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Dual-Polarized Microwave Near-Field Reflectometer for Non-Invasive Inspection of Carbon Fiber Reinforced Polymer (CFRP) Strengthened Structures

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Abstract – Carbon fiber reinforced polymer (CFRP) composites are increasingly being used in strengthening structures of civil infrastructures, aerospace and automotive industries. Subsequent to the application of CFRP, detection and evaluation of the structural integrity of the member becomes a critical issue. Microwave non-invasive inspection techniques have been successfully used for inspecting these structures. A novel inspection system with a dual-polarized microwave near-field waveguide probe for detecting defects such as disbond between CFRP laminates and strengthened structures is presented. It is shown that this system provides automatic removal of the influence of undesired standoff distance (or surface roughness) variations. It may simultaneously generate three images of defects: two at orthogonal polarizations and one after the influence of the undesired variations is removed. The novel measurement system provides for detection and evaluation of different types of defects in CFRP reinforced composite structures, reducing the time required for data acquisition. This paper also presents the design of the dual-polarized reflectometer at X-band (8.2 – 12.4 GHz) and details of the measurement system as well as the results of application of this system for inspecting CFRP reinforced composites cement-based structures including some from an actual bridge. The results clearly illustrate the utility of this system for non-invasive inspection of CFRP strengthened structures.

Keywords – microwaves, dual-polarized reflectometer, non-invasive, CFRP, composites, near-field.

I. INTRODUCTION

Carbon fiber reinforced polymer (CFRP) composites are increasingly being used in civil infrastructures, in aerospace and automotive industries. For instance, CFRP composites are externally bonded to concrete members to provide additional flexural, shear or confining reinforcement based upon the retrofit deficiency [1-3]. The quality of the bond between the CFRP and concrete is extremely important. The transfer of stresses from concrete component to CFRP is only obtained through effective adhesion. Disbonds between the CFRP laminate and the concrete may occur due to a variety of reasons including improper application of the CFRP laminate, presence of moisture near the concrete surface, impact damage, etc. Thus, it is of great interest to develop a *one-sided, non-contact, real-time, fast, robust, inexpensive and portable* inspection system capable of detecting such disbonds and evaluating their properties. Moreover, this

system should be able to detect potential structural damage under CFRP, misalignment of fibers and provide information about the integrity of any subsequent repair of a disbonded CFRP laminate. Standard non-invasive techniques may not always be able to effectively test CFRP composites for disbond, damage and misalignment. On the other hand, microwave near-field non-invasive techniques, utilizing open-ended rectangular waveguides, have demonstrated the ability to detect defects such as disbonds, delaminations in composite structures [4] and evaluate their various properties using simple microwave reflectometers and imaging techniques. To this end, measurement systems including a near-field microwave reflectometer and a computerized 2D scanner were developed and investigations were conducted for detecting defects in CFRP reinforced cement-based structures [5-8]. The investigations have clearly shown the capabilities of this technique for detecting such defects. They have also shown that polarization of the incident microwave signals is an extremely important parameter. Microwave signals do not penetrate inside of highly conducting materials such as metals and high-density carbon-loaded composites. Carbon fibers are highly conductive at microwave frequencies. However, when laminates are made into fibers their interaction with microwave signals is strongly influenced by the relative orientation of the fibers and the microwave signal polarization. For strengthening purposes, CFRP laminates are commonly unidirectional in order to provide additional strength in a particular direction. The rectangular waveguide probes produce linearly polarized microwave signals. Consequently, when using a unidirectional CFRP laminate, microwave signals easily penetrate through the laminate when the fiber directions and the signal polarization are orthogonal to one another. However, when the fiber directions and the signal polarization are parallel to one another, the signal reflects off of the laminate, resulting in very little signal penetration beyond the first layer. The former case is well-suited for detecting and evaluating disbonds and concrete damages, whereas the latter case only provides information about surface roughness, and fiber breakage in the CFRP, etc. [5-8]. Moreover, it is possible to obtain two sets of data, corresponding each polarization, and then remove the undesired effect of surface roughness and standoff distance

variation using the data obtained with parallel polarization. However, conventional microwave near-field reflectometers with an open-ended rectangular waveguide probes only provide single polarization data. Thus, it is of great interest to develop an inspection system producing two images simultaneously and enabling the automatic removal of the influence of undesired variations. This paper presents a novel inspection system using a relatively simple dual-polarized microwave near-field probe for non-invasive testing and evaluation of CFRP reinforced composite structures. The results of detecting disbonds between CFRP laminates and cement-based structures are also presented.

II. DESCRIPTION OF THE SYSTEM

Figure 1 shows a schematic of a novel inspection system. This system consists of a computerized automated 2D scanning mechanism, two microwave circuits incorporated into a dual-polarized near-field waveguide probe, and a conditioning circuit (signal processing section). The open-ended dual-polarized waveguide probe simultaneously transmits two linear orthogonal polarized signals onto the structure under inspection (SUI) and receives two linear and orthogonal polarized reflected signals. These signals vary as a function of standoff distance, which is defined as the distance between the SUI and the probe aperture. However, if the electric field polarization vector of one of the transmitted signals is perpendicular to the fiber orientation of CFRP laminate the signal penetrates through this laminate and senses an interior defect, while the other signal is sensitive to standoff distance variation and SUI surface roughness since its electric field polarization vector is parallel to the fiber orientation causing the signal to totally reflect off of the CFRP laminate. Subsequently, the reflected signals are fed to two phase detectors (microwave circuits) providing for two corresponding DC output voltages which are proportional of phase (and/or amplitude) difference between the transmitted and reflected signals of each polarization. Then, these DC output voltages are applied to a conditioning circuit which includes a compensator, a means for signal processing and indicator or image display. The output of the conditioning circuit, which is also a DC voltage, is used to generate 2D image which provides information about the internal structure and defects (i.e., disbond, concrete damage, etc.) while removing the undesired influence of standoff distance (or surface roughness) variations from the measurements at the same location on SUI. A computerized scanning mechanism provides raster scan of the SUI by moving of the probe over it. The measured voltages from the output of the microwave circuits are also used to generate separate images for each polarization. Thus, three images of scanned area may be generated and used simultaneously for inspection. For instance, image for parallel polarization may be used for non-contact sensing of standoff distance variation and/or detecting surface defects (i.e. fiber misalignment, fiber breakage, cracks, etc.). Consequently, this novel inspection system

provides detection and evaluation of different types of defects in CFRP reinforced structures, reducing the time required for data acquisition due to an automatic removal of undesired variations.

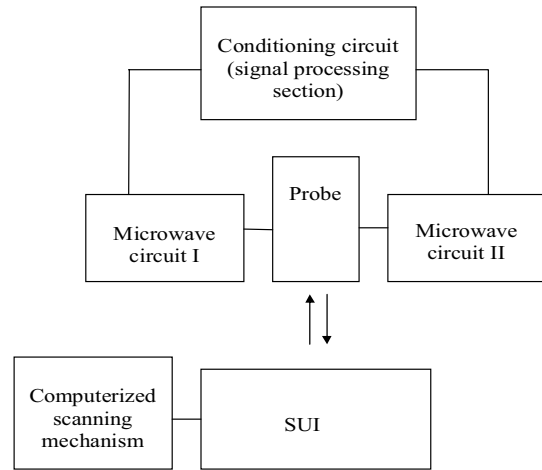


Fig. 1. Schematic of the inspection system with a dual-polarized microwave probe.

Such a dual-polarized inspection system with a square waveguide probe was designed and constructed at X-band (8.2–12.4 GHz). This frequency range was chosen because of successful previous investigations of CFRP reinforced cement-based structures [5-8]. Figure 2 shows a schematic of two microwave circuits and an open-ended square waveguide probe. Each microwave circuit consists of a microwave source (S), an isolator (I), a directional coupler (DC) and a mixer (M). Portions of the transmitted and reflected signals of each polarization are combined in the mixer to produce DC

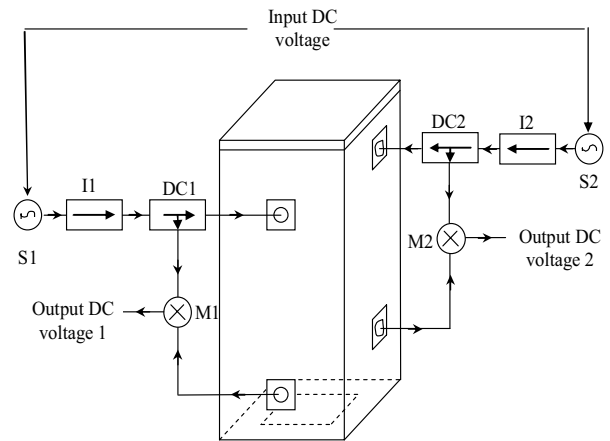


Fig. 2. Schematic of microwave circuits and a square waveguide dual-polarized probe.

output voltages which are proportional of their phase (and/or amplitude) difference. Frequency dependency of coupling between the two orthogonally polarized ports was investigated for providing minimum unwanted coupling and increased internal isolation between them. As a result, two microwave signals of different polarizations with corresponding frequencies, 9.4 GHz and 11.2 GHz, were used for the reflectometer. Microwave 2D images of CFRP reinforced cement-based (mortar, concrete) structures were produced by making raster scans of the structures.

III. APPLICATION

A. CFRP cement-based samples

Several CFRP cement-based samples were investigated for the purpose of detecting and evaluating of disbonds and other defects. One of the samples used in this investigation was a 380 mm by 520 mm-wide and 90 mm-thick mortar slab adhered with CFRP laminate as shown in the Figure 3a. A 60 mm by 80 mm rectangular disbonded region was intentionally produced by inserting a thin foam slab between the CFRP laminate and the substrate mortar. Figure 3b shows a schematic of the sample with marked disbonded region and scanned area. To better demonstrate the utility of this system, the sample was intentionally tilted, with respect to the probe scan plane, to produce a relatively severe standoff distance variation over the scan area. Subsequently, an area of 140 mm by 140 mm including the disbonded region was imaged using the measurement system. Figure 4 shows the microwave images of the scanned area. As expected, the disbonded region is clearly visible in the image for perpendicular polarization (Fig. 4a). However, the indication of the disbonded region is also clearly visible in the image for parallel polarization (Fig. 4b). The image in Fig. 4b is an indication of the slight surface bulging due to the presence on the thin foam insert. The image obtained by using perpendicular polarization shows non-uniform structure of the disbond in contrast to image for parallel polarization in which the presence of the thin foam insert as well as the slight surface bulge are detected in the image. Moreover, both images show a gradual intensity change mostly along the horizontal axis representing the intentionally induced standoff distance change. Figure 4c shows the image obtained after compensation of the standoff distance variation using the image data for both polarizations. It can be seen from Fig. 4c that the disbonded region is clearly visible and it is non-uniform. The non-uniformity of the disbonded region was confirmed by results of taping and may be explained by the changes in thickness of the foam during the process of bonding the CFRP laminate, the foam slab and the mortar structure. The black area around the disbonded region is uniform. This is in contrast to the non-uniform area around the foam insert in Fig. 4a. It must be noted that the dimensions of the disbonded region associated with its image

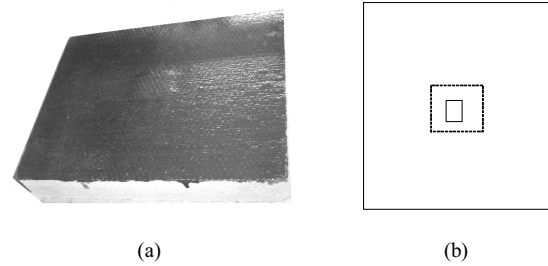


Fig. 3. (a) Picture of the CFRP mortar sample and (b) its schematic with marked disbonded region (solid line) and scanned area (dash line).

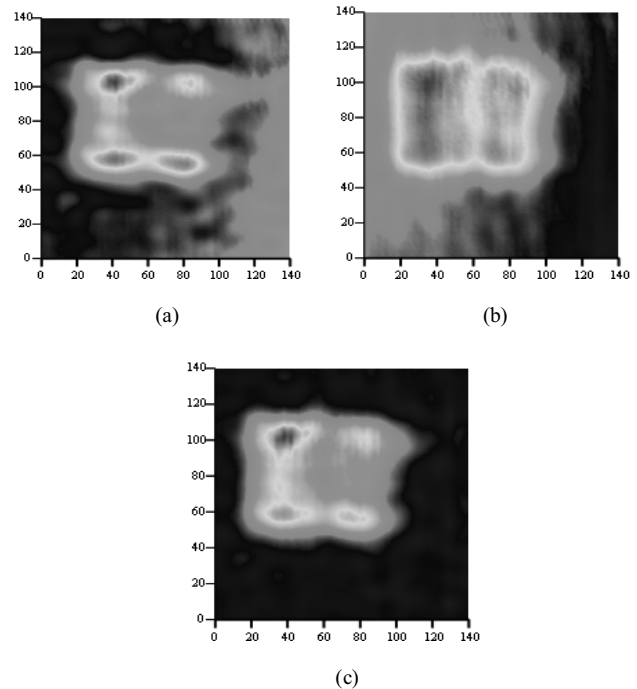


Fig. 4. Microwave images of the disbond in CFRP mortar sample (a) at perpendicular polarization, (b) at parallel polarization, and (c) compensated image.

in Fig. 4c correspond well with its actual dimensions. It means that the effect of bulging is also removed.

B. In-field measurements

In-field inspection and monitoring of CFRP-strengthened concrete members was conducted on the structures of an actual bridge [7]. Several 600 mm by 600 mm CFRP patches were bonded to the abutment and the bent of the bridge. A number of artificial disbonds (intentional defects) were manufactured by injecting air between CFRP patches and concrete members. Figure 5 shows the microwave images of the 260 mm by 320 mm scanned area of the bonded CFRP patch in the abutment of the bridge. The black spots in the image for perpendicular polarization (Fig 5a) represent the areas of two disbonds. The indications of the slight surface

bulging due to the presence of air between CFRP and concrete are also clearly visible in the image for parallel polarization (white spots in Fig. 5b), The compensated image (Fig.5c) was generated automatically after the influence of the standoff distance variation was removed from the data for the perpendicular polarization using data for the parallel polarization. The locations and sizes of the detected disbonds, indicated by this compensated image, agree well with their locations and sizes on the bonded CFRP patch. These features were verified using tap testing.

The details of this measurement and its results will be reported in the final extended paper.

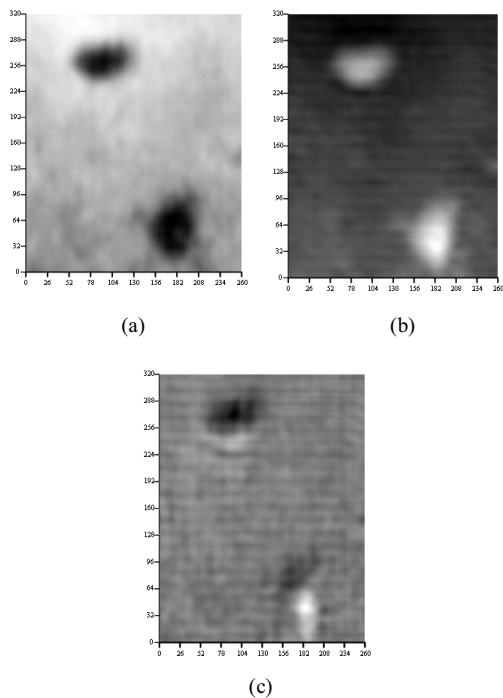


Fig. 5. Microwave images of the abutment CFRP patch (a) at perpendicular polarization, (b) at parallel polarization, and (c) compensated image.

IV. SUMMARY

Defects in the form of disbonds, damages, cracks, fiber misalignment, and fiber breakage in CFRP reinforced composite structures can significantly reduce their strengthening effectiveness. Microwave NDT methods are viable candidate for *life-cycle* inspection of the CFRP cement-based structures. A novel inspection system with a dual-polarized microwave near-field waveguide probe is proposed for detecting these defects. This system provides automatic removal of the influence of undesired variations and may simultaneously generates three images of the defects, namely: two images at orthogonal polarizations and one image after removing undesired variations. The results

from the application of this system for detecting and evaluating disbonds in CFRP cement-based structures, including some from an actual bridge, clearly show the utility of this system. Microwave images, produced using this system, provide a close estimate of the spatial dimensions of disbonded regions. In addition, the system may provide non-contact sensing of standoff distance variation and/or detecting surface defects (i.e. fiber misalignment, fiber breakage, cracks, etc.) of the CFRP composites.

The system is small, robust, and inexpensive and provides a significant amount of real-time useful information about the nature of an anomaly (e.g., size, location, etc.) without the need for complex image processing. The application of the system is currently ongoing and additional results will be provided in the final paper.

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