II.10

Research Results

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AN INTEGRATED FRP STRENGTHENING AND DAMPING SYSTEM FOR MULTIPLE PERFORMANCE LEVEL SEISMIC RETROFIT OF RC COLUMNS

SUMMARY

The concept of an integrated strengthening and damping retrofit system was proposed to design reinforced concrete (RC) columns for their optimal performance under multi-level earthquake hazards. As illustrated in Figure 1, the system consisted of fiber reinforced polymer (FRP) sheets wrapping around a column and viscoelastic (VE) layers on the FRP sheets. The motion of the outer surface of the VE layers was constrained to the footing by applying another FRP sheet outside the VE layers and properly anchoring it into the footing. As such, two critical issues that will affect the performance of the proposed system are bonding between FRP sheets and VE layers, and anchorage of the outer FRP sheets into concrete. Both bond and anchorage mechanisms were investigated with laboratory tests. The FRP-VE interface failed in tearing of the VE materials and the FRP anchorage failed in concrete rupture. Design equation for anchorage has been developed as a result of this study.

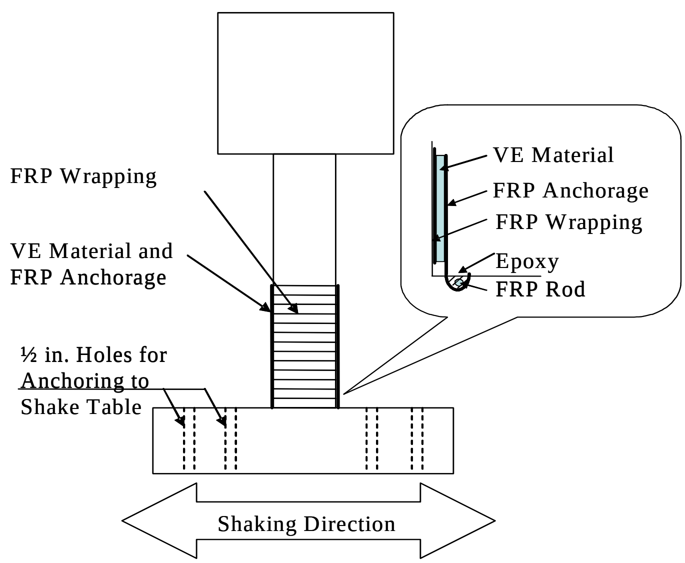

Figure 1. Proposed Retrofit System

BACKGROUND

The concept of performance-based seismic design of structures has been introduced in building and bridge design guidelines. However, no guidelines of how to achieve an optimal design of a structure for multiple performance objectives have been developed yet. This study is aimed at introducing a novel retrofit concept towards this direction and focused on two critical issues related to the interfaces among damping, strengthening, and concrete components.

This report includes the results from a series of bond and anchorage tests under static and dynamic loading conditions. The test results will help understand the interfacial behaviors and the development of the design equation for anchorage.

OBJECTIVE

This project was originally proposed to characterize lap-splice joints of grid glass fiber reinforced polymer (G-GFRP) materials with spray-on saturant, and study the curvature effect on the strength of G-GFRP materials when wrapped around circular columns. Since the test specimens have not yet been cast due to the requirement for special spray-on equipment, the focus was shifted to mainly characterize the bond behavior between carbon FRP sheets (CFRP) and VE layers under static and dynamic loading as well as the anchorage failure mechanism of CFRP sheets into concrete under static loading.

SPECIMENS

Small-scale VE specimens were designed with CFRP sheets and Sorbothane rubber layers. Two VE layers were sandwiched between three FRP sheets, as shown in Figure 2. The middle FRP sheet was made with two plies and the top and bottom sheets were of single ply of FRP materials. The mechanical properties of FRP sheets provided by the manufacturer are summarized in Table 1.

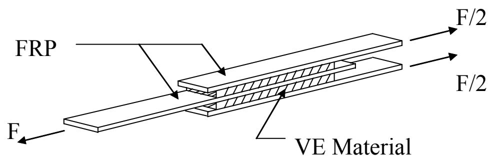

Figure 2. VE Specimen

Table 1. Material Property of FRP Sheets

Fiber Type	Thickness (in.)	Design Strength (ksi)	Design Strain (in./in.)	Tensile Modulus (ksi)
Carbon	0.0065	550	0.017	33000

Sorbothane is a thermoset, polyether-based, polyurethane material. It has low creep rate, high damping coefficient, and wide effective temperature range. The properties of Sorbothane provided by the manufacturer are shown in Table 2.

Table 2. Material Property of VE Layers

Duro-meter	Tensile Strength (psi.)	Elongation at Break (%)	Young's Modulus at 5 Hz (psi)	Temp. Range (°F)
70	206	399	120	-20~160

A total of five types (A, B, C, D and E) of VE specimens as illustrated in Figure 2 were tested for bonding strength. Their dimension and hardness are given in Table 3.

Table 3. VE Specimens

Type	Duro-meter	One-side Area (in^2)	Thickness (in.)	Volume (in^3)
A	70	3.0	1/8	0.375
B	70	6.0	1/8	0.75
C	70	9.0	1/8	1.125
D	70	6.0	3/16	1.125
E	50	6.0	1/8	0.75

To study the anchorage capacity, a total of twenty 6"×6"×6" concrete blocks were cast. Each block was cut on one side to provide a 4-inch-long and 0.5-inch-wide groove of varying depth (0.5", 1.0", and 1.5"). An FRP anchorage into concrete was constructed according to the following procedure. First, MBrace Saturant resin, the same epoxy as used for bonding FRP and VE material, was poured to fill half of the groove. A 2-inch-wide FRP sheet was then pushed into the groove with a 4-inch-long #3 FRP rod. Finally, additional MBrace Saturant resin was poured on top of the FRP rod to fill up the groove. After having cured for a day, the concrete block into which an FRP sheet anchored is ready for testing. The cured FRP anchorage specimens can be seen in Figure 3. These specimens were used for both static (12 units) and dynamic tests (8 units) to investigate the behavior of FRP anchorages.

Figure 3. Anchorage Test Specimens

TEST SETUP

Each VE specimen was tested in a displacement-controlled mode on the MTS 858 testing machine in the Geotechnical Laboratory. The testing machine MTS 858 and test setup is shown in Figure 4. The anchorage tests were conducted on the MTS880 machine in the Structures Laboratory as illustrated in Figure 5.

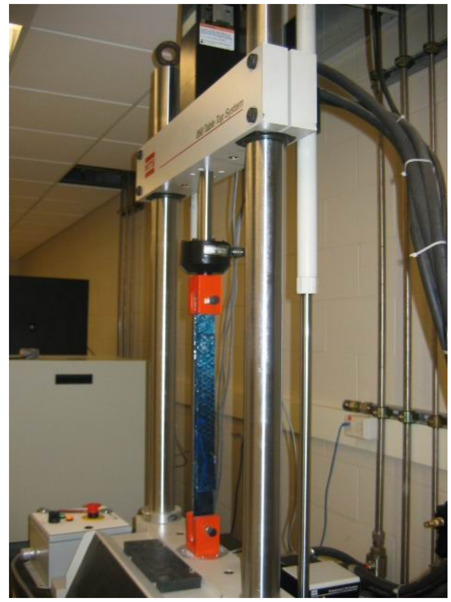

Figure 4. Test Setup for VE Specimens

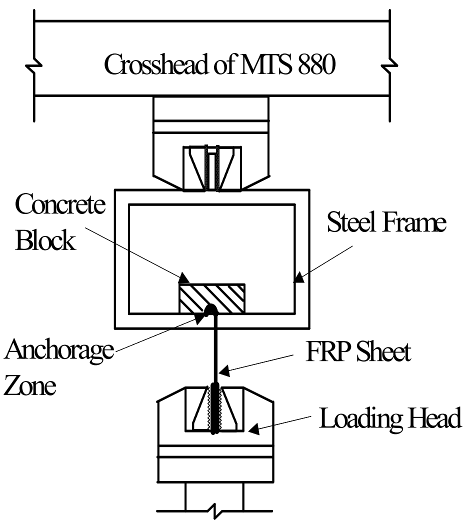

Figure 5. Anchorage Test Setup

INSTRUMENTATION AND TEST PLAN

For bond and anchorage testing, both load and displacement were recorded during each test with an internal load cell and an internal LVDT of the test's machine. The temperature at the surface of each specimen was measured with an infrared thermometer, as shown in Figure 6.

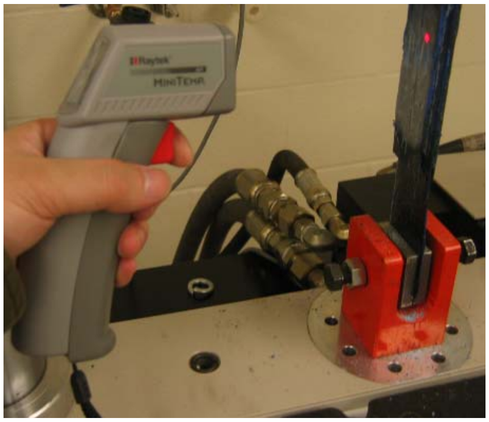

Figure 6. Infrared Thermometer

Bond tests started first under static loading with five Type-B VE specimens by applying displacement at a rate of 0.1 in/min. After the ultimate shear strength and strain have been determined, dynamic testing is planned on eight Type-B VE specimens (designated D1 to D8) according to the test matrix in Table 4 and the loading protocol depicted in Figure 2. Since buckling of each thin FRP sheet occurs under compression, the sinusoidal load will have a non-zero mean value so that the FRP sheets will always be subjected to tension.

Table 4. Dynamic Bonding Test Matrix

Specimen	Initial Temp .(°F)	Initial Strain (in./in.)	Initial Stress (psi)	Frequency (Hz)
D1	0	1.0	20	2.0
D2	0	1.5	30	2.0
D3	75	2.0	40	0.1
D4	75	2.0	40	2.0
D5	75	1.5	30	2.0
D6	75	1.5	30	4.0
D7	120	1.5	30	2.0
D8	120	2.0	40	2.0

Twelve out of the twenty concrete blocks (designated as AS1 to AS12) were tested for anchorage strength under static loading in a displacement-controlled mode. In addition to the groove depth, different loading rate was considered as another test perimeter. The planning matrix for FRP anchorage static bonding tests is given in Table 5.

Table 5. Matrix for Static Anchorage Test

Specimen	Groove Depth (in.)	Loading Rate (in./min)
AS1	1.0	0.007
AS2	1.0	0.025
AS3	1.0	0.025
AS4	1.0	0.025
AS5	1.0	0.100
AS6	1.0	0.300
AS7	0.5	0.025
AS8	0.5	0.025
AS9	0.5	0.025
AS10	1.5	0.025
AS11	1.5	0.025
AS12	1.5	0.025

RESULTS AND DISCUSSIONS

Bonding tests were conducted under both static and dynamic loading. It was observed that all specimens failed in tearing of the VE layers, as illustrated in Figure 7, and there were no indication of bonding detects. This indicated that the simple bonding between a CFRP sheet and a VE layer with Mbrace saturant resins was sufficiently strong.

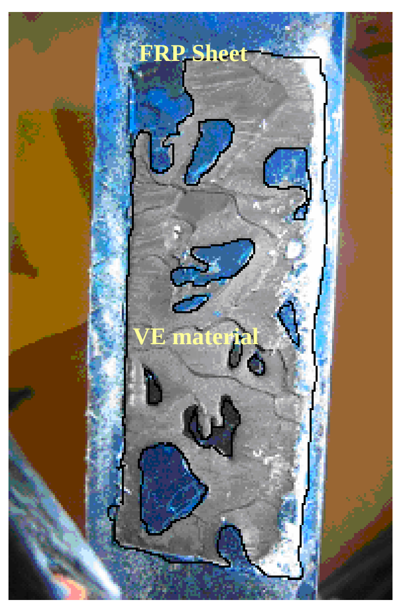

Figure 7. Failure Mode between FRP Sheet and VE Layer

The shear stress and strain curves of five VE specimens are presented in Figure 8 at five different temperatures under static loading. All stress-strain curves in Figure 8 consistently indicate the linearity between stress and strain at small strains. As strain further increases, the stress-strain curve becomes concave upward due mainly to the reduced thickness of a VE layer so that the shear stiffness of the VE layer is increased. At low temperature, the VE material exhibits relatively higher ultimate strength and ultimate shear strain. The stiffness of the VE material also decreases as temperature increases. All these can be explained by the softening effect of VE materials under high temperature. The ultimate strains of the tested specimens are all over 350% in the temperature range from 0°F to 120°F. This indicates that the value (400%) suggested by manufacturer is only slightly over estimated at high temperature. For this reason, a design ultimate strain of 300% is recommended.

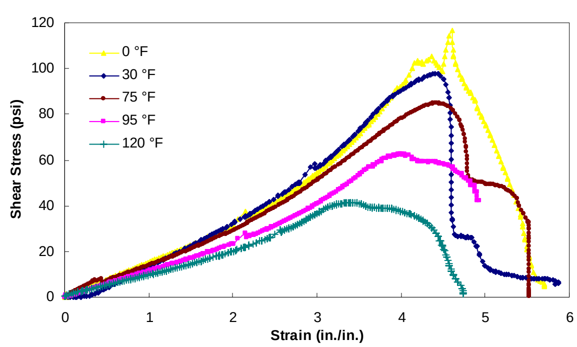

Figure 8. Stress-strain Curves under Static Loading

To investigate the dynamic bonding behavior between the VE material and FRP sheet, dynamic bonding tests were carried out on eight specimens (designated as D1 to D8) made according to the design of Type B specimens in Table 3. Each specimen was tested to failure under a harmonic load of incrementally-increasing amplitude as schematically shown in Figure 9. At each level, loading is repeated for ten cycles. The excitation frequency or period (T), the increment of amplitude (a), and the average load (F_0) are fixed for each test. The average tension load (F_0) was introduced to prevent potential buckling of the test specimens under dynamic loading.

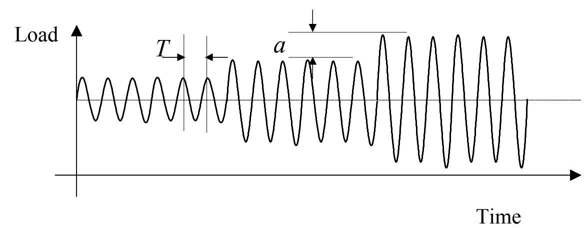

Figure 9. Dynamic Bond Test Loading

Dynamic bond tests were conducted according to the test matrix in Table 4. The test results are summarized in Table 6. Specimens D1, D4, D5 and D8 did not fail during dynamic tests. This means that each of these specimens can withstand such cyclic displacements without failure. Specimens D2, D3 and D7 failed in the same mode (tearing VE material) as observed during static bond tests. During dynamic testing, stress relaxation of VE materials was observed especially for Specimen D3 that was tested for approximately 27 minutes at a frequency of 0.1 Hz.

Table 6.Dynamic Anchorage Test Results

Specimen	Max. Stress (psi)	Strain Range in Last Cycle	Temp. after Test (°F)	Specimen Condition
D1	92	-1.0~3.0	20	U
D2	122	-0.5~3.5	18	D
D3	121	0.6~3.4	82	D
D4	122	0.0~4.0	80	U
D5	92	-0.5~3.5	83	U
D6*	75	0.0~3.0	82	U
D7	68	-0.5~3.5	123	U
D8	73	0.9~3.1	124	D

D=Damaged, U=Undamaged, * means that a test is incomplete.

In comparison with Figure 8, Table 6 indicated that bonding performance of the specimens under dynamic loading is quite different. In general, the bonding strength increased while the strain range at failure was reduced under dynamic loading, especially for those specimens tested under a higher initial loading. However, all the specimens were able to withstand a maximum strain of over 300% before VE layers were torn apart or at the end of each testing. Indeed, for the damaged specimens, the minimum VE strain was 314%. Considering that Specimen D8 failed after 50 cycles of loading, the recommended strain of 300% for the design of VE layers from static bonding tests is acceptable under dynamic loading.

The anchorage tests resulted in several load-displacement curves as shown in Figure 10 for those specimens with a 1″ deep groove. An ideal load-displacement curve is a straight line up to failure. The curved parts in the early stage of tests are attributable to the imperfect contact between the concrete block and the steel plates, which results from either a rough concrete surface or small debris particles between the concrete and the steel plates. During testing, those small particles or bumped-out concrete will be crashed due to stress concentration, leading to reduction in the load at a given displacement. After an even contact surface is formed, the interfacial force is distributed evenly on the contact area and increases proportionally with the displacement the test specimen experiences.

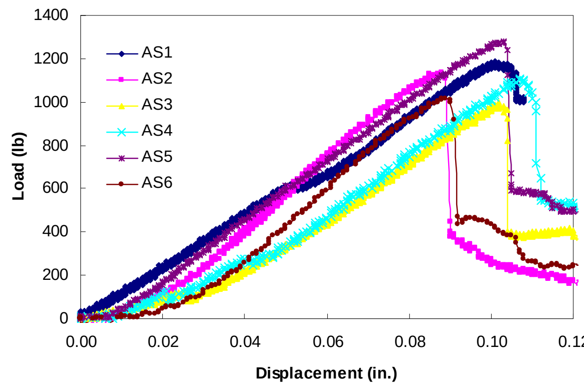

Figure 10. Load-displacement Curves of FRP Anchorages

All anchorage specimens were observed to fail due to rupture of the concrete, as indicated by sudden drop in the load-displacement curves, Figure 10. Concrete strength is thus a controlling factor for the FRP anchorage. A typical failure mode of the specimens is shown in Figure 11. It is seen from Figure 11 that the crack in concrete starts somewhere away from the side of a steel plate. This indicates that the potential impact of the steel plates on the formation of a failure mechanism is no longer a major concern.

Figure 11. Anchorage Failure Mode

Based on the static test results and failure mechanisms from all 12 specimens shown in Table 5, a design equation for the anchorage strength is proposed as follows:

$$V_c = 4\sqrt{f_c^{'}}\, l_R d_G \qquad (1)$$

in which f'_c is the compressive strength of concrete, $d_G\, l_R$ represents the vertical area counted for shear resistance, d_G is the depth of the groove, and l_R is the length of the FRP rod.

To validate Equation (1), the predicted shear strengths of the specimens in Table 5 are compared with the average experimental results in Table 7 for each groove depth. Clearly, the predicted results are in good agreement with the experimental data.

Table 7. Predicted versus Average Experimental Shear Strength of FRP Anchorages

Groove Depth (in.)	Experimental (lb)	Predicted (lb)	Difference (%)
0.5	572	527	8
1.0	1107	1054	5
1.5	1519	1582	-4

CONCLUSIONS

Based on the test results, the following conclusions can be drawn:

- The bonding mechanism between VE layers and FRP sheets with Mbrace saturant epoxy was found very effective. It failed by tearing the VE layers apart. The bond strength was therefore controlled by the ultimate strain of VE materials. A design shear strain of 300% is recommended for the proposed retrofitting system.
- The strength of a mechanical bond between FRP sheets and VE layers increases under dynamic loading while the strain range at failure decreases. However, all the specimens tested were able to withstand a maximum strain of over 300% before VE layers were torn apart or at the end of each testing. Therefore, the recommended strain of 300% for the design of VE layers from static bonding tests is acceptable under dynamic loading.
- The anchorage mechanism of FRP sheets into concrete by a FRP rod can effectively transfer damping forces from column through VE layers and FRP anchoring sheets to column footing. The potential failure mode of the anchorage is concrete rupture. For a given depth, the strength of the anchorage depends on the concrete strength due to the high strength of FRP sheets.
- A simple design equation was developed based on the shear rupture of concrete along two surfaces between FRP and concrete. The equation proposed for the design of anchorages can predict the anchorage strength that agrees very well with experimental results.

WANT MORE INFORMATION?

Details on this research project and additional information will be available in the final report.

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