Building Design for Extreme Events

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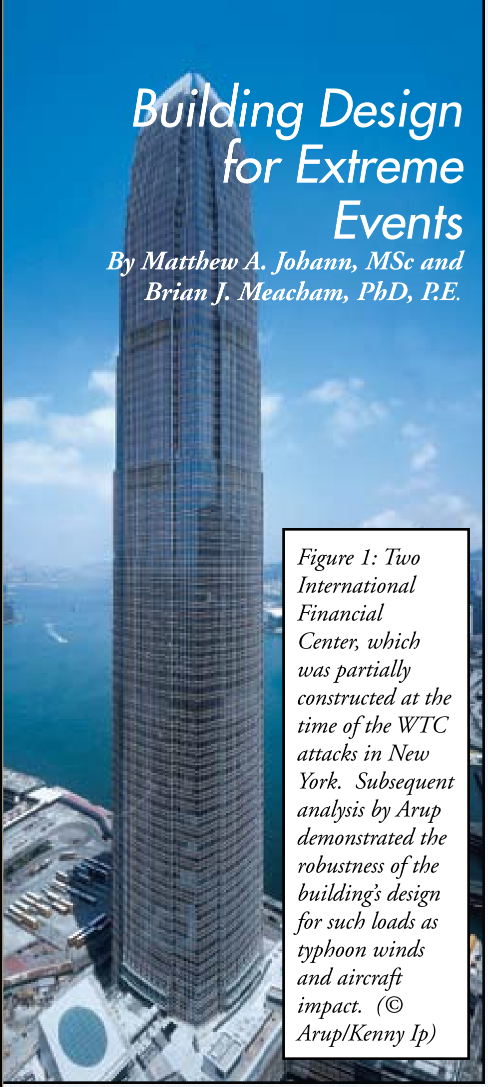


Figure 1: Two International Financial Center, which was partially constructed at the time of the WTC attacks in New York. Subsequent analysis by Arup demonstrated the robustness of the building's design for such loads as typhoon winds and aircraft impact. (© Arup/Kenny Ip)

As recently as five years ago, few building designs considered the potential impact of multiple extreme events, particularly with respect to acts of terrorism, but also from the perspective of interrelated events. Building codes and design standards essentially considered hazard events as individual and unconnected, with the single hazard that was considered having the most severe consequences driving the design (e.g., seismic, wind, fire), with consideration of secondary effects being given lower priority (e.g., post earthquake fire). The events of September 11, 2001, and more recently of September 2005, made it clear that in some cases, and for some buildings, multiple concurrent events or more rare extreme events may need to be considered. Acts of terrorism, multiple-event scenarios, extreme natural hazard events, and building design to tolerable levels of risk are now on the agenda for designers and regulators alike. Now, not only very tall buildings, but selected moderate high-rise and even low-rise buildings, depending on their locations, intended uses and other factors, must be designed with attention to extreme event scenarios. This is not to say that all buildings must now be bunkers, but rather that risk-informed performance-based thinking and decision-making must play a larger role in building design. In recent years, risk-informed engineering techniques and the consideration of extreme events in building design have become more common, even though building codes currently require neither.

This article is the first in a series focused on the design of buildings for protection against the hazards of extreme events. As a starting point, this initial discussion examines the drivers behind the need to consider extreme events in building design, and presents the basic concepts used to guide such design. The subsequent articles will delve further into specific hazards and events, and the methodologies available to protect buildings from these hazards.

The information presented draws heavily from the book *Extreme Event Mitigation in Buildings – Analysis and Design* [1]. The focus is on mitigation concepts for various events, set within the framework of risk-informed performance-based analysis and design.

Drivers for Extreme Event Design

The potential impacts resulting from extreme events can be devastating. This has been made evident by many past events, including the bombing of the Murrah Federal Building in Oklahoma City, the tragic fire at the Station Nightclub in West Warwick, Rhode Island, and the attacks on the World Trade Center towers and the Pentagon. The potential outcomes of such events are themselves the primary drivers for specialized design approaches. Specific concerns for the various types of extreme events are discussed below.

September 11, 2001 and the NIST World Trade Center Investigation

There is no need to review in detail the attacks on the World Trade Center towers and on the Pentagon on September 11, 2001. The events of this day are burned into the minds of people around the world. With the exception of those who lost loved ones in these events, perhaps no community was moved as much as building designers and engineers, who watched in horrified amazement as these steel and concrete pillars of strength and design prowess were reduced in total or in part to dust-enshrouded piles of rubble live on national television. The subsequent efforts in answering the questions "how" and "why" demand attention in any discussion of building engineering for extreme events, since these incidents have defined the term *extreme event* for many in the current environment.

Focusing on the attacks on the World Trade Center (WTC), a great deal of effort has been devoted to determining the building-related factors that led to the collapse of the towers. While the WTC towers themselves and the circumstances of their destruction were clearly unique, an understanding of the mechanisms that resulted in their collapse could be critical in helping prevent such building responses in the future. Under the National Construction Safety Team (NCST) Act of October 2002, the National Institute of Standards and Technology (NIST) carried out an extensive technical investigation into the collapse of the WTC towers. According to NIST, this was the single largest technical investigation of a building failure ever conducted [2]. The final report of the investigation included 30 different recommendations "designed to improve the safety of tall buildings, their occupants, and first responders" [3].

The recommendations included in the NIST report on the World Trade Center investigation point out many of the issues that designers considering extreme events must consider, and can be used to help guide design practices.

Fire Hazards

The problem of protecting buildings from the hazards associated with fire has a long and storied history, starting with protection against conflagration. However, prior to the attacks on the World Trade Center and the Pentagon, design approaches in the latter half of the 20th Century focused on protecting against limited or confined fires within single buildings, with unconfined fires considered only sometimes, such as following earthquakes. September 11, 2001 demonstrated the severe hazard associated with unconfined fires within buildings.

Given desires for openness, inviting interior environments, and other visual and spatial attributes, it is difficult, in a purely prescriptive design environment, to include general provisions to protect against unconfined fires. In part, this is because structural response to fire has traditionally not been treated as a structural problem. Current and past design methodologies have been aimed at reducing the exposure

The recommendations of the NIST report were divided into eight groups, as follows:

- Increased Structural Integrity. Specifically, this recommendation includes nationwide adoption of building code provisions to help prevent progressive collapse, better prediction of wind forces on structures, and enhanced resistance to building sway under high wind and earthquake conditions, as well as development of reliable methods for predicting complex failure mechanisms when multiple hazards are present.
- Enhanced Fire Resistance of Structures. Part of this recommendation is the codification of improved methods for the determination of construction classifications and appropriate fire resistance requirements. Also, NIST recommends that the methodology for determining the fire resistance of structural members and assemblies be updated, and that standard methods be developed for testing fire proofing materials in the as-applied state. Lastly, this recommendation calls for members that connect to columns and bracing members that carry gravity loads to have the same fire rating as columns.
- New Methods for Fire Resistance Design of Structures. NIST has recommended that buildings be designed to withstand, without total collapse, uncontrolled fires that result in full burn-out. Performance-based design is noted as a method of considering real fire conditions in the design of structures, but NIST recommends the development of code provisions to govern performance-based approaches. There may be great potential benefit in novel protection materials and advanced high-performance structural materials, but barriers to their use exist and need to be removed.
- Active Fire Protection. The performance, reliability, and redundancy of active fire protection systems, including sprinklers, standpipes, detection and alarm systems, and smoke control systems, should be increased.
- Improved Building Evacuation. NIST recommended that egress systems be designed to allow timely full evacuation of buildings during large-scale emergencies. It is acknowledged that significant public education may be necessary to support this, and this is likewise recommended. It is important that the design of egress components include sufficient remoteness of egress routes, provisions for maintaining the integrity of egress systems in a wide range of emergencies, and consistent and recognizable components and signage to support ease and rapidity of evacuation. Equally important is clear and efficient dissemination of information to occupants during an emergency, and this will require efforts by and coordination between building owners, managers, and emergency responders.
- Improved Emergency Response. NIST recommends that provisions for emergency response should be improved to provide for better access to all parts of buildings as well as improved communication, command, and control capabilities to support emergency operations. Elevators protected against fire and loss of structural integrity can greatly aid in evacuation and access throughout a tall building.
- Improved Procedures and Practices. NIST recommends that nongovernmental and quasi-governmental agencies that are not typically obligated to comply with building codes be encouraged to do so. Also, they recommend that state and local jurisdictions retroactively enforce (for existing buildings) current building code provisions regarding sprinklers and egress requirements.
- Education and Training. NIST has called for the improvement of the structural design and fire protection skills of building and fire safety professionals through a national education and training program for professional structural engineers, fire protection engineers, and architects. Also, additional training is necessary to improve the skills of building regulators and fire service personnel in reviewing, inspecting, and approving building designs.▪

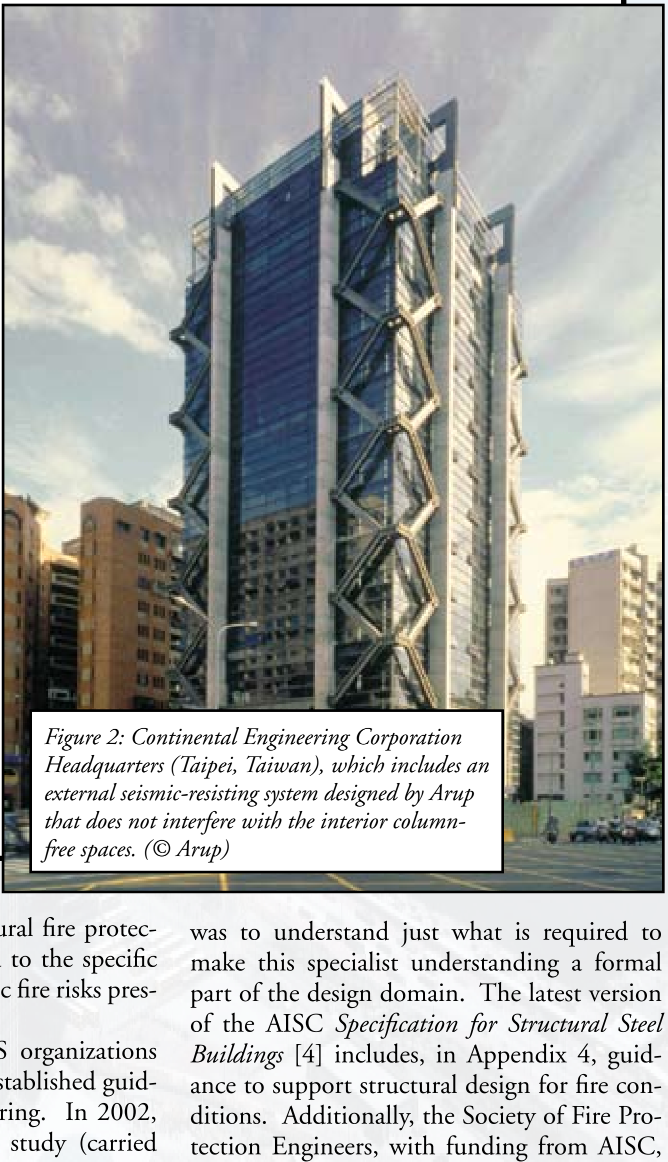
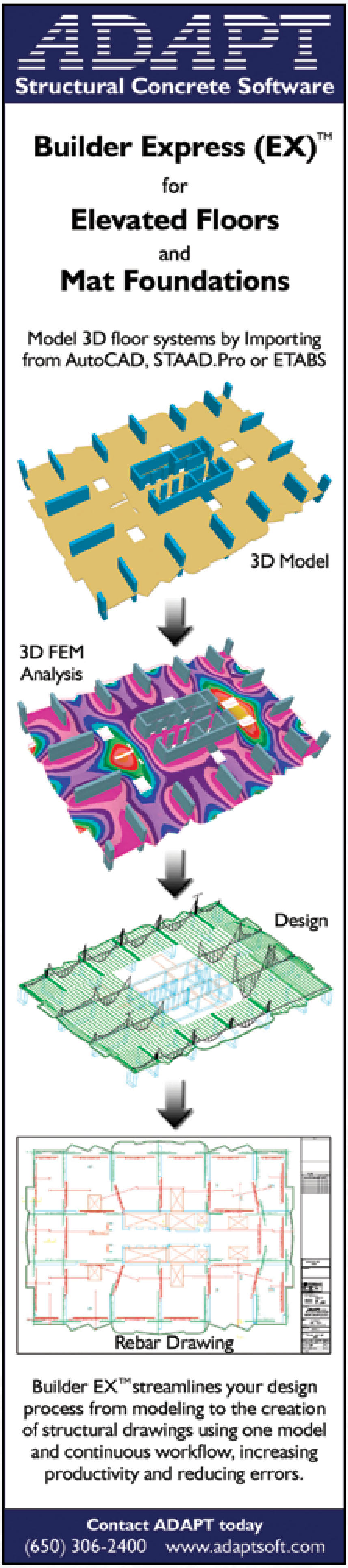


Figure 2: Continental Engineering Corporation Headquarters (Taipei, Taiwan), which includes an external seismic-resisting system designed by Arup that does not interfere with the interior column-free spaces. (© Arup)

of structural elements to high temperatures by applying fireproofing or otherwise protecting them. This type of approach has been based on the heating of single elements or limited assemblies in test furnaces. While this approach has served the design community and the public well, increased understanding of real structural response to fire can support the development of new approaches that can explicitly quantify fire exposures to structures, however severe they may be, and can determine true structural performance under a range of fire conditions for individual buildings. This means that a building's structural fire protection strategy could be tailored to the specific type of building and the specific fire risks present.

In recent years, various US organizations have recognized the need for established guidance in structural fire engineering. In 2002, AISC commissioned a major study (carried out by Arup) on the state of the art of structural fire engineering, from gaps in technical knowledge to the needs of regulators, educators, and engineers. The intent of this study was to understand just what is required to make this specialist understanding a formal part of the design domain. The latest version of the AISC *Specification for Structural Steel Buildings* [4] includes, in Appendix 4, guidance to support structural design for fire conditions. Additionally, the Society of Fire Protection Engineers, with funding from AISC, has recently published its *Guide to Fire Exposures to Structural Elements* [5], and is currently developing a *Standard on Calculating Fire Exposures to Structures*.



Earthquake Hazards

There are currently no methods for reliably predicting the timing and magnitude of earthquakes. Because of this, they can present significant design challenges. Earthquakes typically cause less annual economic loss than other natural hazards, but when they do occur, they have the potential to cause widespread devastation in a very short amount of time [6]. The risk of death and injury from an earthquake varies greatly depending on the location of its occurrence. This is because construction practices can vary greatly from place to place, and also because the magnitude and nature of an earthquake, as well as the forces experienced by a given building during an earthquake, can be very location specific [7].

Blast Hazards

Use of explosives against buildings has long been a common weapon of terrorists. In 1946, for example, a terrorist group destroyed a hotel in Jerusalem. In 1982 and 1983, terrorists used truck bombs to attack the US military barracks and embassy in Beirut. Numerous buildings in London were attacked using bombs in the early 1990s, and the World Trade Center in New York was bombed in 1993. An American terrorist bombed the Alfred P. Murrah Federal Building in 1995. Most recently, in July of 2005, multiple bombs were detonated almost simultaneously on subway trains and a public bus in London. This has simply been a list of selected bombings, but it makes it clear that the threat of the blasts against structures is real.

Chemical and Biological Hazards

There has long been a concern over the potential for governments to use chemical and biological agents during wartime. While the threat of a serious, large scale chemical or biological attack from state- or non-state-sponsored groups is alarming, a more likely scenario may include terrorists using an improvised weapon to disseminate agents. The likely targets of such an attack would be buildings and other areas where people gather and where an agent could be contained. Even relatively inefficient release methods could result in significant deaths and casualties; this was made evident by the 1995 sarin attacks in the Tokyo subway. The delivery of weapons-grade anthrax through the US postal system demonstrated that small-scale, unsophisticated attacks can cause deaths and severely disrupt businesses and governments. The recent discovery of a terrorist cell producing ricin near London demonstrated that the raw materials required to produce some agents are relatively inexpensive and are surprisingly easy to obtain.


Figure 3: Arrangement for full-scale testing of the blast resistance of exterior windows in the Scotish Parliament Building. (© Arup)

Combined Hazards

It is important to note that one extreme event may lead to another. For instance, given the right conditions, fires resulting from an earthquake can cause more damage than the earthquake itself [8]. Similarly, blasts may lead to fires, and fires may initiate blasts. The designer may need to consider such possibilities.

Protecting Buildings against Extreme Events

The previous section made clear the range of concerns a building designer may need to consider. However, since the building code generally does not require or guide the consideration of extreme events, how does the designer decide specifically what events need to be considered in the design of a given building? And what magnitude is appropriate for each of those credible events?

There are three major challenges in design of buildings for extreme events: the wide range of events that are possible, the potentially low likelihood of any of these events occurring in a building's lifetime, and the costs associated with implementing certain protective measures. The designer must therefore carefully weigh event scenarios, likelihood of occurrence, tolerable risk, acceptable costs, and desired protection levels, considering a building's occupancy, mission, location, and value (human, monetary and operational). This is where the risk-informed performance-based approach comes in.

Risk-informed performance-based analysis and design is a concept that integrates risk characterization and performance-based analysis and design concepts by considering threat and risk data along with stakeholder and societal risk perceptions and performance expectations, establishing agreed upon building performance targets for a broad set of hazard events, and utilizing a mix of established and emerging technology and materials to design and construct a building to agreed performance objectives. It requires risk characterization (including threat, risk, and vulnerability analysis), agreed upon performance goals, objectives and criteria, and comprehensive analysis of building response to the agreed upon design loads and criteria (performance-based analysis and design), and analysis of the cost and effectiveness of mitigation measures in the selection of design solutions [1].

Egress Design

While it is important to provide adequate protection for a building against extreme events, it is equally important to protect the occupants of that building, including during the time needed to evacuate the affected floor(s) or the entire building, if necessary, during an event.

Since their early development, building codes have included provisions for the design of egress systems within buildings subject to fires of limited size (i.e., sprinkler-controlled or otherwise confined fires), power outages, some nontoxic hazardous material releases, or other similar incidents. Egress strategies and evacuation plans did not typically include consideration of extreme events, such as uncontrolled fires, earthquakes, or blasts. Building code provisions traditionally set specific maximum and minimum limitations for egress features to help ensure safe evacuation. The World Trade Center and Pentagon attacks in 2001 made clear the need for new approaches and strategies capable of addressing “nontraditional” events.

When considering extreme events, building egress strategies generally include prescriptive-code-compliant life-safety components and features, but implement these through a performance-based overall strategy. Because building codes do not include provisions governing such design approaches, special analysis methods, such as timed egress analyses, are necessary to verify the performance of the strategy [9]. Timed egress analyses enable comparison of actual evacuation times with the times available for evacuation in different portions of the building prior to the onset of hazardous conditions. Additionally, such strategies may include novel egress elements, such as protected elevators. Performance-based egress strategies enable the designer to consider the actual hazards expected for a given building, rather than simply applying a set of “universal” prescriptive provisions.

Summary

The overview provided here is but the tip of a large iceberg. This iceberg’s size is driven by the vast range of possibilities inherent in the concept of extreme events. Protecting buildings and their occupants from such hazards is necessarily quite complex. This series of articles will chip away at this iceberg in an effort to clarify the concerns, technology, and design approaches that drive building design for extreme events. Future articles will discuss specific types of extreme events, as well as the design methodologies that have been developed to protect against those events, in greater detail.▪

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