Experimental and Analytical Studies on Post-Punching Behavior of RC Flat Slabs: Local Failure and Progressive Collapse Analysis of Structures

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Abstract

Column failure due to an explosion, impact, or other accidental events can propagate in the structure through punching shear failure at the location of the neighboring columns, leading to progressive collapse. Using a mechanical model previously developed by Mirzaei, an analytical model is developed to be used in finite element models of flat plate/slab structures to estimate the initiation of punching shear failure as well as post-punching shear response using ABAQUS. The mechanical model is used to determine the mechanical properties of the analytical model of the connection zone, which is between a rigid zone of slab directly above the column and the rest of the slab. The model of the connection zone simulates the contribution of the reinforcing bars to the shear transfer after a punching shear failure. The analytical model and the results of system level study can be of interest in assessing progressive collapse resistance of existing structures and in design of new structures.

Background

On January 25, 1971, two thirds of a 16-story apartment building collapsed at 2000 Commonwealth Avenue, Boston, Massachusetts. Four workers died after a failure on the roof instigated a progressive collapse all the way to the basement, where the men were found.

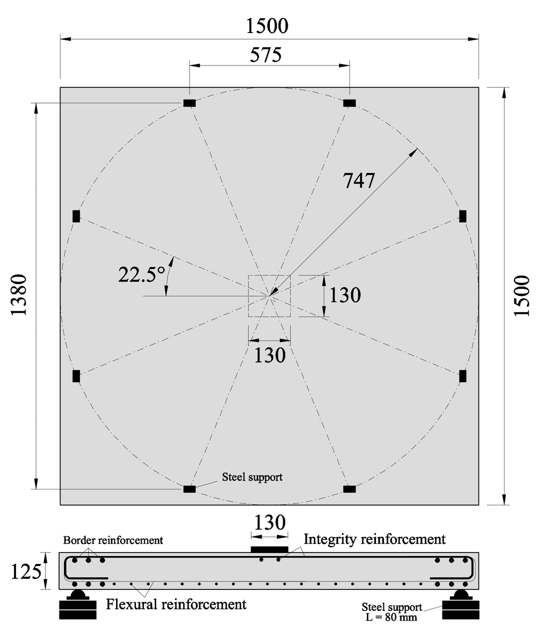
Research to Reality

Following the Alfered P. Murrah Federal Building attack in 1995 and the establishment of the Interagency Security Committee (ISC) for development of construction standards for federal buildings subject to terrorist attack, the General Services Administration (GSA) published guidelines for progressive collapse analysis and design of structures. The outcomes of this research are aligned with an urgent need to enhance such guidelines for punching shear in flat slab structures, which can be used to mitigate the likelihood of progressive collapse.

Experiments

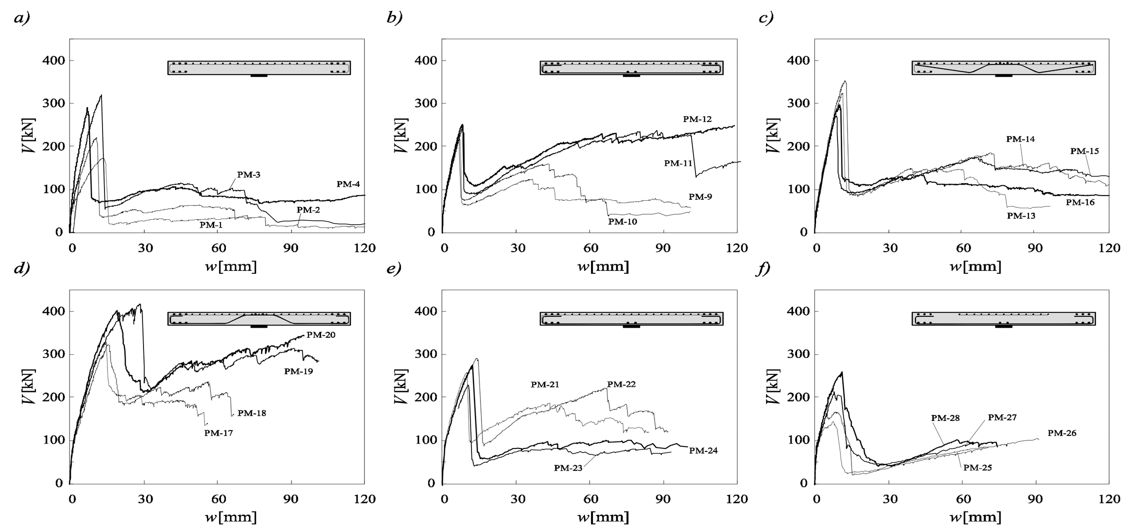
a) Local behavior

- A total of 24 slab specimens with various reinforcement layouts were tested at the EPFL, Switzerland.
- Effects of tensile reinforcement, integrity reinforcement passing through the column, bent-up-bars, and anchorage details were investigated.



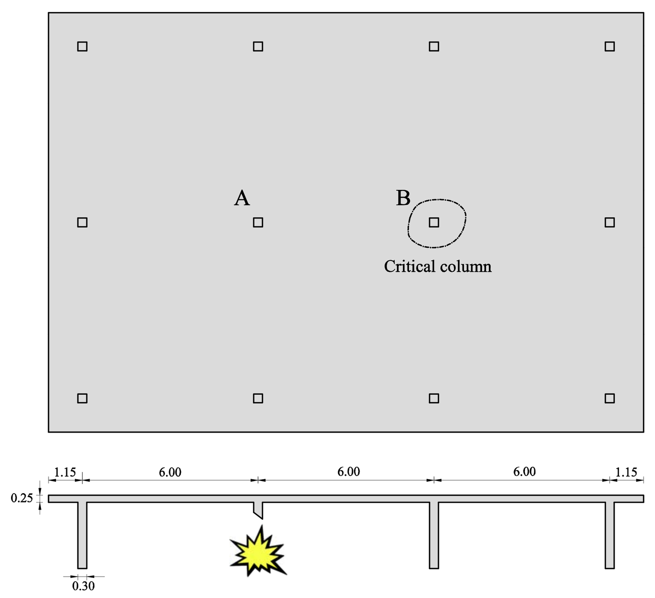
Test setup and typical slab plan section

- Tensile reinforcement contribution is not significant because of concrete spalling and possible anchorage problems
- Integrity reinforcement and bent-up bars provides considerable post-punching resistance
- Hot-rolled steel is strongly recommended for integrity reinforcement to provide large deformation capacity



Load-deflection response of all test specimens

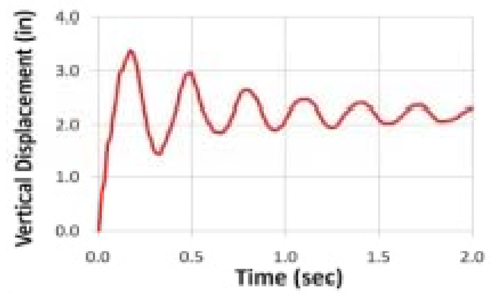
b) System-Level Response



Response of an actual two-story parking garage with flat slab following column explosion is experimentally evaluated (recorded deformation shown below)

a) Parking garage 1st Floor column before explosion

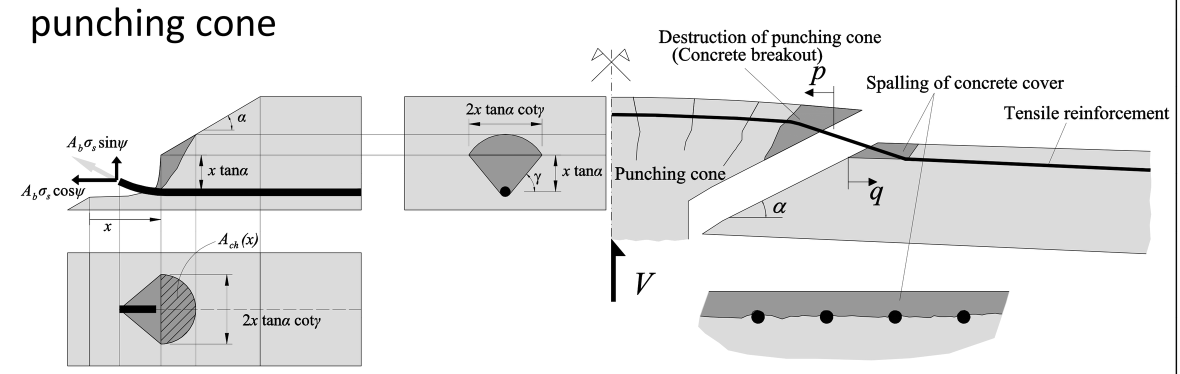
b) Parking garage 1st Floor column after explosion



c) Vertical displacement of flat slab following explosion versus time

Mechanical Model

- A generic procedure was developed capable of predicting the behavior of all possible mechanisms
- Concept of concrete breakout strength, maximum concrete breakout strength, spalling strength of concrete cover, and strain-based failure criterion in post-punching were introduced
- Various approaches were proposed to consider both the elastic and the plastic behavior of reinforcing bars crossing the punching cone

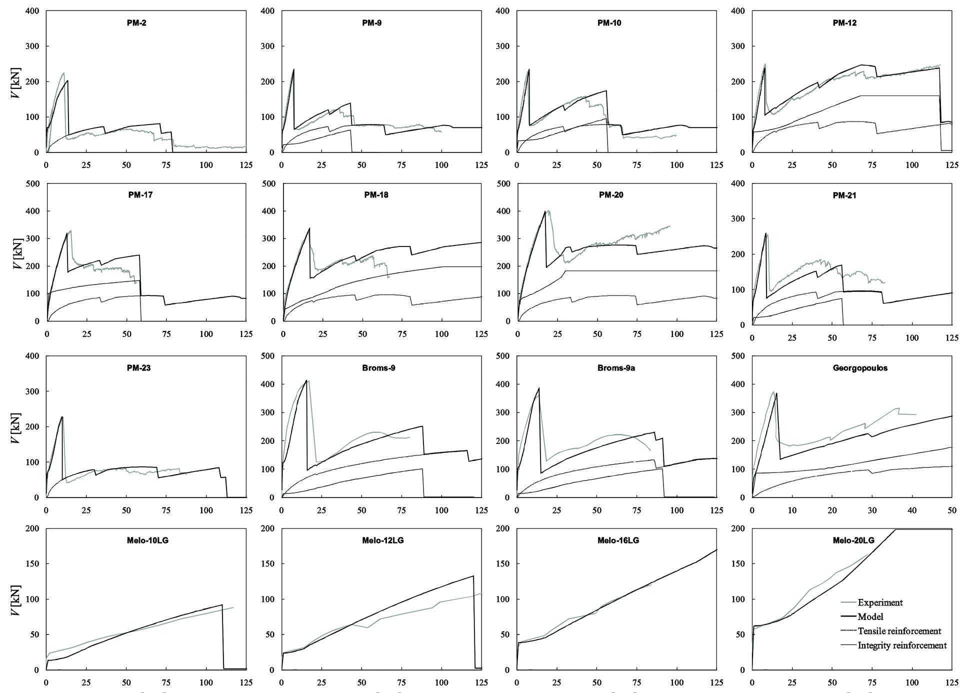


Integrity reinforcement **Tensile reinforcement**

$$V_{M,i} = N_I \sin\psi_M + \frac{Ø^3}{3L} f_{sy}\left(1 - \frac{N_I^2}{N_y^2}\right)\cos^2\psi_M$$

$$V_{D,i} = N_I \sin\psi_D + \frac{Ø^3}{3L} f_{sy}\left(1 - \frac{N_I^2}{N_y^2}\right)\cos^2\psi_D$$

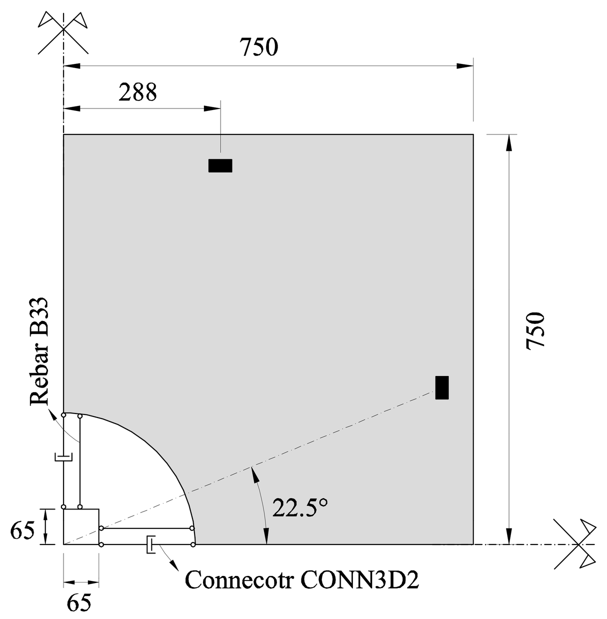
$$V_{pp} = V_M + V_D = \sum_i^m V_{M,i} + \sum_i^n V_{D,i}$$

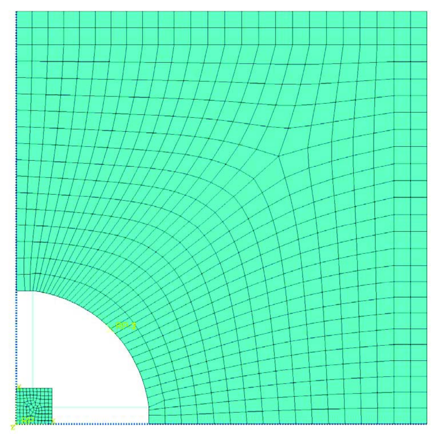


Comparison of theoretical and experimental results

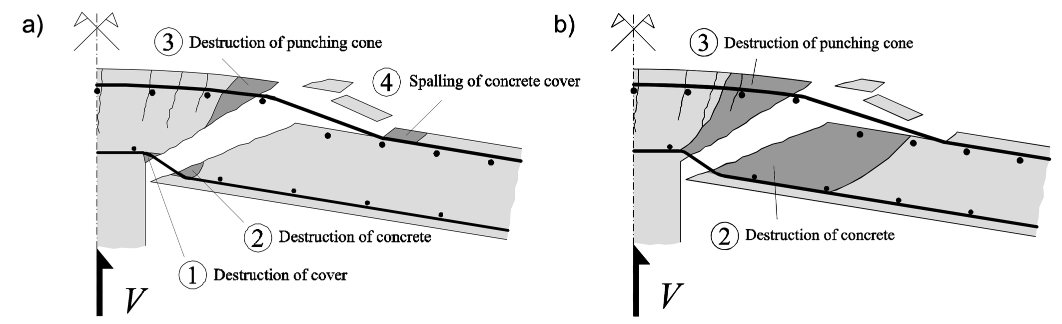
Analytical Simulation

a) Local behavior

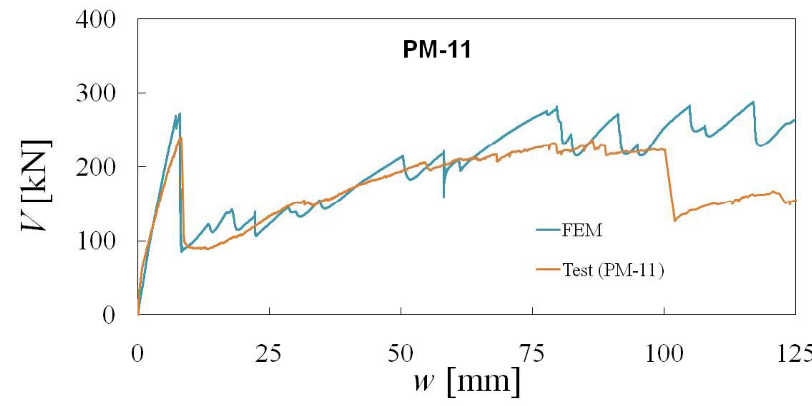




Geometry and mesh generation of the finite element model (simulation of the local post-punching behavior)

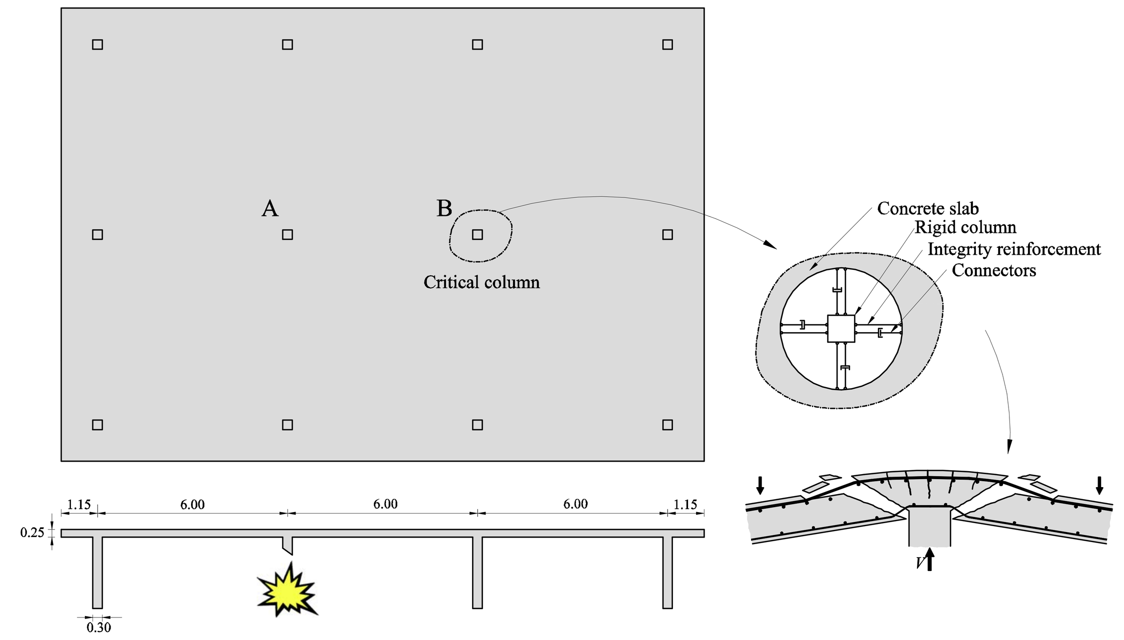


a) Various critical zones due to interaction between concrete and reinforcing bars and b) critical zone of concrete breakout over integrity reinforcement

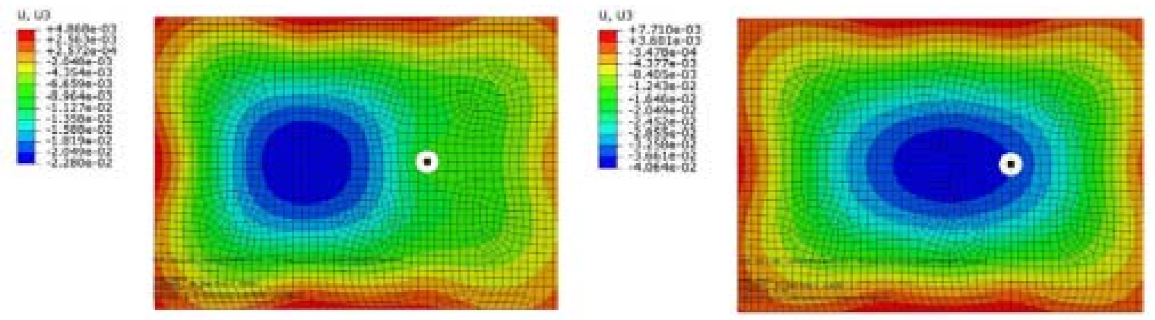


Comparison of theoretical and experimental result

b) System-Level Response



Analytical model of the system level study of progressive collapse due to punching shear failure



Slab deflection right before (0.00228 m) and right after punching shear failure of column B (0.00408 m)

References

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[4] Mirzaei Y., and Sasani, M, "Finite Element Modeling of Post-Punching Behavior of Reinforced Concrete Flat Slab Structures," IMPLAST 2010, Plasticity, Impact, and Blast Symposium, Society for Experimental Mechanics, Providence, RI, October, 2010.

This material is based upon work supported by the U.S. Department of Homeland Security under Award Number 2008-ST-061-ED0001. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied of the U.S. Department of Homeland Security.