MICROWAVE FIELD MEASUREMENT OF DELAMINATIONS IN CFRP CONCRETE MEMBERS IN A BRIDGE

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Abstract: The use of carbon fiber reinforced polymers (CFRP) laminates for strengthening concrete members and for concrete bridge rehabilitation is rapidly increasing. However, the presence of defects in the form of delamination between a CFRP laminate and a concrete substrate significantly reduces the effectiveness of this rehabilitation method. Microwave near-field nondestructive testing and evaluation (NDT&E) techniques, utilizing open-ended rectangular waveguides, have demonstrated the ability to detect these defects and evaluate their various properties. A measurement system including a near-field microwave reflectometer and an automated 2D scanner were developed for detecting such delaminations on-site, with the intent to investigate their growth with time in a bridge in Dallas County Missouri. Two types of delaminations were detected; namely, intentionally and unintentionally produced delaminations. This paper presents the results of this investigation and a discussion of the future activities associated with this endeavor.

Introduction and Background: Carbon fiber reinforced polymers (CFRP) have gained importance as an effective means for bridge rehabilitation [1-3]. CFRP composite laminates are externally bonded to the surface of a concrete member to provide additional flexural or shear strength to deficient structural members. A proper bond between the CFRP laminate and the concrete member is significantly important for transfer of the stresses from the concrete member to the CFRP laminate. Delamination between the CFRP laminate and the concrete can occur due to a number of factors including improper application of the CFRP laminate, moisture present near the concrete surface, large temperature gradient, impact damage, etc. Thus, there is a great interest in developing a nondestructive testing technique (NDT) that is capable of detecting these delaminations with a high degree of robustness and to provide information about their spatial extent and severity. Such an NDT technique must also be fast, one-sided, non-contact, real-time, robust and the system must be readily portable. Finally, it is also important to be able to examine the quality of repair (e.g., epoxy injection of delaminated regions) using this same technique. Near-field microwave NDT techniques have long shown great promise for fulfilling all of these requirements [4].

Microwave near-field NDT techniques, utilizing open-ended rectangular waveguides have been used extensively in detecting delaminations and disbonds in a wide variety of layered composite structures [5-8]. Investigations into the capabilities of near-field microwave NDT techniques for detecting delaminations in CFRP reinforced concrete structures have also been carried out [9-10]. These previous laboratory investigations were conducted on samples with artificially created delaminations. The investigations have provided ample evidence showing the capabilities of the technique for detecting such delaminations. In this investigation, several CFRP laminates bonded to bridge members were investigated for the presence of delaminations, and also for monitoring their growth over time. To this end, an automated 2D scanning system was developed suitable for on-site measurements. Near-field microwave reflectometer was incorporated into this system and on-site measurements were performed on several CFRP laminates bonded members of a bridge in Dallas County, Missouri. For this investigation, 2 ft. by 2 ft. CFRP laminates where bonded (using epoxy adhesive) to the abutment and the girder of the bridge. A number of artificial delaminations were manufactured in these laminates by injecting air between the concrete substrate and the CFRP laminates when the epoxy adhesive was in its fresh state. The size and thickness of the delaminations (i.e., severity) was also varied using this process. The CFRP laminates in the abutment were used as reference measurements since this part of the bridge is not usually where CFRP laminates are used for strengthening.

Measurement Approach: The measurement system consists of an automated 2D scanning platform, a near-field microwave probe and signal processing section. This automated scanning platform is easy to use and suitable for on-site measurements. A picture of this scanner is shown in Figure 1.

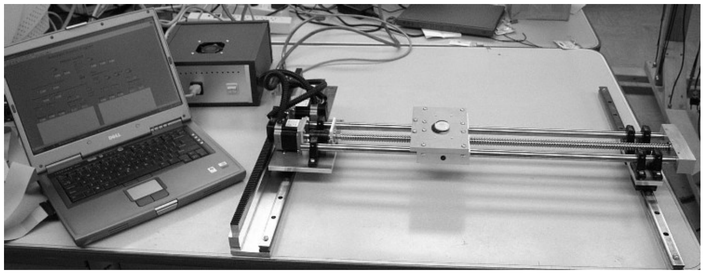


Figure 1: Automated 2D scanning platform suitable for on-site measurements.

The near-field microwave probe consisted of a simple reflectometer. The reflectometer transmits an incident microwave signal onto the region under test, via an open-ended rectangular waveguide probe, and receives the reflected microwave signal. Subsequently, the incident and the reflected signals are combined and detected using a microwave detector which produces a dc voltage output. This voltage is proportional to the magnitude and/or phase of the reflected microwave signal from the CFRP laminate under test. As the probe scans over different regions the reflected signal changes and so does the probe output voltage. This voltage, in concert with the scanning process, which gives the precise location of the open-ended probe at any given time during the scanning process, is used to produce a raster scan or microwave image of the scanned region of interest. Due to the fact that CFRP contains carbon fibers, the dielectric constant contrast between CFRP and air (i.e., delamination) and the concrete substrate is relatively large. Thus, usually, detection of a delaminated region is relatively easily using this technique, since this dielectric contrast results in a relatively distinct reflection at these boundaries [9-10]. X-band (8.2–12.4 GHz) frequency range was used as the operating frequency range of choice for this investigation based on the results of previous findings [9-10]. Figure 2 shows a simplified schematic of the measurement setup. The scanner is placed over the bridge member bonded with a CFRP laminate using scaffolding or suction cups. The microwave probe is fixed to the probe holder at a certain standoff distance (distance between the waveguide flange and the CFRP laminate). The standoff distance is optimally chosen such that a relatively large voltage difference between delaminated and non-delaminated areas is produced while providing small voltage output variations as a function of standoff distance and surface roughness variations [10-11]. The output from the microwave probe along with the positional information of the probe is fed into a laptop using a National Instruments data acquisition card. LabVIEW-based automation software was used to control the motion of the probe as well as to obtain the output voltage from the microwave probe. In this way, raster scan of a region under the scanner is produced yielding a real-time two dimensional image of the scanned area. The measured voltages from the output of the microwave probe are normalized with respect to a predefined maximum, and different grayscale values are assigned to the normalized output voltage values. The images obtained in this way can be subsequently processed by passing the data through a desired filter to minimize the effect of noise and to produce a smoother image. Polarization direction of the incident microwave signals is also an important parameter. Unidirectional CFRP laminates, as used here, behave as a relatively lossy dielectric material when the carbon fibers are perpendicular to the signal polarization direction (i.e., perpendicular polarization). In this case, the incident microwave signal can penetrate through the laminate and exposes the presence of a delamination. However, when the polarization direction is parallel to the fiber directions (i.e., parallel polarization) the CFRP behaves as a good microwave reflector and no signal can penetrate inside of it. The former case is well-suited for detecting and evaluating delaminations, whereas the latter case only provides information about surface roughness, standoff distance variations, bulging of the CFRP, etc. [9-10]. Therefore, it is possible to produce two images, one at each polarization, and then remove the effect of unwanted surface roughness and standoff distance variation using the data obtained with parallel polarization [11].

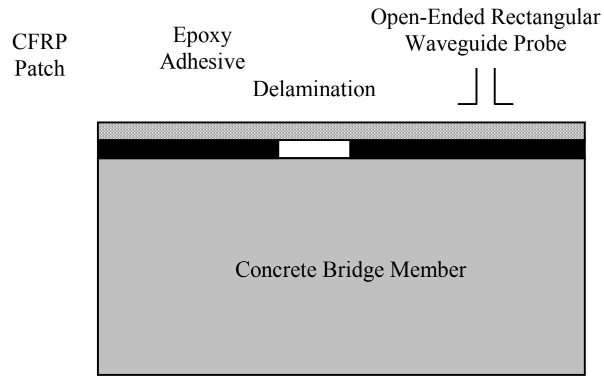


Figure 2: Schematic of the measurement approach.

Results: The CFRP laminates that were bonded to the abutment and the girder of the bridge in Dallas County, Missouri were scanned using the method described earlier. A picture of one of the patches adhered to a section of the abutment is shown in the Figure 3. Several relatively small delaminated regions (some smaller than 20 mm by 20 mm) were produced in this patch using the air injection method described earlier. The scan area is marked in Figure 3 by the thick outer solid line along with six delaminated regions outlined with the thin solid lines. The white spots are paint spots used as a reference grid for another investigation. Figure 4a shows the microwave image of this scanned area using perpendicular polarization (the dimensions are in mm). As mentioned earlier the image is normalized with respect to a predefined maximum and minimum. The relative variation in intensity, from bright to dark, represents the areas of delaminations. The severity of the delaminations is also indicated by the relative brightness associated with the images of the six delaminated regions. The locations and sizes of the six delaminated regions, indicated by the microwave image in Figure 4a, agree well with their locations and sizes on the bonded CFRP laminate. These were verified using tap testing. In Figure 4a, there is a small region in the bottom of the picture that indicated the potential presence of an unintentional delamination that may have been produced during the placement of the laminate. The relative location of this delamination is shown by the dashed-line square in Figure 3. Originally, this region was not designated as a delaminated region on the CFRP laminate. Subsequent to obtaining its microwave image, it has been determined that this region is a potential delamination. This demonstrates the robustness of this method for detecting and evaluating small and relatively non-severe delaminations. A similar situation was also encountered in a previous study [9].

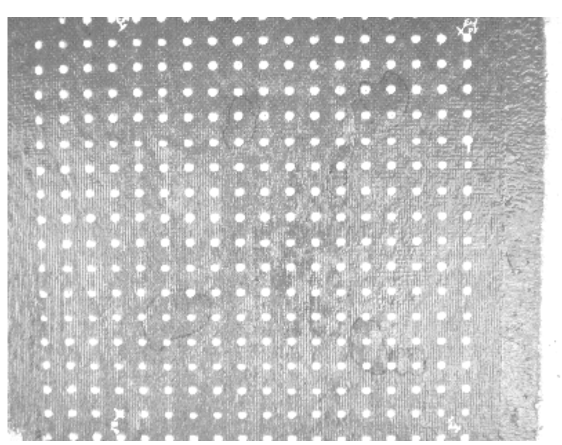
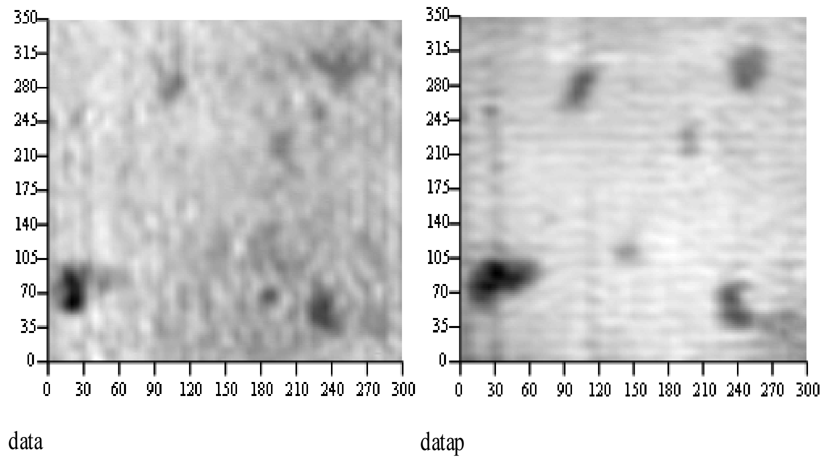


Figure 3: Picture of a CFRP patch bonded to the abutment of the bridge in Dallas County, Missouri with the boundary of the scanned area and the delaminated regions shown.



(a) (b)

Figure 4: Microwave image of the scanned area in Figure 3 using: a) perpendicular polarization, and b) parallel polarization.

Next, the laminate was scanned using parallel polarization. This measurement is expected to provide information about the surface variation associated with the laminate including any standoff distance variations that may exist due to the scanning mechanism. Figure 4b shows the resulting microwave image. This image primarily shows the effect of surface roughness and standoff distance variation (caused by the surface roughness).

Discussion and conclusion: The results of this investigation clearly show the capability of near-field microwave nondestructive testing techniques for detecting intentional and unintentional delaminations, in addition to providing qualitative information about their relative severity. Microwave images produced using these techniques also provide a close estimate of the spatial dimensions of a delaminated region. This information is important for repair purposes. In this study an automated scanning mechanism was utilized along with a near-field microwave reflectometer at X-band, using an open-ended rectangular waveguide probe, to investigate laboratory-produced CFRP bonded concrete and those applied to the abutment of a bridge in Dallas County, Missouri. The capability of this method to provide quick and informative images of the bonded CFRP abutment (in-field) was clearly demonstrated as well. At the time of the writing of this manuscript, the investigating team had not investigated the laminates on the girder and also changes in the laminates properties (i.e., possible growth of delaminated regions) due to cyclical loading of the bridge due to normal traffic. The results of these investigations will be presented at the conference. However, it is expected that if there is adequate change in the properties of these laminates, located at different places on the girder, due to traffic loading, that this inspection methodology will be able to detect the change. It is also important to establish the minimum in-field detectable delamination size and the critical delamination size. Additionally, future efforts should include correlating the measured microwave signal attributes to the delamination severity. This method has been demonstrated to be a valuable tool for evaluating epoxy injection repair quality of delamination regions. It will be interesting to also correlate repair quality and longevity to the measured microwave signal attributes.

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