Abstract
Under the sponsorship of the US Nuclear Regulatory Commission, a research program was carried out on the dynamic behavior of anchors (fasteners) in concrete. As part of that program, full-scale seismic tests were conducted at dynamic loading rates on 16 multiple-anchor connections to concrete. Test variables included anchor type, loading history, and the presence of cracks. Multiple-anchor connections designed for ductile behavior in uncracked concrete under static loading, in general behaved in a ductile manner in cracked concrete under dynamic loading.

1. Background
A few studies have investigated the behavior of connections under impact loading, seismic loading and reversed loading [1, 2, 3, 4]. Loading patterns primarily involved dynamic loading far below the anchor's ultimate capacity, followed by monotonic loading to failure [3, 4]. Only a few investigations [5, 6, 7] have studied the influence of loading rate on the overall load-displacement behavior of anchors. Some tests have been conducted in cracked concrete or in high-moment regions [1, 3, 5, 8]. To the best of the authors’ knowledge, the testing program described here is the first published testing on multiple-anchor connections under seismic loading.

2. Anchors, Test Setups and Procedures
Based on their use in nuclear applications, this research program involved one wedge-type expansion anchor (“Expansion Anchor II”), with some tests on one normally opening undercut anchor with large bearing area (“UC Anchor 1”). Anchors were 5/8 in. (16 mm) diameter, installed with an effective embedment of 7 in. (178 mm) to develop ductile response. Expansion Anchor II (EAII) is described in Figure 1. Undercut Anchor 1 (UC1) is described in Figure 2.
The target concrete compressive strength for this testing program was 4700 lb/in.\(^2\) (32.4 MPa), with a permissible tolerance of ±500 lb/in.\(^2\) (±3.45 MPa) at the time of testing. Aggregate was river gravel.

The overall test setup for Task 4 is shown in Figure 3. Reversed cyclic loads were applied to the connection through a loading attachment, shown in Figure 4. The stiff baseplate was 2 in. (51 mm) thick; the flexible one, 1 in. (25 mm). Both baseplates had stiffeners.

External load on the connections was measured with a load cell. Tension in each anchor was measured with a force washer placed between the normal washer and the baseplate. Slip of the baseplate was measured with a potentiometer placed against the back of the baseplate, and displacement of the vertical beam was measured at 12 in. (305 mm) from the surface.
The prescribed displacement history that simulated earthquake loading was developed by idealizing the attachment as a bilinear single-degree-of-freedom (SDOF) system with a concentrated mass at 12 in. (305 mm) above the concrete surface, sufficient to give a realistic period of vibration, and to produce yielding of the attachment under the selected ground motion. The response of the SDOF system was calculated using as input the earthquake history of El Centro 1940 (NS component). The most significant portion, consisting of the first 6.0 sec. of that record (Figure 5), was used as the prescribed displacement history.

Some specimens had cracks with an initial width of 0.012 in. (0.3 mm), introduced using wedge-type splitting tubes of high-strength steel. Anchors were installed to the torque specified by the manufacturer. To simulate the reduction of prestressing force in anchors in service due to concrete relaxation, anchors were first fully torqued, then released after about 5 minutes to permit relaxation, and finally torqued again, but only to 50% of the specified torque. For multiple-anchor shear tests, two separate cracks were initiated parallel to the loading direction. Crack widths were monitored during tests, but not controlled.

![Figure 4 Loading attachment used for Task 4](image)

Figure 4 Loading attachment used for Task 4

![Figure 5 History of estimated attachment displacements for seismic tests](image)

Figure 5 History of estimated attachment displacements for seismic tests
For static tests, the load was applied slowly and monotonically under displacement control. For dynamic tests, the loading pattern was dynamic reversed cyclic loading (Figure 5), applied under displacement control. During tests, the loading sequence was first applied with a maximum displacement of 0.6 in. (15.2 mm). If the connection did not fail, loading sequences were applied with maximum displacements of 1.0 in. (25 mm) and then 1.5 in. (38 mm). Further cycles, to a maximum displacement of 15 in. (38 mm), were applied until failure. Before each loading sequence, the anchors were finger-tightened to eliminate any initial lack-of-fit, which would have increased the displacement required to reach any particular load level. Tests are listed in Table 1. For all tests, the edge distance was 5 in. (127 mm), and the embedment was 7 in. (178 mm).

<table>
<thead>
<tr>
<th>Test</th>
<th>Description</th>
<th>Anchor</th>
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<tbody>
<tr>
<td>4101</td>
<td>static, 4-anchor group, rigid baseplate, uncracked concrete, $e = 12$ in. (305 mm)</td>
<td>UC1</td>
</tr>
<tr>
<td>4102</td>
<td>static, 4-anchor group, rigid baseplate, uncracked concrete, $e = 18$ in. (457 mm)</td>
<td>UC1</td>
</tr>
<tr>
<td>4203</td>
<td>dynamic, 4-anchor group, flexible baseplate, uncracked concrete, $e = 12$ in. (305 mm)</td>
<td>UC1</td>
</tr>
<tr>
<td>4204</td>
<td>dynamic, 4-anchor group, rigid baseplate, uncracked concrete, $e = 12$ in. (305 mm)</td>
<td>EAI</td>
</tr>
<tr>
<td>4205</td>
<td>dynamic, 4-anchor group, rigid baseplate, uncracked concrete, $e = 12$ in. (305 mm)</td>
<td>UC1</td>
</tr>
<tr>
<td>4206</td>
<td>dynamic, 4-anchor group, rigid baseplate, uncracked concrete, $e = 18$ in. (457 mm)</td>
<td>UC1</td>
</tr>
<tr>
<td>4307</td>
<td>dynamic, 4-anchor group, rigid baseplate, cracked concrete, $e = 12$ in. (305 mm)</td>
<td>EAI</td>
</tr>
<tr>
<td>4308</td>
<td>dynamic, 4-anchor group, rigid baseplate, cracked concrete, $e = 12$ in. (305 mm)</td>
<td>UC1</td>
</tr>
<tr>
<td>4309</td>
<td>dynamic, 4-anchor group, rigid baseplate, cracked concrete, $e = 18$ in. (457 mm)</td>
<td>UC1</td>
</tr>
<tr>
<td>4310</td>
<td>dynamic, 4-anchor group, rigid baseplate, cracked concrete, $e = 18$ in. (457 mm)</td>
<td>EAI</td>
</tr>
<tr>
<td>4411</td>
<td>static, near-edge, 4-anchor group, rigid baseplate, uncracked concrete, no hairpins, $e = 12$ in. (305 mm)</td>
<td>UC1</td>
</tr>
<tr>
<td>4412</td>
<td>static, near-edge, 4-anchor group, rigid baseplate, uncracked concrete, no hairpins, $e = 18$ in. (457 mm)</td>
<td>UC1</td>
</tr>
<tr>
<td>4513</td>
<td>dynamic, near-edge, 4-anchor group, rigid baseplate, uncracked concrete, no hairpins, $e = 12$ in. (305 mm)</td>
<td>UC1</td>
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<tr>
<td>4514</td>
<td>dynamic, near-edge, 4-anchor group, rigid baseplate, uncracked concrete, no hairpins, $e = 18$ in. (457 mm)</td>
<td>UC1</td>
</tr>
<tr>
<td>4615</td>
<td>static, near-edge, 4-anchor group, rigid baseplate, uncracked concrete, close hairpins, $e = 12$ in. (305 mm)</td>
<td>UC1</td>
</tr>
<tr>
<td>4616</td>
<td>dynamic, near-edge, 4-anchor group, rigid baseplate, uncracked concrete, close hairpins, $e = 12$ in. (305 mm)</td>
<td>UC1</td>
</tr>
<tr>
<td>4617</td>
<td>dynamic, near-edge, 4-anchor group, rigid baseplate, uncracked concrete, close hairpins, $e = 18$ in. (457 mm)</td>
<td>UC1</td>
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3. Test Results

In Figures 6 and 7, the load-displacement envelopes of dynamic tests under eccentric shear at 12 in. (305 mm) and 18 in. (457 mm) respectively, are compared with the static tests on the same configuration (Test 4101 versus Test 4203, and Test 4102 versus Test 4206). The following observations can be made:

1) The dynamic load-displacement curves follow the static load-displacement curves over most of the displacement range, differing only near the ultimate load.

2) The maximum dynamic capacity was close to the maximum static capacity. It was 7% higher at a 12 in. (305 mm) eccentricity, and 7% smaller at an 18 in. (457 mm) eccentricity. Due to the small number of tests, however, this observation is not definitive.

3) The most significant effect of dynamic reversed cyclic loading is the increase in total displacement, due to spalling of the concrete in front of the anchors, to the gaps between the baseplate and the anchors and between the anchors and the concrete, and to the larger tensile displacement of the anchors under dynamic cyclic loading.

Seismic tests on a connection with EAII under dynamic reversed cyclic loading (Test 4307) showed large displacements of about 1 in. (25.4 mm) measured at 12 in. (305 mm) above the concrete, although there is no corresponding static test with which this can be compared.

In Figures 8 and 9, load-displacement curves for tests with dynamic loading in cracked concrete (Tests 4308 and 4309) are compared with the corresponding curves for tests with static loading in uncracked concrete (Tests 4101 and 4102). The dynamic load-displacement envelopes for these tests also follow the static load-displacement curves well, except near the ultimate load.

Figure 6  Static versus seismic load-displacement curves, multiple-anchor connections, UC1 Anchors, at 12 in. (305 mm) eccentricity (Tests 4101 and 4203)
Figure 7  Comparison of static and seismic load-displacement behaviors of multiple-anchor connections with UC1 Anchors under shear at 18 in. (457 mm) eccentricity (Tests 4102 and 4206 respectively)

Figure 8  Comparison of seismic load-displacement behavior of multiple-anchor connections with UC1 Anchors at 12 in. (305 mm) eccentricity in cracked concrete (Test 4308) with static behavior in uncracked concrete (Test 4101)
Comparison of Test Results and Analytical Predictions
Test results were compared with predictions of BDA5, a macro-model program developed at the University of Stuttgart for the static analysis of multiple-anchor connections loaded by eccentric shear [9]. It requires as input data a complete set of load-displacement curves of the anchor under oblique loading at angles from 0 to 90 degrees, and assumes a rigid baseplate. Comparisons were reasonable, and are discussed in more detail in Zhang [10].

**Figure 9** Comparison of seismic load-displacement behavior of multiple-anchor connections with UC1 Anchors at 18 in. (457 mm) eccentricity in cracked concrete (Test 4309) with static behavior in uncracked concrete (Tests 4102)

Comparison of Test Results with Plastic Analysis Methods
The Plastic Method [11] and the Modified Plastic Method [7] predict the capacity of multiple-anchor connections with large edge distances, loaded in shear and failing by steel fracture. For the connection with a loading eccentricity of 18 in. (457 mm), the capacities calculated by the Plastic Method and the BDA5 program are very close to the test results. The Modified Plastic Method [7], however, underestimated the static capacity by as much as 10%. For the connection with a loading eccentricity of 12 in. (305 mm), both the Plastic Method and the BDA5 program overestimated the static capacity. The Modified Plastic Method [7] was very close to the test results.
4. Conclusions and Recommendations

1) Multiple-anchor connections in uncracked or cracked concrete, with or without edge effects, and with or without hairpins, loaded dynamically under reversed cyclic loading histories representative of seismic response, behaved consistently with the results of previous single- and double-anchor tests of this study. Previous observations regarding the load-displacement behavior, and failure mechanisms of single and double anchors, were applicable in predicting the behavior of complex, multiple-anchor connections under simulated seismic loading. The implications of this are clear. Multiple-anchor connections designed for ductile behavior in uncracked concrete under static loading, will probably still behave in a ductile manner in cracked concrete under dynamic loading.

2) Anchors that show relatively good performance when tested individually in cracked concrete (CIP headed anchors, UC1, and 20 mm diameter Sleeve) will probably also show relatively good performance in multiple-anchor connections subjected to seismic loading. Anchors that show relatively poor performance when tested individually in cracked concrete (Grouted Anchor, EAI, and 10 mm diameter Sleeve) will probably also show relatively poor performance in multiple-anchor connections subjected to seismic loading.

3) Cyclic load-displacement behavior of multiple-anchor connections is accurately bounded by the corresponding static load-displacement envelope, and also by the static load-displacement envelope predicted by the BDA5 program. Dynamic cycling does not significantly influence the fundamental load-displacement behavior of multiple-anchor connections.

4) Under dynamic reversed cyclic loading in both uncracked and cracked concrete, the load-displacement envelopes of multiple-anchor connections with the UC1 Anchor basically follow the static curves in uncracked concrete over most displacements, differing only near the ultimate load. Dynamic reversed loading did not significantly affect the maximum dynamic capacity. In uncracked concrete, the connection had larger displacements under reversed dynamic than under static loading. Under dynamic reversed loading, connections in cracked concrete had slightly larger displacements than those in uncracked concrete.

5) Under dynamic reversed cyclic loading, multiple-anchor connections with Expansion Anchor II had very large displacements. In both uncracked and cracked concrete, the connections loaded at 12 in. (305 mm) eccentricity failed by steel fracture. The test in cracked concrete had a larger displacement and smaller capacity than that in uncracked concrete. The connection loaded at an 18 in. (457 mm) eccentricity experienced gross pull-out failure of the anchors.
6) The capacity of multiple-anchor connections at large edge distances was predicted with reasonable accuracy by the plastic design procedures [7, 10, 11].

7) Capacities were reasonably predicted by the BDA5 program [9].

5. Acknowledgement and Disclaimer

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6. References


