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Nondestructive Testing of FRP Composite Structural Components and FRP Rehabilitated Bridge using Digital Tap Testing

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***Abstract*— Use of Fiber Reinforced Polymer (FRP) composites in structural components such as bridge decks and retrofitting jackets can help address the problem of infrastructure aging with enhanced durability in future constructions. The features of FRP composites such as light-weight, high strength-to-weight ratio, durability, high resistance to corrosion and low maintenance cost make it a very suitable material for use in civil infrastructures. However, proper installation of newer material in structurally important infrastructure requires a reliable method for field evaluation or testing. Nondestructive Testing (NDT) techniques can help in detecting subsurface defects in the FRP structures during new construction or rehabilitation of in-service structures. Digital Tap Testing (DTT) is one of the convenient NDT techniques for field inspection of infrastructures, because of the equipment portability and easy-to-handle features. The DTT technique also provides a scientific alternative to the traditional coin tap method which is subjective. This paper discusses the DTT method to detect subsurface defects in FRP composite bridge components. The extent of applicability of the DTT method was studied using several FRP composite specimens in the laboratory. The results show that DTT evaluation was limited to defects at shallow depth, such as debonds underneath thin FRP wraps, and the technique could not detect delaminations in thick FRP members. The method was found to be very useful for rapid field testing of concrete box beams rehabilitated with carbon FRP fabrics. The field testing enabled the detection of debonds which helped in their immediate repair.**

Keywords*— *GFRP; CFRP; Composite; Concrete; Box Beams; Digital Tap Testing (DTT)

I. Introduction

The aging of civil infrastructure has been a constant problem for engineers in the field and the major challenge has been to make a decision on whether rehabilitation of a structure is sufficient, or a total replacement is required. Therefore, a reliable method of testing or evaluation of the infrastructure is needed. Several conventional destructive testing and nondestructive testing methods have been in use to evaluate structural condition. The conventional testing method involves physical inspection of the structures for determining the condition [1]. This method is time-consuming where in-depth assessment requires complicated procedures of destructive physical analysis and subjective evaluation through visual inspection [1]. Modern nondestructive testing (NDT), on the other hand, consists of scientific techniques used to evaluate the structural component without causing any damage. NDT is a quick and convenient method, which, as the name suggests, provides an unbiased in-situ evaluation of the structure.

Digital Tap Testing is an NDT technique, which offers a scientific alternative to the traditional coin tap or tap hammer testing. Digital Tap Testing is a numerical based approach to determine the presence of defects in the structure. Since the conventional coin tap method depends on the inspector's ability of hearing and interpretation, the results are highly subjective and not always accurate. Boeing engineers accounted for the problem of subjectivity along with the interference from the surrounding noise while developing a new low-cost tap testing method which results in a number display that is easy to record and interpret during field testing. This was done by instrumenting the traditional tap hammer with a force transducer and related electronic system [2].

This paper presents the laboratory experiments and field-testing results using Digital Tap Hammer for FRP composite components and FRP wrapped/bonded concrete members.

II. Digital Tap Testing Equipment

The digital tap hammer (Fig. 1) is an electronic device that displays a number in microseconds (corresponding to the width of the recorded signal at half-amplitude) when a test object is tapped. As per the user manual for this device, for an area to be classified as a debond or subsurface defect, the tap number should be at least 10% higher than the number from defect-free areas. It should be noted that this device has been developed for thin aerospace composites (typically up to 5-10 mm thickness) and does not work for thick members (e.g., thick composites, reinforced concrete). The device works very well for detecting debonds between FRP composite wraps and underlying concrete member. For FRP composite bonded concrete, a tap hammer reading in the range of 1000 to 1175 represents good bond. A reading exceeding 10% of this value, that is exceeding about 1200, represents debonded region. The device offers an easy way to cross check the results from other NDT techniques (e.g., infrared thermography) and can also be used independently. It should be noted that the tap hammer device offers point-by-point measurement while infrared thermography is an area scanning technique [3].

Fig. 1. *Digital tap hammer*

III. Laboratory Experimentation

Digital Tap Testing could only be performed on smooth surfaces, such as FRP composite wrapped cylinders and FRP composite bridge deck specimens with no wearing surface. The sharp, pointy surface of a polymer concrete wearing surface can damage the head of the hammer and tapping on this surface would not provide any useful result. So, digital tap testing was limited to GFRP specimens with smooth surface (decks without wearing surface and composite tubes) and the GFRP- or CFRP-wrapped concrete cylindrical specimens (Fig. 2). The test procedure included tapping the surface with hammer attached to the handheld module (Fig. 1). The RD3 displayed corresponding number for each tap and change in this number helped determine defective areas from good areas. First, a tap testing number range is defined for good areas. Then, rest of the area is tapped and any number that is 10% greater than that of good areas is considered as defective area. The concrete cylinders with GFRP wraps were also tested, along with the GFRP square tube specimen. The tap test results for various specimens are shown in Table 1.

The specimen WJD2 had Side 1 with no wearing surface and the digital tap testing could be done on this side (Fig. 2(a)). The defect-free area had tap testing number in between 1090 – 1109 while over the embedded subsurface defect, it was around 1116 – 1135. These numbers do not suggest good results for digital tap testing on FRP bridge deck specimens which had flange thickness of 0.45” (11.4 mm) with defect depth of 0.3” (7.6 mm). Likewise, Side 2 of another bridge deck specimen WJD3 also gave similar results with numbers for good areas as 1101 – 1116 compared to 1098 – 1128 for defects. The deck specimen JD1, with no wearing surface on either side, was tapped using the digital tap hammer. Side 1 gave tap testing number in the range of 1097 – 1113 (microseconds) for good areas and in between 1120 – 1148 for the 3” x 3” sized defect. The tap testing numbers for the defect was not significantly higher than the good areas, therefore digital tap testing did not produce satisfactory results for the bridge deck specimen. For bridge deck specimen AS3, the uncovered Side 2 had a 3” x 3” sized debond which gave tap testing numbers as 1109 – 1130. The tap testing number for good areas on Side 2 of AS3 was in the range of 1083 – 1114, which shows the numbers for debonds are not 10% greater than good areas. Thus, AS3 is another specimen that provides unsatisfactory results for digital tap testing.

Digital Tap Testing, on the other hand, proved very effective when the GFRP wrapped concrete cylinders were tested. The air-filled and water-filled debonds gave numbers significantly higher than the surrounding good areas. Since the wraps were quite thin (1 layer and 3 layers, with thickness of less than 1 mm per layer or 3 mm total), the digital tap testing gave satisfactory results for these specimens. The defect-free areas on GFRP wrapped cylinder had tap test numbers in the range of 1075 – 1151 while the area above air-filled subsurface defect gave tap test readings in the range of 1801 – 2104. These numbers show that the defects underneath the thin FRP wraps can be easily detected using digital tap hammer. Similarly, the water-filled subsurface defects resulted in tap test numbers in the range of 1380 – 1475, which when compared to 1108 – 1130 reading for defect-free areas, could clearly be distinguished as defects (Fig. 2(b)). The composite square tube specimen gave numbers in between 2848 – 3178 for the delaminated area while the good area had numbers in the range of 1108 – 1128 (Fig. 2(c)). Table 1 summarizes the results of digital tap testing on bridge deck specimens, FRP wrapped cylinders and the square tube specimen.

(a) (b) (c)

Fig. 2. *Laboratory specimens – (a) GFRP bridge deck (side without wearing surface), (b) GFRP composite wrapped concrete cylinder, and (c) GFRP square tube section*

Table 1. *Digital Tap Testing (DTT) Results from Laboratory Experiment*

Specimen	Digital Tap Testing Numbers (microseconds)		Success of DTT in Detecting Sub-surface Defect
	Good (Defect-free) Area	Defective (Debond) Area	
JD1 – Side 1	1097 – 1113	1120 – 1148	Not Good (defect under thick composite)
JD1 – Side 2	1084 – 1101	1093 – 1111	Not Good (defect under thick composite)
WJD2 – Side 1	1090 – 1109	1116 – 1135	Not Good (defect under thick composite)
WJD3 – Side 2	1101 – 1116	1098 – 1128	Not Good (defect under thick composite)
AS2 – Side 1	1093 – 1110	1094 – 1125	Not Good (defect under thick composite)
AS3 – Side 2	1083 – 1114	1109 – 1130	Not Good (defect under thick composite)
Air-Filled Cylindrical Defect	1075 – 1151	1801 – 2104	Excellent (defect under thin composite layer)
Water-Filled Cylindrical Defect	1108 – 1130	1380 – 1475	Excellent (defect under thin composite layer)
Square Tube	1108 – 1128	2848 - 3178	Excellent (defect under thin composite layer)

IV. Field Testing

This section talks about the field testing conducted on a concrete box-beamed bridge over the Whiteday Creek, West Virginia (Fig. 3). The box beams of the Whiteday Creek Bridge, which had significant corrosion damage, were repaired by a contractor using Carbon Fiber Reinforced Polymer (CFRP) fabric (Fig. 4). Digital Tap Testing was conducted on the CFRP bonded beams on July 15, 2017 to locate debonds between the CFRP fabric laminate and the underlying concrete surface, so that the contractor could immediately repair them. While conducting the test with Digital Tap Testing, the striking force should be high enough to give numbers on the digital display on the device. Low tapping force results in error message in the display. However, it should be noted that very strong strikes can cause harm to the thin layer of the carbon composite members as well as to the tapping sensor. The areas of the beam that were bonded with the CFRP laminates were tapped throughout. The number for good areas were set for each beam by tapping on consistently good areas, which was in the range of 1000 to 1175. As mentioned in the previous section, a debond can be distinguished by the number that is over 10% from the number for the good area. Thus, the spots with numbers over 1200 were considered as debonded spots. The debonded areas identified from the tap testing were marked and numbered for each beam, as shown in Fig. 5. The size of each spot was also recorded.

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Fig. 3. *West Elevation of the Whiteday Creek Bridge [4]*

Fig. 4. *Underside of the Whiteday Creek Bridge – (a) with exposed prestressing strands [4], and (b) repaired with CFRP laminates*

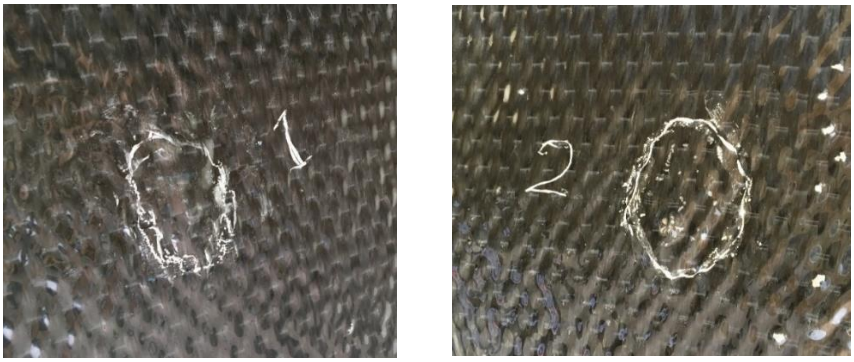

Fig. 5. *Marked and labelled debonded areas in the CFRP bonded concrete box beams of Whiteday Creek Bridge*

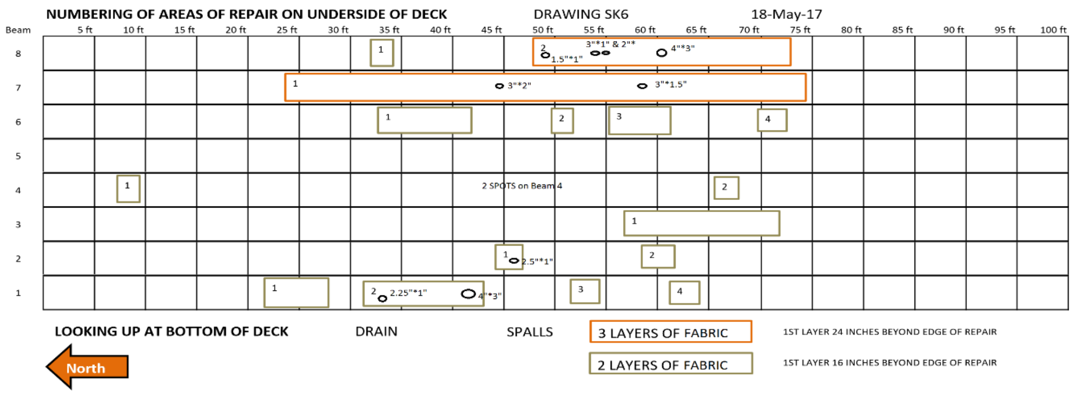

Fig. 6. *Plan of the Whiteday Creek Bridge with numbering of beams and positioning of CFRP fabric laminates with debonds*

Table 2. *Digital Tap Testing Results from the Whiteday Bridge*

Beam	Spot	Location	Debond Size	Tap Testing Reading for Debonds (µs)	Tap Testing Reading for Good Area (µs)
1	1-1	Central Area	4" x 3"	1228 – 1269	1042 – 1189
	1-2	Central Area	2.25" x 1"	1260 – 1411	
	1-3	North Side	2" x 1"	1336 – 1408	
	1-4	North Side	2" x 1.5"	1238 – 1368	
2	2-1	Central Area	2.5" x 1"	1258 – 1380	1033 – 1162
3	NO DEBONDS DETECTED				
4	4-1	Central Area	1.5" x 1"	1205 – 1325	1055 – 1168
	4-2	Central Area	1.5" x 0.75"	1216 – 1365	
5	NO DEBONDS DETECTED				
6	NO DEBONDS DETECTED				
7	7-1	Central Area	3" x 1.5"	1252 – 1339	1042 – 1172
	7-2	Central Area	3" x 2"	1432 – 1437	
8	8-1	Central Area	1.5" x 1"	1358 – 1422	1041 – 1160
	8-2	Central Area	4" x 3"	1211 – 1239	
	8-3	Central Area	3" x 1" & 2" x 1"	1338 – 1390	
	8-4	North Side	1.75" x 1.25"	1215 – 1328	

Table 3. *Digital Tap Testing Results from the Whiteday Bridge after Repair Work*

Beam	Spot	Location	Debond Size	Tap Testing Reading for Debonds (µs)	Tap Testing Reading for Good Areas (µs)
1 – 6	NO DEBONDS DETECTED				
7	7-1	Central Area	2" x 1"	1151 – 1222*	1042 – 1172
	7-2	Central Area	2" x 1"	1233 – 1250	
8	8-2	Central Area	4" x 3"	1250 – 1269	1041 – 1160
	8-5	Central Area	Edge Patch	1293 – 1480	

*Hollow sound coming from concrete, which indicates delamination in concrete rather than a debond between CFRP fabric and concrete

The Digital Tap Testing was conducted throughout the length of the CFRP bonded areas of the box beams. The tap testing results helped in detecting debonds between the CFRP laminate and the underlying concrete with debond sizes ranging from 1.5" x 0.75" to 4" x 3". Spots of size less than 1.5" x 0.75" (~ 1.1 inch^2) were also located but these do not require any special attention. According to ACI 440.2R-17 [5], debonds of size less than 2 inch^2 are permissible as long as the area with debond is less than 5% of the total bonded area. In our field test, however, even the detected debonds of size as small as 1.5" x 0.75" (~ 1.1 inch^2) was repaired using resin injection and the large ones (size ~ 4" x 3") were repaired by cutting off the CFRP fabric and replacing them with new fabric. Table 2 lists of all the debonds detected by digital tap testing along with their sizes and the corresponding tap testing readings. Fig. 6 shows the plan of the main span with location of the debonds between CFRP fabric laminate and the underlying concrete.

The debonds identified from the nondestructive testing were marked so that the repair work could be conducted immediately by the contractor. Small sized debonds were repaired by injecting resin into them while large debonds, especially bulges, were repaired by cutting off the CFRP fabric and replacing them with new fabric. After the repair works, a quick assessment of the CFRP bonded beams was needed to ensure that no more debonds were present. Thus, digital tap testing was done again on October 2, 2017 to evaluate all the previously detected and repaired debonds.

Beams 1 through 6 were found to be free of debonds. However, Beams 7 and 8 had couple of debonded spots left.

Table 3 shows the list of debonds detected using digital tap testing during this second round of field testing. The previously identified debonds on Beam 7 – namely 7-1 and 7-2 – were still detected but the sizes of these debonds had decreased. The size of spot 7-1 had reduced from 3” x 1.5” to 2” x 1” and that of spot 7-2 reduced from 3” x 2” to 2” x 1”. Debond 7-1, however, did not show a high number in tap testing reading but a hollow sound could be heard from the concrete upon tapping. This indicated that there was no debond between CFRP fabric and underlying concrete; instead, there was a delamination within the concrete itself as indicated by the hollow sound. For Beam 8, debond 8-2 of size 4” x 3” was still present, which was the bulge in the CFRP fabric. At the edge of the CFRP fabric on central area of Beam 8, tap testing gave readings that indicated there was debond in that area. This was called Spot 8-5, which could have formed during the repair work. All the debonds were marked and the contractor was asked to repair these by either injecting resin or cutting and replacing the debonded CFRP laminate.

V. Conclusions

Digital Tap Testing is a quick and convenient method of nondestructive testing, but it had its limitations when the thicker bridge deck specimens were involved. The method was unable to detect delaminations at 0.3” (7.6 mm) depth within the flange of deck specimens. Another downside of this method was that it could not be used on specimens with wearing surface. However, the digital tap testing method was capable of detecting defects underneath thin layers of FRP fabric wraps. The concrete cylinders wrapped by GFRP composite fabric were successfully evaluated using tap testing method. The delamination in FRP square tube specimen was also detected by digital tap hammer. Therefore, digital tap testing is an effective NDT method in case of FRP composite wraps used in rehabilitation of structural components; however, it fails in inspection of thicker composite structural members (over 5 mm thickness) like FRP bridge decks. The major advantage of digital tap testing is that it is very simple to use and is a low-cost device.

The debonds detected by the digital tap testing in case of CFRP bonded concrete box beams in the field were immediately repaired by the contractor. Small debonds (size ~ 1.5" x 0.75”) and somewhat larger (up to 3” x 2”) were repaired by injecting resin into them while very large debonds (size ~ 4” x 3”) were repaired by cutting out the old CFRP fabric and replacing them with new ones. These repair works are not always guaranteed to be successful in providing complete design strength of the repair system unless the debonds are detected and repaired during the rehabilitation stage. The first round of testing detected around 13 debonds, which were repaired and tested again. The second round of testing also showed some debonds even after the repair work was done, but the number of debonds decreased significantly. This shows that even after repairing, there can always be some debonds present between the CFRP fabric laminate and the underlying concrete. However, it should be noted that identifying the debonds using digital tap testing and subsequent repair of the debonds reduced the number of debonds significantly as shown in the second round of testing. Following the second testing, repair of the additional debonds was conducted by the contractor. Thus, the major advantage of using digital tap testing is that it allows quick condition assessment of the FRP bonded structures, leading to timely repair of the debonds which ensures better quality of the rehabilitation work.

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