

# FATIGUE BEHAVIOUR OF ADHESIVE SYSTEMS USED FOR EXTERNALLY-BONDED FRP APPLICATIONS

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## ABSTRACT

Fatigue loading is recognised to have a deleterious effect on the performance of externally bonded FRP retrofit systems. Recent studies suggest that there is fatigue-induced degradation of the bonding adhesive. The present study investigates this effect through fundamental mechanical testing of adhesive systems suitable for bonded FRP repair systems. Single shear adhesive tests based on those prescribed by ASTM D3983 are reported. Commercially available adhesives having different moduli are tested. Each adhesive series involves specimens subject to increasing levels of fatigue conditioning (fatigue loading not resulting in fatigue failure) followed by monotonic tests to failure. The effect of fatigue conditioning on the adhesive performance is thereby quantified for the systems considered. Adhesive line stiffness is observed to have a significant effect on fatigue behaviour of the adhesive. This test program indicates the importance of adhesive selection in a fatigue-prone environment.

## 1. INTRODUCTION

Durability of FRP-to-concrete bond is recognised as being critical to the performance of an externally bonded FRP repair system. Previous work by Harries et al.<sup>1-6</sup> has clearly identified the degrading effect of cyclic (fatigue) loading on the performance of externally-bonded FRP systems. Deleterious effects have been observed in full-scale CFRP-retrofit beam specimens subject to fatigue conditioning that imparts a stress range in the CFRP as low as  $0.04f_{tu}$ ; where  $f_{tu}$  is the strength of the CFRP<sup>2</sup>. Fatigue-induced failure of CFRP-retrofit beam specimens has been regularly observed at induced stress ranges on the order of  $0.14f_{tu}$ <sup>4</sup>. In a recent study addressing the effects of adhesive modulus on bond performance under fatigue loading conditions, results were obtained which pointed to fatigue-induced degradation of the adhesive itself<sup>6</sup>. The present study attempts to quantify this effect through fundamental mechanical testing of the three adhesive systems used in the earlier studies of bonded FRP repair systems.

## 2. FATIGUE BEHAVIOUR OF ADHESIVES CONNECTIONS

While the study of adhesive structural connections in civil infrastructure applications is limited, the behaviour of adhesive connections has been extensively studied in the

mechanical and aerospace fields. Adhesive joints are typically assumed to have better mechanical properties when subject to fatigue loads than discrete connections such as bolts or rivets due to the uniform stress distribution the latter afford<sup>7</sup>.

The mechanical properties of adhesive joints are largely dependent upon interlaminar stresses and strains which exhibit large concentrations in close proximity to the free edges of the joint<sup>8</sup>. When subject to cyclic loading, these stresses and strains intensify and accumulate until failure takes one of two forms<sup>8</sup>:

1. Cohesive failure characterised by a shear fracture mode within the adhesive layer; or
2. Adhesive failure characterised by delamination along the adhesive/adherend interface.

Several authors have reported experimental results involving fatigue loading of adhesive joints. Some fundamental observations of adhesive fatigue behaviour include:

1. Adhesive behaviour follows Paris' Law indicating that crack growth rate is a function of the fracture parameter described by the J-integral<sup>9</sup>.
2. The thickness of the adhesive layer is not significant when determining the fatigue life of an adhesive joint: it has been shown that while a statistical difference is present when comparing a 0.1 mm and 0.3 mm thickness adhesive layer in a static (or monotonic) test, no statistical difference is present for a similar cyclic experiment<sup>10</sup>.
3. Adhesive joints will fail at lower loads if they have undergone fatigue loading, as opposed to a simple monotonic load<sup>7</sup>.
4. Adhesive joints will exhibit a shorter fatigue life and more pronounced creep when tested at low frequencies<sup>7</sup>.

### **3. EXPERIMENTAL PROGRAM**

#### **3.1 Test Specimens**

Single shear adhesive tests based on those prescribed by ASTM D3983<sup>11</sup> were conducted. As shown in Figure 1a, the test specimens consisted of two 101.6 x 25.4 x 13 mm aluminum adherends bonded to make a single lap shear specimen. The 25.4 mm square bonded surfaces were prepared by power sanding with a 320 grit emery cloth followed by thorough cleaning using a degreasing agent. The specimens were individually prepared in aluminum alignment jigs (Fig. 1b) which fixed specimen alignment, held constant the size of the bonded area (645 mm<sup>2</sup>) and ensured a constant adhesive thickness for each specimen (although the thickness varied by approximately 0.25 mm from specimen to specimen as indicated in Table 2). A fillet was provided at the ends of each bonded area to mitigate stress raisers in this area.

#### **3.2 Adhesive Systems**

Three commercially available epoxy-based adhesives systems were used in this study. Each adhesive had been used in previous investigations of externally bonded FRP retrofit systems applied to reinforced concrete beams and found to perform adequately in this

application<sup>5,6</sup>. Nonetheless, some degradation of bond behaviour associated with fatigue conditioning has been observed in the use of all three systems<sup>1-6</sup>. Adhesives B and C are commonly specified for use with commercially available FRP systems. Adhesive A is a softer adhesive not traditionally used with FRP systems but included in previous studies to examine adhesive system stiffness as an experimental parameter<sup>6</sup>. All adhesives are reported to be appropriate for use with concrete, ferrous and non ferrous metals and timber substrates. All adhesives were stored, handled, mixed and applied in conformance with their manufacturers' recommendations. Manufacturer reported material properties for each adhesive system are given in Table 1.

Table 1: Manufacturer reported material properties of adhesive systems tested.

Property	ASTM test method	Adhesive		
		A	B	C
tensile strength, MPa	D638	13.8	24.8	31.0
tensile modulus, MPa	D638	2230	4480	n.r.
elongation at rupture	D638	0.060	0.010	0.025
modulus of rupture, MPa	D790	33.1	46.9	n.r.
tangent modulus of elasticity, MPa	D790	3250	11720	3960
shear strength, MPa	D732	20.7	24.8	n.r.
bond strength, MPa	C882	17.9	22.1	n.r.
compressive strength, MPa	D695	35.5	59.3	n.r.
compressive modulus, MPa	D695	880	2690	n.r.

n.r. = not reported

### 3.3 Test Set-up

Having assembled the test specimens, they were allowed to cure in their template jigs for at least 72 hours in ambient laboratory conditions. For testing, each specimen was installed in a steel “grip” designed to ensure that the line of action of the applied load passes through the bonded joint (Fig. 1a). The test grip was designed to be essentially “rigid” at the relatively low test loads applied mitigating affects of bending of the adherends. The entire assembly was placed in a 90 kN capacity servo-hydraulic load frame having hydraulic-actuated wedge grips to facilitate fatigue testing (Fig. 1c). High precision variable resistance displacement transducers were fixed to each side of the specimens (Fig. 1c) and their results averaged to determine the relative displacement along the adhesive joint in the direction of the applied load. A 90 kN load cell calibrated at 18 kN was used to determine the applied load.

### 3.4 Test Protocol

Only six samples were prepared for each adhesive batch. The first two tests from each batch were conducted using a monotonically increasing load to failure. These control specimens were intended to establish the shear capacity of the adhesive. The remaining four tests were intended to fatigue-condition the specimen, after which the specimen was tested monotonically to failure to assess the effects of fatigue conditioning. The fatigue conditioning protocol involved tension-tension cycling from a minimum applied load of

890 N (corresponding to a shear stress in the adhesive of 1.4 MPa) to a maximum load selected to affect the desired stress range (Table 2). Sinusoidal wave-form fatigue loading was applied for 1000 cycles at 1Hz. The slow rate of cycling is selected to avoid self-heating while the low number of cycles counteracts the relatively large stress ranges selected. The third test in each series was subject to an applied load ranging from 890 N to 4450 N (stress range in the adhesive of 5.5 MPa). Based on the observed behaviour of this specimen, subsequent stress ranges were selected for testing as indicated in Table 2. Both control and fatigue-conditioned monotonic tests were conducted at a loading rate of 50 N/s (applied shear in adhesive of 77 kPa/s).

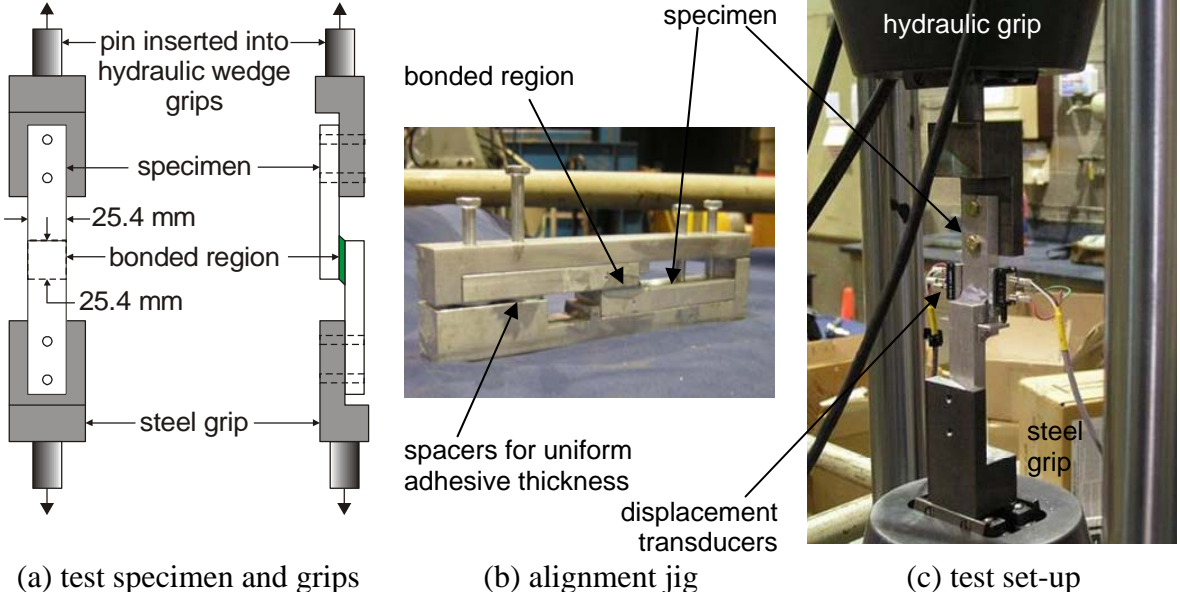


Figure 1: Adhesive test specimen details and test set-up.

**4. EXPERIMENTAL RESULTS**

Test results are presented in Table 2. For each specimen, the actual adhesive thickness was measured. Although the thickness varies from specimen-to-specimen (Table 2), variability in a given specimen was less than 0.03 mm. Due to the use of jigs (Figure 1b), the size of the bonded area was quite consistent and assumed in every case to be 645 mm<sup>2</sup>. This area was not observed to vary more than about 2% across all tests. All adhesive systems exhibited a brittle failure. The values reported in Table 2 for ultimate failure are the applied shear stress (calculated as the applied load divided by the 645 mm<sup>2</sup> bonded area) and corresponding shear strain (calculated as the measured axial deformation in the direction of loading divided by the measured thickness of the adhesive) at the maximum applied load recorded immediately prior to failure. In Table 2, an entry given as “N =” indicates that the specimen failed during fatigue conditioning at cycle number N. Figure 2 shows the shear stress versus shear strain plots obtained for each specimen tested monotonically to failure. Each curve is offset to the right for clarity.

Figure 3 shows representative photographs of the failed adhesive test specimens. In each case, the specimens shown in Figure 3 are those that were subject to fatigue conditioning at a stress range of 5.5 MPa. Adhesives B and C exhibited adhesive failures in all tests with the failure plane forming along the adhesive-aluminum interface as shown in Figures 3b and c. Adhesive A exhibited a combined failure in all test specimens with the failure plane forming along the adhesive-aluminum interface and crossing through the adhesive layer near the middle of the specimen to continue along the other adhesive-aluminum interface. Figure 3a shows a representative Adhesive A specimen having adhesive on both adherends and a rough line through the adhesive where the failure passed through the adhesive layer. Fatigue conditioning of Adhesive A specimens also resulted in multiple shear fractures in each specimen occurring through the adhesive thickness as illustrated schematically in Figure 3a.

Despite the nature of the adhesive failures observed, the quality of the bond was considered relatively good: in all cases adhesive material remained on the aluminum test specimen, captured by the mechanically roughened surface.

Table 2: Test results.

Adhesive	Test	adhesive thickness, mm	cyclic load range, MPa	ultimate failure	
				shear stress, MPa	shear strain
A	1	1.27	monotonic	12.07	0.417
A	2	1.52	monotonic	12.49	0.488
A	3	1.78	1.4	12.21	0.348
A	4	1.52	3.4	11.07	0.268
A	5	1.27	5.5	9.36	0.277
A	6	1.78	specimen damaged during set-up		
B	1	1.78	monotonic	16.35	0.040
B	2	1.78	monotonic	17.34	0.039
B	3	1.78	5.5	16.84	0.033
B	4	2.03	7.6	15.69	0.034
B	5	1.78	9.6	failed at N = 504	
B	6	1.52	9.6	13.75	0.041
C	1	2.03	monotonic	11.04	0.050
C	2	1.52	monotonic	12.56	0.023
C	3	2.23	specimen damaged during set-up		
C	4	2.03	monotonic	12.74	0.023
C	5	1.78	monotonic	11.80	0.027
C	6	2.03	5.5	12.91	0.016
C	7	1.78	5.5	failed at N = 734	
C	8	2.03	5.5	12.27	0.027
C	9	2.03	6.6	12.00	0.021
C	10	1.78	7.6	failed at N = 3	
C	11	1.78	7.6	failed at N = 705	
C	12	2.03	7.6	8.88	0.019

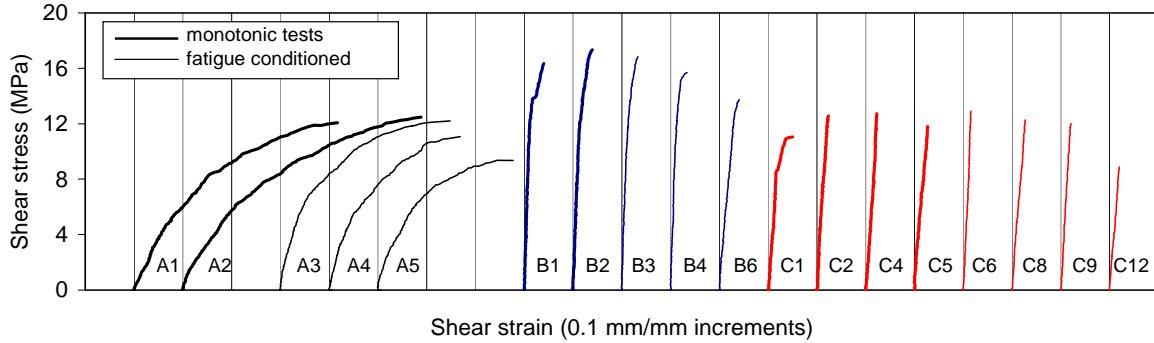


Figure 2: Shear stress versus shear strain from monotonic tests.

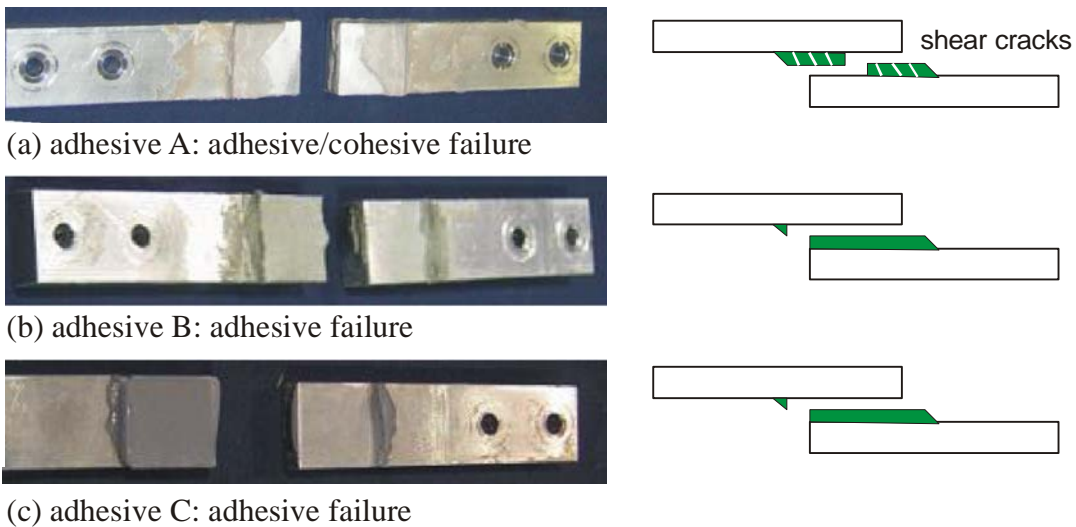


Figure 3: Representative adhesive failures.

## 5. OBSERVATIONS AND DISCUSSION OF EXPERIMENTAL RESULTS

The ultimate shear stress obtained in monotonic tests is consistent among adhesives types although is only 60-65% of that reported by the manufacturers (compare Tables 2 and 1). This is a function of the test performed: in the present study the test is based on single lap shear tests promulgated by ASTM D3983, whereas the manufacturers report using ASTM D732<sup>12</sup> to assess shear capacity. The D732 standard is based on a die punching mechanism and necessarily results in a cohesive shear failure, whereas the D3983 specimen allows an adhesive failure as exhibited in this test program (Figure 3). It is proposed that the D3983 test more accurately represents the expected adhesive behaviour in a bonded FRP retrofit application.

Adhesives B and C both exhibited a high shear stiffness and essentially linear behaviour as shown in Figure 2. The softer adhesive A exhibited a much more nonlinear behaviour and consequently exhibited greater strains.

The effects of fatigue conditioning are summarised in Figure 4. The degradation of ultimate shear stress obtained following fatigue conditioning is apparent for all adhesive types tested. Nonetheless, the stress range at which degradation becomes apparent is different in each case. This sensitivity to the stress range is comparable to the adhesive’s toughness. Adhesive A exhibited little degradation due to fatigue conditioning at 1.4 MPa (approximately 11% of the adhesive’s ultimate monotonic shear capacity) but marked degradation beginning at a stress range of 3.4 MPa (28% ultimate monotonic shear capacity) and further degradation at 5.5 MPa (45%).

Apparently tougher Adhesives B and C exhibited little degradation at fatigue conditioning stress ranges of 5.5 MPa (approximately 33% and 44% of the ultimate monotonic shear capacities of Adhesives B and C, respectively). However, both Adhesives B and C showed significant degradation at higher stress ranges (Figure 4). Adhesives B and C also exhibited failures during fatigue conditioning as reported by the N values in Table 2. However, other specimens tested at the same stress range survived the conditioning and exhibited capacity degradation consistent with the observed trends. The apparent variation in test results may be attributable to the sensitivity to damage of the stiffer adhesive systems.

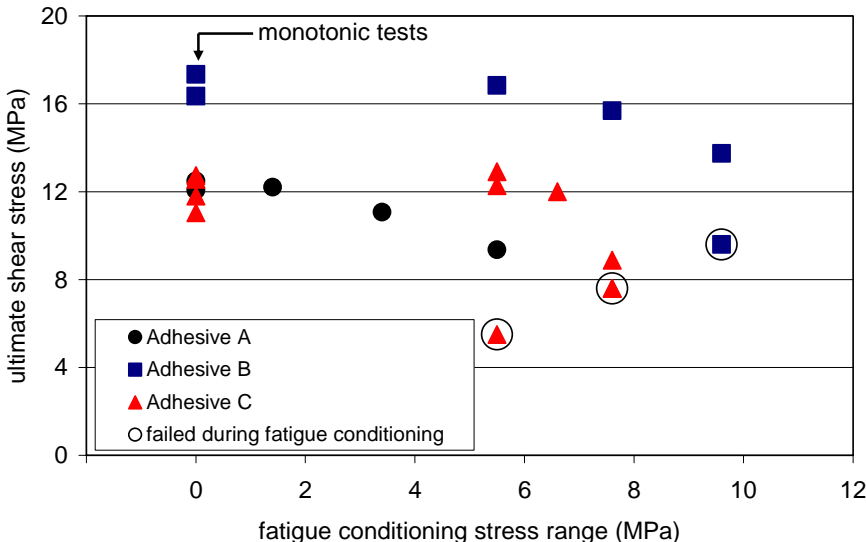


Figure 4: Effects of fatigue conditioning.

**6. CONCLUSIONS**

Although this study represents a limited number of results, it nonetheless clearly identifies deleterious effects of fatigue loading on the ultimate mechanical properties of epoxy adhesive systems typically used in FRP retrofit applications. The degradation in behaviour is comparable to that observed in FRP retrofit concrete beams subject to fatigue conditioning<sup>1</sup> suggesting that observed behaviour of such beams is a function of the adhesive bond line more so than the FRP or the concrete substrate. Significantly more study is warranted to adequately quantify this effect. Nonetheless, this study, coupled with previous studies on fatigue behaviour of FRP-retrofit concrete beams<sup>1-6</sup>, suggests that a

reduction factor for allowable FRP strain associated with fatigue is appropriate. Such a factor will be a function of the adhesive stiffness and the expected fatigue stress range. Finally, the results of this study indicate that for relatively low expected fatigue stress ranges, a stiffer adhesive will exhibit minimal degradation. At higher stress ranges, however, degradation should be expected and a softer adhesive will provide greater ductility and may be expected to behave in a more predictable manner.

## 7. ACKNOWLEDGEMENTS

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