mil Mylar film inserts.

The instruments consisted of three main components, exciting instruments, measuring instruments, and signal processing instruments:

The exciting instruments included a signal generator, filters, power amplifiers and an electromagnetic exciter with a small hole. Through this hole, a laser beam was pointed to sense directly the specimen region being magnetically excited. The excitation magnetic field was generated by an alternating current (AC) and a direct current (DC) in the different solenoid coils of the electromagnet. The DC coils created a static bias flux density to magnetize the particles and maximize the excitation to improve signal-to-noise ratio and suppress the non-linear frequency component, while the AC coils created an alternating magnetic flux density to produce vibrations of the particles.

The measuring instruments consisted of the laser Doppler vibrometer and a Gaussmeter. The measuring instruments accomplish the conversion of the physical quantity into an electrical quantity. After conversion and conditioning of the physical data, the test data could be either displayed, using oscilloscopes, or recorded and stored in the computer for further signal processing.

The signal processing instruments consisted of a Fast-Fourier-Transform (FFT) analyzer and a computer. In our experiments, the signal generator, the filter, and the Fast-Fourier-Transform (FFT) analyzer were united into one instrumentation system constructed around a Macintosh Quadra 950 computer. Both the input, measured with the Hall probe of a Gaussmeter, and the output, measured by the laser Doppler vibrometer, were passed to the frequency analyzer. Processing of these signals yielded frequency response curves. Search for the anomalies in the frequency response curves and comparison of natural frequencies of the evaluation specimens with an established accept-reject criteria would assess integrity of composite elements.

TEST PROCEDURES

Because NDE by DCEUMI is based on the fact that internal defects will generally result in changes in structural stiffness which leads to changes in the natural frequencies and in the frequency response signature, magnetic excitation is used to cause the tagged specimens to vibrate in order to measure the vibration characteristics. The responses induced by this vibration are measured with the laser Doppler vibrometer. The velocity and flux density signals from the laser Doppler vibrometer and from the magnetic field probe are input to the frequency response analyzer. The time record of the structural response to the magnetic excitation is converted to the corresponding frequency spectrum. The resulting frequency spectrum indicates the natural frequency peaks and frequency response signature pattern. The frequencies of the test specimen are readily identified from the peaks of the spectrum. The detection of defects can be done by comparison of the changes in the frequency responses of specimens. In this study, we concentrated our attention on the examination of the high-order mechanical resonance frequencies of the excited specimen as a possible way to identify local defects and thus develop an effective NDE technique.

CALIBRATION

The system needs to be calibrated using control specimens regarding of accept-reject criteria. The frequency response signature pattern of the control specimens will be stored in PC memory as reference. Meanwhile a meaningful definition of what is a “comforting” and a “non-conforming” material condition needs to be achieved.

SPECIMEN SUPPORT

Since the method utilizes high-frequency excitation, only the small-wavelength vibration modes are excited. Hence, the method is relatively insensitive to boundary conditions, as long as they satisfy the StVenant principle. The specimen can be supported either as a cantilever beam, or on end supports. To satisfy the StVenant principle for a typical defect length of 1-in, a distance of approximately 1-ft (i.e. > > 1-in) between the interrogation window of the equipment and the nearest specimen support is recommended.

RESULTS AND DISCUSSIONS

The experiments have been performed for proof-of-the-concept of full-scale composite elements inspection. The experiments have been carried out with sinusoidal signal sweep. Broad-band random excitation was also tried, but it was found that, due to some limitations of the equipment, the resulting structural response was not powerful enough to give a good signal processing result. Hence, harmonic force excitation with frequency sweep was used. Thus, the frequency response of the specimen was determined. The response signal obtained during excitation of the specimen over a frequency sweeping range of 500 - 1500 Hz was found to contain several natural frequency peaks. The frequency response of control specimen was compared with this of specimen having simulated defects in the form of delamination. Figures 2a presents the frequency responses of the control and delaminated specimens. It can be noted that the presence of the defects created significant changes in the shape of the frequency response and in the location of the resonant frequency peaks.

Note that frequency responses not only depend on the geometry of specimens but also on material stiffness. For specimens with the same geometry made from the same material, differences in frequency response signature may occur due to the defects. For the specimen without defects, the first few resonant peaks of the response (Figure 2a) were greater than that of delaminated specimen. Since each specimen was tested under the same experimental conditions, these changes could be directly correlated with the presence of the defects in the specimen. The resonant frequencies of the delaminated specimen were significantly lower than those of the control specimen.

When driven by the magnetic field, the embedded particle sensors interacted with their host matrix and generated measurable signatures of the structural response which could be interpreted as structural information about damage. The sensory signature of the frequency response from the tagged specimen could be extracted as a result of the interaction between embedded particles and their host matrix. Relationships between the responses of tags and important physical and structural parameters have been experimentally studied previously to understand the fundamental physics and mechanisms involved in using the active tagging method (Rogers, *et al*. 1995).

Figure 2b presents the frequency response of the control specimen when excited at different locations along its span. As expected, performing the measurement at different locations resulted in variations of the frequency response curve. The reason for this lies in the mode shapes of the structural modes. Therefore, the sensors may pick up a dominant mode at one location and another dominant mode at a different location. However, as seen in Figure 2b, there is consistent pattern of resonant frequency peaks that is found at all locations, though the peak amplitudes may differ somehow. This aspect needs more research, such that carefully conducted calibration and training experiments can be devised to develop an effect and reliable defect detection procedure for full-scale composite element inspection in a real-life environment.

The overall result of these preliminary tests indicate that the active tagging technique of dynamic characteristic evaluation using magnetic interrogation (DCEUMI) has been found to be effective and sensitive enough to detect the simulated defects.

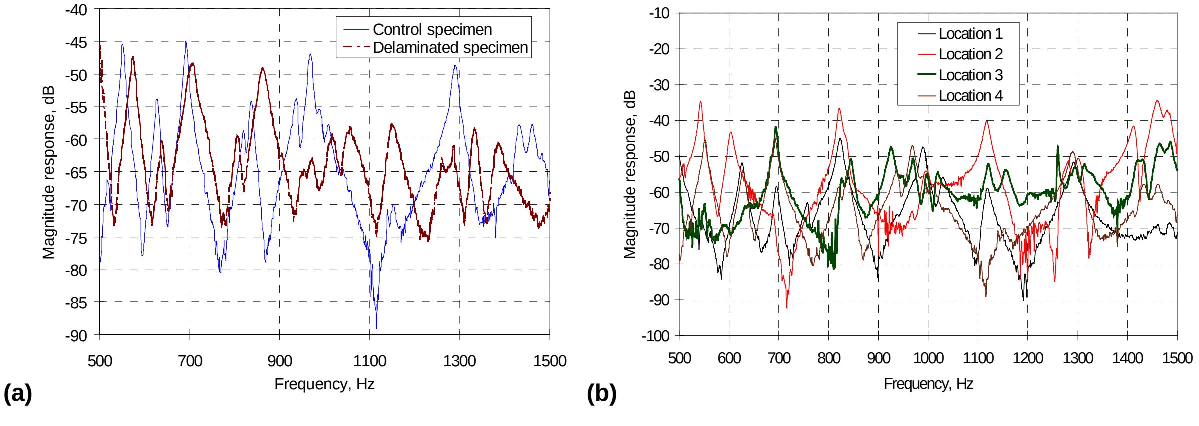

Figure 2 **Comparison of frequency response curves: (a) Control *vs.* delaminated specimens; (b) variation with location on a control specimen.**

CONCLUSION

The ferromagnetic active tagging NDE technique based on the use of an electromagnetic excitation in conjunction with laser Doppler vibrometer and a computer-based FFT analyzer has been developed for the inspection and evaluation of full-scale GFRP composites elements. The preliminary experimental results presented in this paper indicate that the proposed technique is effective in exciting the tagged composite specimens in the design frequency range 500-1500 Hz. The experiments have also shown that the proposed technique is sensitive enough to detect simulated delaminations defect purposely places in the specimen by the manufacturer. The graphs shown in Figure 2a indicate clear differences in the frequency response between the control and the delaminated specimens. In the presence of local defects (1.5-in diameter, 4-mil Mylar film inserts), the resonant frequency peaks presented a clearly identifiable shift towards lower frequency values. This fact can be directly related to the lowering of the local plate-bending stiffness associated with the presence of delaminations in a laminated composite material structure.

Preliminary investigation of the repetitiveness and consistency of the method has shown that the frequency response spectrum appears to be highly repetitive when measured at the same location, but it can show some variations from location to location. The latter phenomenon is to be expected due to the wavelength of the structural mode shapes, and its influence on the on the smallest size of detectable defect, together with calibration and training experiments, needs to be investigated in further research and correlated with the excitation frequency range.

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