MICROWAVE NDE OF RC BEAMS STRENGTHENED WITH CFRP LAMINATES CONTAINING SURFACE DEFECTS AND TESTED UNDER CYCLIC LOADING

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Abstract: Carbon fiber reinforced polymer (CFRP) laminates are externally bonded to reinforced concrete (RC) members to provide additional strength such as flexural, shear, etc. However, the presence of defects in the form of delaminations between the CFRP laminate and concrete substrate may significantly affect the structural integrity and stiffness of the structural section. Microwave near-field nondestructive evaluation (NDE) techniques, utilizing open-ended rectangular waveguides, have the ability to detect these defects. This paper presents the results of an investigation on the influence of cyclic loading on delaminations in reinforced concrete beams fabricated and strengthened with CFRP laminates. The delaminations were formed in the beams by applying pressured air beneath CFRP sheets when epoxy was in fresh state. The beams were exposed to severe environmental conditionings and sustained load of 40% of the ultimate moment capacity. All the beams were cycled under fatigue loading for 2-million cycles. A microwave reflectometer and an automated scanner were used in order to study the behaviour of the delaminations under cyclic loading.

Introduction & Background: The development of new material systems like carbon fiber reinforced polymers (CFRP) used for strengthening and rehabilitation of existing structures are getting higher demands and wide range of applications in recent years. CFRP laminates gained importance over steel plate bonding because they offer superior performance such as resistance to corrosion, and high stiffness-to-weight ratio. Even though CFRP laminates are produced and utilized in different applications, the most common form is built-up woven fabric that is externally bonded to a structural element by the wet lay-up method. Because the CFRP strengthening provides additional flexural or shear reinforcement, the reliability for this material application depends on how well they are bonded and can transfer stress from the concrete component to CFRP laminate. Ideally designers desire a CFRP laminate that is perfectly bonded to substrate concrete. Any kind of surface defect such as void and delamination (disbond) between CFRP laminate and substrate may effect and significantly weaken the structural integrity and performance of the system; moreover it may limit the life expectancy of the structure [1-3, 4, and 5]. Shih (2003) noted that the un-bonded voids influence the sectional flexural performance of RC beams retrofitted using CFRP laminates [6]. Delamination can be caused by several reasons such as presence of moisture in the concrete, significant changes in temperature during curing, and improper application. An undetected delamination may also cause fracture of the material [7]. Therefore, these defects should be properly and efficiently detected and accurately located before delamination growth occurs due to cyclic service loads or thermal effects. The American concrete Institute (ACI) Committee 440 document requires the evaluation of delaminations and air voids between multiple plies or between the FRP system and the concrete with a minimum detectable size of 1300 mm^2. Some other criteria from ACI Committee 440 may be noted as: total delamination area should be less than 5% of the total laminate area and no more than 10 delaminations per 1 m^2, large delaminations (greater than 16,000 mm^2) should be repaired by cutting away and applying a new patch, and delaminations smaller than 16,000 mm^2 maybe repaired by resin injection or ply replacement. Senthilnath (2001) reported in his paper that ACI Committee 440 requirements are very conservative [8]. He also reported an insignificant growth in delamination sizes after fatigue testing for 2-million cycles without environmental conditioning. Since some structural members such as girders in bridge structures are constantly subjected to repetitive stresses, it is reasonable to accept the fatigue-cyclic loading as the worst-case condition for propagation of delaminations. These repetitive stresses under varying climatic conditions may lead to internal cracking of a structural member and alter its stiffness and load carrying characteristics, which increase stresses on the externally bonded laminate. Effect of environmental conditioning further combined with fatigue loading may also contribute to propagation of delaminations and of keen interest in this research study.

Based on the discussion presented above, there is a need for an efficient and reliable nondestructive testing (NDT) method to detect and characterize surface defects in the form of delaminations at the CFRP laminate and substrate concrete interface. Even though there is a great interest to develop a high quality, and non-contact procedure, presently there is no standard method available to assess the efficiency of CFRP bonded civil structures [9, 10]. The most commonly used method is to use a small hammer or a steel bar to tap the CFRP surface (after curing) to detect air voids because a perfectly bonded CFRP generates a different audible sound than a delaminated one. This method is low technology and simple but more subjective and less reliable since it needs an operator with a discerning hearing ability [4, 6]. The NDT method should be able to detect not only the smallest defect, but also capable of inspecting large areas as well. Moreover, the system should be portable, cost effective and user-friendly.

Near-field microwave nondestructive testing (NDT) techniques employing open-ended rectangular waveguide probes have shown the ability to detect delaminations and delaminations in layered composite structures [11-13]. In the case of CFRP bonded to concrete structures, near-field microwave NDT techniques have shown the ability to detect the presence of these delaminations [3, 5]. These techniques are not only able to detect the presence of delaminations but also their severity and spatial extent. Subtle delaminations can be potentially detected as well. The measurement systems can make one-sided measurements, they are non-contact, quick and easy to use and inexpensive. In this investigation, cyclically loaded beams that were bonded with CFRP and artificial delaminations created in them were scanned using an open-ended rectangular waveguide probe and the microwave images were obtained at X-band (8.2-12.4 GHz). These images were analyzed to detect increase in the size of the delaminations. The results show the ability of the technique to detect and monitor intended as well as unintended delaminations

Sample Preparation: Three RC beams were fabricated in the laboratory for the purpose of NDT evaluations of delaminations along with a control sample with CFRP strengthening and perfect bond. The beams were 254 mm x 165 mm in size, with a length of 1981 mm. The dimensions and cross-sectional details of the test beams are shown in Figure 1. All three beams were strengthened with CFRP sheets. The CFRP sheet was 8 inches wide and 0.0065 inches thick and was applied as single ply throughout the length of the test span. The CFRP sheets were attached to the tension face of test specimens. Except cleaning, no other surface preparation method was applied in order to simulate a worse case bond situation. Delaminations were produced in all three beams. Delaminations were formed right after the final layer of epoxy application was applied when the epoxy was still in fresh state. Three spots on the laminate were pinned and a small amount of pressured air compressed beneath the CFRP sheet, which created delaminations. The excess amount of air sucked out by using a syringe. In order to give the final shape to delaminations, spike-roller rolled around the perimeter of delaminations. The delaminations were formed as one at the middle, and two after the constant moment zone is surpassed as shown in Figure 2.

All these three beams with delaminations were stored under different environmental exposures. One sample was kept in open air for a year, whereas the other two were kept inside of a chamber where they were exposed to severe environmental conditionings (Figure 3). One sample in the chamber was conditioned under 4 environmental cycles, whereas the second pair was kept to 8 environmental cycles. One conditioning cycle contained 50 freeze and thaw cycles between -18^{o} and 4^{o} Celsius, 120 (40x3) extreme temperature cycles between 27^{o} and 49^{o} Fahrenheit, and 60 (20x3) relative humidity cycles between 60% and 100%. All these three beams were also kept under sustained loading. The beams were paired with another CFRP strengthened beam and stacked one above the other. Two springs were placed between the paired beams to transfer the load. Sustained load was determined as 20.0 kN, which corresponds to approximately 40% of the ultimate moment capacity of the beam. One of the delaminations on one of the beams, which was kept in environmental chamber for four cycles, was also equipped with two strain gages; one placed at the center of delamination, another one attached to disbond interface of delamination-concrete to observe the behaviour of delamination during cycling.

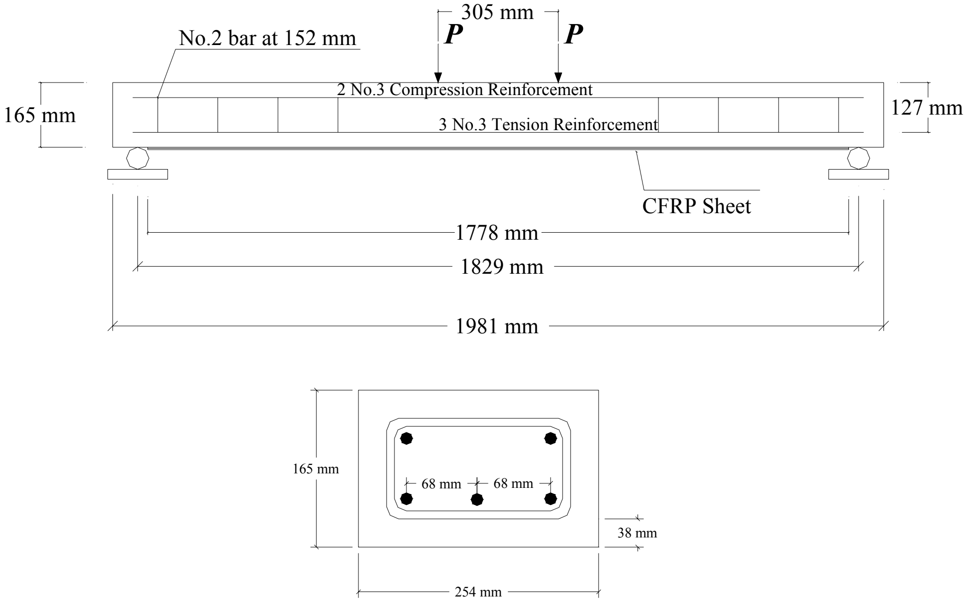


Figure 1. Beam longitudinal and cross sections.

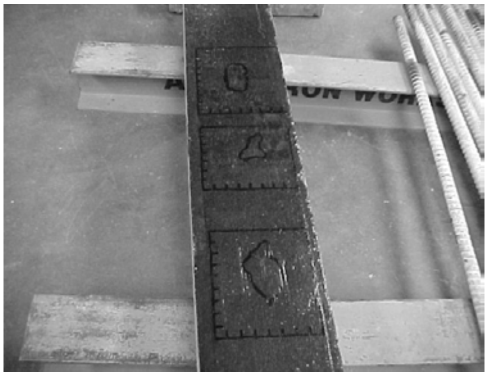


Figure 2. Test beam with delaminations. Figure 3. Environmental conditioning of beams.

Experimental Details:

Material Properties: The design strength of the concrete and the yield strength of the steel were determined as 27.5 MPa and 413 MPa, respectively. The modulus of elasticity of concrete was measured as 25.8 MPa. The ultimate strength and the elastic modulus of the CFRP sheets were 3.8 GPa, and 227.5 GPa, respectively. The ultimate tensile strain was 0.0167.

Fatigue Testing: All beams were tested under cyclic loading over a simply supported span of 1829 mm. The beams were loaded with two concentrated loads placed at equal distance (152.5 mm) from the beam centerline. The supports were placed 76 mm away from the end points. Sketch of the test set-up is also presented in Figure 1. All of the beams were tested under fatigue loading of 33% (17.3 kN) and 63% (33.4 kN) of ultimate moment carrying capacity. The frequency applied during the fatigue testing was determined as 2 cycles per seconds (Hz). The tests were planned to be terminated either when the beam failed or reached to 2-million cycles, which ever occurred first. Prior to fatigue testing, a pseudo fatigue test was performed to measure the mid-span displacement. The same tests were performed during the fatigue testing after every 500K, 1000K, 1500K, and 2000K cycles. The frequency was adjusted to 0.1 Hz during this pseudo fatigue test in order to capture adequate number of data points. The displacement at mid-span was measured by using linear variable digital transducers (LVDT). The data was captured via a data acquisition system.

Measurement approach by Microwave: Figure 4 shows the schematic of a near–field microwave measurement system employing an open-ended rectangular waveguide probe. A microwave signal at a specific frequency and standoff distance is transmitted via the probe and interacts with the composite structure under inspection. A portion of this signal is then reflected by the composite structure and is picked up by the probe. The phase and magnitude of the reflected signal depends on the material properties of the various layers of the composite.

When microwave signals are incident upon any dielectric material, a part of the signal is reflected while the other part of the signal is transmitted through it. The amount of signal reflected depends on a complex parameter called the relative dielectric constant, ε_r. The real part of this parameter is known as the relative permittivity, ε'_r, which is the ability of the material to store microwave energy and the imaginary part is known as the relative loss factor, ε''_r, which indicates the ability of the material to absorb microwave energy [11].

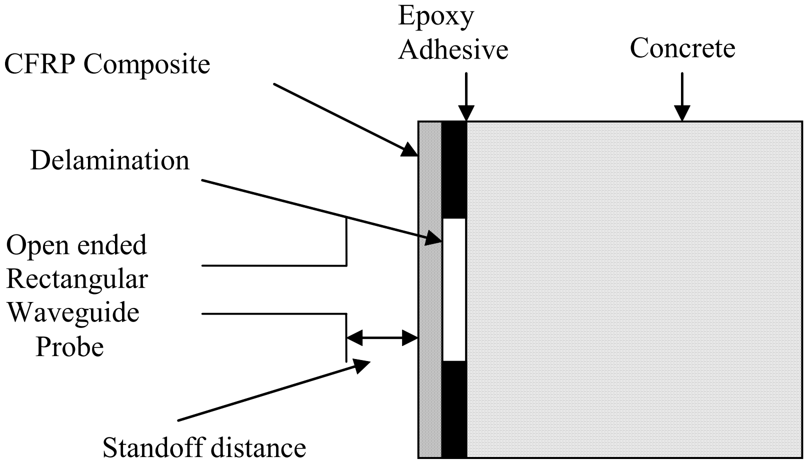


Figure 4. Schematic of a near-field microwave measurement system.

When microwave signals are incident upon layered composite structures it reflects at each boundary interface. The amount of signal reflected will depend on the dielectric constant contrast or impedance mismatch [14]. If the difference in dielectric constant is higher then the amount of signal reflected is higher. The signals reflected at each boundary are combined coherently and it is this signal that is picked up by the microwave detector. CFRP bonded to concrete is a layered structure. The carbon fibre along with epoxy adhesive forms one layer, the concrete forms another layer and when there is a delamination between CFRP and concrete it makes up another layer (air) in the structure. The microwave signals do not penetrate through metal (carbon) but when made into fibres that are unidirectional, under the proper polarization, some of the signal penetrates through the fibres. The signal penetration is maximal when the signal polarization is orthogonal to the orientation of the carbon fibres. When oriented parallel to the signal polarization there is very little penetration as all the signals are reflected from the surface of the CFRP. Thus measurements with parallel polarization can be used to get surface variation and measurements with perpendicular polarization can be used for detecting delaminations. Under the proper polarization (orthogonal) the signal reflects at the CFRP-concrete interface. When there is a delamination there are two interfaces with higher dielectric constant contrast. They are the CFRP-delamination (air) boundary and delamination (air)-concrete boundary. Since the contrast higher the reflected signals also increases. The microwave probe's standoff distance, signal frequency and power level can be optimized for sensitivity to the delamination.

In this investigation a manually operating scanning platform fixed with the microwave probe operating at a frequency of 10.5 GHz (X-band) was placed over the concrete beams and line scans were made at regular intervals. The voltage output from the microwave probe was fed into a laptop using a national instruments data acquisition card and stored. The stored line scan data was put together and then imaged by assigning different brightness levels to different voltages. The relative difference in brightness represents change in voltage output by the probe which in turn implies changes in the reflected signal. The optimal standoff distance (the distance from the probe to the surface of the CFRP bonded to the beam) was determined by performing standoff distance analysis at two different locations on the same (one over a delaminated region and one over region with no delamination). The standoff distance analysis is measuring the probe output voltage as a function of changing standoff distance. The optimal standoff distance is selected such that the difference between the two voltages measured is relatively large, while slight variations in standoff distance produces minimal change. The images are then passed through a low pass filter to remove the effect of noise. The delaminationed region in each beam, to be cycled, is scanned before cycling and then scanned after 500K cycles, 1-million cycles and 2-million cycles to monitor their growth.

Test Results:

Fatigue Test Results: The calculated stiffness loss at 2-million cycles relative to first cycle for each beam is shown in Table 1. Table 1 also presents the stiffness loss of test samples relative to CFRP strengthened control sample. Stiffness is defined as the slope of the load vs. mid-span displacement relation between the maximum and minimum specified loads. As seen in Figure 6, it has been observed that most of the stiffness loss occurred between first and 500K cycles with the samples with delaminations exhibiting the highest stiffness loss. Figure 5 exhibits the strain measurements obtained by the strain gages positioned over and at interface of a delamination on the beam which was kept in environmental chamber for four cycles. The increase in strain value obtained by interface straingage till it gets even with the stain readings of center straingage can be interpreted as the growth in delamination.

Table 1. Stiffness Loss of Fatigue Beams at 2-Million Cycles.

Description	Change in Stiffness (%)*	Change in Stiffness**
CFRP sheet strengthening (Control Sample)	15	100
CFRP sheet strengthening with delaminations- 4 env. cycles	25	79
CFRP sheet strengthening with delaminations- 8 env. cycles	30	66
CFRP sheet strengthening with delaminations- exterior conditions	24	77

* Relative to Initial Cycle

** Relative to Control sample

Microwave Test Results: As per the approach outlined earlier, the three beams were fatigue cycled and scanned. Figure 7 presents a picture of two delaminations in the first beam. One large delamination at the centre of the picture (marked in black) and another at the lower left corner. The larger one is an artificially created delamination and the other is an unintended delamination that is subtle. The scanned images are shown in Figure 8. Figure 8(a) is the scanned microwave image of the delamination in beam 1 before cycling. Figure 8(b) was made after 500,000 cycles, Figure 8(c) after 1 million cycles and Figure 8(d) after 2 million cycles. The area scanned was 190.5 mm by 203.2 mm.

It can be seen that the created delamination was clearly detected. This is shown by the dark region at the center of each image. The dark area to the lower left hand corner was observed in the microwave image. Later this area was tap tested and found to be a delaminated region and was marked. The Figure 9 shows the filtered image of the scans shown in Figure 8.

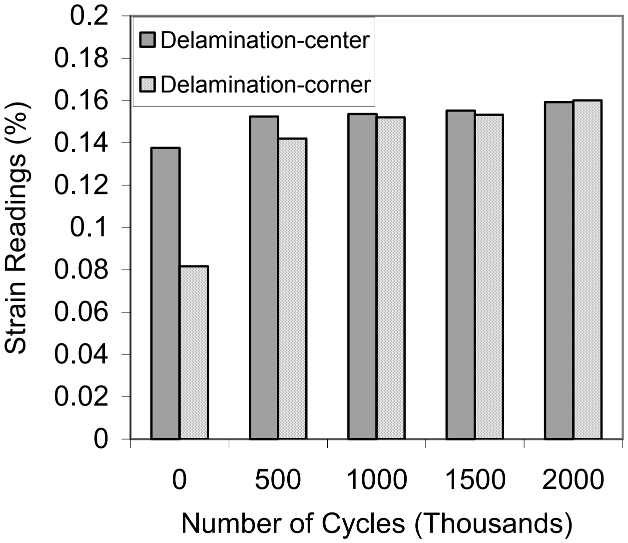


Figure 5. Strain readings at the center and disbond interface of a delamination.

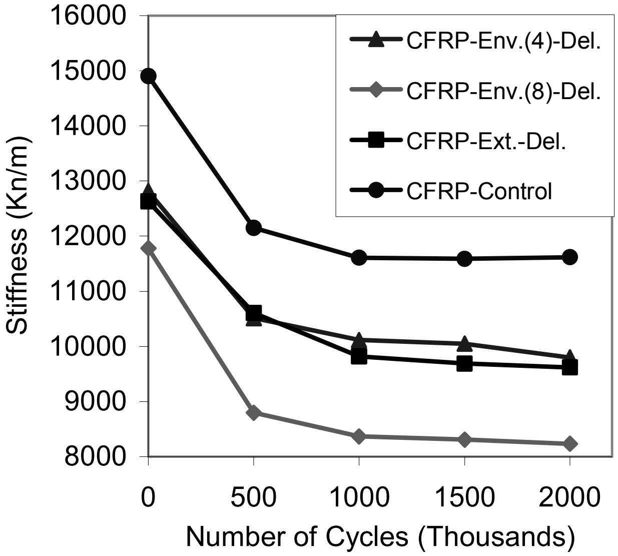


Figure 6. Stiffness vs. number of cycles.

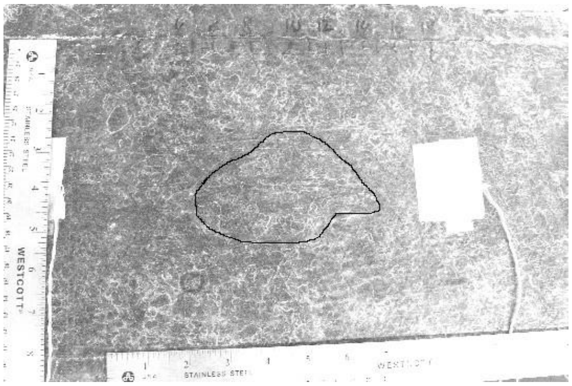
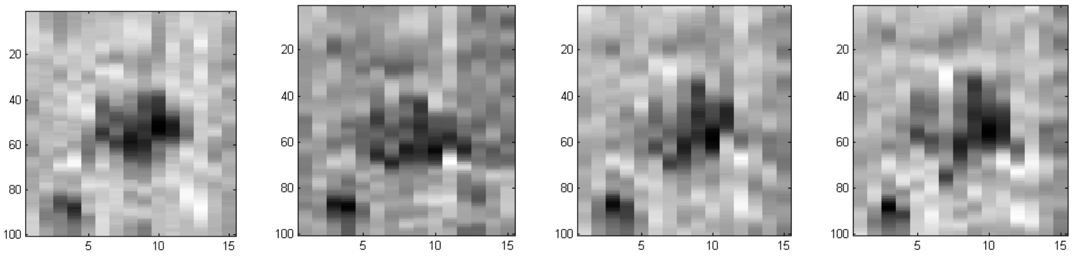


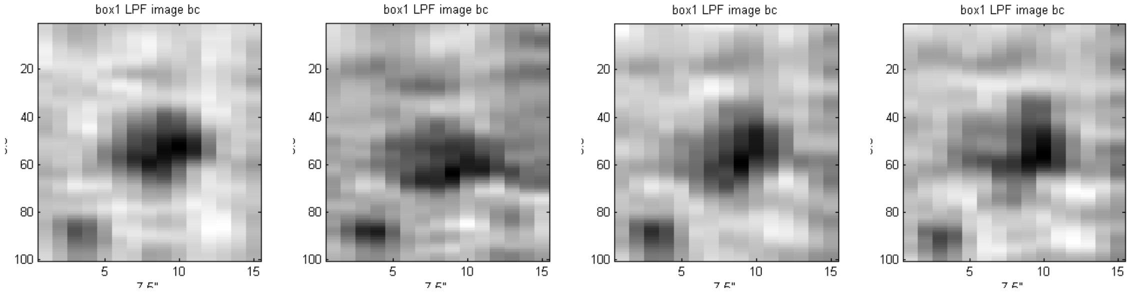
Figure 7. Picture of the delamination.



(a) (b) (c) (d)

Figure 8. Image of the delamination in Figure 1 under perpendicular polarization. (a)before cycling, (b) after 500K cycles, (c) after 1-million cycles and (d) after 2-million cycles.

Size of the unintended delamination is less than 2 cm square. The fact that this delamination was detected gives effective evidence of the capability of this technique in detecting unintentional or subtle delaminations.



(a) (b) (c) (d)

Figure 9. Filtered image of the scans of the delamination in Figure 8. The size of the scanned area is 190.5 mm and 203.2 mm.

Summary and Discussions: Based on the findings presented herein, the fatigue resistance of RC beams strengthened with CFRP sheets is significantly affected by the presence of delaminations, environmental conditioning and sustained loading. The lowest and highest decrease in stiffness as compared to the control sample was exhibited by the samples which were environmentally conditioned for 4 and 8 cycles, respectively. The sample which was kept in exterior conditions performed similar to the sample kept in chamber for 4 cycles. All of the beams survived after two million cycles. The strain gage readings on the disbond interface can be speculated to be related to the growth in the size of the delamination; however, this cannot give an idea of the magnitude of the delamination size.

The scanned images show the potential of the microwave NDT technique in detecting delaminations. The ability to detect unintentional or subtle delaminations is also shown. The edge of the delamination was not clear in the microwave image because the images were made using a manually operated scanning system. The delaminations on one the beam exposed to environmental conditions was imaged using the microwave NDT technique as well as tap tested at before cycling, after 500K cycles, after 1-million cycles and after 2-million cycles. The images as well as the tap testing showed that the area of the delamination did not change significantly as a function of increased loading.

Acknowledgements:

The authors would like to acknowledge J. Nadakuduti, S. Kharkovsky, and D. Hughes for their interest and involvement in this research study. The authors would also like to acknowledge the Federal Highway Administration (FHwA), The University Transportation Center (UTC) at the University of Missouri-Rolla (UMR), the Applied Microwave Nondestructive Testing Laboratory (amntl) at UMR, and the Repair of Buildings and Bridges with Composites Cooperative Research Center (RB2C) at UMR for supporting this research.

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