F4-K: Science of Progressive Collapse Resistance of Reinforced Concrete (RC) Structures

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Abstract

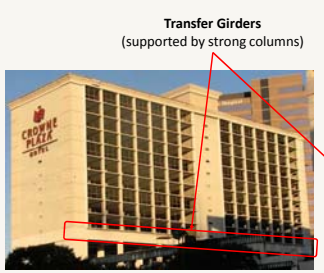
The Alfred P. Murrah Federal Building in Oklahoma City, OK, was the target of the April 19, 1995 bombing. The explosion of a truck containing a highly explosive substance near the building caused progressive collapse of a large portion of the nine-story reinforced concrete (RC) structure. About 85% of the 168 casualties were due to progressive collapse, which was extended well beyond the portion of the structure directly damaged by the blast. The collapse of the structure has been the subject of several studies. However, the failure modes and their sequence, and in turn, the progressive collapse of the structure has not been studied quantitatively at the system level. This is primarily due to a lack of proper modeling techniques and methods for analyzing element failure as well as the complexity of numerical modeling of discontinuity, separation and failure sequences, which will be addressed in this study. The results of this study can help evaluate progressive collapse resistance of RC structures and develop effective collapse mitigating techniques.

Relevance

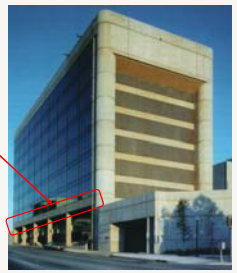
Developing reliable numerical simulation techniques for local failure and global collapse evaluation is a required step towards early warning systems for collapse prediction and is directly aligned with the following DHS mission: Enhancing the nation's capabilities to respond to major disasters and emergencies, including catastrophic events, particularly in terms of situational assessment and awareness, emergency communications, evacuations, search and rescue.

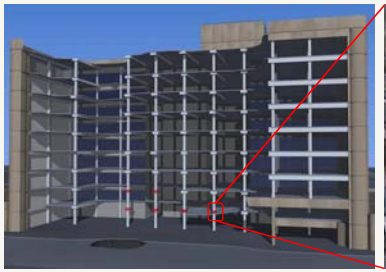
The Department of Defense (DOD) and the General Services Administration (GSA) published guidelines for progressive collapse analysis of structures. The outcomes of this research are aligned with an urgent need to enhance such guidelines, which will be used to mitigate hazards due to potential progressive collapse of structures caused by man-made hazards such as explosions.

Technical Approach

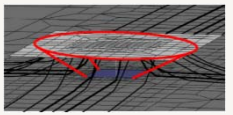


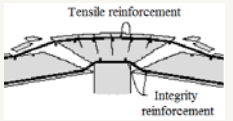
Crown Plaza Hotel


Murrah Federal Building (MFB)


MFB after progressive collapse


Punching Shear


Post punching response of RC slabs based on our numerical simulation



Deformation of slab following punching failure

Modes of Failure in RC Structures

- ***Flexural failure***
- ***Shear and Punching shear failure***
- ***Axial failure***
- ***Torsional failure***

ASCE / BPAT Studies

The primary mode of failure of the Murrah Federal Building (MFB), based on a report by **ASCE Building Performance Assessment Team (BPAT)**[9, 10] is ***flexural failure*** of the transfer girder following loss of three columns. It is concluded that even static removal of one column, would have resulted in structural instability and progressive collapse.

FEMA / US&R Studies

John Osteraas, the chief structural engineer of **FEMA**'s **Urban Search and Rescue (US&R)** program describes a different failure sequence that led to structural collapse [11]. Exertion of an upward pressure to the floor slabs caused reverse flexural and shearing cracks in the floor slabs and beams. Then, as a result of a downward movement due to the gravity loads, the beam-column connections failed in ***punching shear***, leaving the transfer girder at 3rd floor laterally unsupported. The ***torsional failure*** of the third floor girder led to progressive collapse of the building.

This Research: Methods and tools required for Progressive collapse analysis of the MFB

The sequence of failure and progressive collapse of the Murrah Federal Building (MFB) is described in two significantly different ways in the previous studies. This is primarily due to lack of reliable failure criteria and the complexity of numerical simulation of progressive collapse. The research team[2, 3, 5, 7] experimentally and analytically studied progressive collapse resistance of the Crown Plaza Hotel. Transfer girders were used in the structural systems of both the hotel and the MFB. Based on this study, it is demonstrated that the beam and floor tendency to grow as they deform can have significant effects on progressive collapse resistance of the structure. The contribution of such effects on the collapse of the MFB is under evaluation. In order to evaluate post punching resistance of slabs, the research team has proposed a numerical simulation technique, which is verified against experimental data [1, 4, 8] and will be used to evaluate the progressive collapse of the MFB. This research develops failure criteria and modeling techniques and methods, accounting for discontinuity, residual strength, and element loss. After their implementation, numerical simulations will be used to study the sequence of progressive collapse of the MFB.

Accomplishments Through Current Year

- Response of an actual two-story parking garage with flat slab following column explosion is evaluated.
- A method is proposed for finite element modeling and analysis of RC elements that accounts for bar fracture.
- A new mechanical-based modeling technique is developed to account for post-punching response of flat slabs, which is verified against experimental data.
- The new modeling technique is used to evaluate progressive collapse resistance of a flat-slab structure following the explosion of a column, in which the collapse was arrested in part due to the proper modeling of the slab post punching response.

Future Work

- The development of modeling techniques and methods for up to complete local failure of RC elements in RC structures
- The implementation of modeling techniques and methods in numerical simulations of progressive collapse of RC structures at the system level
- The quantitative and system level evaluation of the progressive collapse of Murrah Federal Building

Opportunities for Transition to Customer

The Unique and pioneering experimental program on response of actual structures following an explosion and the complementing numerical simulation in this project is a direct response to an urgent need identified by the Multihazard Mitigation Council of the NIBS (2003): "General structural integrity needs to be founded on **substantiated data**." Developing a reliable understanding of progressive collapse resisting mechanisms is a required step in establishing methods and corresponding technologies for early warning systems for progressive collapse evaluation, which would be an asset for **first responders** as well as for **effective evacuation of integrity of damaged structures**.

Publications Acknowledging DHS Support

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Other References

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