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THE WORLD TRADE CENTER AND 9/11: A DISCUSSION ON SOME ENGINEERING DESIGN ISSUES

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ABSTRACT

This paper discusses the collapse of the World Trade Center towers in New York, on September 11, 2001, may affect structural design philosophies. There is a brief description of the WTC structural system, followed by a short explanation of how the towers collapsed. Survivor accounts are given to consider how the impact and fire affected emergency egress from the structures. The conclusions from the initial report from the US Federal Emergency Management Authority (FEMA) are outlined. Some recent changes to structural design standards are considered. The paper concludes by briefly describing the redevelopment plans being considered by the Lower Manhattan Development Corporation.

KEYWORDS

World Trade Center, WTC, 9/11, aircraft impact, fire engineering, collapse, structural robustness, structural design, building standards, structural steel.

THE WORLD TRADE CENTER

Manhattan Island was much smaller in 1664 when the English took over a Dutch fort in New Amsterdam, and the city of New York was born. Since European settlement, not only has the population grown, but Manhattan has physically changed, as parts of both the Hudson and East Rivers have been reclaimed. Figure 1 shows how the coastline of lower Manhattan has expanded since 1730. The WTC site was once part of the Hudson River.

The architect for the WTC was Minoru Yamasaki, with the structural engineering led by John Skilling and Leslie Robertson of Worthington, Skilling, Helle and Jackson. The ground breaking ceremony was August 5, 1966, with the official ribbon cutting on April 4, 1973.

The two tower 100 storey office blocks, each 110 storeys high, are part of larger development with four 8-storey and 10-storey buildings around the towers as shown in Figure 2. The 110 upper floors contain open-plan offices, free from internal supports, each with 2900 m² of effective floor area. In the

six basement floors there are stations for the New York subway system and New Jersey train services, as well as underground parking, air-conditioning plant and other technical services. Each tower was approximately 411 m high, 63.5 x 63.5 m square on plan, with a core 24 x 42 m.



Figure 1: Manhattan circa 1730, showing original and current island profile and location of the WTC site.

(source: <http://www.renewnyc.com>)



Figure 2: WTC site.

(source: FEMA report)

The primary design concern for these very tall towers was wind load. The primary structural system is formed by the walls, which comprised of 59 box-section columns (spaced at 1.02 m centres). These walls, and the flooring system, form a torsionally rigid framed tube which is fixed to the foundations and transmits all wind loads. The floors span without intermediate columns between the external columns and the core. The core carried vertical loading only. The external walls were comprised from prefabricated three-storey units.

The composite floors comprised of light trusses spaced at approximately 2 m centres and braced transversely by secondary joists. Troughed steel decking was connected to the trusses, and 100 mm concrete was laid on the decking. Viscoelastic shock absorbers between the trusses and the external columns were designed to reduce wind induced vibrations of the building.

Some lower floors of WTC 1 were originally fire protected with a spray-applied product containing asbestos, but this was later replaced or encapsulated. The rest of WTC 1 and all of WTC2 was sprayed with an asbestos-free was used. Each element of the steel floor trusses was protected with spray-applied material with average thickness of 20 mm. The FEMA report notes that *“In the mid-1990s, a decision was made to upgrade the fire protection by applying additional material onto the trusses so as to increase fireproofing thickness to 1-1/2 inches. The fireproofing upgrade was applied to individual floors as they became vacant. By September 11, 2001, a total of 31 stories had been upgraded, including the entire impact zone in WTC 1 (floors 94–98), but only the 78th floor in the impact zone in WTC 2 (floors 78–84).”*

Since 1990 automatic sprinklers were progressively installed and by 9/11 most of both towers had sprinkler systems. Each building had standpipes running through each stairway. Pumps were located outside the towers, as well as 3 additional pumps in each tower to provide suitable pressure for water in the buildings.

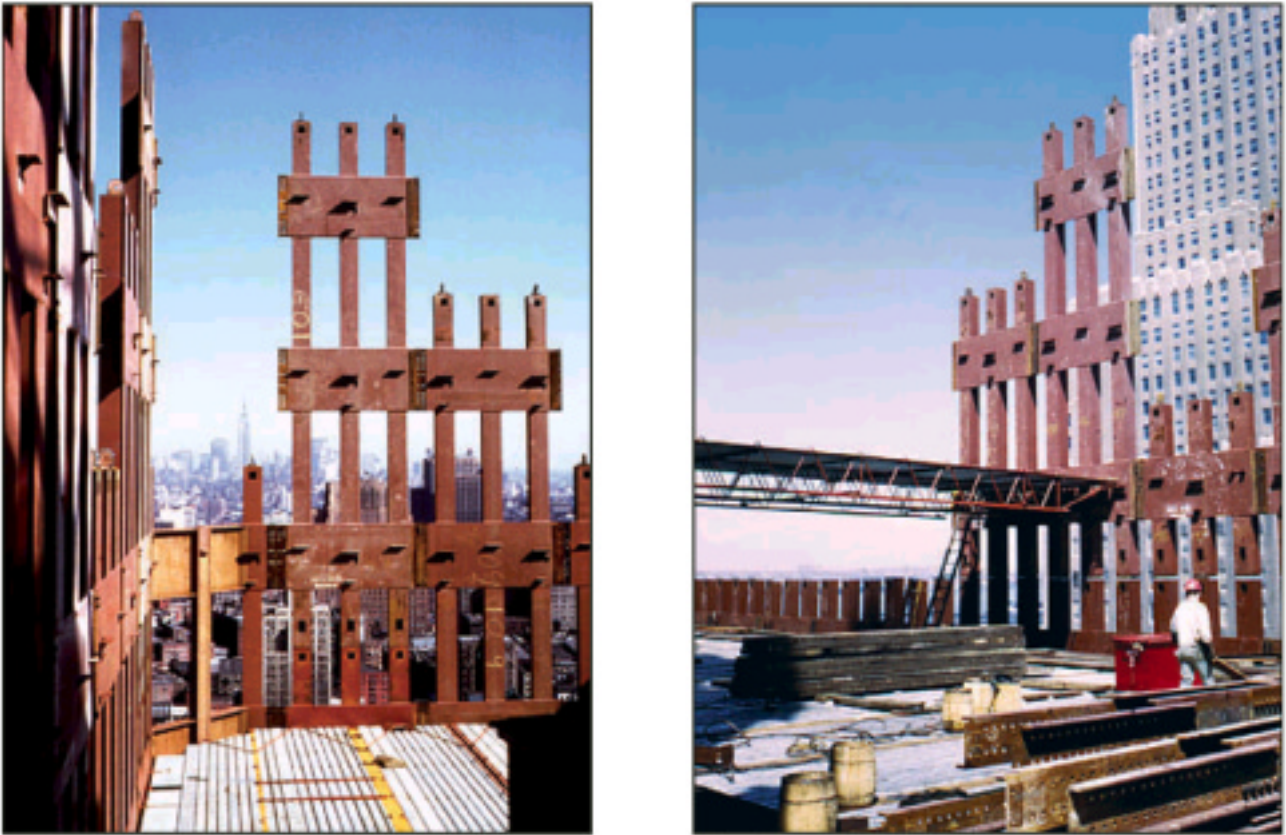


Figure 3: WTC Towers under construction (*Source: FEMA report*)

IMPACT AND COLLAPSE

Impact and Subsequent Fire

Readers would be well aware of the terrorist attacks on the World Trade Center on September 11, 2001. Hijacked Boeing 767s were flown directly into the towers. Figure 4 gives a representation of the impacts. No further elaboration is required.

The Boeing 767-200ER has a wing span of approximately 48 m, whereas each side of the WTC towers was approximately 64 m. Each impact was roughly centred on a building face, and consequently, as shown in Figure 5, the corners of the building were relatively “unharmd”. However, several of the external columns were completely destroyed. The extent of the damage to the core is unknown. The force of the impact removed a significant amount of the fire retardant from structural elements.

The impact created significant vibrations throughout the building, as identified in survivor statements, and created small, but significant permanent deformations to the structure. Analysis from fire/combustion experts suggests that most of the 10000 gallons of fuel in each plane were consumed in the initial fireballs and near the impact floors within a few minutes.



Figure 4: Representation of Impact
(Source: FEMA report)



Figure 2-13 Impact damage to the north face of WTC 1.

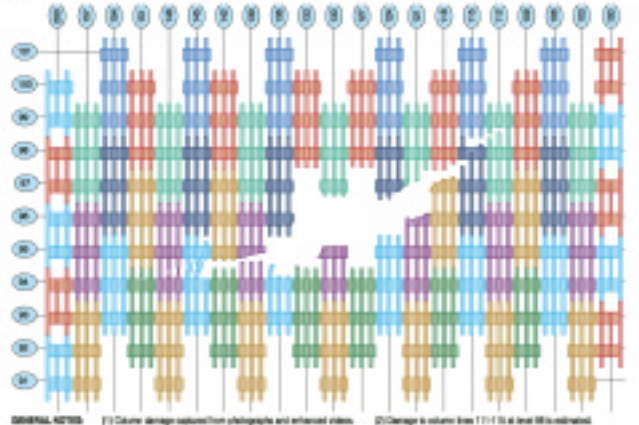


Figure 5: Damage to North Face of WTC 1
(Source: FEMA report)

The towers did not collapse immediately due to their structural redundancy. Load from the damaged sections was redistributed to other parts of the structure. This allowed sufficient time for the occupants on lower floors to escape. However, the impact completely blocked all but one set of 3 fire stairs in the core of each building. Only 4 survivors from upper floors managed to use this exit.

The mechanical properties of steel change with prolonged exposure to high temperatures as illustrated in Figure 6. After approximately 1 hour at 600°C the elastic modulus and yield strength of steel drops by approximately 50%. This implies that the remaining beams and columns in the towers around the impact zone had their strength cut in half, and the deformations of the beams would have been roughly doubled.

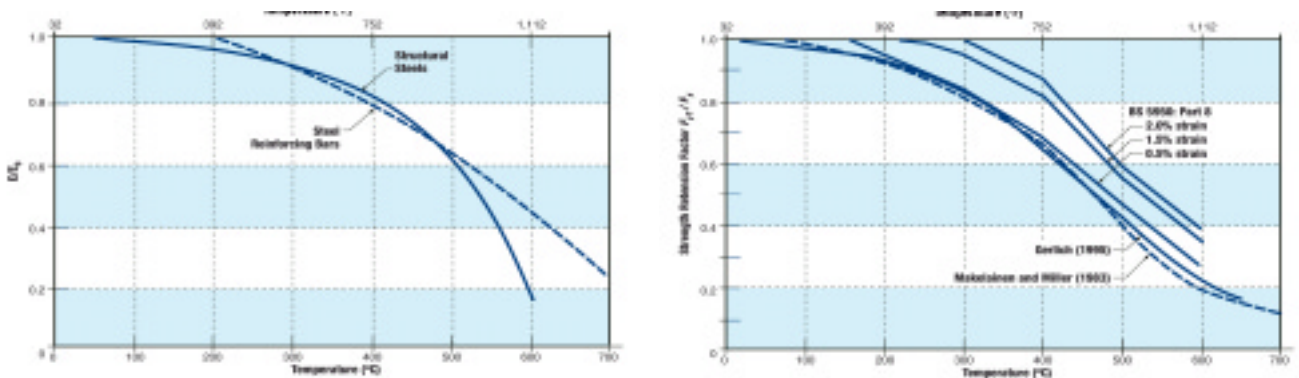


Figure 6: Effect of Fire on Elastic Modulus and Yield Stress of Steel
(Source: FEMA report)

The exact mechanism that initiated failure is not known, but it is most likely that a combination of loss of strength, increased sagging, and stresses due to thermal expansion caused a failure of the joint

which connected the floor system to the external columns. This removed the restraint provided to the external columns and allowed the columns on a floor to buckle outwards as illustrated in Figure 7. Progressive collapse followed.

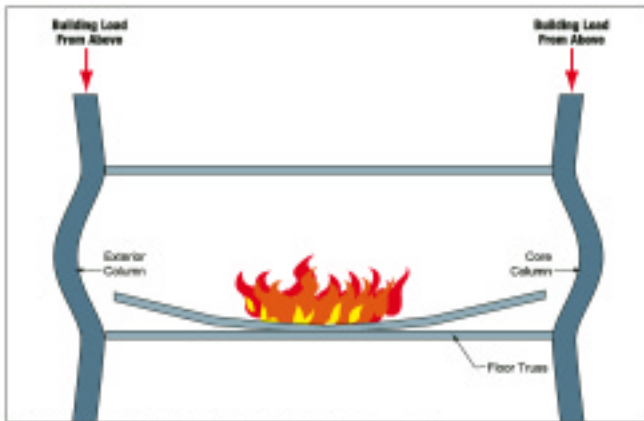


Figure 7: Possible Column Failure Mechanism
(Source: FEMA report)



Figure 8: Progressive Collapse
(Source: Internet - unknown)

SURVIVOR ACCOUNTS

The Sydney Morning Herald (June 1, 2002) reprinted portions of a New York Times special focussing on stories from the occupants. Two excerpts are given below.

“McIntyre, Sharke and 9 other employees, all uninjured, hustled out of the ABS reception area in the north-west corner and turned left towards the lifts and stairways in the tower core. McIntyre recalls peering into a dim shattered stairwell, billowing with smoke. He heard nothing but water cascading down the stairs, almost certainly from severed sprinkler pipes. He looked up. The stairs were blocked by huge pieces of the light gypsum drywall, often called sheetrock, that had enclosed the stairwell. Huge chunks of it sealed the passage from 92, the floor above. Going down the stairs, it made a slightly less formidable obstruction.”

“About two dozen brokers from Carr’s parent company had been called to a special 8 o’clock meeting. When the building sprang back and forth like a car antenna, door frames twisted and jammed shut, trapping a number of them in a conference room.”

These accounts, and many others like them, give insight into the extent of the damage to emergency systems by the impact and fire. Stairwells were blocked. Firedoors jammed shut. The pipes to extinguishers were severed.

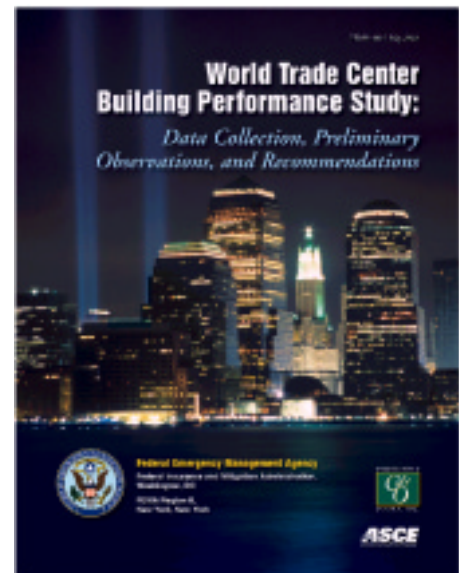
FEMA REPORT

Overview

The Federal Emergency Management Agency (FEMA), the Structural Engineering Institute of the American Society of Civil Engineers (SEI/ASCE), and several other relevant organisation formed a group of civil, structural, and fire protection engineers to study the performance of buildings at the WTC site. Full text of this study is available at <http://www.fema.gov/library/wtcstudy.shtm>.

Quoting directly from the report, its aim was:

“to examine the damage caused by these events, collect data, develop an understanding of the response of each affected building, identify the causes of observed behavior, and identify studies that should be performed. The immediate effects of the aircraft impacts on each tower, the spread of fires following the crashes, the fire-induced reduction of structural strength, and the mechanism that led to the collapse of each tower were studied. Additionally, the performance of buildings in the immediate vicinity of the towers was studied to determine the effects of damage from falling debris and fires. Recommendations are presented for more detailed engineering studies, to complete the assessments and produce improved guidance and tools for building design and performance evaluation.”



Findings and Recommendations

The most important finding is an admission that no structure could have been reasonably expected to withstand the terrorist attack, and the building's robustness allowed for a large number of occupants to escape and survive.

“The structural damage sustained by each of the two buildings as a result of the terrorist attacks was massive. The fact that the structures were able to sustain this level of damage and remain standing for an extended period of time is remarkable and is the reason that most building occupants were able to evacuate safely. Events of this type, resulting in such substantial damage, are generally not considered in building design, and the ability of these structures to successfully withstand such damage is noteworthy.”

The FEMA report identified several important design features of the WTC towers which prevented immediate collapse and allowed most of the building occupiers to escape with a minimum of injury:

- robustness and redundancy of the steel framing system*
- adequate egress stairways that were well marked and lighted*
- conscientious implementation of emergency exiting training programs for building tenants”*

Likewise, FEMA determined some aspects of the design that may have contributed to the catastrophic collapse or the loss of emergency egress systems for upper floor occupants, but stresses that these areas should not be considered as “weaknesses”.

“Similarly, several design features have been identified that may have played a role in allowing the buildings to collapse in the manner that they did and in the inability of victims at and above the impact floors to safely exit. These features should not be regarded either as design deficiencies or as features that should be prohibited in future building codes. Rather, these are features that should be subjected to more detailed evaluation, in order to understand their contribution to the performance of these buildings and how they may perform in other buildings. These include the following:

- the type of steel floor truss system present in these buildings and their structural robustness and redundancy when compared to other structural systems*
- use of impact-resistant enclosures around egress paths*
- resistance of passive fire protection to blasts and impacts in buildings designed to provide resistance to such hazards*

- *grouping emergency egress stairways in the central building core, as opposed to dispersing them throughout the structure.”*

DESIGN STANDARDS

As mentioned above, the FEMA report has identified certain areas of structural design that require further evaluation, but stress that this does not necessarily imply that changes to design standards is required.

Independent of the events of 9/11, there has been a trend in recent design standards to consider “structural robustness” and the need to avoid disproportional collapse.

A new series of loading standards were published by Standards Australia/Standards New Zealand in June 2002. The following is an extract from the commentary to SA/NZS 1170.0 (Clause C6.1).

“A structure should be designed and constructed in such a way that it will not be damaged by events like fire, explosion, impact or consequences of human errors, to an extent disproportionate to the original cause. The potential damage may be avoided or limited by use of the following:

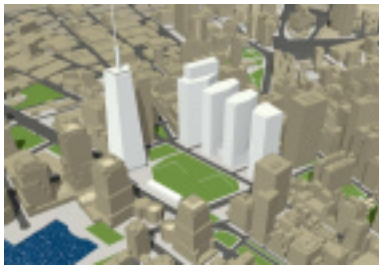
- a. Avoiding, eliminating or reducing the hazards which the structure may sustain.*
- b. Selecting a structural form that has a low sensitivity to the hazards considered.*
- c. Selecting a structural form and design that can survive adequately the accidental removal of an individual element or a limited part of the structure or the occurrence of acceptable localized damage.*
- d. Avoiding as far as possible structural systems that may collapse without warning.*

The design should provide alternate load paths so that the damage is absorbed and sufficient local strength to resist failure of critical members so that major collapse is averted. The materials design Standards usually contain implicit consideration of resistance to local collapse by including such provisions as minimum levels of strength, continuity, and ductility. Connections for example should be designed to be ductile and have a capacity for large deformation and energy absorption under the effect of abnormal conditions.”

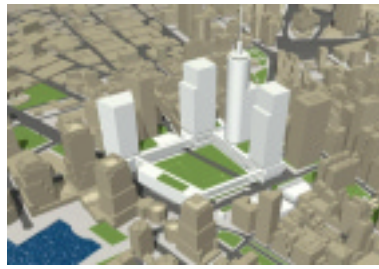
REDEVELOPMENT

In July 2002, the Lower Manhattan Development Corporation released six proposed designs for the WTC site. These are shown in Figure 8. LMDC set a list of goals and objectives for the redevelopment including:

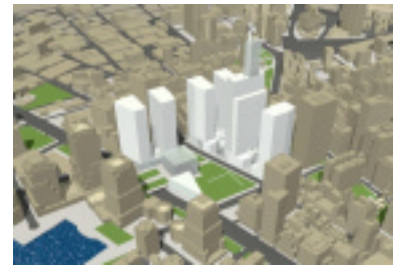
- Respect the site as a place of remembrance and reserve an area as a permanent memorial,
- Create a coordinated transport centre,
- Replace lost commercial office and retail space,
- Create and expand cultural, recreational and open space/park facilities,
- Support sustainable and excellent design, and "green building" technology, state-of-the-art safety and security in design and engineering, and accessible design features, and
- Support excellence in design to ensure the creation of a location that is a symbol of New York City recognized around the world.



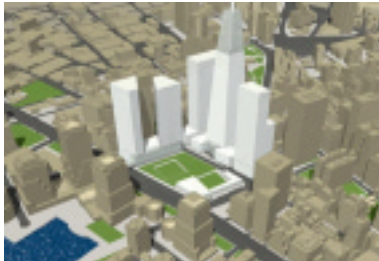
Memorial Plaza



Memorial Square



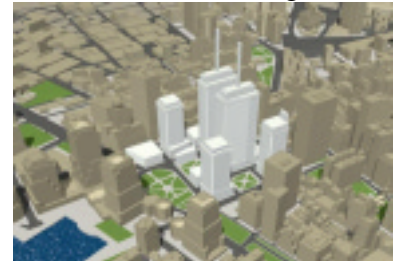
Memorial Triangle



Memorial Garden



Memorial Park



Memorial Promenade

Figure 8: Possible Redevelopment Plans being considered by Lower Manhattan Development Corporation (LMDC) (*source: <http://www.renewnyc.com>*)

SUMMARY

This paper has briefly discussed the structural design of the World Trade Center towers and how the towers collapsed. Survivor accounts are analysed to consider how the impact and fire affected emergency egress from the structures. The initial report from the US Federal Emergency Management Authority (FEMA) is summarised. Most importantly, the FEMA report notes that it was incredible that the structures stood so long, allowing so many occupants to escape, and that it would be unrealistic to design a structure for an event such as this. Some recent changes to structural design standards, such as structural robustness, are considered. The paper concludes by briefly describing the redevelopment plans being considered by the Lower Manhattan Development Corporation.

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