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Learning from Structures Subjected to Loads Extremely Beyond Design

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When considering extreme loads for building design, identify design hazards, performance objectives, and conformance strategies.

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

Much can be learned from investigating structures that have been subjected to loads beyond what initially was considered during their design. The damage patterns and behavior of members and connections gives insight into how to make structures more resistant to these overloads.

The Objectives of "Design"

Building designers cannot design for every remote hazard. Commercial buildings are not designed for meteorite impact, nuclear blasts, or military attacks. However, the design process does examine four major hazards:

- Gravity
- Wind
- Earthquake
- Fire

Gravity is well-defined and extremely predictable. Fire typically is handled by mitigating the hazard through event control, such as sprinklers, fire protection, and active firefighting, so that the structure does not need to absorb the fire load. Wind and earthquake are defined on a probabilistic basis that is quite reliable. For each hazard, performance objectives are developed.

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

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

It is critical 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 requires performance objectives to ensure that it is operational under the same hazard.

Extreme Loadings Beyond "Design"

The magnitude and probability of extreme loadings usually are not predictable. Unfortunately, many of the extreme loadings now considered in designs are blast loadings created by intentional detonations to cause damage and injury.

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

The terrorists in the attack of Sept. 11, 2001 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. 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 Structural 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 stronger horizontal framing systems with

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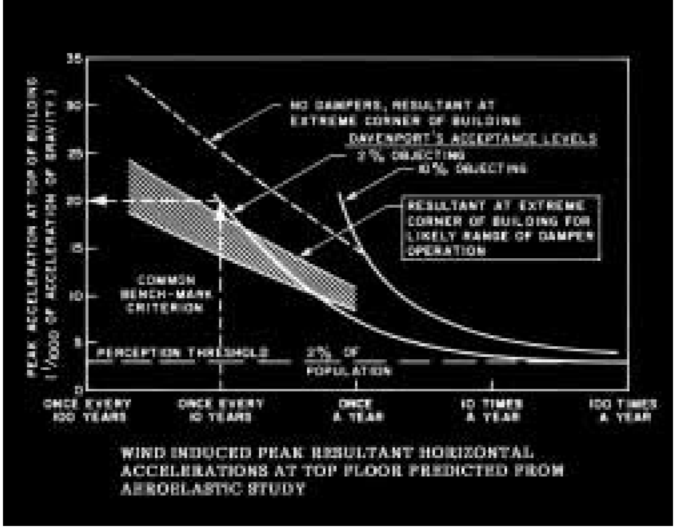
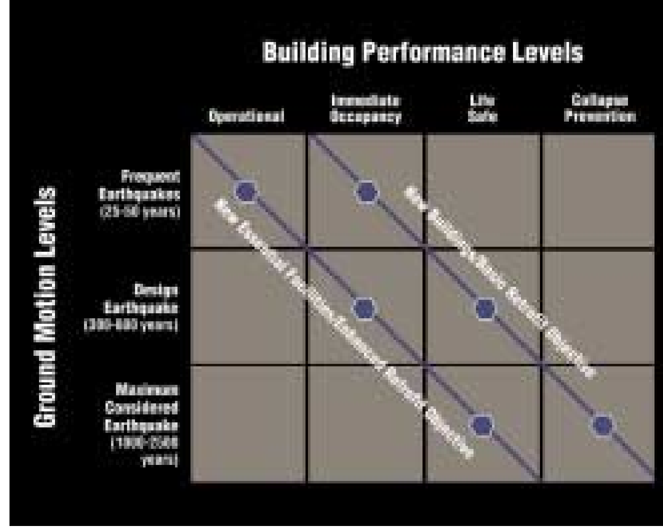
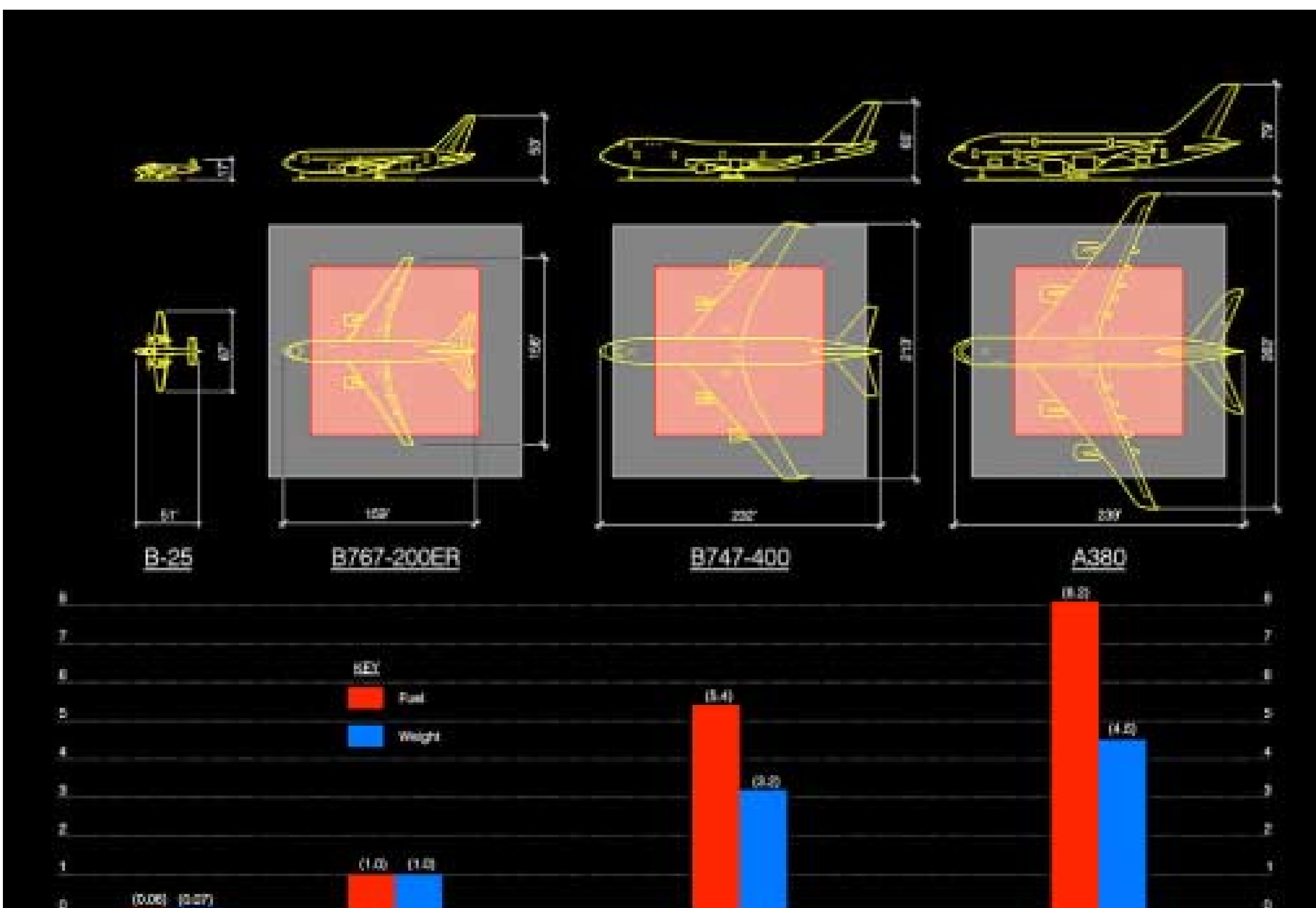




Wind acceleration and seismic ground motion performance objectives

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 most susceptible to progressive collapse are those that are well tied together. Mark Loizeaux of Controlled Demolition, Inc., whose occupation is taking down buildings, also said that the easiest buildings to take down are the ones with high levels of continuity. Designers should consider the possible negative impact of excessive horizontal ties under more extreme loading when using the notional removal technique.

Ronan Point (United Kingdom) is the most famous case of "pure" progressive collapse. There was extensive vertical propagation of the collapse, but almost



How airplane size and building size compare. The gray outline is the floor plate of one of the World Trade Center towers. The red outline is the approximate floor plate of the Empire State Building. A B-25 aircraft crashed into the Empire State Building in the 1945; the B767-200ER is the type of aircraft used in the World Trade Center attack in 2001; the B747-400 is the largest aircraft currently flying; and the A380 is the largest aircraft currently planned. The red and blue color bars compare the weight and fuel capacity of each aircraft with respect to the B767-200ER. For example, the B747-400 weighs 3.2 times as much as the B767-200ER and can carry 5.4 times as much fuel.

no horizontal propagation. If the building had been well tied together and the initiating event was larger, would the entire structure have collapsed?

In the case of the **Murrah Federal Building** (Oklahoma City), there was complete vertical and some horizontal propagation of the collapse. The blast was the equivalent of 4,000 lb. of TNT.

At **600 California** (San Francisco), a crane accident demonstrated tremendous ductility of concrete filled steel pipes.

For **World Trade Center 1 and 2** (New York), the highly redundant steel exterior moment frame was able to bridge about 140′ of missing columns. Intense fires ultimately brought down both buildings.

In the **Bankers Trust** building (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.

At the **World Financial Center 3**, **American Express** (New York), sections of the corner column were destroyed. The corner bay was supported by the cantilevered structure above, and by stiffening that the exterior wall system provided.

The **World Trade Center 3 Marriott Hotel** (New York) 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.

Structural Compartments

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. ★

This paper has been edited for space considerations. To learn more about extreme loads, read the complete text online at ***www.modernsteel.com*** *or in the 2004 NASCC Proceedings.*