Behavior and Design of Cast-in-Place Anchors under Simulated Seismic Loading

Phase I– Cyclic Tests of Cast-in Place Anchors in Plain Concrete

Test Setup

The load frame used to load the test specimens is shown in Figure 1. The UWM structure lab has a strong floor system with 2.25 inch diameter anchoring holes spaced in a three foot by three foot grid across the testing area. These holes are used to fix test specimens and loading frames securely to the floor. Vertical loading was achieved using a frame, consisted of four diagonally braced columns spaced 6 feet square tied at the base using W-sections. This allowed for an unrestricted opening 5 feet 1 inch wide through the load frame perpendicular to the applied shear load. An MTS Model 244.41, 110 kip actuator with a total stroke of 10 inches was suspended from a loading girder at the center of the frame. Height was adjustable by moving the loading girder up and down the columns.

Figure 1: Load frame at UWM Structural Laboratory

A braced-column horizontal loading frame was designed specifically for the tests being performed in this research as shown in Figure 1. Holes were drilled in the column at 4.5 inch increments along the height of the column and a transfer block was constructed to provide adjustability in one inch increments for a horizontally mounted MTS Model 244.31, 55 kip actuator with a full stroke of 10 inches. The actuator was braced against the floor at its bearing pad closest to the piston arm. This ensured that the actuator could not be moved downward during shear testing. This prevented the leading edge of the load plate from contacting the front edge of the concrete, hence eliminating any compression induced on the shear breakout cone by the load plate. For monotonic shear loading, the actuator was free to rotate horizontally while during cyclic loading the actuator was restrained using turnbuckles to eliminate the chances of buckling during compression cycles in shear caused by any potential misalignment.

The loading plate fabricated for this research, shown in Figure 2, used a modular design to allow the same fixture to be used for both tension and shear loading. The shear plate was one inch thick modeled after a similar load plate. The horizontal actuator was connected to the loading plate with two channels bolted to the top and bottom of the plate using four 0.75 inch diameter ASTM A490 bolts. The shear plate was 12 inches wide to accommodate two 12 inch tall channels that attached to a one inch thick fixture plate for connecting the vertical actuator. For tension tests, the channel module connecting the horizontal actuator was removed for ease of installation during test setup. The 0.75 inch diameter test anchors were inserted through a standard 1/8 inch oversized hole in the load plate and fixed to the loading plate using a heavy hex nut. For each test, a steel sleeve shim was inserted between the anchor and the hole in the load plate.

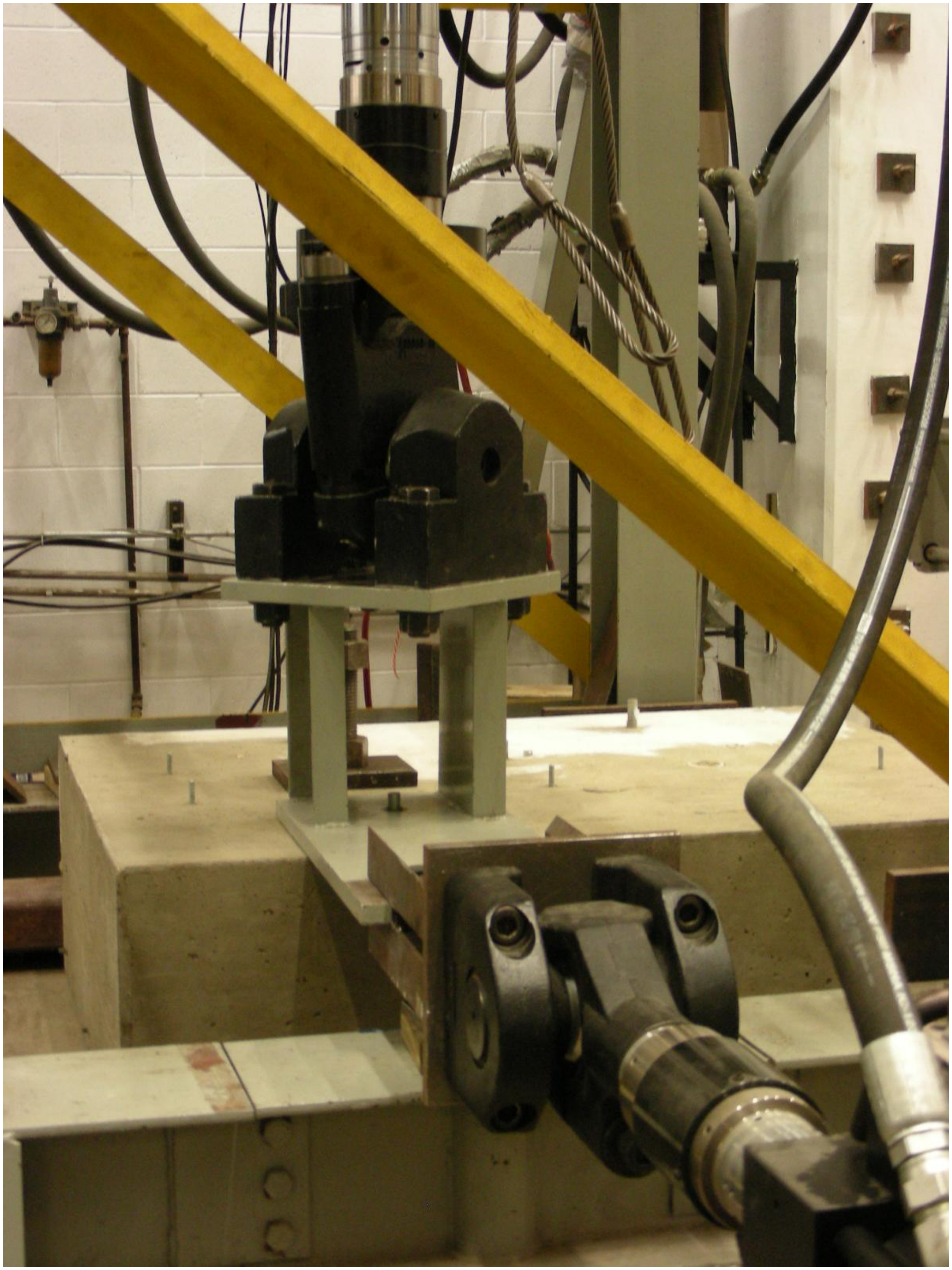

Figure 2: Load plate for combined loading of single anchors

Loading Protocol

Tension and shear loading was applied by controlling the displacement of actuator pistons in all tests. Displacement controlled loading has the benefit of allowing the post peak behavior of tests to be captured more accurately than in force controlled loading scenarios. However, cyclic testing provisions for concrete anchors predominantly refer to force-controlled loading. The Structural Engineers Association of Southern California (SEAOSC 1997) standards for cyclic anchor testing employ stepwise increasing load cycles until failure. Loading cycles starting at 25 percent of the anchor's monotonic capacity with increasing step increments of 25 percent until failure occured was chosen for this study. These provisions were converted in this study to corresponding displacements based on monotonic test results. Programs for individual load types were constructed using the MPT function in the MTS Station manager version 3.5c. The ability to control the actuators from external inputs was unavailable so programmability was limited to the force and displacement channels of the actuators themselves. For this reason, the actual anchor displacements displayed in the test results later in this report do not match the stated displacement levels used for programming as stated in this section due to test block and frame movements during testing.

Quasi static loading rates were targeted to avoid the dynamic loading phenomena wherein capacity inflation takes place (Collins 1988; Hallowell 1996). While seismic loading of structures is dynamic in behavior, using quasi-static loading produces conservative capacities which are preferable for the development of design equations. Klingner (2010) suggested that load rates less than 10 mm/min are sufficient in avoiding capacity increase produced by dynamic loading rates.

Monotonic tension and shear tests were conducted first to develop typical load/displacement behaviors of each anchor setup and load direction. Monotonic tension tests used the vertical actuator only, loading as a linear ramp function using a load rate of 1 mm/min. The slow load rate was chosen because relatively small displacements before concrete failure were expected and because it allowed for a greater amount of data to be collected near the peak capacity.

Monotonic shear tests used the vertical actuator to apply a constant small tension force (200 pounds net) to the anchor. This was used to eliminate any friction between the load plate and the test block during shear tests. The nut fixing the load plate to the anchor was first hand tightened onto the load plate using no tools then loosened 1/8 of a turn to allow slight vertical movement of the loading plate when the tension force was applied at the beginning of the test. The horizontal actuator also ran a ramp function with constant displacement rate to apply shear force to the anchors. Initial tests used the same 1 mm/min load rate as the tension tests, however, it was observed that failure displacements were larger in shear and the duration of each test became excessive at a load rate of 1mm/min. The shear load rate was later increased to 2 mm/min with no measured effect on anchor capacity or behavior.

The monotonic test results were then used to develop the displacement intervals of the actuators to be used in cyclic tests as was discussed earlier. Quasi-static cyclic tests at a displacement rate of 2 mm/min cycled the anchors three times at each increasing displacement step as shown in Figure 3. Displacement levels were chosen to cycle the anchor at pre-peak, peak, and at least one post peak step. Because of slight variability in monotonic tests however, fixed displacement steps were chosen for tension and for shear and used for all anchors loaded in the respective direction. Shear displacements starting at 2 millimeters increasing at 1 millimeter increments for subsequent cycles were chosen with equal displacements used in cyclic tension. After the post peak cycles were concluded, a monotonic ramp load was used to explore the residual capacity in the connection. For most tests, this monotonic load occurred after the failure of the connection with less than fifty percent of the peak capacity remaining. Ramp or saw tooth loading patterns near the ultimate anchor capacity were determined to be an acceptable model of cyclic loading to create low-cycle fatigue in anchors (Collins et al. 1989). The simplicity inherent in ramp/saw tooth loading patterns was favorable for the development of the loading profiles developed in the MTS software for this research, especially for combined loading tests.

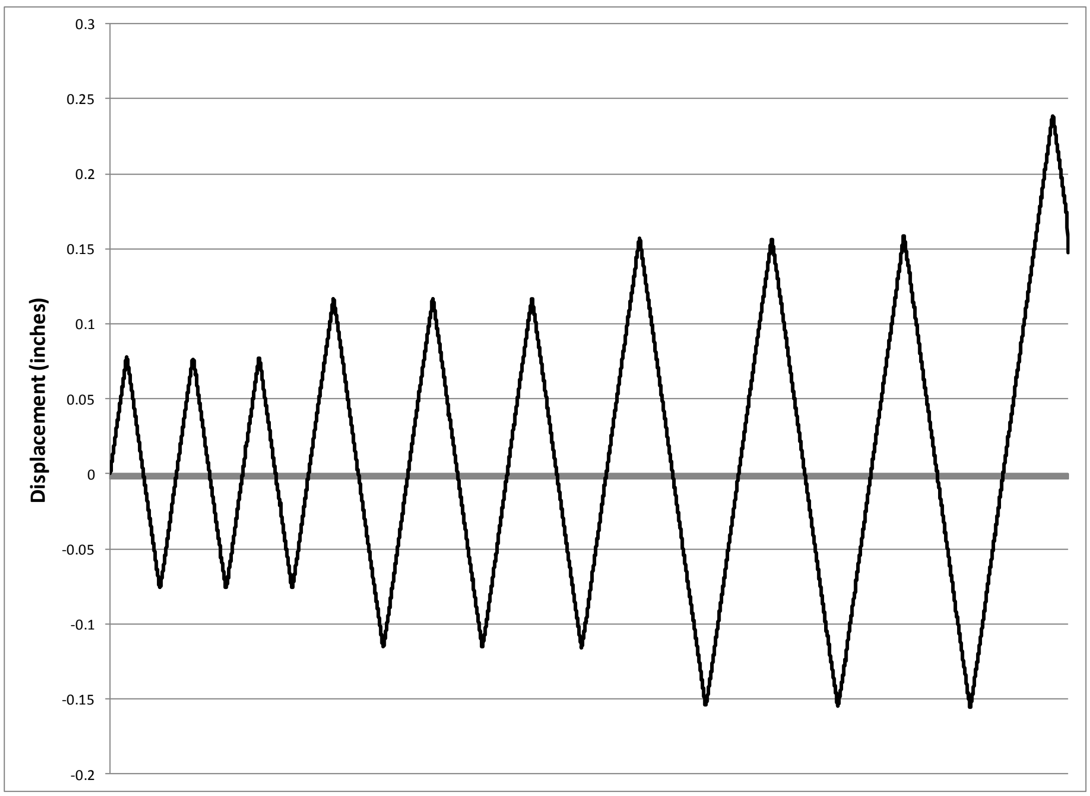

Figure 3: Cyclic shear loading profile (Actuator displacement)

Displacement-controlled combined loading tests were developed to exhibit pseudo force-controlled loading to match previous combined loading tests in the literature that used force-controlled loading. Because the current interaction equations such as those in ACI 318-08 D.7 are based on a ratio of applied load to design capacity, the programs for combined loading needed to follow a similar action. The averages of all cyclic tension and shear tests were used to develop equations for applied force as a function of actuator displacement. Cyclic tests results were also used to determine average cyclic tension and shear capacities for each anchor position to be used in the interaction equations of ACI 318 D.7. Programs for combined loading were then set up to target specific ratios of applied load versus anchor capacity for tension and shear along the interaction curve to generate a moderate spread of data that could be used to verify or disprove the currently used interaction equations.

Peaks of each load cycle in tension and shear were programmed to occur at the same time. To achieve this, displacement loading rates were calculated and varied for each specific cycle to account for differences in peak displacements of the tension and shear cycles. Generally, tensile actuator displacements were smaller than shear actuator displacements. The displacement loading rates of tension and shear loading were targeted around 2 mm/min with a range between 1 and 3 mm/min. Each cycle was split into four individual ramp components. The first cycle consisted of tension loading and shear loading toward the free edge. The tension load was programmed to reach its target displacement slightly before the shear load reached its peak. The tension load would then hold its displacement until the shear load peaked. This would interrupt the tension hold and both actuators would begin unloading to initial condition. Tension would unload in force control to an end load of 200 pounds tension while shear unloaded in displacement control to zero displacement set at the beginning of the test. Tension would then hold force while the shear load went into compression and back to zero under displacement controlled loading to achieve reversed cyclic shear loading. The process would then repeat itself for each of three successive cycles at each displacement interval.

As tests were performed, a trend developed wherein the anchor would show plastic elongation as cycle displacements grew. Because the vertical actuator was programmed to unload to a 200 pound tension target, the displacement corresponding to this load would stray further and further from initial zero displacement. This caused peak synchronism problems between the two actuators during the test because the vertical actuator was set to load in displacement control to an absolute end level determined as discussed earlier in this section. Because the total piston travel required by the vertical actuator grew smaller as the anchor elongated, the original calculated loading rates became increasingly excessive. The hold function set for the tension peak action alleviated detrimental effects of the unsynchronized loadings by holding the force in tension until the shear toward the free edge could peak, however, in initial tests, the hold time sometimes exceeded 10 seconds when the anchors displayed increasing plastic elongation. Ultimately, the displacement loading rates of the vertical actuator at each displacement limit cycle were adjusted so that the tension hold time could be limited to a maximum of 5 seconds and in most cases was less than 3 seconds.