A RISK-INFORMED PERFORMANCE-BASED APPROACH FOR TALL BUILDING DESIGN

B. MEACHAM
Ove Arup and Partners, Westborough, MA 01581 USA

Abstract

In the weeks and months following the collapse of the World Trade Center Towers 1 and 2 as a result of a terrorist attack, there has been significant discussion relative to whether and/or how the design of very tall buildings may need to change to become more resilient. In many respects, this line of discussion can be easily understood, given the tragic loss of life and destruction of a global icon. However, the question of whether all very tall buildings—many of which will be icons—should be designed to withstand a direct terrorist attack aimed at destroying the buildings, is a very complex issue, and one that needs to consider the risk of the event occurring and the performance of the building under extreme loading conditions. To address the myriad complexities of this issue, a risk-informed performance-based analysis and design approach can provide the framework within which to identify and address the problem. Risk-informed performance-based analysis and design is a process in which stakeholder and regulatory goals and objectives are clearly stated and agreed, a threat and risk assessment is conducted to understand the events that may impact on a building and its occupants, and analysis of the building performance in response to these events provides the basis for design. By developing designs in this manner, all parties involved in the design, approval, operation and occupancy of buildings will be able to see how their multitude of objectives—from safety to function to form—are achieved in the resulting design. When done properly, this can occur without unduly compromising openness, aesthetics, symbolism, safety, or any of the myriad other goals for tall building design. This paper outlines a risk-informed performance-based analysis and design process and illustrates how it can be applied to meet the varied objectives of multiple stakeholders.

Keywords: Tall building design, Risk-informed, Performance-based

1. Introduction

As part of normal practice, tall building design considers a number of load effects that result from natural and technological hazards, such as earthquakes, high wind and fire. In the current environment, however, owners, tenants, and design professionals have a new set of load effects to consider—those resulting from terrorist-delivered blast, impact, and chemical/biological hazards. Although analytical tools and methods exist for assessing the load effects, and materials and methods exist for mitigating various loads, the risk of a terrorist attack and the likelihood of a specific weapon being used are much more difficult to predict and address than for "typical" natural and technological hazards.

In general, factors that can impact a building’s risk of terrorist attack include its symbolic importance, its criticality, and/or the consequences of a successful attack. As evidenced by the attack on the World Trade Center towers in New York City, tall buildings fit several criteria in that they serve as symbols of freedom, economic prosperity, and capitalism, and the consequences of a successful attack can be significant. However, owners and design teams face a difficult task in creating tall buildings that provide protection from terrorist threats, while at the same time retaining features that make them desirable spaces for working and living. Located in dense urban areas, there can be a limited ability to restrict access, which can impact standoff distances and perimeter control (Little et al., 2001). In addition, architectural design aesthetics can conflict with threat mitigation objectives. At the end of the day, however, a balance must be struck, because if financiers and tenants do not feel comfortable with the risk (or their perception of the risk), it may be difficult to obtain financing for, or lease or sell the property and spaces therein.

In light of: (a) the uncertainty about terrorist attack and stakeholder perceptions of risk, (b) the architectural and owner goals and objectives for the building, and (c) the limited resources available for physical protection, a new approach is needed to understand and balance these sometimes competing
objectives in a way that meets stakeholder and societal objectives for occupant life safety while accepting some level of damage to the structure, operations and other non-life safety goals, in a cost-effective manner. A risk-informed performance-based analysis and design approach fulfils this need.

2. Risk-Informed Performance-Based Analysis and Design Concept and Framework

Risk-informed performance-based analysis and design is a concept that (i) considers threat and risk data along with stakeholder and societal risk perceptions and performance expectations, (ii) establishes agreed upon building performance targets for a broad set of hazard events, and (iii) utilizes a mix of established and emerging technology and materials to design and construct a building to agreed performance objectives. It requires risk characterization, development of performance goals, objectives and criteria, comprehensive analysis of building response to the agreed design loads and criteria, and benefit-cost analysis in the selection of design solutions.

2.1 Risk Characterization

Risk characterization is the product of an analytic-deliberative decision-making process, wherein there is an appropriate mix of scientific, engineering and statistical data (from "traditional" risk assessment), and input from interested and affected parties throughout the process (Stern and Fineberg, 1996). It is a decision-driven activity, directed toward informing choices and solving problems, which requires a broad understanding of the relevant losses, harms, or consequences to the interested or affected parties. The success of the risk characterization process depends critically on systematic analysis that is appropriate to the problem, responds to the needs of the interested and affected parties, and treats uncertainties of importance to the decision problem in a comprehensible way. Success also depends on deliberations that formulate the decision problem, guide analysis to improve decision participants’ understanding, seek the meaning of analytic findings and uncertainties, and improve the ability of interested and affected parties to participate effectively in the risk decision process. The process will likely require several iterations, as new information and data become available, and as participants gain better understanding and raise more issues. It will not be effective if one group dominates the deliberations or analysis and forces a solution. The process must have an appropriately diverse participation or representation of the spectrum of interested and affected parties, of decision-makers, and of specialists in appropriate areas of engineering and risk analysis at each step. If this is not done, there may be problems in characterizing appropriately, valuing properly, and gaining acceptance of the outcomes at the end of the process.

The risk characterization process begins with a diagnostic stage, in which the problem is defined, the environment is described, and data are collected. This is illustrated in Fig. 1.

Fig. 1. Diagnostic Steps for Risk Characterization (Stern and Fineberg, 1996).
To help focus the diagnostic stage, a number of questions should be asked, including:

- Who is exposed?
- Which groups are exposed?
- What is posing the risk?
- What is the nature of the harm?
- What qualities of the hazard might affect judgments about the risk?
- Where is the hazard experience?
- Where and how do hazards overlap?
- How adequate are the databases on the risks?
- How much scientific consensus exists about how to analyze the risks?
- How much scientific consensus is there likely to be about risk estimates?
- How much consensus is there among the affected parties about the nature of the risk?
- Are there omissions from the analysis that are important for decisions?

A risk characterization process has been applied to the performance-based building regulatory development process in the United States (Meacham, 2000; 2000a; ICC, 2001). The outcomes include a set of building use groupings, importance criteria, occupant risk characteristics, and hazard events, which provide a basis for establishing building performance objectives in terms of tolerable levels of impact.

### 2.2 Linking Risk Characterization to Performance Objectives and Design Criteria

When designing and constructing a building, quantitative, measurable methods and solutions must be used, which are based on stakeholder and societal objectives and expectations. In most countries, quantitative methods and associated solutions are available in the form of prescriptive codes, standards and design approaches. These approaches have generally been successful; however, key linkages needed for risk-informed performance-based design are missing, including an understanding of societal and stakeholder objectives and quantitative criteria (Meacham et al., 2002). Furthermore, the existing approaches likely have not considered the new hazards and load effects related to the terrorist threat, and quantitative data for design against such loads are not widely available. For a risk-informed performance-based approach to be effective, the link between policy makers, building owners and users, and the technical community is essential. An example of the necessary linkages is illustrated in Fig. 2 below.

**Performance System Model**

- **Client Expectations as expressed in Program Requirements**
  - Objectives / Goals
  - Statement of Requirements (SOR) / Task / Functional element
  - Relative importance / Criticality Minimum Threshold Levels / Risk
  - Level 0-9 Users and Owners
  - Level 0-9 Facility Operational Managers
  - Level 0-9 Portfolio & Asset Managers
  - Level 0-9 Condition and Service Life
  - Indicators of Serviceability/Capability
  - Audit / Verification / Assessment
  - Test Methods / Test Standards / Analytical Tools / Design Codes
  - Project / Facility

- **Regulation and Codes**
  - Objectives / Goals
  - Functional Statements
  - Performance Requirements
  - Safety / Health / Fire / Biosecurity / Sustainability, etc.
  - Relative Performance Levels
  - Performance Criteria
  - Verification / Assessment
  - Test Methods / Test Standards
  - Acceptable / Alternative Solutions
  - Performance Solutions

*NOTE: Based on Technology for ASCE Standards on Whole Building Functionality and Serviceability*

![Fig. 2. Linkages between qualitative and quantitative criteria (Meacham et al., 2002).](image-url)
This diagram illustrates the parallel between stakeholder objectives (on the left) and societal/policy objectives (on the right). Although the objectives may be somewhat different, this diagram provides a basis for comparison and discussion. For example, a goal for both may be "safety," and there is a need to provide functional requirements for achieving this goal. The basis for "safety" lies in the tolerable levels of risk, which leads to descriptions of desired performance. To achieve desired performance, one needs to know the metrics, and needs to have test, measurement, prediction, and calculation methods to assess when the desired performance has been reached. Thus, performance criteria need to be developed within the performance framework and not in isolation. The need for the linkages outlined in Figure 2 can be further seen by going into more detail, as illustrated in Fig. 3 below.

Fig. 3. Relationship between components of performance system (Meacham, 1999)

Fig. 3 illustrates the level of data and understanding of overall building performance that are needed to make the linkage from a goal of "safety," described here in terms of "tenable conditions," to the metrics used to define, measure, construct, and evaluate buildings and building components to provide the desired level of performance and safety. As in Figure 2 above, at the center is the connection between tolerable risk and tolerable performance, in this case with an illustration of several factors affecting risk tolerability (building use, importance, occupant risk characteristics, and hazard events: risk characterization outcomes).

2.3 Linking Risk Characterization and Stakeholder Objectives to Tolerable Levels of Impact

The factors of building use, importance, occupant risk characteristics, and hazard events of concern are critical components in a risk-informed performance-based approach, as they serve as a basis for relating risk concerns to design solutions. As illustrated in Figure 4, a framework for relating these concepts has been outlined and implemented (Meacham, 2000, 2001; ICC, 2001). In the ICC Performance Code for Buildings and Facilities (ICC, 2001), Performance Groups contain buildings of different uses for which similar levels of performance are desired (e.g., Performance Group I includes small unoccupied out buildings, and Performance Group IV includes critical facilities), and the Magnitude of Tolerable Impact reflects an expectation of building performance given a specific Magnitude of Design Event.
As can be seen in Fig. 4, for each magnitude of design hazard event, a level of the tolerable impact is provided for each performance group. For example, for a large magnitude of design hazard event, the tolerable levels of impact are Severe, High, Moderate, and Mild for performance groups (PGs) I, II, III, and IV respectively. This means a building in PG IV should have only mild damage when subjected to the large design hazard event, whereas a building in PG I could experience severe damage. For design purposes, the tolerable levels of impact can be considered the inverse of design performance levels to which the structure must conform when subjected to design loads of various magnitudes (expected performance). For the ICC Performance Code for Buildings and Facilities (ICC, 2001), the tolerable levels of impact were developed based on an understanding of current building performance, hazard event and loss experience, and public perceptions and expectations of the level of safety and risk provided by buildings in the event of natural and technological hazards. Two examples of tolerable levels of impact, Mild and Severe, are as follows:

2.3.1 Mild Impact

- There is no structural damage and the structure is safe to occupy. However, cosmetic damage may occur and some clean-up will likely be required, thus requiring some delay in reoccupying some areas.
- Non-structural systems needed for normal building use and emergency operations are fully operational. This includes such systems as electrical power, ventilation and plumbing systems.
- Injuries to building occupants are minimal in numbers and minor in nature, with a very low likelihood of single or multiple life loss.\(^1\), \(^2\)
- Damage to building contents is minimal in extent and minor in cost.\(^1\), \(^2\)
- No hazardous materials are released to the environment.

2.3.2 Severe Impact

- There is substantial structural damage, but all significant components continue to carry gravity load demands. Repair may not be technically possible. The building is not safe for re-occupancy, as re-occupancy could cause collapse.
- Non-structural systems for normal building use may be completely non-functional. Egress routes may be impaired; emergency systems may be substantially damaged and non-functional.
- Injuries to building occupants may be high in numbers and significant in nature. Significant risk to life may exist. There is a high likelihood of single life loss and a moderate likelihood of multiple life loss.\(^1\), \(^2\)

---

\(^1\) Applies only to hazard-related applied loads.
\(^2\) The nature of the load may result in high levels of expected injuries and damage in localized areas (e.g., fire, blast).
• Damage to building contents may be total.  
• Significant hazardous materials may be released to the environment, with relocation needed for several blocks or more.

Note the use of the terms “may” and “likelihood.” These qualifiers reflect the fact that the above levels of tolerable impact are design levels, and that there is some probability that an actual event will exceed the design impact thresholds. Nonetheless, these levels of tolerable impact can be used, with or without modification, for terrorist design events as well (e.g., blast, impact and chemical/biological), where the design loads can be expressed in terms of forces, overpressures, concentrations, densities or rates, in a similar manner as for “typical” natural and technological event loads.

2.4 Analysis and Design Process

In the broadest sense, performance-based analysis and design is a process of engineering a solution to meet specific levels of performance, where performance may be stated in terms of qualitative or quantitative objectives, criteria, or limiting states of damage or injury (Meacham, 1998). In structural engineering, for example, performance levels are often defined in terms of specific limiting damage states against which a structure’s performance can be objectively measured (Hamburger et al., 1995). In the fire safety community, performance-based fire safety design has been defined as an engineering approach to fire protection design based on (1) established fire safety goals and objectives; (2) deterministic and probabilistic analysis of fire scenarios; and (3) quantitative assessment of design alternatives against the fire safety goals and objectives using accepted engineering tools, methodologies, and performance criteria (SFPE, 2000). Once the stakeholder goals are clear and the risk-informed performance objectives and requirements are agreed (as per the above discussion), the design team can focus on developing solutions to meet these objectives. The basic process for this is outlined in Fig. 5 (adapted from Meacham, 1998).

![Diagram showing iterative nature of performance-based design evaluation process]

Fig. 5 Iterative Nature of the Performance-Based Design Evaluation Process (adapted from Meacham, 1998)

The advantage of a performance-based analysis and design approach lies in the flexibility that can be achieved, while not compromising on safety, cost, or other important factors. It allows all parties involved to agree upon the goals, objectives, criteria, and analysis and evaluation methods, resulting in a design that best fits all parameters – a performance-based design solution.
3. Application of Concept to Protective Design

Assume there is a desire for blast protection for a tall building, where the primary goal is life safety. In general, there are four basic features of physical protection for buildings from blast: the establishment of a secure perimeter, the prevention of progressive structural collapse, the isolation of internal threats from occupied spaces, and the mitigation of debris resulting from the damaged façade and window glazing (Little et al., 2001). Other considerations, such as the securing of non-structural components and the protection of emergency services, are also key design objectives that require attention. The estimated size of the explosive threat (design load) will determine the requirements for each of these protective features and the magnitude of resources needed to protect the occupants.

The first step is to undertake a risk characterization process, wherein such factors as the country where the building will be constructed, the current and projected terrorist threat in that country, and potential threats are considered. The process should include a broad cross-section of stakeholders, with input from law enforcement, emergency services, and other risk, security and technical experts as appropriate. Factors to consider include: not all countries may be significant targets, not all tall buildings fit the high risk profile, and building design to withstand any event is not practical or cost effective. Such issues need to be discussed at the outset, and changes late in the process may be impossible or impractical and very costly. Several tools can be helpful in this stage, from qualitative Threat and Risk Assessment (TARA) approaches, which use risk ranking techniques, to complex computerized risk assessment tools, such as the Infrastructure and Architectural Surety Risk Assessment Model developed by Sandia National Laboratories in the United States (Matalucci, 2001). The level of assessment necessary will be highly dependent on the location of the building and the perceptions of the stakeholders and of the local market.

Once the threat and risk characterization is complete, decisions can be made as to selecting a performance level for the building, which as discussed, will be a function of the magnitudes of design loads that are used and the tolerable level of damage (which is a function of the tolerable risk). Although different performance levels may be considered for different parts of the building, it is generally best to maintain a constant level throughout, as this will help to minimize the likelihood of having unanticipated vulnerabilities. In this example, assume a Performance Group III level of performance is selected as a baseline (as outlined in the ICC Performance Code for Buildings and Facilities), with levels of tolerable impact and magnitudes of design loads developed specific to the blast threat that is agreed for the building.

A performance-based analysis and design can then be undertaken, using the agreed design loads, performance objectives, and performance criteria. This stage will likely require the application of complex analytical tools (e.g., computational fluid dynamics and finite element analysis models) to assess such factors as blast energy from the design load and response of the structure (individual components, systems and entire frame). As noted above, it will be an iterative process and may result in several mitigation (design) options. To help in the decision of which option to select, a benefit-cost analysis (absolute or relative) can be helpful. This is especially true when multiple threats are being considered.

As with the performance-based analysis, the benefit-cost analysis can range from simple to complex, relative to absolute. In the first instance, a simple matrix-based approach can be helpful, in which key criteria are identified, ranked and factored (many of the data for this will come from the risk characterization process). For example, a simple matrix might include:

- Ease of Delivery: relative ranking of ease in which threat could be delivered
- Operational Impact: relative impact on the operations given an attack
- Life Safety Impact: relative impact on occupant life safety given an attack
- Relative Risk: a relative measure of overall risk (incorporating the above three factors)
- Relative Mitigation Effectiveness: relative effectiveness of mitigation measures
- Relative Mitigation Cost: relative cost of mitigation measures
- Relative Cost Effectiveness: a relative measure of cost effectiveness given Relative Mitigation Effectiveness and Relative Cost
- Relative Risk/Cost Ranking: a relative measure of Relative Risk and Relative Cost Effectiveness
The matrix might take the following form, and would be populated by the spaces/functions/elements of concern, with the appropriate rankings:

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 6: Example matrix for ranking relative risk-cost-benefit for mitigation selection

Conclusions

The design of tall buildings following the events of September 11, 2001 has become more complex, with new discussions being held on what level of terrorist risk tall buildings and their occupants face, and how to address these risks in a manner that is cost effective and acceptable to the stakeholders and to society. These complex issues can be addressed by utilizing a risk-informed performance-based approach to tall building design, which engages stakeholders, policy officials, law enforcement and emergency response personnel in discussions with the design team to characterize the risks, establish performance objectives, and enable a cost-effective and acceptable design.

References


