Innov. Infrastruct. Solut. (2016) 1:12
DOI 10.1007/s41062-016-0012-0

ORIGINAL PAPER

Evaluation of external FRP-concrete bond in repaired concrete bridge girders and columns

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Received: 19 March 2016 / Accepted: 23 May 2016 / Published online: 21 June 2016

Abstract Fiber reinforced polymer (FRP) is increasingly used to strengthen damaged or structurally unsafe concrete bridges. The FRP wrapping on eight concrete bridges was evaluated with ASTM pull-off testing to assess the condition of the bonding. A majority of samples failed in the concrete substrate. However, large variations in failure modes and pull-off strengths were observed, possibly due to environmental degradation or improper application. A majority of samples failed in the ASTM Mode G in concrete. Average bond strength from columns samples was 20 % lower than that from girders, due to the difficulty of pull-off testing on round column surfaces.

Keywords Carbon fiber · Fiber-matrix Bond · Strength · Mechanical testing

Introduction

A considerable number of concrete highway bridges are regularly damaged due to vehicle collision, fire, corrosion of steel reinforcement, and material deterioration. Design and/or construction flaws may render a bridge to be structurally deficient. According to the ASCE Report Card for America's Infrastructure, one in nine of the nation's bridges is structurally deficient [3]. As per the Federal Highway Administration, the estimated total cost to repair or replace structurally deficient bridges was $71 billion in 2009. It is clear that there is an urgent need to strengthen the deficient bridges to extend the service life and make them safer. Depending on the severity of damage to the concrete bridge components, various strengthening methods are available, such as surface patching, pneumatic concrete placement, post tensioning, metal sleeve splicing, and fiber reinforced polymer (FRP) wrapping. FRP strengthening is an increasingly popular method for concrete bridge rehabilitation and strengthening, due to the high strength and stiffness, light weight, durability, low transportation, and construction costs [9]. Shorter installation time means less interruption of traffic and added economic savings. Carbon FRP (CFRP) repair of bridges is the most common type, using high-strength carbon fibers [15]. CFRP strengthening increases the axial, flexural, shear, and impact resistance of the repaired bridge components. Figure 1 shows a damaged concrete girder due to over height vehicle collision and the finished CFRP strengthened girder. The process involves removing loose and unsound concrete, splicing of any damaged prestressing strands, re-tensioning of the strands, sand blasting of the repair surface, and shotcreting. After curing, epoxy adhesive is applied on the repaired surface and also on the FRP wrapping, and the wrapping is installed over the girder surface as needed (the wet layup process). Multiple FRP layers may have to be used, and a layer of surface epoxy coating is applied over the FRP wrap.

The authors performed a survey of all highway departments in USA to determine the extent of FRP usage for strengthening concrete bridges. Currently, 24 highway

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Fig. 1 CFRP strengthened concrete bridge girder

departments in USA are using the technique, and several others states are in the process of adopting it.

The efficacy of the FRP rehabilitation scheme depends on the combined action of the entire system with emphasis on the integrity and durability of the bond between the FRP and concrete substrate [11]. Another study concluded that changes in mechanical properties and bond strength are the best indicators of changes in the performance of FRP [6]. Without the presence of a strong bond, improper transfer of stresses may lead to pre-mature debonding and failure of repaired structures when subjected to environmental exposure [10].

The important bond behavior at the epoxy-FRP-concrete interface can be evaluated by various available methods. The non-destructive methods include acoustic sounding, chain dragging, and thermographic imaging. The destructive evaluation methods include differential scanning calorimetry and the ASTM FRP pull-off testing. The latter method determines the greatest tension force that the FRP-epoxy-concrete bond can resist. The method consists of adhesively bonding a metallic circular loading fixture (dolly) normal to the testing surface (Fig. 2). The dolly contains a threaded hole in the center that allows for attachment of the fixed alignment adhesion testing device (pull-off tester, Fig. 3). After attaching the tester, a tension force is applied gradually to the dolly until a partial or full detachment of the dolly is witnessed. The load witnessed at the time of rupture is regarded as the maximum bond force [4]. The observed modes of failure can shed light on the condition of the epoxy-FRP-concrete interface, the long-term performance, and also quality of the initial FRP installation. The method has the following advantages: (a) quick and economic; (b) on-site testing with only minimal damage to the FRP; and (c) immediate test results.

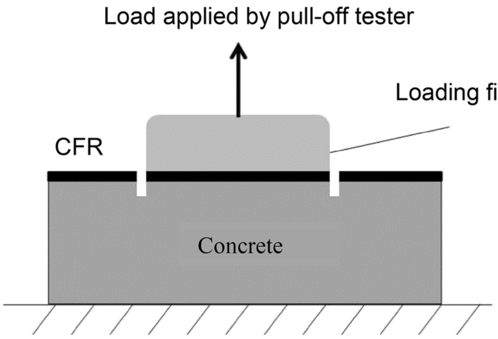

Fig. 2 Pull-off test mechanisms

Fig. 3 ASTM pull-off testing apparatus

A few past studies evaluated the ASTM pull-off testing, mainly in laboratory settings. Malvar et al. [12] evaluated the effect of moisture and chloride content on the CFRP bond to concrete using the pull-off test. Square concrete pile exposed to the saltwater and marine conditions for 48 months were strengthened with CFRP. Results indicated that hydroblasting helped remove some of the chlorides already present on the surface, and application of primer enhanced the adhesion of the reinforcement. Dai et al. [8] undertook pull-off and flexural tests on FRP strengthened concrete specimens after exposing them to wet-dry sea-water cycles. The bond strength was degraded as the number of cycles increased. Allen [1] conducted a field assessment of the Castlewood Canyon Bridge, Ft. Collins, CO, which was strengthened with FRP in 2003. Pull-off tests, tensile tests, and differential scanning calorimetry were used. The tensile strength of the substrate decreased with age, along with average, maximum, and minimum strength values. Results indicated deterioration of the bond between the CFRP and the concrete over time.

Carrillo [7] studied the behavior of the bond between concrete and the CFRP when subjected to various environmental conditions. Pull-off tests and three-point bending tests were used. Various modes of failure and some discrepancies, inconsistencies in the depth of the core drilling, improper mixing of epoxy, varying volumes of epoxy used for each dolly, and experimental errors were noted. Benzarti et al. [5] investigated the bond durability

Table 1 Selected bridges for evaluation

Bridge no.	Location	Component strengthened	Date of strengthening	Date of inspection	Date of pull-off testing
1	SH 183 over Loop 12	Girder	11/07/2006	05/28/2013	09/15/2013
2	LP 12 over Irving Blvd.	Girder	07/14/2011	05/28/2013	09/15/2013
3	SH 183 over MacArthur Blvd.	Column and Girder	12/21/2005	05/28/2013	09/15/2013
4	Gross road over U.S. 80	Girder	03/04/2011	05/28/2013	10/27/2013
5	Corinth St. over Trinity river	Pier Bent	02/09/2009	05/28/2013	10/27/2013
6	Corinth Street over IH 35E	Girder	03/08/2007	10/02/2013	10/27/2013
7	CR 470 over IH 20	Column	09/01/2007	07/06/2013	12/19/2013
8	Loop 344 over SH 199	Girder	10/01/2008	07/06/2013	12/19/2013

between concrete and CFRP system under the accelerated aging conditions. Hygrothermal aging induced significant decrease in the pull of strength. The failure mode was initially cohesive within the concrete substrate. However, an increasing number of mixed or adhesive failures were observed over time.

Due to the difficulties in achieving realistic field conditions in the laboratory, the laboratory test results may differ substantially from the actual field results [10]. Likewise, relationships linking accelerated exposure data in laboratory and real-time performance in field are not yet confidently determined [6].

The objective of the current study was to evaluate the bond performance of CFRP strengthening on girders and columns from several concrete bridges in the greater Dallas-Fort Worth (DFW) metroplex. The Texas Department of Transportation (TxDOT) has successfully utilized FRP retrofitting of concrete bridges since 1999 [15]. TxDOT specifications allow only CFRP wrapping for such strengthening [14], and do not include any provisions for the in situ condition assessment of the CFRP performance. Therefore, a field assessment of and the evaluation of long-term behavior is helpful in better understanding of FRP wrapping as a bridge strengthening material. The ASTM pull-off test results were used herein to evaluate the long-term performance of FRP strengthening, any degradation over time, and identifying potential problems that need to be addressed. This will help in utilizing the strengthening technique with more confidence and also allowing any improvements to the initial FRP strengthening.

Materials and methods

As part of the field evaluation, the Bridge Division of the TxDOT Dallas District was contacted to get an inventory of FRP strengthened concrete bridges in the DFW area. The information included bridge location, County, District, National Bridge Inventory (NBI) number, type of FRP repair, and the date of repair. Based on the information review, eight bridges were selected for field evaluation, based on the scope of the TxDOT contract agreement with UT Arlington and proximity to the university. The selected bridge information is presented in Table 1, and the bridge locations are shown in Fig. 4.

Pull-off testing

Based on the location of the FRP strengthened components in relation to the traffic lanes, lane closures were scheduled for the day of the pull-off test for each bridge. Required permissions were obtained from Bridge Division of the TxDOT Dallas District. Thereafter, the pull-off test was performed according to the specifications of ASTM D7522/D7522M on selected locations of FRP strengthened girders and columns [4]. The locations were selected to be free of cracks, voids, and pitting, away from edges and discontinuities.

A diamond coated hole saw was used to score through the FRP laminate into the concrete substrate (Fig. 5a). The test surface was sanded to remove small surface imperfections, cleaned with rubbing alcohol, and a coarse brush. A two-part high strength epoxy was mixed in a 1:1 ratio and applied evenly over the surface of the test dolly, the circular loading fixture 50 mm in diameter, and the test surface. The dolly was then fixed with manual pressure to the cored location on the FRP, excess epoxy removed and glue tape applied to hold the dolly in place. After allowing the epoxy to cure for 24 h, the pull-off test was performed on the following day. The central grip of the adhesion tester was connected to the dolly and loading applied (Fig. 5b), until a partial or full detachment of the dolly (failure) occurred or the maximum capacity of the adhesion tester reached. For failed samples, the test dolly was removed, labeled and the failure type and the load reading

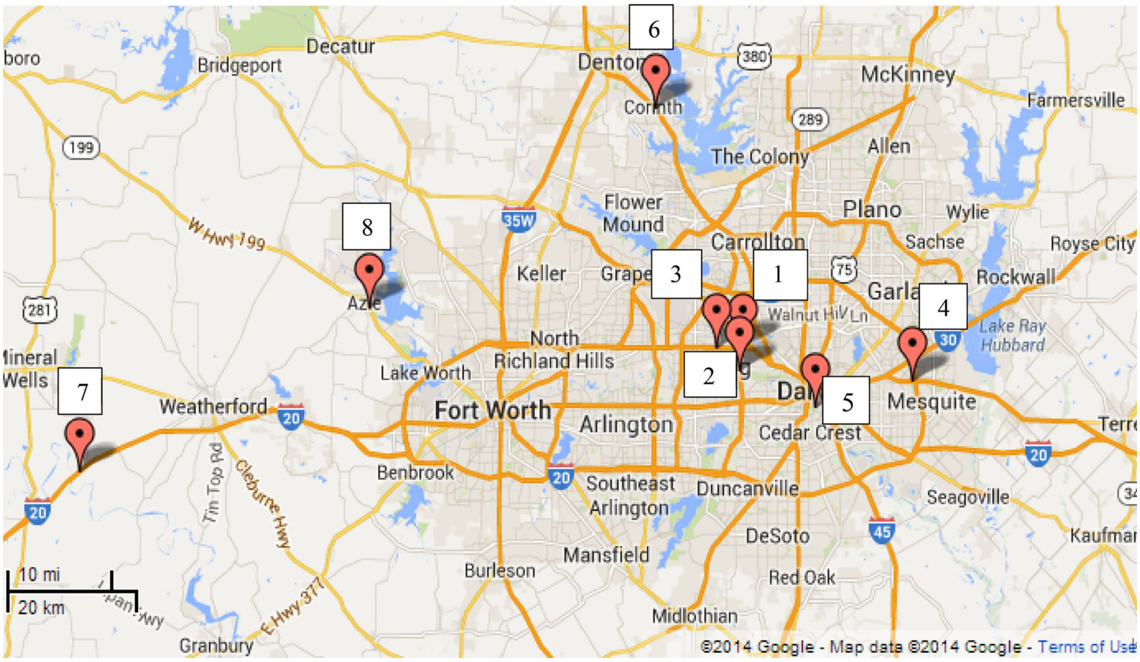

Fig. 4 Selected bridge locations (http://www.google.com)

Fig. 5 Pull-off testing procedure

from the tester were recorded. The failed surface was then patched with new FRP and epoxy.

The maximum force witnessed in the pull-off testing at the time of rupture is regarded as the bond strength of the FRP-concrete substrate. According to ASTM, seven failure modes are possible depending on the location of failure interface, Mode A through G, as shown in Fig. 6 [4]. Explanation of each mode is presented in Table 2. During testing, some samples failed in modes that may not be explained entirely through any of the A–G ASTM modes (e.g., a mix of Modes C and G). The installed FRP had a top external layer of epoxy surface, on which an elastomeric breathable coating was provided for minimizing ultraviolet ray effects and increasing aesthetics. In some

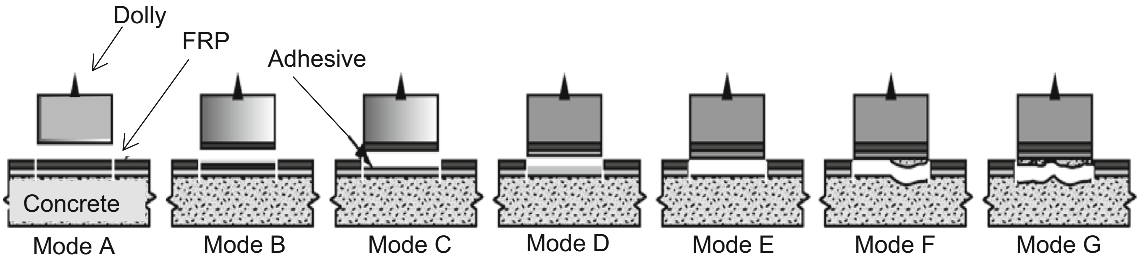

Fig. 6 ASTM failure modes for pull-off test (ASTM D7522/D7522M-09)

Table 2 Pull-off test failure modes (ASTM D7522/D7522M, [4])

Failure mode	Failure type	Possible causes of failure
A	Bonding epoxy failure at dolly (loading fixture)	Use of an inappropriate bonding epoxy system for affixing the dolly
B	Cohesive failure in FRP laminate	Incomplete epoxy saturation of the fibers or environmental degradation of the FRP material itself
C	Epoxy failure at FRP/epoxy interface	Improper selection of epoxy, contamination of epoxy, improper or incomplete epoxy curing, contamination or improper preparation or cleaning of adherent surfaces, or environmental degradation
D	Cohesive failure in epoxy	Contamination of epoxy, incomplete curing, and environmental degradation of material
E	Epoxy failure at FRP/concrete interface	Improper selection of epoxy, contamination of epoxy, improper or incomplete epoxy curing, contamination or improper preparation or cleaning of concrete surfaces or environmental degradation
F	Mixed cohesive failure in concrete and epoxy at the epoxy/concrete interface	Inconsistent FRP-concrete adhesion. Failure is partly in epoxy and partly in concrete
G	Cohesive failure in concrete substrate	Proper adhesion of FRP-concrete. Desirable failure mode

samples tested herein, this elastomeric coating (top coat) failed partially, which is also not recognized in the ASTM testing specifications. Such non-ASTM failure modes are categorized in this study as “Mode M”. Mode G is the most desirable, where the failure occurs entirely in the concrete substrate, and not in the FRP or epoxy.

Results and discussion

A total of 29 pull-off tests were performed on various FRP strengthened sections on the selected bridges. Three of the samples failed in the core, while scoring the FRP laminate before attaching the dollies, leaving 26 valid samples. The test results are presented in Table 3, and selected failed samples are shown in Fig. 7.

The pre-dominant failure mode observed was the 100 % cohesive concrete failure in Mode G per ASTM, in 15 samples (58 %) out of 26 valid samples, followed by 15 % in mixed non-ASTM Mode M and 11 % in Mode A. It may be noted that Mode A failure at the epoxy glue next to the testing dolly is most likely associated with improper surface preparation of the dolly or improper application and/or curing of the epoxy on the dolly. Therefore, the underlying FRP-epoxy combination could still be sound in a Mode A failure. The combined Modes C, E, F, and M percentage is 31. The possible causes of failures in these modes are: (1) improper initial storage, surface preparation or preparation/application of the epoxy and FRP, and (2) age-related environmental degradation.

Column samples

Seven samples from various locations on FRP strengthened columns were tested (Table 3). Pull-off strengths ranged between 1.08 and 2.03 MPa. The dominant failure mode in the majority of samples was Type G (83 %). Large variation in the column bond strength was witnessed, possibly due to improper initial application of FRP and variations in the depth of core cut before attaching dollies, which in turn might have affected the pull-off test results.

Girder samples

A total of 20 girder samples were tested, of which two samples failed in the core during the scoring operation. Again, the pre-dominant failure mode was Type G (50 %). The bond strengths were scattered, with a range of 0.18 MPa to 3.31 MPa, much larger than the scatter in the column results. More proportion of samples failed in Mode G in columns (83 %) than in girders (50 %). The probable reasons for this are: (a) Greater possibility of improper initial application of FRP on girder surfaces. Application on girder surfaces is more difficult (due to various sides, change in angles between surfaces, and accessibility issues) than application on column surfaces.

Out of 13 samples tested from the girder web faces, five samples (38 %) failed in Mode G. Conversely, four out of five samples (80 %) from the bottom face of girders failed in Mode G. Relative difficulty of installing FRP wrapping on the chamfered girder sides may cause improper application and resulting non-Mode G type failures.

Table 3 Summary of pull-off test results

Sample no.	Bridge	Sample location	FRP age, months	Failure stress, MPa	Failure mode
1	Bridge 1	Girder	82	1.10	E (98 % E, 2 % G)
2	Bridge 1	Girder	82	0.18	A
3	Bridge 1	Girder	82	1.80	M (30 % C, 70 % G)
4	Bridge 1	Girder	82	N/A	Core broke off
5	Bridge 1	Girder	82	1.75	M (10 % B, 40 % top coat adhesion, 50 % FRP to top coat adhesion)
1	Bridge 2	Girder	26	2.43	G
2	Bridge 2	Girder	26	1.94	A
1	Bridge 3	Column	93	1.80	M (25 % B, 75 % top coat cohesion)
2	Bridge 3	Column	93	1.22	G
3	Bridge 3	Column	93	N/A	Core broke off
4	Bridge 3	Column	93	1.87	G
5	Bridge 3	Girder	93	0.26	C
6	Bridge 3	Girder	93	1.09	G (10 % E, 90 % G)
7	Bridge 3	Girder	93	3.11	M (80 % E, 10 % G, 10 % top coat adhesion)
8	Bridge 3	Girder	93	2.51	G
9	Bridge 3	Girder	93	2.23	G
1	Bridge 4	Girder	30	2.43	G
2	Bridge 4	Girder	30	3.30	G (1 % C, 99 % G)
1	Bridge 5	Pier Cap	55	2.32	F (12 % C, 88 % G)
2	Bridge 5	Pier Cap	55	2.56	G (5 % E, 95 % G)
1	Bridge 6	Girder	78	2.87	A (40 % A, 60 % epoxy to top coat adhesion)
2	Bridge 6	Girder	78	1.65	F (20 % G, 80 % E)
3	Bridge 6	Girder	78	N/A	Core broke off
4	Bridge 6	Girder	78	1.92	G
1	Bridge 7	Column	74	1.08	G
2	Bridge 7	Column	74	2.0	G
3	Bridge 7	Column	74	2.03	G
1	Bridge 8	Girder	61	3.31	G[a]
2	Bridge 8	Girder	61	3.31	G[a]

[a] Maximum capacity of the tester reached

(a) Mode C, Sample 5, Bridge 3

(b) Mode G, Sample 9, Bridge 3

Fig. 7 Selected failed samples

Column vs. girder results

To better understand the FRP strengthening performance on columns and girders, test results from Bridge 3 was reviewed; the only bridge herein where both column and girder samples were obtained. The results from samples failing in Mode G only are shown in Table 4. The average bond strength from columns samples was lower than that from the girder samples by about 20 %. The strength of the concrete substrate plays a major role in the bond strength of FRP-concrete systems. Due to the controlled manufacturing conditions at the pre-cast site and also the likelihood of higher concrete strengths, pre-cast girders may have more

Table 4 Bridge 3 results

Sample no.	Sample location	Bond strength, MPa	Average strength, MPa
2	Column	1.22	1.55
4		1.87	
6	Girder	1.09	1.94
8		2.51	
9		2.23	

strength as compared to the cast in place columns. However, the repair document for Bridge 3 states that a 20.7 MPa strength fiber reinforced mortar was sprayed on the column and girder surfaces before the FRP application, making both underlying substrate strengths identical [13]. The other possible reason for the lower column strength could be the curvature of the column surface, as opposed to the flat surfaces of the girder test areas. Although the column curvature is small as compared to the test dolly surface (flat), this could have caused an uneven pulling stress during testing, resulting in lower bond strengths in column samples.

Figure 8 shows that Bridges 3, 4, 7, and 8 had mostly to all Mode G sample failures. Mode G occurred in some samples in Bridges 2 and 6, while only non-Mode G failures were seen in Bridge 1. Interestingly, almost equal percentage of samples failed in Mode G on Bridge 3, showing that the quality of FRP application and/or testing was similar for girders and columns on this bridge.

There are some significant variations in the test sample failure strength and failure modes. Two possible reasons are: (1) improper and/or inconsistent initial application of FRP; and (2) Improper pull-off testing. ACI 440 and various FRP manufacturers provide detailed information and step-by-step procedure for the initial FRP application on the concrete substrate [2]. Important quality control steps in the initial FRP application are: surface preparation, FRP and epoxy combination selection, epoxy mixing, epoxy application on FRP and concrete substrate, FRP placement on concrete, finishing, epoxy curing, and following manufacturer's specifications for environmental conditions. Compromise on any of these steps may result in inadequate quality of the FRP application, leading to ASTM non-Mode G failure and/or low tensile strength from the pull-off test procedure. For the pull-off testing, the pertinent quality control steps include: surface preparation (dirt and grime, uneven surface), scoring through FRP/epoxy/concrete (skewed scoring, scoring thickness uneven or not within the ASTM range), selection and application of epoxy for dolly (improper epoxy selection, uneven epoxy on dolly), dolly attachment to FRP surface (dolly not aligned with scored surface, inadequate pressure), epoxy curing, and pull-off tester orientation and application (twisting action, tester not perpendicular to test surface). Inadequate attention to any of these steps may result in improper pull-off testing, leading to faulty test results, including failure modes and bond strength.

To adequately assess the FRP-concrete-epoxy bond condition, Mode M failure in the top coat should be avoided through the following alternate steps: (1) avoid top coat application altogether (if possible and allowed) to allow proper in situ inspection of FRP strengthened structures; or (2) remove existing top coat with a sandpaper in the area of the pull-off dolly.

Conclusions and recommendations

The following conclusions and recommendations may be made based on the results from this study:

1. The in situ condition assessment of FRP strengthening on concrete bridge components is important to determine the extent of the adequate placement and the long-term performance of the FRP wrapping. The ASTM pull-off testing can be a good avenue for this assessment when properly administered with quality control.

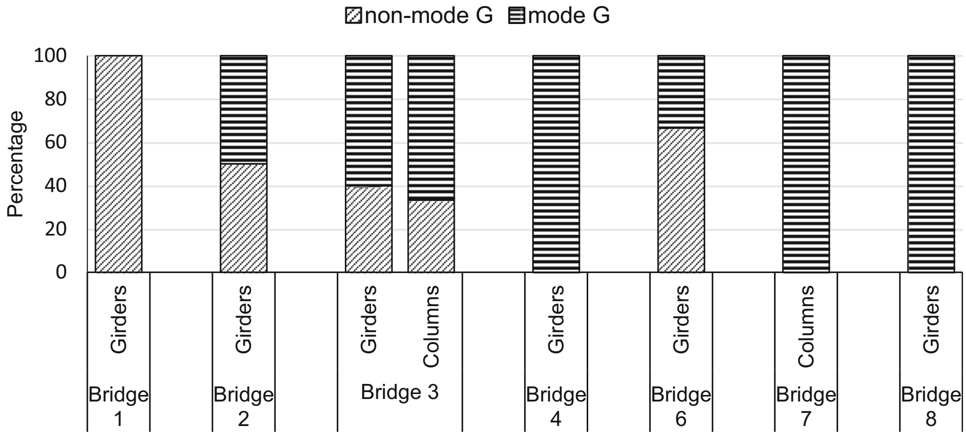

Fig. 8 Failure modes for girders and column samples

2. The long-term FRP wrapping performance in the eight selected concrete bridges in the DFW area is good, but mixed. The desired type of failure from the ASTM pull-off testing (Mode G) in the concrete substrate was witnessed in 58 % of the valid tested samples (15 of 26). Other significant failure modes were top coat of the FRP wrapping (the non-ASTM Mode M defined herein, 15 % of samples), epoxy failure on the testing dolly (11 % of samples), and mixed concrete-epoxy failure (8 % of samples).
3. About 31 % of the tested samples failed in ASTM Modes C, E, and F, and the non-ASTM Mode M defined herein. This could be due to: (1) improper initial storage, surface preparation or preparation/application of the epoxy, and FRP; (2) age-related environmental degradation; and (3) pre-mature top coat failure. It is difficult to determine the cause of these failure modes with the in situ testing performed herein. Availability of pull-off test results at the initial FRP installation would be helpful in determining the quality of the application (factor 1 above).
4. The majority (83 %) of column FRP samples failed adequately in the desired ASTM Mode G failure. Large scatter in the test results was observed, possibly due to inadequate initial FRP application and/or core cut depth variations in the pull-off test.
5. Girder FRP samples pre-dominantly failed in Mode G (50 %), less in proportion than that in column samples (83 %). The probable reason is a greater chance of improper initial application of FRP on girder surfaces. Such application is more difficult (due to various sides, change in angles between surfaces, and accessibility issues) than that on column surfaces.
6. The strength of the concrete substrate plays a major role in the bond strength of FRP-concrete systems. The surface curvature of columns may cause uneven placement of the straight test dollies on the FRP surface, resulting in lower bond strengths from testing. Dolly placement is level on the straight girder surfaces.
7. Guidelines for the FRP wrapping installation should be properly followed to achieve quality FRP-epoxy performance, such as adequate surface preparation, FRP and epoxy combination selection, epoxy mixing, epoxy application on FRP and concrete substrate, FRP placement, finishing, epoxy curing, and adhering to environmental conditions for installation.
8. Improper testing protocols for the ASTM pull-off testing may compromise the test results. Proper attention (from guidelines) to surface preparation, scoring through FRP/epoxy/concrete, selection and application of epoxy for dolly, dolly attachment to FRP surface, epoxy curing, and pull-off tester orientation and application are important.
9. The ASTM standard does not recognize pre-mature pull-off failure on the elastomeric coating (top coat) of the FRP that may be have been applied in bridges. To avoid this type of failure, it is recommended that the top coat be entirely eliminated at FRP application, or it be removed at the dolly site before pull-off testing.

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