Collapse of the World Trade Center Towers

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Introduction

Construction of the World Trade Center Towers began on August 5 1966 and they were officially opened on April 4 1973. Fig 1. shows the two towers prior to the attack. As will have been forever seared on the memory of all readers, they were destroyed in a terrorist attack on 11 September 2001. The method of destruction was simple and devastating, namely suicide attack by aircraft. The resulting images of the towers burning and collapsing were ones no-one ever expected to see.

The first airplane hit the North Tower at 8.45am local time and that tower collapsed at 10.28 am or 1 ¾ hours after the impact.

The second tower was hit at 9.03 am but collapsed more quickly, at 10.05 am.

Fig 1
World Trade Center Towers Before Attack
(Associated Press photo)

This article has been written by Charles Clifton, HERA Structural Engineer and gives my thoughts on the possible sequence of damage and collapse. I am writing this from 17 years of experience in the research, design and construction of steel framed buildings. A significant part of the research has been determining the behaviour of steel framed buildings under the extreme events of severe earthquake or severe fire. This has given me some insight into what may have happened to these towers under the much more severe event of a direct hit from a near fully loaded large modern airplane. It is important to note that the explanation given is only my considered opinion, based on the information available six to eight days after the event.

Before presenting those details, some details of the building are given, followed by brief details of the impact. The effect of the impacts can only be assessed in light of these details, in particular the devastatingly high local impact force on the buildings from the planes. This is followed by my assessments of the effects of this impact on each of the two towers, which showed some significant differences.

There has already been considerable speculation on the severity of the fire and its role in the collapses. On the basis of what I have seen and heard reported to date, it is my opinion that the effect of the fire was of much less importance than the effect of the initial impact, especially on the first tower to be hit (the North Tower). The reasons behind this opinion follow details of the effects of the impacts on each tower and the article ends with a personal footnote on the tragedy and a reference.

Details of the Buildings

Fig 1 shows the two towers in service. These towers were the principal buildings in a complex of city development. The location of these towers on the World Trade Center site is shown in Fig.2, along with the direction of impacts.

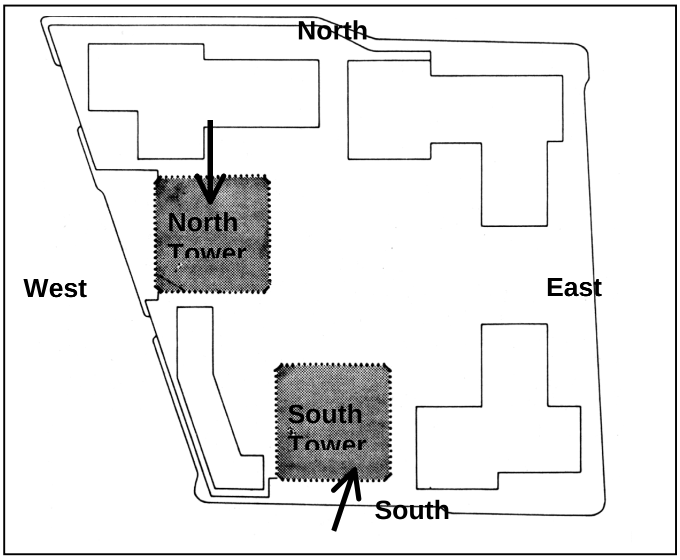

Fig. 2
Site Plan of World Trade Center Development Showing Location of the Two Towers
(The direction of arrows adjacent to each tower shows the approximate direction of the planes on impact)

Each tower was 411 metres high, 63.5 x 63.5 metres square on plan, core 24 x 42 m. There were 110 storeys in each tower.

The towers were one of the best examples of “tube tower construction”, a structural form ideally suited to providing the strength and stiffness required for very tall buildings. On each façade a rigid moment-resisting frame was formed comprising 59 box-section columns, spaced at 1.02 metre centers, connected by deep spandrel beams. The frames did not run into the corners, however, there a shear connection between the two adjacent frames was provided so that the frames, together with the floors, formed a torsionally rigid framed tube fixed to the foundations. This framed tube carried all wind loads. The floors spanned without intermediate columns to the core, which was supported on 44 box-section columns designed and detailed to carry vertical loading only. Fig 3 shows this concept in an isometric view, while one of the 450 x 450 mm exterior frame box columns is shown in Fig. 4.

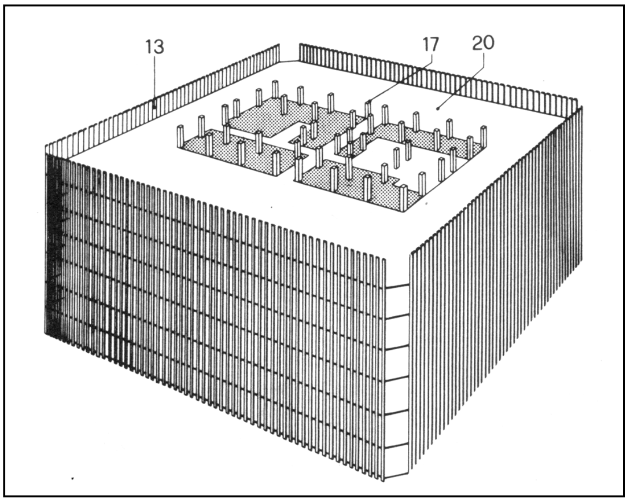

Fig. 3
Isometric View of Building (from [1])

The numbers in the figure are taken from [1] and denote:
13 – Perimeter frame
17 – Core box columns 450 mm square
20 – Floor slab

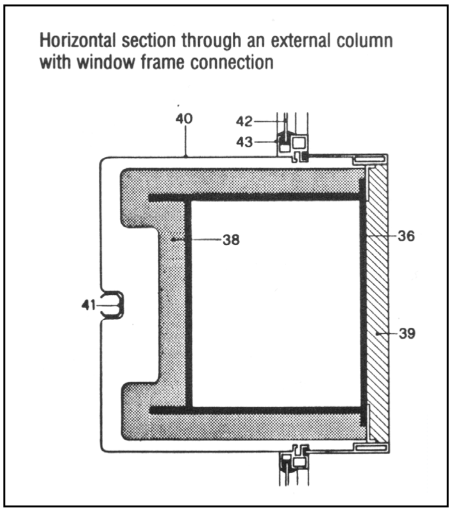

Fig. 4
Cross Section Through Exterior Box Column (from [1])

The numbers in the figure are taken from [1] and denote:
36 – Steel column
38, 39 – Fire resistant plaster
40 – Aluminium façade
42 – Window glass
43 – Window frame

The access and services were carried through the central core, as shown in Fig 5.

The floor system comprised 900 deep bar joists spaced at 2.04 m centers and braced by secondary joists. These secondary joists then supported a profiled deck on which was poured a 100 mm thick light-weight concrete slab. The top of the bar joists stood above the soffit of the decking and was cast into the concrete slab to make the bar joists composite in a similar manner to the *Speedfloor* system.

The bar joists spanned between the perimeter frames and the core, as shown in Fig 6. Fig 7 shows an isometric of part of the floor and exterior wall , illustrating some of the details described above.

The gravity and lateral load-resisting systems were designed to deliver the strength and stiffness required from a 110 storey building with minimum dead load. This was achieved very well, with a steelwork weight of only 44.5 kg/m^2 floor area. The very light and open structure, superbly engineered to meet the design serviceability and ultimate limit state conditions on a building of this height and size, probably made the buildings more vulnerable to collapse from the aircraft impact than would have been the case for a more inefficient and heavier structural system.

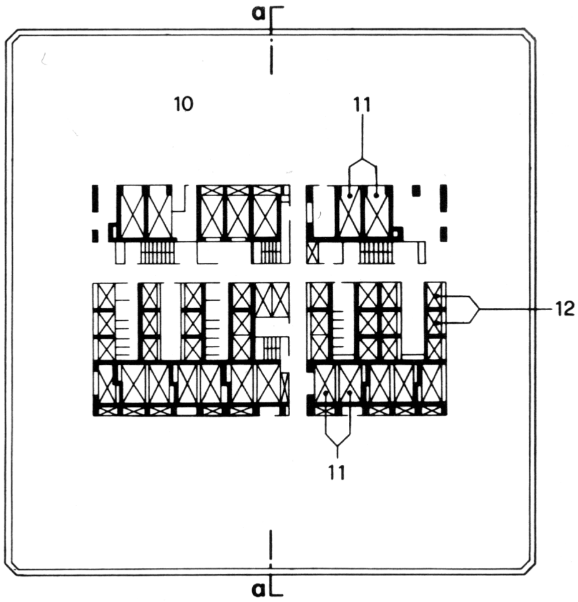

Fig. 5
Plan View of Typical Floor (from [1])
The numbers in the figure are taken from [1] and denote:
11, 12 – Lifts
10 – Open plan offices

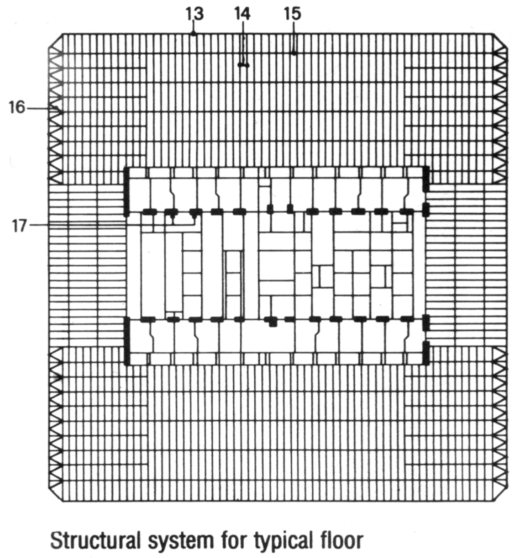

Fig. 6
Structural System for Typical Floor (from [1])
The numbers in the figure are taken from [1] and denote:
13 – Perimeter frame
14 – Bar joists 900 mm deep
15 – Secondary joists
16 – Horizontal floor bracing
17 – Core box columns

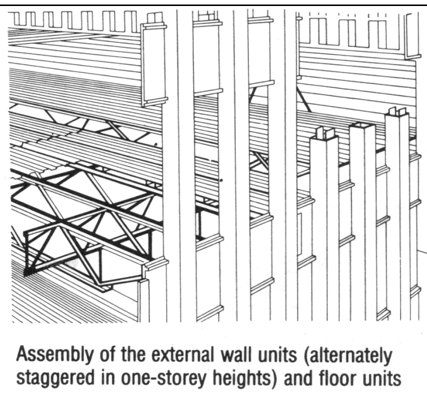

Fig. 7
Isometric View of Floor and Exterior Wall System

Passive fire protection was provided to the columns by vermiculite plaster and to the underside of the floor systems by a fire rated suspended ceiling.

Each tower had an effective floor area of 319,000 m^2 and used 87,000 tonnes of steelwork.

The Impacts

Each tower was hit by a Boeing 767. The impact on the North tower was near the center of the North face at around the 95th storey, with the plane hitting the side of the building square on and flying level. The impact on the South tower was some 15 storeys lower, with the plane hitting the South face near the South East corner and impacting at an angle to the face of the tower. Fig 2 shows the impact directions and Fig 8 shows the plane about to hit the South Tower.

Fig. 8
Plane About to Hit South Tower
(Photo from CNN)

The potential force of the impact from each plane can be approximately calculated and the figures are very large. The weight of each plane would have been approximately 150 tonnes, according to the media reports and Boeing data on this type of plane. The plane would have been traveling at around 800 kms/hour at impact. This gives a momentum of 150x800/3.6=33,333 tonnes.m/sec. If the plane was arrested by the building in 1.5 seconds, which is a reasonable estimate based on the video footage, then the force exerted on the building is the momentum/time to arrest, ie Force=33,333/1.5=22,222kN. To put that in perspective, the ultimate limit state design wind pressure over the entire height of the building is 220 kg/m^2. This gives a ULS wind force on one face of the building of 58, 400 kN. Thus the potential force of impact from the plane is over 1/3 of the design ultimate limit state wind load on the building! Especially in the case of the North Tower, not much of the plane was ejected from the building, so it is reasonable to assume the most of that potential force was absorbed by the building. Also the above calculation also does not take into account any additional force generated inside the building from blast loading due to, for example, exploding jet fuel.

Having done this calculation it is more easy to understand what our eyes showed us – namely the planes slicing through the perimeter frames " like a knife through butter" as one reporter has stated. I contend that, having penetrated the perimeter frames the planes would have done much more that just stripping the fire protection off the columns as has been surmised by some commentators. The effect would have been to completely shatter and eliminate large areas of floor slab and many of the internal supporting columns, thereby immediately destroying much of the vertical load carrying system and leaving the rest vulnerable to any subsequent fire attack. This impact damage - not the severity of the fire – I contend is the principal cause of the ultimate collapse. However the nature and position of impact was different in each case and this led to different effects on each tower, with different collapse mechanisms. These effects are now discussed in as much detail as is possible based on the known information.

Considered Effect of Impact on North Tower.

The North Tower was hit first, with the plane slicing into the North face of the building, as shown in Fig.2. The video footage that has been shown of that impact shows the plane disappearing into the building followed by a fireball erupting from the West and East sides of the building and back out of the entry hole on the North side. Subsequent footage and photos of the South side – the side opposite to the impact – show a large amount of façade destruction and smoke being discharged. This shows that a considerable amount of material exited the building on the opposite side to the impact.

Fig. 9
North Tower After Impact Viewed From the Impact Side
(Photo from CNN)

Fig 9 shows the view looking into the impact hole. Given that the floor slabs are at 3.66 m centers and the façade column centers are at 1.03 metre centers with façade window widths of only 0.48 m, the number of façade columns and perimeter beams severed by the airplane in its passage though the perimeter frame is considerable. From the major damage to the side opposite the impact it is also apparent that much of the airplane would have passed through the core. It is likely that the impact destroyed most of the floors, at least on the impact side, and the core on at least three levels, removing many of the core supporting columns, at least on the North side of the core, and leaving the remainder buckled and stripped of their passive fire protection. This would have caused the floors above the impact level to sag downwards in the center, with the gravity columns above the impact region now acting as tension ties between each of the upper floors, through to the top floor. Each upper floor would now have had to be at least partially supported off the perimeter frame. HERA has developed a method (based on UK fire research) allowing the design of unprotected secondary beams in composite floor systems by using the dependable inelastic reserve of strength from a region of floor slab supported around its perimeter. I have applied this in a very approximate manner to a typical WTC floor slab supported off only the perimeter frame and the result shows that this is just about possible with regard to the membrane capacity of the floor system, but not possible in terms of the vertical load carrying capacity of the connection between the floors and the perimeter frame. As the vertical load carrying capacity of the core diminished, requiring more load to be transferred from the floors to the perimeter frames, the mode of failure would have most likely been failure of this connection, leading to floor collapse.

I contend that, immediately following the impact, the core region of all the floors above the impact region would have sagged downwards due to the loss of vertical support in the core region. This sag would have progressively grown as the fire and ongoing yielding of the remaining damaged core columns reduced the core vertical load carrying capacity. This would have placed severe overstress on the connection between floor and perimeter frame around each floor at every level, with the greatest effect at the top floor, due to the core columns interconnecting each floor above the impact region now acting as tension ties. This would also have put extra vertical load on the perimeter frames, however these are sized to resist the lateral loading and would have had more than sufficient capacity to resist this extra load, especially as it would have distributed itself symmetrically around the perimeter frames.

The sagging of the core region on the upper floors could have been the reason for a phonecall from the upper levels shortly after the impact saying that the building was breaking up. The sagging around the core and the impact damage would also have made the stairs impassible through the impact region, cutting off escape from the upper floors.

The strength, stiffness and redundancy of the perimeter frames would also have been more than adequate to redistribute vertical load around the severed members on the impact side, thus preserving the intergrity of these frames above the impact region.

The likely influence of the fire in the time from impact to collapse would have been to progressively weaken the residual vertical load carrying capacity from the remaining core columns, increasing the need for slab panel action from the floor slabs above the impact region back to the perimeter frame. This would have been transmitted up through the floors above the impact region through the tension tie effect from the core columns, increasing the severity of shear action between the top floor or floors and the perimeter frame.

Finally, it is likely that the interconnection between one or more floors and the perimeter frame failed at or near the top of the building. This would have resulted in the immediate collapse of these floors. From the video footage this collapse appeared to occur uniformly around the building and spread very rapidly down to the floor above the impact region. That region then pancaked causing a brief gout of flame to be expelled most noticeably from around the South and East sides as the areas within the impact region still on fire collapsed.

The collapse then continued down the building, with the floors pancaking leaving the perimeter frames briefly standing unsupported until they too collapsed. The effect of the floors pancaking nearly straight down inside the perimeter frames lead to the North tower effectively imploding, with some sections of the perimeter frame remaining standing unsupported for a few seconds before collapsing. This is seen from a number of video footages and pictures, including the collapse sequence shown in Fig 10.

Fig. 10
Sequence of Collapse of North Tower
(Photo from CNN)

Considered Effect of Impact on South Tower.

At 9.03 am the plane impacted the South side of the south tower towards the South East corner. It struck the building at an angle across that corner and on a slight downwards heading, as shown in Fig.2. The plane passed into the building and then exploded out of the adjacent East side, causing a large fireball to erupt from both the entry and exit sides adjacent to the South East corner. Fig. 8 shows the plane immediately before impact and Fig 11 shows the expanding fireball erupting from both sides of the building.

In contrast to the North Tower impact, in the case of the South Tower only one corner of the core would have been directly in front of the plane’s path through the building, along with the floor slabs over several levels in the South East corner. It is likely that the initial impact destroyed all the floor slabs in that corner over at least four levels and maybe over as many as six. It would have also severely damaged the South East corner core, removing an unknown number of columns there, buckling many more and destroying most of the core walls (which are drywall construction). We do know that at least one stairwell in the core remained intact after the impact, as there were reported to be survivors from the floors above the impact floor who must have had access to an intact stairwell to escape.

Immediately after the impact the perimeter frame in the South East corner would have been severely weakened, being reduced to an unknown number of intact box columns in towards that corner on each of the two sides. However, these columns would have lost the lateral support from the floor slabs over many levels and would have had to function as isolated columns spanning multiple storey heights. They would likely have suffered blast damage and loss of alignment, however immediately following the impact they still retained sufficient compression capacity to resist their share of the loads from the 30 or so floors above the impact region.

Fig.11
Fireball From Impact on South Tower
(Associated Press photo)

Fig.12
Top of South Tower Collapsing
(Photo from CNN)

The fires started by the impact would have then progressively weakened the vertical load carrying capacity of the remaining core, causing progressively more load to have to be carried by the perimeter frame system. In my opinion, based on the footage taken of the building over that time, the fire would have had little impact on the strength and stiffness of the perimeter frames, even in the damaged corner. The stiffness of this system above the impact region would have distributed this load approximately uniformly around the perimeter frames, increasing the loading on these frames through the impact region, including on the residual columns in the damaged corner.

Finally the combination of increasing compression load on these damaged columns, with second order effects from this load acting on the buckled shape of these columns over their unsupported length, would have caused their collapse. This collapse would have initiated in the damaged corner and spread rapidly over the impact region, causing the tower above to fail by toppling sideways with the floors above the impact region momentarily in an intact condition. This stage of the collapse is shown in Fig. 12.

However, even with the top floors toppling sideways, sufficient material would have impacted straight down on the floors below the impact region to have caused these to start to pancake downwards, leading to the tower below the impact region collapsing in much the same manner as the North tower.

With both towers, the forces created by the falling floors above on the floors below would have been orders of magnitude greater than the resistance of these floors, leading to the complete collapses then observed.

How Severe Were the Effects of the Fires?

In my opinion the fires had a less important role to play in the collapse of both towers than the damage from the initial impact. It took both to cause the collapse, however the fire was in no way severe enough to have caused the collapse on its own. The reasons for this opinion are as follows:

1. If the temperatures inside large regions of the building were in the order of 700+ deg C, then these regions would have been glowing red hot and there would have been visible signs of this from the outside. Also there would have been visible signs of flames. If one looks at the photos of the Cardington fire tests, the flames and glowing of the steelwork is clearly visible even in the large enclosure test where the maximum fire temperature was only 700 Deg C. In contrast, the pictures of the towers after the collapse and prior to the impact show sign of severe burning over only relatively small regions of the tops of the towers, even pictures taken from the air looking horizontally into the impact region (eg Fig.9).

   Photos of the First Interstate Bank fire in Los Angeles in the early 1990s? show what appears to be greater heating effects and over larger regions than were apparent in either tower.

   This does not mean that there were no regions subjected to severe heating. It is likely that temperatures in some parts of the impact region would have exceeded 700 deg C for some or all of the time between impact and collapse, especially on the South side of the North tower. However, the extent of impact damage would have been such as to leave the residual vertical load carrying system within the core regions of both buildings vulnerable to further weakening at temperatures lower than 700 deg C.

   In contrast, had the columns in the core and the perimeter frames remained intact and protected (an impossible scenario given the magnitude of the impact) then it is expected that the building would have remained standing, with significant floor damage, even when subjected to fire temperatures of 1000 deg C and having suffered the loss of the fire rated suspended ceiling to the floor slabs.

2. When fully developed fire conditions (temperatures of over 700 deg C) are reached within a region of a building, this results in the breaking of glass in any external windows within that region. This continuous breakage of glass as the fully developed fire spread through the floor of the First Interstate Bank, for example, was the most hazardous feature of the fire to those at ground level around the building.

   In contrast, once the blast and fireball effects of the impacts had subsided, there appeared to be little ongoing window breakage from either tower, either as evidenced from pictures/video footage or as reported from the ground. Significant areas of window even remained intact within the impact region (see eg Fig.9). This is further evidence that fully developed fire conditions did not spread much through and beyond the initial devastated region, following the impacts.

3. If there had been severe fires burning in the core regions of the building due to the fire load from the plane combining with the fire load from the buildings, this would have adversely impacted on the conditions in the stairwells below the impact region. This would have especially been the case for the North Tower, where the core was destroyed by the impact, leaving the regions within the core below fully exposed to fire conditions within the impact region, such as the ingress of burning fuel and other combustables. However the stairwells below the impact region on the North Tower were sufficiently clear to allow some occupants close to the impacted floors to escape and to allow firemen to reach at least the floors around the 70^{th} level, as reported by survivors from the building. In the South Tower, at least one stairwell remained operable past the impact region after the impact. Given the damage that must have been done by the impact to the walls surrounding this stairwell, the resulting fire is unlikely to have been "incredibly severe", otherwise the few survivors from the South Tower above the impact region would not have been able to escape.

4. When the North Tower finally collapsed, the collapse started from the top down onto the impact region. If the fire in this region had been very severe at the moment of collapse, then I would have expected to see a significant burst of fire and burning debris expelled from all around the perimeter of the impact region as it was compressed by the collapse. In reality, the footage of the collapse does not show much flame issuing from the impact region as it is compressed by the collapse.

5. It is reasonable to assume that the force of the impact and subsequent fireball would have stripped the passive fire protection from most if not all of the steel members that remained in place within the impact region. If this is the case and the fire had been as severe as some have stated, the buildings would not have remained standing for as long as they did. Left unprotected, elements of any steel members exposed to severe fire conditions would have quickly reached temperatures close to the fire temperatures. We know this from the large-scale real fire tests conducted in recent years, in which the

bottom flange and webs of unprotected beams and columns exposed to the fires reach 90% or more of the fire temperature and closely follow the fire time-temperature curve. The floor beams and exterior columns of these towers were relatively light members and would have heated up rapidly. Unprotected core columns would have heated up more slowly, but even in that case would not have survived 1 ¾ hours of severe fire exposure prior to collapse, especially if they had also been distorted by the impact. This is because the columns would have tried to expand with the heating and, being unable to do so by the surrounding cold building, would have instead buckled sideways leading to further loss of load carrying capacity. That was probably the mode of failure of any damaged core columns following the initial impact, however the fact that the buildings survived as long as they did after the impact indicates to me that most of the members that survived the initial impact were not then heated to very high temperatures.

The effect of the initial impact was so severe that the fire did not have to do much additional damage to collapse the buildings. It is likely that the fire was a more significant contributing factor for the South Tower, however for the North Tower this is less obvious and it was probably progressive shear failure of the system connecting the floors to the perimeter frames that initiated the final collapse.

In fact it is likely we will never be able to establish with absolute certainty the exact sequence between impact and collapse in either case. The above are simply my best guesses based on the information available and my experience of steel building behaviour in extreme events.

A Personal Footnote.

The two towers were exquisitely well engineered and, as we now know, very well built. It is a tribute to those involved in their design and construction that they absorbed the massive impact from the planes and remained standing long enough to allow many occupants to escape. It is however sobering to reflect on the 5000+ that have been killed in the attack and destruction of these magnificent buildings and the suffering that this has caused and will continue to cause for a long time to come.

Although I did not know anyone directly affected by the attacks, they have left a deep impact on me. As an engineer, part of my response to this is to try and provide my hopefully educated best guesses as to what may have happened to the two towers from the time of impact to collapse. The details given above come from my background of 17 years experience and practice in the research and education into steel building behaviour and design, especially research into their behaviour under severe earthquake and fire attack.

I hope that as much as possible can be learned from this tragedy so that whatever practical steps can be taken to lessen the vulnerability of this type of building to similar attacks (or accidents) in the future can be implemented.

Reference

1. Godfrey, GB (Editor); Multi-Storey Buildings in Steel, Second Edition; Collins, London, England,1985, ISBN 0 00 383031 4