Design and Construction of Skyscrapers

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Abstract. Designing and construction of skyscrapers were always considered as complex projects. This was because the designing and construction of skyscrapers required special considerations not only related to technological factors but also with respect to their safety and security. The considerations of safety and security in the design and construction of buildings in general and tall buildings in particular have taken a new dimension following the tragic events of September 11, 2001 leading to the collapse of World Trade Center (WTC towers). An awareness and acceptance of the threat by policy makers, building owners and importantly the various players involved in the design and construction process from the architect to the structural engineer is necessary for the application of blast-effects mitigation technologies and design methodologies to be effective. The engineering and the architectural professions thus have a strong ongoing need for proper guidance to develop and enhance safety and security of the tall building structures.

This paper examines the key recommendations proposed by the New York City Task Force (NYCTF). It summarizes the key recommendations and provides an overall view of considerations relating to the design and construction of tall buildings in the aftermath of September 11, and puts forward recommendations through which it is possible to provide practical levels of enhanced safety and security.

Keywords: Skyscrapers, Design Considerations, Structural Failure, Security, World Trade Center.

Introduction

Skyscrapers are recognized worldwide as symbols of power and prestige; they have emerged as the most vulnerable targets of terrorist attacks [1]. This is primarily due to their propensity to suffer widespread
damage to life, property and other valuable assets when they become targets of such an attack. In this context, it has hence become necessary to examine whether buildings can be built to either withstand bomb blasts or to minimize the arising consequences in such an event.

Concepts of protective design to shield buildings from such catastrophic events have thus attracted widespread attention. Methods of “hermetically sealing” important buildings from terrorist attacks have been propounded. However since people do not wish to live and work in a city of fortresses, it is necessary to achieve a delicate balance between protecting people and property and providing a pleasant work environment. Security and protection must be incorporated into buildings to act as a passive, non-intrusive shield to such random acts of terrorism [2]. The sacrifice of open spaces, prominent windows, atriums and convenient underground parking in buildings is not always required and must be thoroughly weighed against the potential threat to the building [3-5].

The tragic events of September 11, 2001 have created a sense of uncertainty regarding the safety and security of our built environment in general and tall buildings in particular. The events have heightened the general public anxiety about living and working in high rise buildings, thus questioning the future of such buildings.

While the September 11 terrorists’ attacks and subsequent collapse of WTC towers were an international tragedy, it does not signify any inadequacies in the current building design codes or management practices. It is generally recognized by the building professionals that it is not practical to design a conventional building for extreme events such as September 11 and/or other similar imaginable situations. However, the events have forced the Department of Buildings in New York City, and professionals of the world over to review and where necessary, enhance the current practices to ensure the safety of occupants in tall buildings. The task force set up to review the current design provisions has made several key recommendations to further enhance the safety in high rise buildings [6].

**Key Recommendations of Task Force**

Some of the key recommendations made by the NYCTF include:
1. Improving structural redundancy to prevent progressive collapse.
2. Hardening of stairwells and lift shafts.
3. Prohibit the use of scissor-stairs in high rise commercial buildings.
4. Clarity of egress paths.
5. Mandatory evacuation plans for fire and non-fire related events.
6. Provide automatic fire sprinkler systems for buildings taller than 30m.
7. Air intakes in all new buildings to be located at least 6m above ground and away from exhaust discharges or off-street loading bays.
8. Require controlled inspections to ensure that fireproofing is fully intact on all structural members, after subsequent renovations.

Some or all of these recommendations should be given due consideration in buildings that are being designed to specific performance levels under possible extreme events or unnatural disasters. However, more studies need to be carried out to make definitive recommendations applicable to general buildings. The key design considerations are examined in greater detail in the subsequent sections of this paper.

**Structural Performance Under Extreme Conditions**

The following key design features can affect the performance of a structure under extreme conditions [7]. These include:
1. The overall strength of the floor system.
2. The redundancy and robustness of overall structural framing system.
3. The performance of fireproofing under blast/impact and fire.
4. The ability of stairways/lift enclosures to resist impact.
5. Avoiding concentration of emergency escape paths in the central core.
6. Robustness and redundancy of transfer systems.
7. Performance of structural connections under impact and fire.

**Structural Redundancy and Robustness of Framing Systems**

Buildings are generally designed for combination of gravity, wind and earthquake forces [5, 8, 9]. Whilst forgiving to some misuse from minor overloads, construction defects or local accidental damage, most buildings are not specifically designed to resist an extreme event similar to the WTC.
To mitigate the effects of such events or unnatural disasters, attempts should be made to improve the current provisions of overall structural integrity and robustness through enhanced structural redundancy, and prevention of progressive collapse. These factors are discussed as below.

**Structural Redundancy**

Structural redundancy which defines the ability of the structure to redistribute loads from lost/damaged elements to other members is heavily dependent, in high rise buildings, on the lateral force resisting system and detailing adopted for the structural framing \(^9\).

Relative merits and de-merits of various commonly adopted lateral force resisting systems in steel framed buildings are discussed below.

**Interior Lateral Force Systems**

Common framing examples include Concrete Core Systems as shown in Fig 1, and Steel Braced Core Systems. The advantage of this system lies in the lateral load resisting system being protected in the interior of the building and therefore less vulnerable to extreme level events from outside \(^7\). However the typical framing outside the core generally comprises simple pin-connections and therefore, unless appropriately framed and tied to the bracing elements, is prone to partial collapse and/or significant collapse of floor areas, in the event of loss of an exterior column.

**Exterior Lateral Force Resisting Systems**

Common framing examples include Tubular Systems (similar to WTC), Exterior Braced Systems, as shown in Fig 2, and Moment Frame Systems. The advantage of this system is that the exterior bracing or moment connections offer redundant load paths for exterior columns. However significant damage to the exterior system could compromise the overall stability, leading to possible collapse. It has been hypothesized in the case of the WTC that the eventual implosion-like failure resulted from the collapse of the inner core due to loss in strength from extreme temperatures generated from the fuel fire.
Combined Interior and Exterior Lateral Load Resisting Systems

Common framing examples include Core plus Outrigger Systems, as shown in Fig 3, and Core plus Moment Frame Systems. The advantage of
this system is that redundant load paths can be created with much greater efficiency than either the Interior or Exterior Lateral Load Resistant Systems through the elimination of weak structural links. The primary drawbacks are related to possibly larger column sizes in prime floor space, dedicating floors to incorporate outriggers (e.g. mechanical floors) and comparative loss of erection speed in erecting beam-column moment connections and/or constructing non-typical floors with outriggers. Whilst the Combined Lateral Force Resisting System provides the greatest benefit in terms of structural redundancy, a cost - benefit analysis is nevertheless required for each high rise building to establish the optimum structural system for the defined performance level of the building.

**Progressive Collapse**

While some national Building Regulations provide generic recommendations for the prevention of progressive collapse, most regulations do not deal with the subject specifically or in detail. Even in regulations which contain recommendations, these are primarily limited to concepts of tying the building together and increasing continuity, designing for static weight of falling debris, and in some cases identifying critical elements for static pressure design (e.g. simulating gas explosions). The effectiveness of such recommendations is limited since no reference is made to dynamic loads or ductility requirements. It is therefore necessary to re-examine current design approach used to assess progressive collapse.

![Core Plus Outrigger System](image)

**Fig. 3. Combined interior and exterior lateral load resisting systems.**
It is well known that the energy transmitted from dynamic impact when a floor above collapses onto a floor below, \textit{i.e.}, floor weight multiplied by the height of fall, usually exceeds the energy absorption capacity of a floor designed primarily for static loads \cite{4, 6}. The domino-like progressive collapse of the WTC demonstrated this effect in shocking detail. The key to mitigate this effect is to design floor members with high energy absorption capacity through ductility based design and detailing of beams, slabs and their connections. Increasing ductility whilst maintaining strength, gives a more robust design. Such an approach is currently adopted in seismic design and careful consideration should be given to partially extending such energy absorption design methods for general floor design.

\textit{Performance of Fireproofing}

The WTC collapse has raised serious questions about the performance of passive fire protection systems. The existing prescriptive fire resistance rating methods are based on standard ‘time-temperature’ tests which approximate the heat of cellulosic fires only, \textit{i.e.} from burning desks, carpets, paper, \textit{etc}. This does not provide sufficient information to determine how long a building component in a structural system can be expected to perform in an actual fire. Furthermore, the type of fire, \textit{i.e.} hydrocarbon or cellulosic, determines the rate of temperatures gains thereby affecting the response of the structural materials and performance of fire-proofing materials.

A method of assessing performance of structural members and connections forming part of a structural system in building fires is therefore needed for designers and emergency personnel. The behavior of the structural system under fire conditions should be considered as an integral part of the structural design philosophy \cite{4, 5, 8}. Performance criteria and test methods for fireproofing materials relative to their durability, adhesion, and cohesion when exposed to abrasion, shock, vibration, rapid temperature rise and high-temperature exposures need further study.

\textit{Design of Stairwells / Elevator Shafts}

Safe and rapid evacuation of building occupants requires appropriate egress paths. The key considerations for designers are:

1. Structural integrity of stairwells/lift shafts.
2. Capacity and location of escape stairs.
3. Clarity of egress paths.
4. Planning and training for evacuation.
5. Auxiliary systems, technologies and construction (for example, protected elevators/stairs lobbies, phase 3 elevators).

Current provisions require the stairs and lift shafts to be designed for designated fire ratings only. There is no requirement to design the stairwells and lift shafts to resist impact. The designers should consider designing such critical elements using impact-resistant materials such as reinforced concrete. Hardened stairwells and shafts can improve the ability to resist impact while providing safe evacuation paths for a longer period in case of emergencies. Following an extreme event, it is imperative that alternative secure evacuation routes are available from all parts of the building. Avoiding scissor stairs, widening escape stairs to accelerate evacuation in tall buildings and clarity of egress paths should be duly considered for implementation\textsuperscript{[5]}. In parallel, it is also proposed that providing such enhanced escape paths above the minimum requirements, be considered for exemption from the GFA calculations.

The position of lifts and stairs should be carefully considered to ensure that any single event cannot entirely disrupt the planned escape routes. Rapid access for fire fighters to all parts of the building and fail-safe communication systems should be given primary consideration. Evacuation of disabled should be part of training plans. Studies are being carried out to provide elevators in waterproof, fire and smoke-proof shafts with uninterrupted power supply which can be used to evacuate the occupants quickly and safely during such events. This is contrary to the current practice of not using the lifts during an emergency.

**Design of Transfer Systems**

It is recommended that the transfer structures be made continuous over several supports with substantial structural framing into these members in two directions to create a two-way redundancy that provides an alternative load path in the event of a localized failure. The column connections which support transfer structures should provide sustained strength despite inelastic deformations and be designed as full moment connections. Concerning transfer structures and columns supporting, these should be strengthened to the requirements of the specific local resistance. The same applies to all other elements that have no
redundancies. The transfer systems and non-redundant key elements (such as tension members) should be designed to sustain extended exposure to fire corresponding to the affected floor on which these are located.

**Performance of Connections**

Contrary to the common practice of treating connections as secondary to the design of structural members, it is recommended that the design of connections both in steel and concrete buildings be treated as an integral part of the structural design to ensure that the connections do not fail prematurely in an otherwise well conditioned structure designed to withstand such abnormal events. The structural elements and their connections should be designed to protect against a reduction in capacity and differential thermal expansion that may result in a progressive collapse from extended exposure to fire. Both should be designed to have a fire response appropriate to their design function.

Fire produces a differential thermal expansion, reduces the modulus of elasticity and reduces the yield strength of steel [8]. The performance of test structures has shown that the connections having adequate tension capacity to absorb the load transfers played a key role in preventing sudden collapse. The performance of concrete buildings is dependent on cover to reinforcing steel. Design of connections using friction grip bolts should consider that due to differential expansion during a fire, some or all of the contribution from friction may be lost. The connections should therefore have adequate capacity to withstand failure in case of fire. The performance of friction grip bolts under impact loading should be carefully considered. Similarly, all the key members and their connections should be designed for the associated hazards, threats and credible fire loads, the predicted fire intensity and duration with due consideration to the risk associated with each building and other concomitant factors, e.g. fire safety features provided and proximity to other buildings [8].

The guidelines for general structural design are generally in the form of prescriptive requirements for minimum joint resistance. In determining the response to progressive collapse when a primary load-bearing member is damaged or removed, the most likely load combinations along with inelastic response of the damaged structure should be considered. Connections should be strengthened to accommodate the additional forces arising from such eventualities.
Conclusions

Designing and construction of skyscrapers were always considered as complex projects \[^{[1]}\]. This was because the designing and construction of skyscrapers required special considerations not only related to technological factors but also with respect to their safety and security. The considerations of safety and security in the design and construction of buildings in general and tall buildings in particular have taken a new dimension following the tragic events of September 11, 2001 leading to the collapse of WTC Towers. An awareness and acceptance of the threat by policy makers, building owners and importantly the various players involved in the design and construction process from the architect to the structural engineer is necessary for the application of blast-effects mitigation technologies and design methodologies to be effective \[^{[5]}\]. The engineering and the architectural professions thus have a strong on-going need for proper guidance to develop and enhance safety and security of the tall building structures \[^{[6]}\].

The key recommendations proposed by the New York City Task Force were examined in the previous sections. Recommendations are now suggested based on the review, which may enable the project team to provide practical levels of enhanced safety and security. The recommendations are given as below.

- In view of the events of September 11, the safety and evacuation of occupants in tall buildings should be given primary consideration.
- Design provisions to enhance redundancy and mitigation of progressive collapse are critical to improving safety in tall buildings.
- Properly planned and structurally safe stairwells and elevator shafts improve the safe and quick evacuation of the occupants.
- Design for fireproofing and connections should be an integral part of the design philosophy.
- Practical evacuation plans and training of safety personnel should be given due consideration.
References

تصميم وإنشاء ناطحات السحاب

فيصل منصور عرين
قسم البناء، كلية التصميم والبناء، جامعة سنغافورة الوطنية، سنغافورة

المستخلص. إن تصميم وإنشاء ناطحات السحاب لمن المشاريع المعقدة، فتصميمها وإنشاؤها يتطلب اعتبارات خاصة، ليس فقط ذات صلة بعوامل تكنولوجية، وإنما أيضاً ذات صلة بالسلامة والأمان.

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كلمات مفتاحية: ناطحات السحاب، اعتبارات واحتياطات التصميم، الفشل الإنشائي، السلامة والأمان، مركز التجارة العالمي بنيويورك.