# CONVENTIONALLY DESIGNED BUILDINGS: BLAST AND PROGRESSIVE COLLAPSE RESISTANCE

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## INTRODUCTION

The purpose of this paper is to review the inherent resistance of conventionally designed buildings for which specific blast or progressive collapse requirements have not been included in the design. Current blast and progressive collapse design guidelines are outlined and assessment of ordinary structural design vulnerabilities are discussed. Simple concepts are introduced to provide a more robust structure with respect to blast and progressive collapse threat.

## BLAST AND PROGRESSIVE COLLAPSE

The loadings produced by blast events are typically much higher than the design loadings for which an ordinary structure is designed. These loadings, referred to as overpressures in the technical literature, have been extensively studied by the Department of Defense and other military agencies for their effect on various structures. Important parameters are the size of charge, distance of explosion to structure, ground or air burst, etc. The overpressures are usually measured in PSI – pounds per square inch on the element being impacted. This is noteworthy since most code design loads for ordinary structures are given in pounds per square foot. Relationships for the overpressure have been developed and given the size of the charge and distance from the structure a value can be calculated. As noted, these overpressures are usually well beyond the capacity of the structure. Local failures of structural elements in the region of the explosion is likely.

Since the risk or threat level is highly variable and local capacities are easily exceeded, more detailed analysis is unnecessary and it is commonly assumed the element impacted will fail. The effect of the blast is then studied by removing the impacted element (or elements) from the structure and then analyzing the modified structure.

The effect of the blast can be in the opposite direction for which the design loads were considered, resulting in existing capacities to resist blast being further reduced. Upward pressures from blast effects on the lower floors can put beams and girders into a reverse bending mode resulting in bottom flanges becoming compression elements with large unbraced lengths. The overpressures can easily overcome the downward design loads. The Oklahoma City Federal building is an example of the blast loading resulting in loading the concrete structure in a direction opposite to the main design resistance. Also, blast can produce significant side loading on elements that had no original design loads in that direction. Local floor failure can result in significant unbraced lengths on columns as witnessed in the first attack on the World Trade Center.

For ordinary buildings the best preventive measures are to keep the blast away from the structure with barriers, etc. (i.e. Defensive Design). The GSA (1) and DOD (2) have developed stand-off distances, barrier designs etc. for various threats. These documents address requirements for new and existing government buildings. ASCE has published a state of the art reference (3).

Progressive collapse is the disproportionate collapse of a structure due to a failure of a much smaller (albeit important) element. Obviously this includes but is not limited to blast effects. Since progressive collapse can encompass a much larger portion of the structure (or the entire structure) with many different collapse possibilities, a specific assessment approach is not possible. It is best to look at the specific guidelines outlined in the above documents and comment on what is missing in ordinary buildings to provide an evaluation of a design. Progressive collapse is a global assessment of the structure whereas blast is usually a local element assessment.

The GSA document provides an insight to current thinking related to mitigating progressive collapse. Basic to this approach is the concept of multiple load paths and structural redundancy which will produce a robust structure. Simply stated, the vulnerable element is removed and the structure should not collapse. The structure must have another load path to prevent collapse. Conditions from the structure which are considered "fundamental" by the GSA in new designs and upgrades are the "double span" design of beams and girders. Beams and girders need to be continuous through columns so that if a column is removed, the resulting structure can develop an alternate load path and carry the existing loads. Clearly most ordinary buildings could not meet this guideline even though a progressive collapse consideration does exist in some codes. In addition the GSA guideline recommends connection resilience similar to that developed with the AISC seismic standards for connections.

From a lateral system consideration the guidelines would develop designs with uniformly distributed moment frames on all the column grids as a first approach to robustness and redundancy. Bracing systems, which could be severely impacted by local blast effects are less robust than uniform moment frames and would be discouraged or combined with uniform moment frames. A perimeter moment frame strengthened on the first level above grade is also recommended.

As demonstrated clearly in the World Trade Center collapse, serviceability (wind stiffness) and redundancy can provide considerable reserve strengths for unexpected demands on a structure. The lateral system designed for wind and gravity had the strength and robustness to provide an alternative load path for a severely disrupted gravity system.

A brief list of some of the guidelines noted in the General Services Administration document is listed below:

- Continuity of floor members to produce alternate load paths.
- Redundancy for alternate load paths.
- Provide extra strength on first supported level above grade.
- Moment frames on the perimeter for protection of exterior elements. Keep girders same, oversize connections.
- Tie everything together – beneficial effects of composite construction.
- Provide extra reinforcing in first supported slab – to strengthen membrane effect.
- Consider longer effective lengths for first tier columns considering a local loss of floors.
- Consider loss of localized lateral system – bracing most vulnerable, uniformly distributed moment frames best.

## EXISTING STRUCTURE - EVALUATION

After the events of a 9/11, many owners have requested a vulnerability analysis of their buildings. As an example of a structure not designed for any specific threat, a 39 story tower was investigated for the specific threat of losing one or two of its main vertical supports at the street level. Of interest here is not damage but collapse potential. The purpose of the analysis is not an "exact" simulation of a structural collapse, but to provide the analyst with useful information for assessing the performance of the structure and to make judgments on its safety. Capacity evaluation should be done without the usual factors of safety and member strength modifications.

The 39 story structure under consideration was comprised of typical structural steel construction with metal deck and concrete floors, steel beams and columns and several transfer girders at the lowest level. The lateral system is a fully welded perimeter moment frame of beams and columns. Because of transfers on several levels above the ground level the frame possessed additional strength in these levels. This is recommended in the guideline but came about because of gravity transfers.

An analysis of the structure was carried out incorporating the GSA load conditions of 2 (DL & .25L) with the columns removed. This analysis used a "push down" methodology (similar to the "push over" analysis) to capture the non-linear behavior of the perimeter frames as the full load was applied. Figures 1 through 4 show the results of analysis for two different locations of missing columns. The perimeter frame, originally controlled by wind drift design, indicated a capacity to redistribute the load to adjacent columns. As seen from the "push down " diagrams yielding did not begin until well above the original design load levels. An important consideration in this study was the investigation of the actual connection capacity to transfer the loads in the new load path. This analysis is approximate in that the membrane action of the slab is not considered which would provide additional resistance to the structure. More detailed programs such as RAM's PERFORM – COLLAPSE are now available which do include the important membrane effect.

## CONCLUSIONS

By considering the recommended design guidelines of the current GSA progressive collapse and DOD Anti-Terrorist standards one can apply design standards to existing structures to evaluate their vulnerability. The following items are a brief summary of essential features.

Blast
- Defensive Design – Keep blast away from structure
- Element resistance – not available, capacity << demand, accept local failure
- Local analysis unnecessary – Remove element from structure and prevent progressive collapse

Progressive Collapse
- Alternate load paths, imperative
- Redundancy (goes hand in hand with above)
- Resilient connections.
- Over strength connections to create alternate load paths.
- Overall design continuity vs. local element resistance.

## REFERENCES


1. "Progressive Collapse Analysis and Design Guidelines for New Federal Office Buildings and Major Modernization Projects", General Services Administration, June 2003.
2. "DoD Minimum Anti-Terrorism Standards for Buildings", Department of Defense, UFC, 4-010-01, July 31, 2002
3. "Structural Design for Physical Security": State of the Art Practice, ASCE Tech Committee, SEI-ASCE, 1999

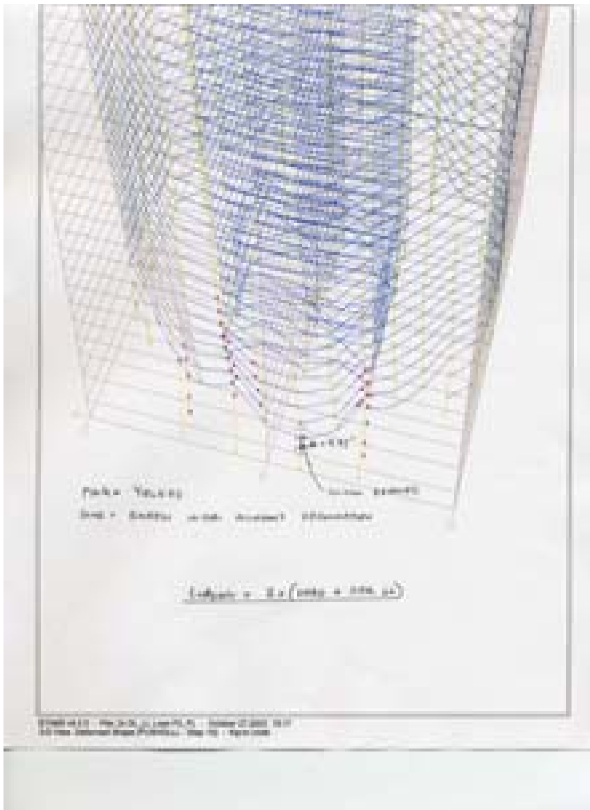

Figure 1

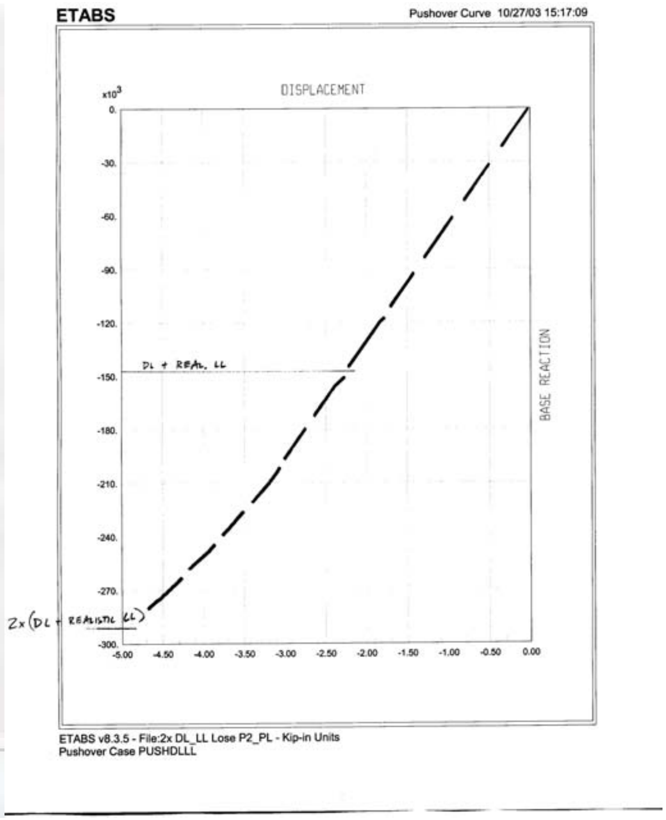


Figure 2

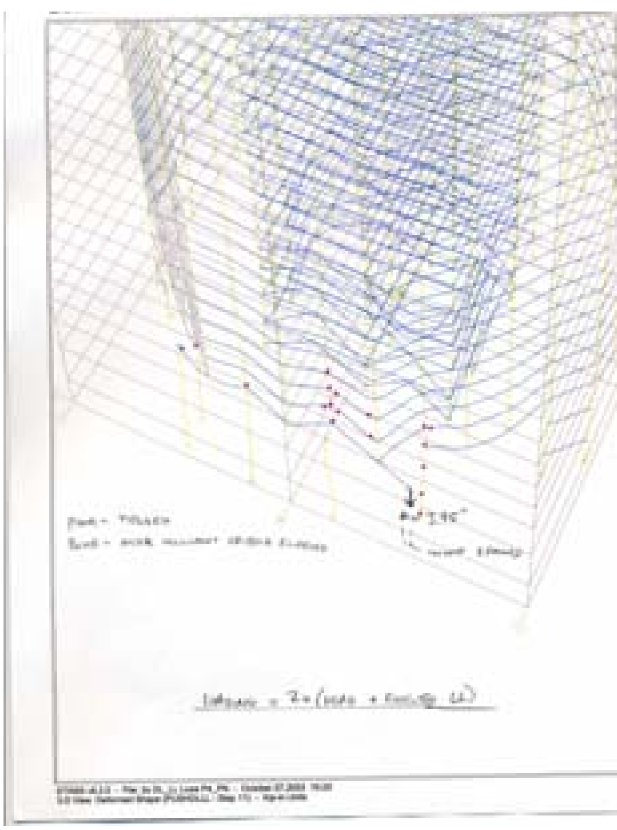

Figure 3

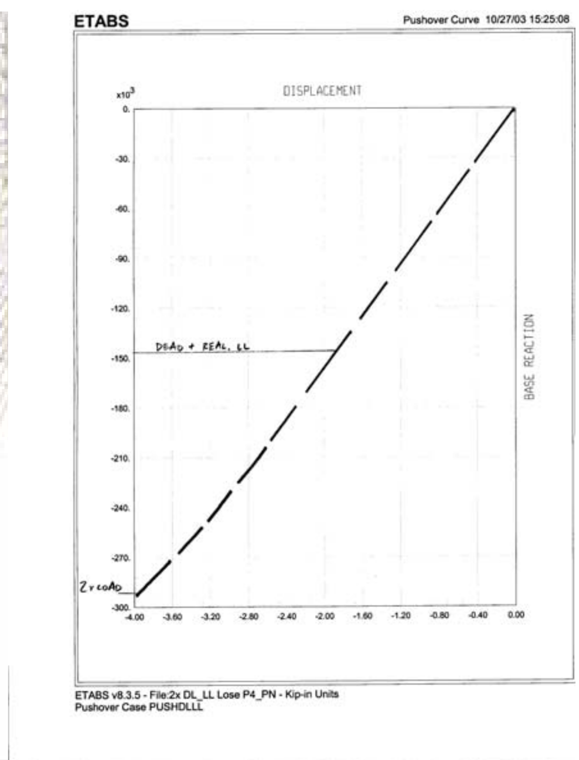


Figure 4