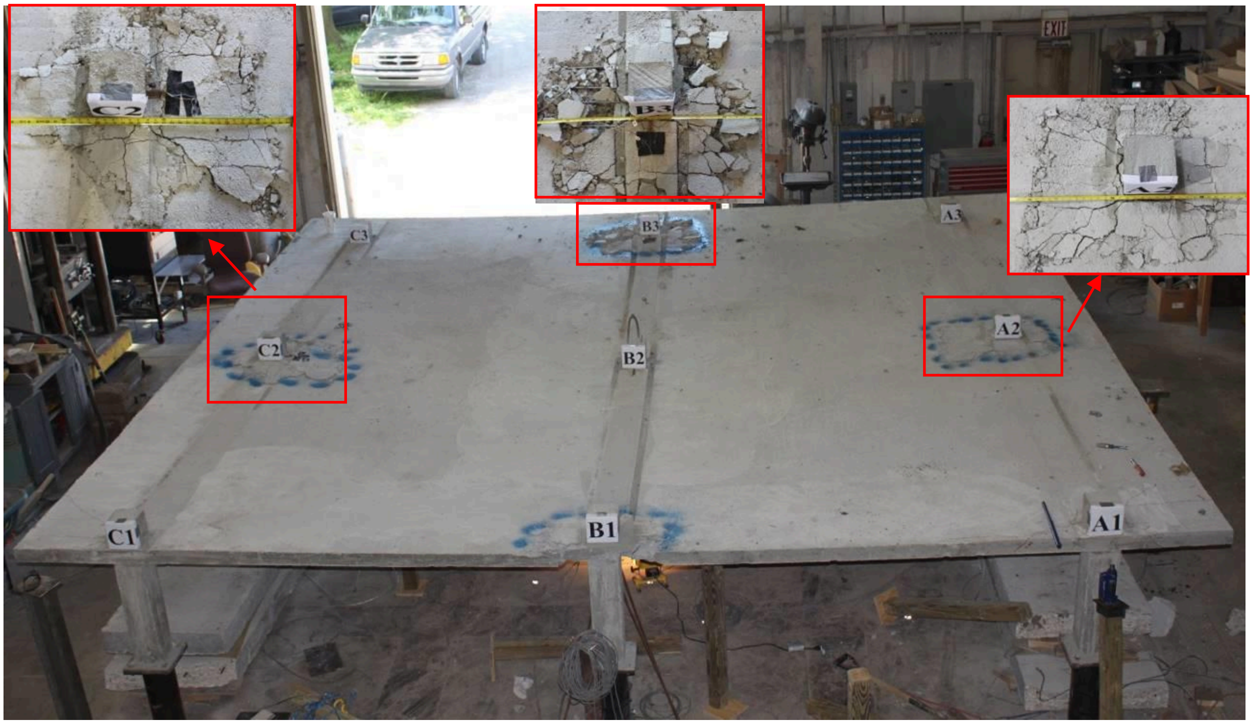


Figure 3 – Multi-panel flat plate specimens without progressive collapse due to post-punching resistance of slab-column connections (Peng 2015).

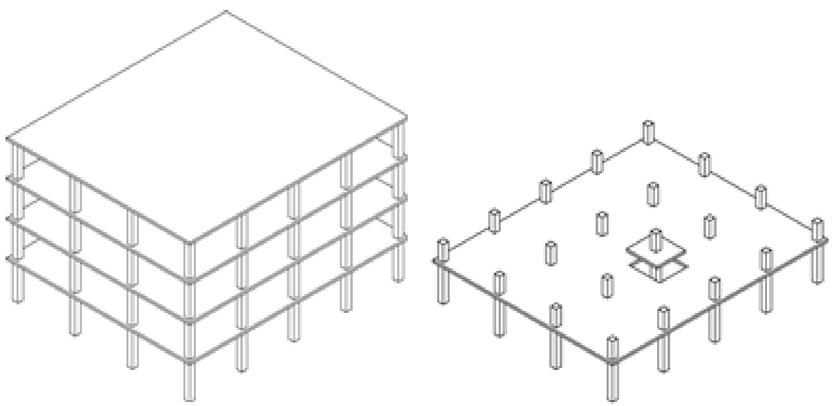


Figure 4- The relationship between tested specimens and prototype

The design of eight slab-column connections followed the provisions of ACI 318-71 (1971). The reinforcement details are shown in Figure 5 and Table 1. As seen in Figure 5, the compression reinforcement (bottom bars) are not continuous. Specimens with "RE" in the name denote specimens that were restrained laterally. Specimens with "UN" denote specimens that were unrestrained laterally. The effect of the lateral restraint on pre-punching capacity was documented with details by Peng (2015). The lateral restraint did not have a significant effect on the post-punching response (the focus of this paper). Specimens with "NH" in the name did not contain anchored top reinforcement. Additionally, one specimen (1.0RE-CONT) was constructed with continuous integrity reinforcement and tested statically to investigate the effects of integrity reinforcement on post punching and compare the effectiveness between integrity reinforcement and anchored tensile reinforcement in post-punching response.

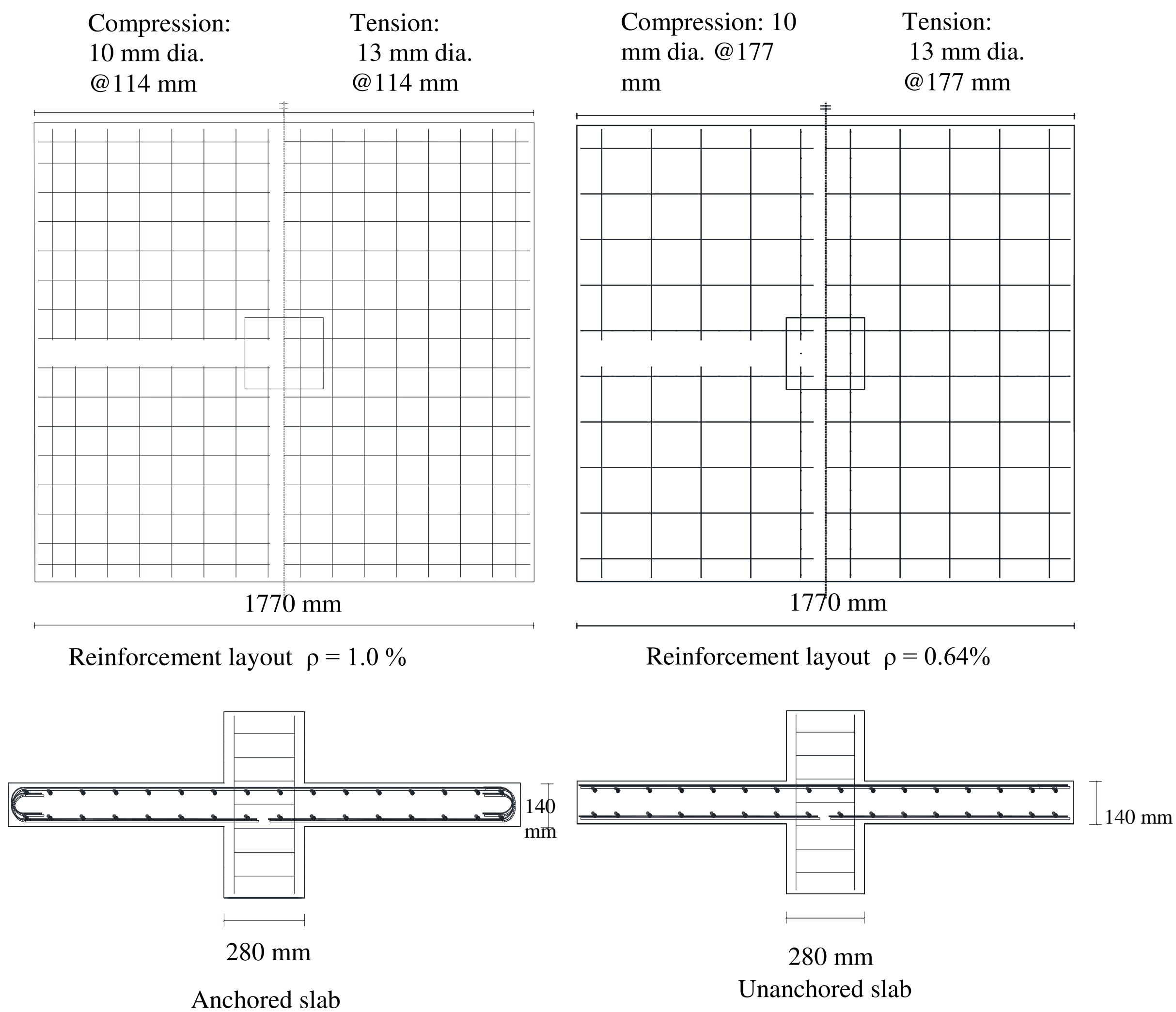


Figure 5 - Dimension and reinforcement layout of specimens

Table 1 - Details of specimens and test results

| Specimen | ρ (%) | Concrete strength at testing (MPa) | Loading condition | Anchorage | Peak post-punching capacity kN (kip) | Punching capacity kN (kip) | Percentage of peak residual capacity to the failure load |
|---|---|---|---|---|---|---|---|
| 1.0RE | 1.0 | 36.4 | Static | Anchored | 245 (55.3) | 328 (73.9) | 74.8% |
| 1.0UN | 1.0 | 33.4 | Static | Anchored | 256 (57.6) | 307 (69.1) | 83.4% |
| 1.0RE-CONT | 1.0 | 30.3 | Static | Anchored | 309 (69.4) | 311 (70) | 99.1% |
| 1.0D3 | 1.0 | 32.0 | Dynamic | Unanchored | 149 (33.5) | 302 (68.0) | 49.3% |
| 0.64RE | 0.64 | 44.3 | Static | Anchored | 213 (48.0) | 241 (54.3) | 88.4% |
| 0.64UN | 0.64 | 32.4 | Static | Anchored | 184 (41.3) | 231 (51.9) | 79.6% |
| 0.64RE-NH | 0.64 | 29.2 | Static | Unanchored | 141 (31.6) | 238 (53.6) | 58.9% |
| 0.64RE-NH 2 | 0.64 | 37.0 | Static | Unanchored | 121 (27.3) | 251 (56.4) | 48.4% |

In the prototype design the slab tensile reinforcement extends 530 mm (21in.) beyond the edge of a test structure. To simulate the anchorage of the top tensile bars provided by the additional embedment length and investigate the possible robustness of anchored tensile reinforcement against a progressive collapse, four specimens (1.0RE, 1.0UN, 0.64RE, and 0.64UN) were constructed with 90 degree anchored bars at the edge of slabs as seen in Figure 5 and Table 1. Additionally, two specimens (0.64RE-NH and 0.64RE-NH2) were constructed without anchored bars as references to allow the top bars to rip out of slab concrete during large post-punching deflections.

**Test setup**

All slabs were loaded through the center column and supported at eight locations around slab edges, as shown in Figure 6. The specimens were tested in the inverted position for ease of testing. The supports provided vertical restraint and, in the RE series of tests, horizontal restraint, but allowed slab rotation at the edge. The supports in the unrestrained series of tests are shown in Figure 6b. The supports were comprised of steel angles bolted into the slab. The loading protocol was displacement controlled in the static series of tests. The applied load was measured through a load cell directly below the loading ram. The center displacement was measured through a string pot beneath the slab column. Additional LVDTs were used to measure vertical and horizontal movements at the supports. Strain gages were attached to reinforcing bars and concrete in compression. Unfortunately the majority of the gages or gage wires were damaged at punching failure; thus, they were unable to provide readings during post-punching. More details of the reinforcement, dimensions of the specimens, test setup as well as the results of the static and dynamic tests have been presented by Orton et al. (2014) and Peng et al. (2015).

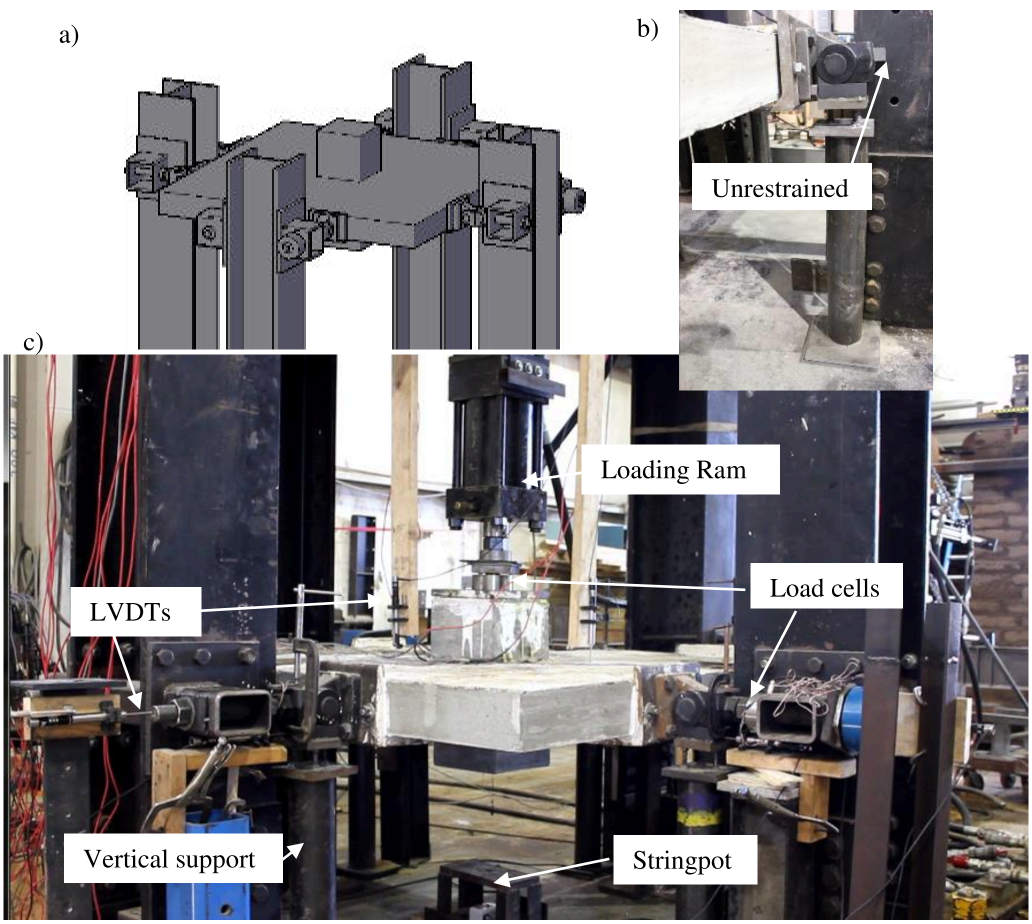


Figure 6 – Test setup: (a) test schematic, (b) support for specimens without lateral restraint, and (c) test setup and instrumentation of restrained specimens.

One slab (1.0D3) was tested dynamically and two slabs (1.0RE and 1.0UN), with identical dimension and reinforcement details, were tested statically as references to determine the dynamic effects on post-punching capacity. The dynamic test setup was the same as static tests other than the use of a dynamic hydraulic ram at a loading speed of approximately 5 in./sec to apply a dynamic load. The target loading rate of the ram was determined from a numerical analysis to represent the transfer of load from the neighboring lost column.

**Effects of slab reinforcement ratio on post punching capacity**

The post-punching capacity was defined in this study as the maximum load carried by a slab-column connection after a punching failure. Figure 7 illustrates the different post-punching behaviors of slabs with anchored top reinforcement and differing tensile reinforcement ratios. For specimens 1.0RE and 1.0UN, the post-punching strength was almost identical at 250 kN; for 0.64RE and 0.64UN, the post-punching strength was about 200 kN. The 0.64RE and 0.64UN retained an average of about 85% of punching capacity right after failure while 1.0RE and 1.0UN had a stable post-punching capacity of 80% of their punching capacity. The capacities after punching were similar because it was observed that there were two identical tensile bars crossing the slab-column interface regardless of slab reinforcement ratio. This indicated that the ratio of punching capacity to post-punching capacity was likely proportional to the amount of anchored tensile reinforcement crossing through the slab-column interface, which was capable of developing a tensile membrane action. In fact, in several code provisions used to size integrity reinforcement (SIA 262 2003, CSA A23.3 1994, NYC building code 2008), only bars passing through the column are considered. However, the code provisions only consider the bottom bars continuous through the column as capable of providing post-punching capacity. The test series presented here, without continuous bottom bars, shows that the top bars are able to provide significant post-punching capacity if they are well anchored. The anchoring of top bars may provide a viable means to retrofit older flat plate structures to reduce the likelihood of progressive collapse.

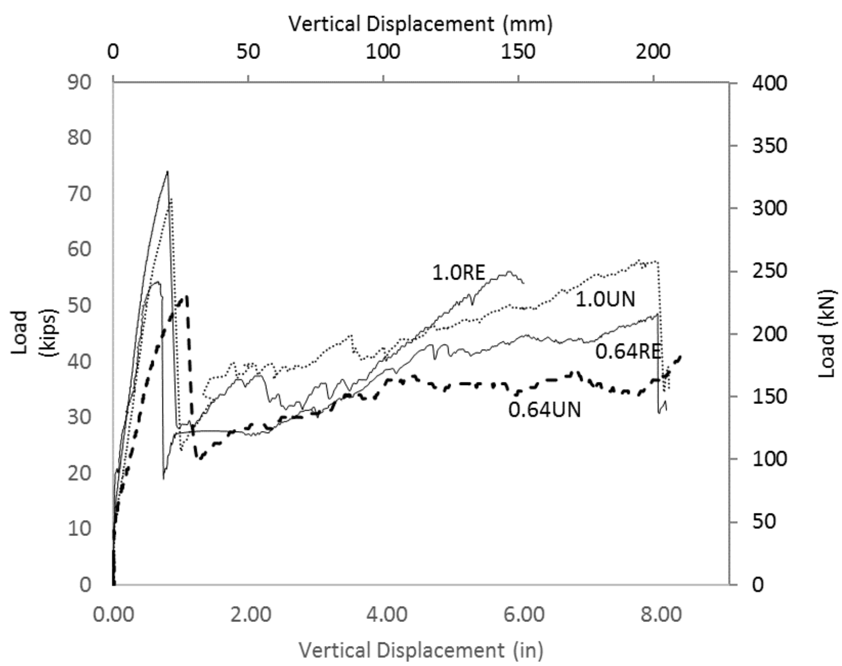


Figure 7 - Effects of reinforcement ratio on post-punching capacity.

**Effects of anchorage on post punching**

Figure 8 compares the post-punching capacity of anchored (0.64RE and 0.64UN) and unanchored (0.64RE-NH and 0.64RE-NH2) slab-column connections. Figure 9 compares the failure modes of the two types of connections. Anchored slabs were able to reach an average of 84% peak post-punching strength while unanchored slabs had an average of 53% peak post-punching strength. The post-punching capacity immediately following punching shear failure was nearly the same for all tests because the majority of load capacity in this deflection range was from the dowel action of the discontious compressive reinfocement and breakout of the concrete cover over the top bars. Starting at a value of 2.63 in. for 0.64RE-NH and 1.7 in. for 0.64RE-NH2, the load-carrying capacity dropped. On the contrary, the post-punching capacity of 0.64RE and 0.64UN with anchored tops bars begun to benefit from tensile membrane action and kept increasing. This was due to fact that the anchorage allows tensile membrane action to be fully developed until the bars fractured or the failure of anchorage as shown in Figure 9. However, unanchored slabs experienced a gradually decreased post-punching capacity due the ripping out of the top bars. The decreasing post-punching capacity may inhibit the structure from finding a stable equilibrium (prevent collapse) in an actual building. The ability of the anchored continuous top bars having a stable post-punching response would assist in reducing the likelihood of progressive collapse. Based on the test observations made in this study, anchoring top bars in existing structures, possibly via FRP wraps or steel bolts placed over the bars and through the slab to engage their participations in tensile membrane action, may be a method of improving the collapse resistance of a flat-plate structure.

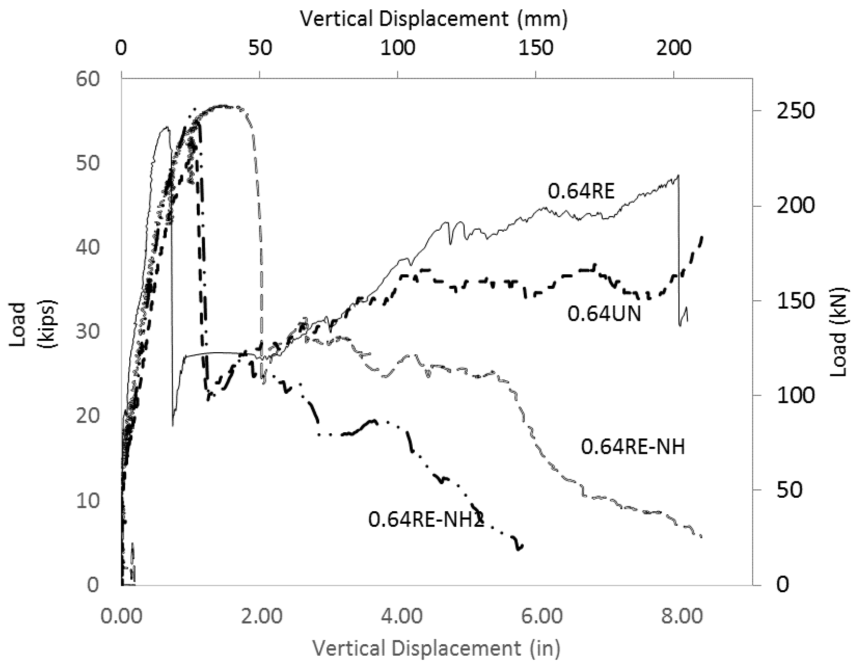


Figure 8- Post punching of anchored and unanchored tensile reinforced slabs

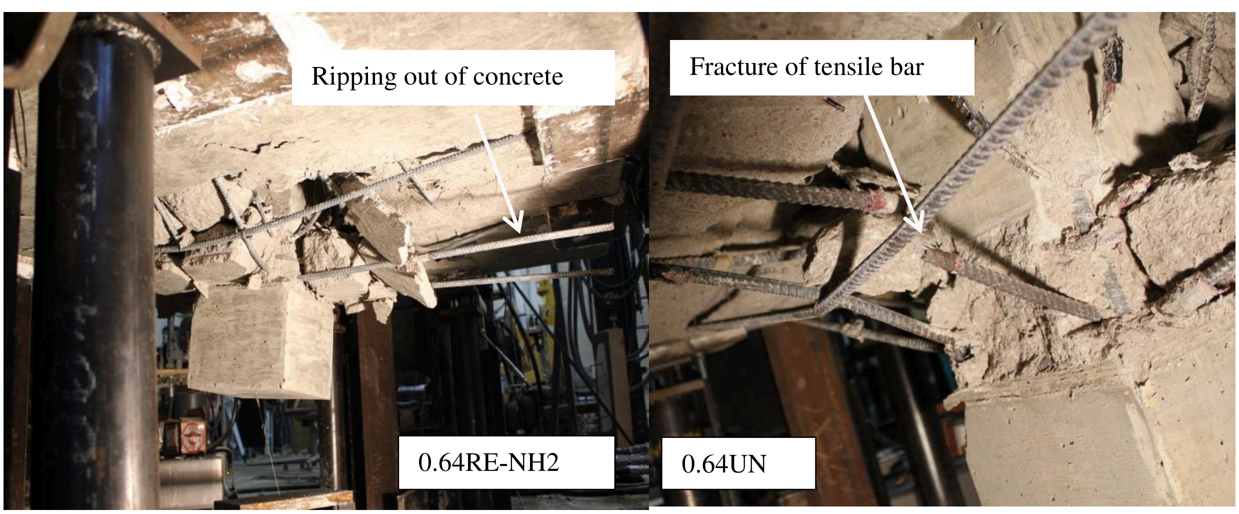


Figure 9- Post-punching failure modes: 0.64RE-NH2 without anchored bars and 0.64UN with anchored bars.

**Dynamic loading effects on post-punching capacity**

An additional test was conducted to determine if the reponse of the slab changes under loading rates that would be present in a collapse senario. The dynamic pre-punching response was more ductile than the static response. As shown in Figure 10, the deflection at punching failure was 31 mm for the dynamically tested 1.0D3 but only 17 mm for the statically tested 1.0RE. The reason for this difference may be due to a change in slab behavior to a more flexure-controlled failure mode in the dynamic test. The post-punching response, however, was very similar between the two tests. Boths tests presented a stable post-punching strength at about half the punching capacity. The dynamic test was stopped at a displacement of 78 mm due to the lack of ram stroke. It is anticipated that, if loading can be continued in 1.0D3, its response would have followed that of the static tests.

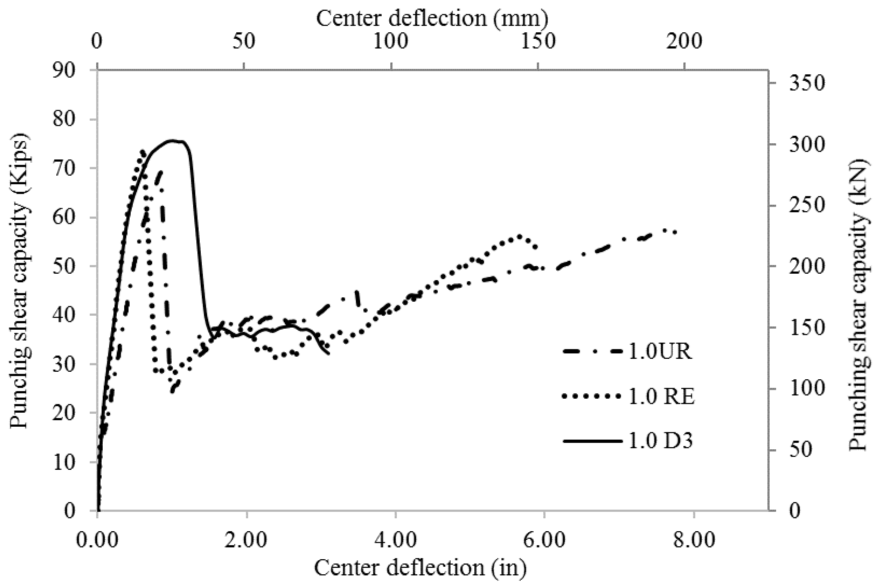


Figure 10- Comparisons of post-punching capacity between static and dynamic tests.

**Effects of continuous compressive reinforcement (integrity reinforcement)**

One test, 1.0RE-CONT, was conducted with continuous bottom reinforcement consistent with the code integrity reinforcement requirement in ACI 318-14 (2014). Figure 11 shows the difference in post-punching capacity regarding the effects of integrity reinforcement and anchored tensile reinforcement. It should be noted that the deflection for 1.0RE-CONT include support movement which was not measured during the test, but was approximated to be about 17 mm at the peak load. In addition the slab was unloaded and reloaded at about 36 mm of displacement due to loss of stroke capacity in the ram.

With slab integrity reinforcement, the peak post-punching capacity of 1.0RE-CONT was 99% of its punching capacity while discontinuous reinforcement allowed for only 79% peak post punching capacity for specimens with anchored tensile reinforcement (1.0RE and 1.0UN). In addition, the post-punching strength increased at a more rapid rate in 1.0RE-CONT. This illustrates that using integrity reinforcement (continuous bottom reinforcement) is more effective than anchoring top reinforcement in improving the post-punching capacity of a slab-column connection.

## CONCLUSIONS

- Slab-column connections with anchored slab top reinforcement achieved a peak post-punching capacity of approximately 80% of their punching strength in this series of tests. This capacity did not change significantly with increased slab reinforcement in these tests because the capacity is likely directly related to the total reinforcement passing through the column which was the same in both reinforcement ratios tested. In addition, the post-punching capacity was stable until the fracture of slab tensile reinforcement. This stable response could assist in reducing the likelihood of progressive collapse.
- The peak post-punching capacity of specimens tested with unanchored top reinforcement was on average 53% of punching capacity in static tests but decreased dramatically as deflection increased. The negative stiffness of the post-punching response may contribute little in resisting a progressive collapse.

- Slabs with integrity reinforcement (continuous bottom reinforcement) can have 100% of post punching capacity and are the best solution for post-punching capacity.
- Dynamic testing of an isolated slab-column connection showed an increase in pre-punching ductility, but a similar post-punching response to that in the static tests.

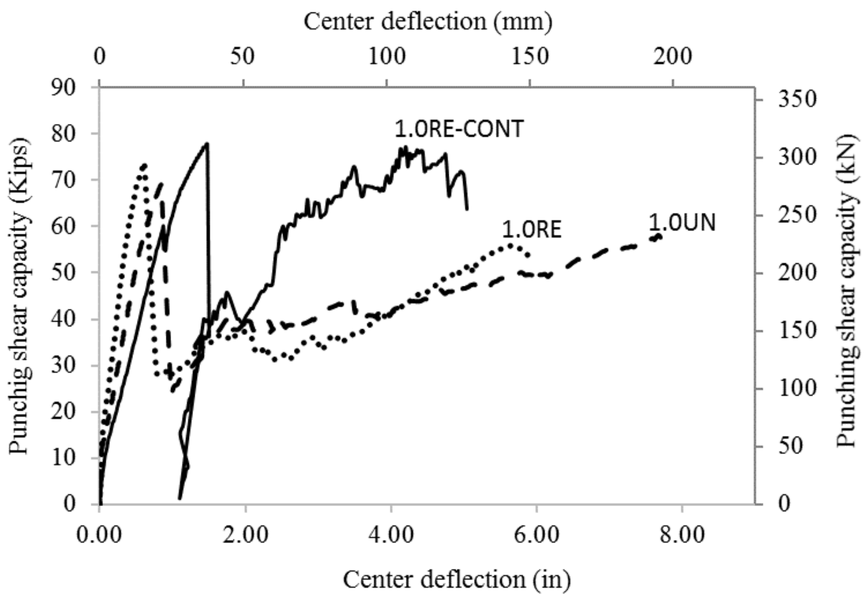


Figure 11- Effects of slab integrity reinforcement on post-punching capacity.

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# RECENT PROGRESS IN UNDERSTANDING OF LOAD RESISTING MECHANISMS FOR MITIGATING PROGRESSIVE COLLAPSE

By: Kai Qian, Bing Li, and Ying Tian

Synopsis: The collapses of Murrah Federal Building, Oklahoma City, in 1995 and Twin Towers of World Trade Center, New York City, in 2001 demonstrated that mass casualties and economic loss can be attributed to the collapse of buildings rather than the initial blast pressure or shock. Thus, designing buildings to prevent progressive collapse has become an imperative in the professional engineering community and standard-writing group in recent years with the increase of terrorist activities. However, it is uneconomical to design structures to resist progressive collapse purely relying on the flexural strength, as progressive collapse is an inherently low-probability event. Fortunately, existing studies indicated that there are some secondary load-resisting mechanisms neglected in conventional structural designs. These secondary mechanisms, depending on the locations of missing columns and types of structures implicated, can be utilized to mitigate the vulnerability of structures to collapse. This paper provides an overview of the advance of understanding in possible load-resisting mechanisms (Vierendeel action, compressive arch action, compressive membrane action, tensile catenary action, tensile membrane action, and dowel action) to resist progressive collapse of RC structures (frames and flat plate/slab).

Keywords: catenary, compressive arch action, dowel action, load resisting mechanism, membrane action, progressive collapse, Vierendeel action