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How the National Earthquake Hazards Reduction Program Is Advancing Earthquake Safety

New Findings to Keep Flat-Plate Frames from Flattening

Infrastructure, so often taken for granted, is attracting more attention these days. In such times, it is worth noting that infrastructure encompasses not just the many constructed resources that directly support our daily routines, but also the research facilities that make those resources safer and more efficient. Researchers from the University of Michigan and the University of Minnesota recently highlighted the value of such facilities. Taking advantage of the unique capabilities of the George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES), they developed important new findings that will help to make a popular building system safer and more efficient to use in earthquake-prone regions.

A Lesson Learned the Hard Way

Many lessons have been learned from the damaging earthquakes that have struck California. One such lesson concerns multistory buildings with reinforced concrete frames, called flat-plate or slab-column frames, consisting of horizontal slabs directly supported by vertical columns. Post-earthquake observations and experimental testing have shown that in this type of structure, lateral movements induced by earthquake ground motions combined with gravitational pull on slabs can make the connections between slabs and columns susceptible to punching shear failures (where the slab fractures around the column as if the column were punching through the slab). Such failures can cause floors or entire buildings to collapse.

Flat-plate frames have nevertheless remained popular, primarily for office and residential buildings, because they are relatively inexpensive to construct and because of the reduced story heights and open floor plans that are possible with such framing. However, their vulnerability to punching shear failure has caused structural engineers to rethink the design of slab-column connections in new flat-plate frames constructed in areas of high seismicity. Several ways have been found to make these connections stronger, but shear stud reinforcement has become the method most commonly used. This type of reinforcement

Shear stud reinforcement in slab-column connection. Photo courtesy of Eduardo Miranda.

consists of headed bars welded to steel rails that typically extend out perpendicular to each side of the column. In recent years, shear stud reinforcement has been used in many medium- and high-rise buildings constructed in west coast cities such as San Francisco and Seattle.

Department store that partially collapsed in California's 1994 Northridge earthquake; punching shear failure was observed. Source: J. Dewey, U.S. Geological Survey.

A Potentially Better Solution

In late 2004, a team of researchers led by Gustavo Parra-Montesinos of the University of Michigan began a multi-year investigation of an innovative new approach for reinforcing slab-column connections. The primary objective of this project, which was funded by the National Science Foundation (NSF) under grant award CMMI-0421180, was to evaluate the potential of using fiber-reinforced concrete (FRC) in such connections.

Fiber reinforcement, produced by adding small, deformed (e.g., hooked, twisted) steel wires to the materials mixed to form concrete, has long been known to strengthen concrete, particularly in tension. More efficient fibers have been developed in recent years, reducing the amount of fibers that must be used and making FRC more workable and affordable for structural applications. Given the cost and construction disadvantages associated with shear stud reinforcement, the researchers hypothesized that FRC could be a cost-effective alternative means of reinforcing slab-column connections.

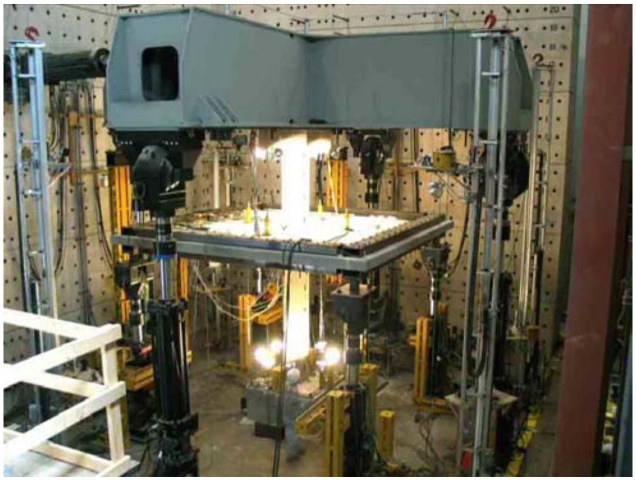
The team first examined the performance of varying forms of FRC to determine which showed the greatest potential for use in slab-column connections subjected to earthquake motions. In a series of tests conducted at the University of Michigan Structural Engineering Laboratory, they evaluated concrete containing fibers of differing shapes, sizes, strengths, and concentrations, building upon the findings of earlier research.

The two types of FRC that showed the most promise were selected for the final project tests. Three near-full-scale, reinforced concrete slab-column subassemblies were constructed, each consisting of a 17-foot-square floor slab (vertically supported at the corners but allowed to displace and rotate) connected to a 16-inch-square column that extended down one story (about 11 feet) below the slab and up half a story above the slab. In two of the subassemblies the slab-column connection was reinforced with FRC, while in the third, the connection was strengthened with shear stud reinforcement designed in accordance with current industry standards. The plan was to subject these connections, in the most realistic manner possible, to the deformations and stresses they would encounter in a flat-plate framed building during an earthquake.

A State-of-the-Art Facility Reveals Much

The facility best suited for this final testing was the NEES Multi-Axial Subassemblage Testing (MAST) Laboratory at the University of Minnesota. The MAST laboratory, which is the largest facility of its type in the world, is designed for testing large-scale structural components up to 28 feet tall and 20 feet by 20 feet in plan. Test specimens are anchored to the laboratory's 7-foot-thick strong floor and attached at the top to a 47-ton steel crosshead, which is moved by hydraulic rams to apply vertical and horizontal forces (and/or displacements) to specimens. The operation of this and other NEES facilities has been funded in large part by NSF, through grant CMMI-0402490.

The three slab-column subassemblies were tested at the MAST laboratory in 2007. In addition to pushing and pulling downward on the specimens to simulate gravitational forces and the weight of floors above, the MAST equipment moved the subassemblies horizontally along both north-south and east-west axes to simulate the lateral displacements generated during earthquakes.



Slab-column subassembly at NEES MAST facility. Photo courtesy of the MAST laboratory.

Two major findings emerged from these tests. First, FRC was found to be a feasible and effective substitute for shear stud reinforcement. The slab-column connections reinforced with FRCs outperformed the shear stud-reinforced connection on both punching shear resistance and deformation capacity. The other, more surprising finding was that shear stud reinforcement, as designed under current standards, is potentially unsafe in areas of high seismicity. The MAST test marked the first time that a typical shear stud-reinforced slab-column connection had been subjected to biaxial lateral displacements, and the reinforcement appeared to have little or no effect in enhancing connection deformation capacity. Together, these findings suggest the need to reevaluate current practice on the design of connections in flat-plate construction and to assess the vulnerability of existing flat-plate structures in earthquake-prone regions.