LEARNING FROM STRUCTURES SUBJECTED TO LOADS EXTREMELY BEYOND DESIGN

JON MAGNUSSON, PE, HON. AIA

Jon Magnusson

Jon Magnusson is Chairman/CEO of Magnusson Klemencic Associates, a Seattle/Chicago structural/civil engineering firm, with completed projects in 43 states and 35 countries. He is a licensed engineer in 24 states. He has worked on the designs for projects that have won national structural engineering excellence awards from the American Council of Engineering Companies (ACEC) twelve times in the last 17 years. His projects have won three awards from the American Institute of Steel Construction in the last 5 years. During that period alone, he has been structural engineer of record for over $2 billion worth of construction.

ABSTRACT

An important part of building structural design is strategically meeting certain performance objectives for a set of defined hazards. Understanding these concepts and communicating them to building owners, and even the general public, is becoming increasingly important.

Many buildings have been subjected to loads greatly in excess of their design criteria and have not collapsed. Lessons learned from several of these buildings are shared, including a "submarine" concept for building construction.

INTRODUCTION

Structures are designed for certain loads and hazards. Structural engineers need to communicate clearly with the building owner, architect, and building officials about what loadings may have been considered, or possibly more importantly, not considered in a project design.

Many things can be learned from investigating structures that have been subjected to loads beyond what was contemplated in their design. The overloads may have been due to intentional malicious acts or accidental hazards. The damage patterns and behavior of members and connections can give hints into how to make structures more resistant to these overloads.

WHAT ARE THE OJBECTIVES OF “DESIGN”?

Building designers can not possibly design for every extremely remote hazard that their project may be subjected to in its life. Commercial buildings are not designed for meteorite impact, or for nuclear blasts, or for other kinds of military attacks. However, the design process does include looking at four major hazards:

1. Gravity
2. Wind
3. Earthquake
4. Fire

Each of these must be defined. Gravity is well-defined and extremely predictable! Fire is typically dealt with by mitigating the hazard through event control such as sprinklers, fireproofing, and active firefighting so that the structure does not need to take the fire load. Wind and earthquake are defined on a probabilistic basis that, while not as precise as gravity, is quite reliable. Figure 1 shows examples of this approach.

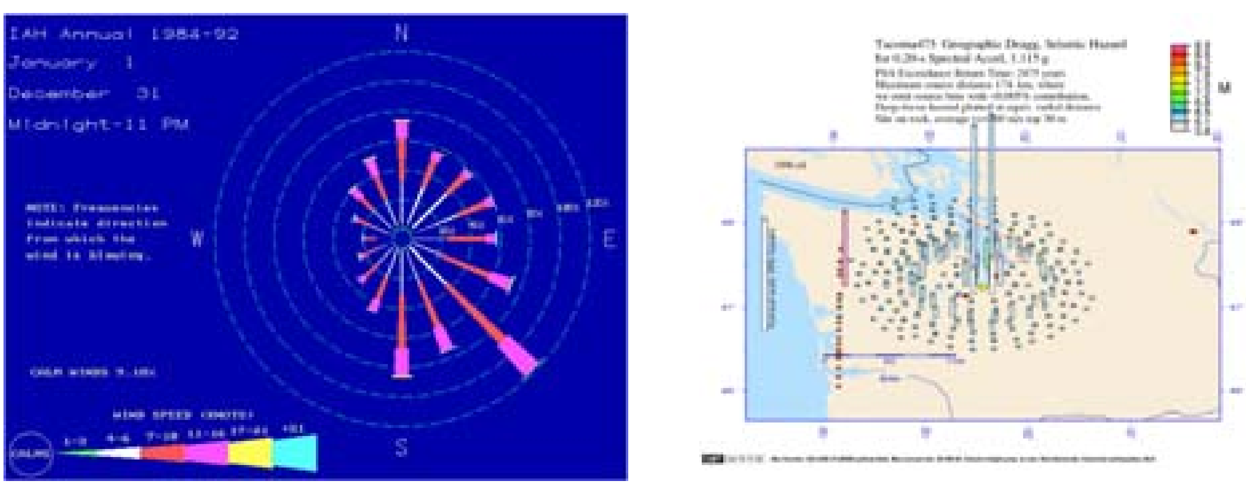

Fig. 1. Wind Speed and Direction Probabilities for Houston, TX and Seismic Hazard for Tacoma, WA

For each hazard, performance objectives are developed. Examples of performance objectives for wind and seismic are shown in Figure 2.

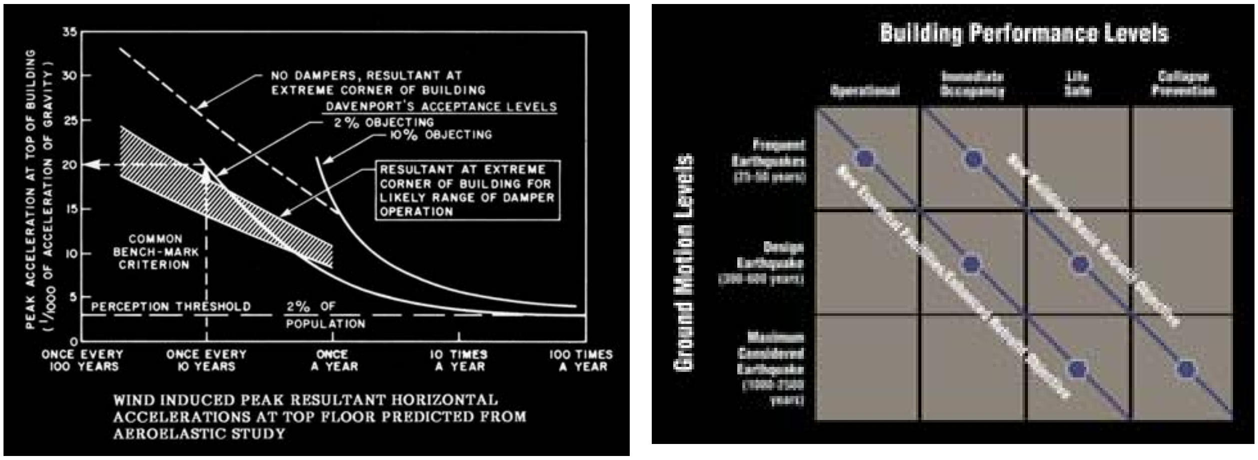

Fig. 2. Wind Acceleration and Seismic Ground Motion Performance Objectives

Once the design hazards and corresponding performance objectives are defined the design can proceed to bring these into conformance. For rational design, these steps must be repeated over and over for each element of the building system:

1. Hazard Definition
2. Performance Objectives
3. Conformance Strategies

It is critically important that all design disciplines have consistent performance objectives for the different design hazards. For example, if a sprinkler system is part of a conformance strategy for the structure, it had better have performance objectives that it be operational under the same hazard.

EXTREME LOADINGS BEYOND "DESIGN"

Usually the magnitude and probability of extreme loadings are not predictable. Unfortunately, many of the extreme loadings being considered now in designs are blast loadings due to intentional detonations intended by the perpetrators to cause damage and injury.

When the Murrah Federal Building in Oklahoma City was attacked the blast was equivalent to 4,000 lbs. of TNT. The hazard associated with a truck bomb could be 60,000 lbs. of TNT, or 15 times greater than the Murrah attack. And again, this is not an upper limit because it is always possible to postulate multiple trucks bombs in an attack.

The terrorists in the attack of September 11, 2001 ultimately had control of three planes (temporarily four) and could have used them all to attack one target. If "plane attacks" are to be considered as a design hazard, then much larger planes need to be considered. Figure 3 compares two planes that have already hit buildings, with two planes that are even larger.

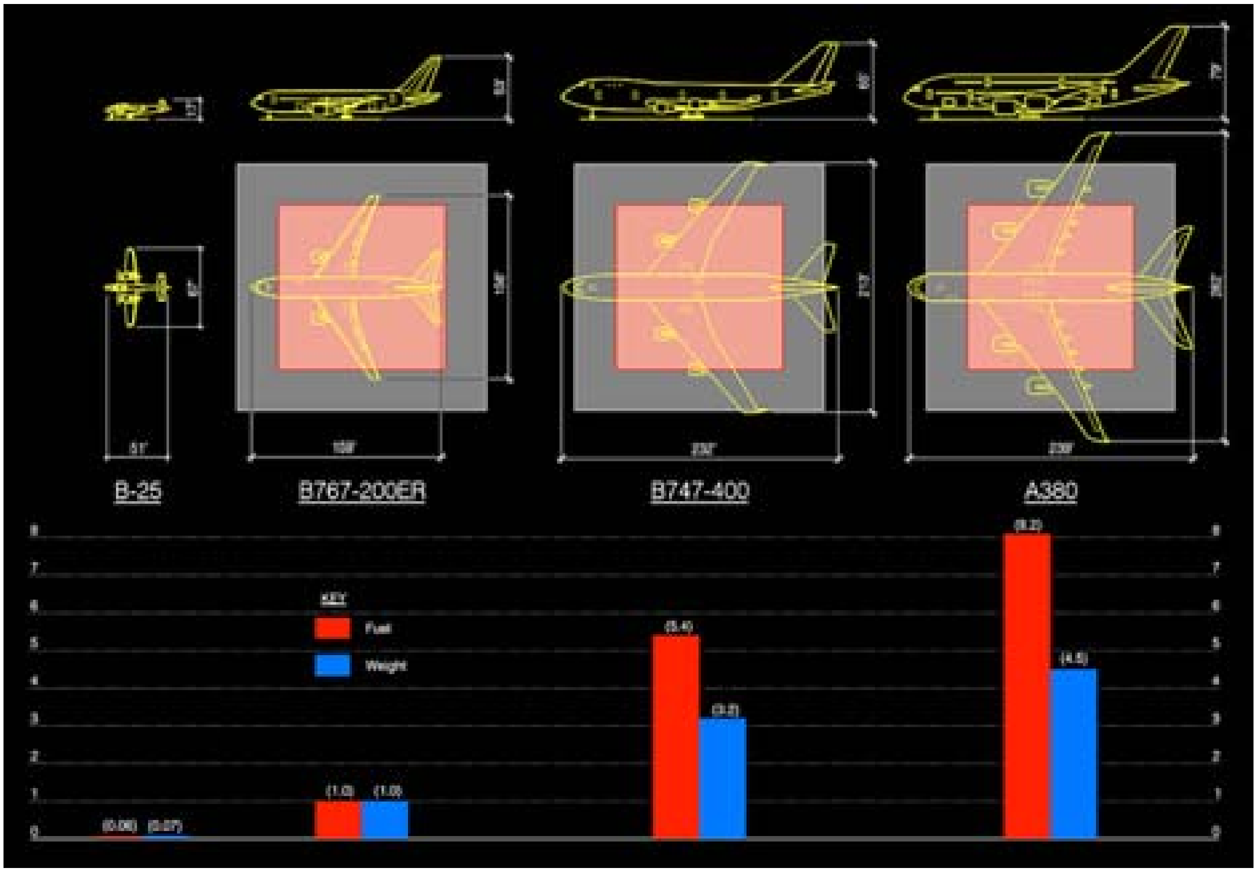

Fig. 3. B-25 hit Empire State Building, 767-200 used in WTC attacks.

Clearly, many of these hazards are beyond the realm of cost effective resistance, and in many cases beyond the ability to overcome the physics of the hazard.

COMMON SRUCTURAL STRATEGIES

One of the most common strategies to resist progressive collapse is to use a notional removal of one exterior element at a time and creating alternate load paths. This does not relate to any specific hazard and therefore does not create a performance objective for a “real” threat. It is simply meant to increase the redundancy of the structure. Many structures that have not been designed for this criterion actually have shown some capacity to lose a column without global collapse.

This approach generally results in much stronger horizontal framing systems with significant axial capacity. It is important to consider what happens when an unexpected hazard occurs that removes two or more columns. Does this strong horizontal construction then cause a horizontal propagation of the collapse? A New York City Fire Chief reported to the World Trade Center Building Performance Assessment Team that the structures that are most susceptible to progressive collapse are the ones that are well tied together. Mark Loizeaux of Controlled Demolition, Inc., whose occupation is taking down buildings, has also said that the easiest buildings to take down are the ones with high levels of continuity.

Designers should consider the possibility of negative impacts of excessive horizontal ties under more extreme loading when using the notional removal technique.

BUILDING CASE STUDIES

Ronan Point – United Kingdom

This is the most famous case of "pure" progressive collapse. There were five deaths. There was extensive vertical propagation of the collapse, but almost no horizontal propagation. If the building had been well tied together and the initiating event was larger, would the entire structure have collapsed?

Murrah Federal Building – Oklahoma City

Complete vertical and some horizontal propagation of the collapse. The blast was the equivalent of 4,000 lbs. of TNT.

600 California – San Francisco

Crane accident demonstrated tremendous ductility of concrete filled steel pipes.

World Trade Center 1 and 2 – New York

The highly redundant steel exterior moment frame was able to bridge about 140 feet of missing columns. Intense fires ultimately brought down both buildings.

Bankers Trust – New York

Debris from collapse of WTC 2 removed an exterior column over a partial height of the building. The redundancy of the structure above provided the necessary bridge to transfer loads from the missing column.

World Financial Center 3, American Express – New York

Sections of the corner column were destroyed. The corner bay was supported by cantilevered structure above and stiffening provided by the exterior wall system.

World Trade Center 3, Marriott Hotel – New York

The Marriott was crushed by debris from both WTC 1 and WTC 2. WTC 2 hit it first and, even though hundreds of tons of debris partially collapsed the southern part of the building, the collapse did not propagate to the north. The floor connections were not strong enough to allow the propagation.

AN ALTERNATIVE STRATEGY

Based on observations of these buildings, the concept of structural compartments seems to have merit. Within each compartment, strong horizontal ties could be used to prevent vertical propagation of a collapse from a relatively small overload. In the event of a massive overload, the collapse would propagate horizontally until it hit an extra strong bulkhead wall (or one with weak connections) to arrest the collapse. This dual level protection concept is similar to the way that a submarine design deals with military hazards.

CONCLUSION

Regardless of the strategies employed it is critical to identify the design hazards, performance objectives, and conformance strategies and discuss these with the building owner, architect, and building officials so that all parties have appropriate expectations and understanding of risk.