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## **RESISTANCE OF TALL BUILDINGS TO LARGE AIRCRAFT IMPACT AND FIRE**

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### **ABSTRACT**

The demolition of the 420m high twin-towers of the World Trade Center on 11 Sept 2001 by terrorist attack has led structural and fire engineers to consider what might be done to reduce the consequences of terrorist attack against heavily-populated tall buildings by large, fuel-laden aircraft.

The paper discusses the different structural behaviour of the two principal forms of structure used in tall buildings – the cantilever core structure and, as in the WTC towers, the framed-tube structure – and comments on the susceptibility of both to massive horizontal impact and progressive collapse. Some data are presented on the missiles and the targets in the WTC incident and some estimates of local impact forces are made, and the author speculates on the effect of these impacts on the structure.

Structural features of some tall buildings in the UK, USA and Asia are given to illustrate differences in structural design. The hazard of progressive vertical collapse is considered in the context of what UK codes imposed on designers following the partial collapse of the Ronan Point block of flats in London in 1968.

Comments are made on the vulnerability of steel and concrete to impact and fire caused by impact of aircraft, and indications are given on how vulnerability can be reduced. Finally some options are considered, ranging from the general to the specific, for protecting people in tall buildings.

The paper was prepared before the Federal Emergency Management Agency published on the internet its first report ‘World Trade Center Building Performance Study’.

**KEYWORDS:** *tall buildings, impact, fire, collapse, framed-tube building, cantilever core building, structure, World Trade Center, terrorism, Sept 11<sup>th</sup>*

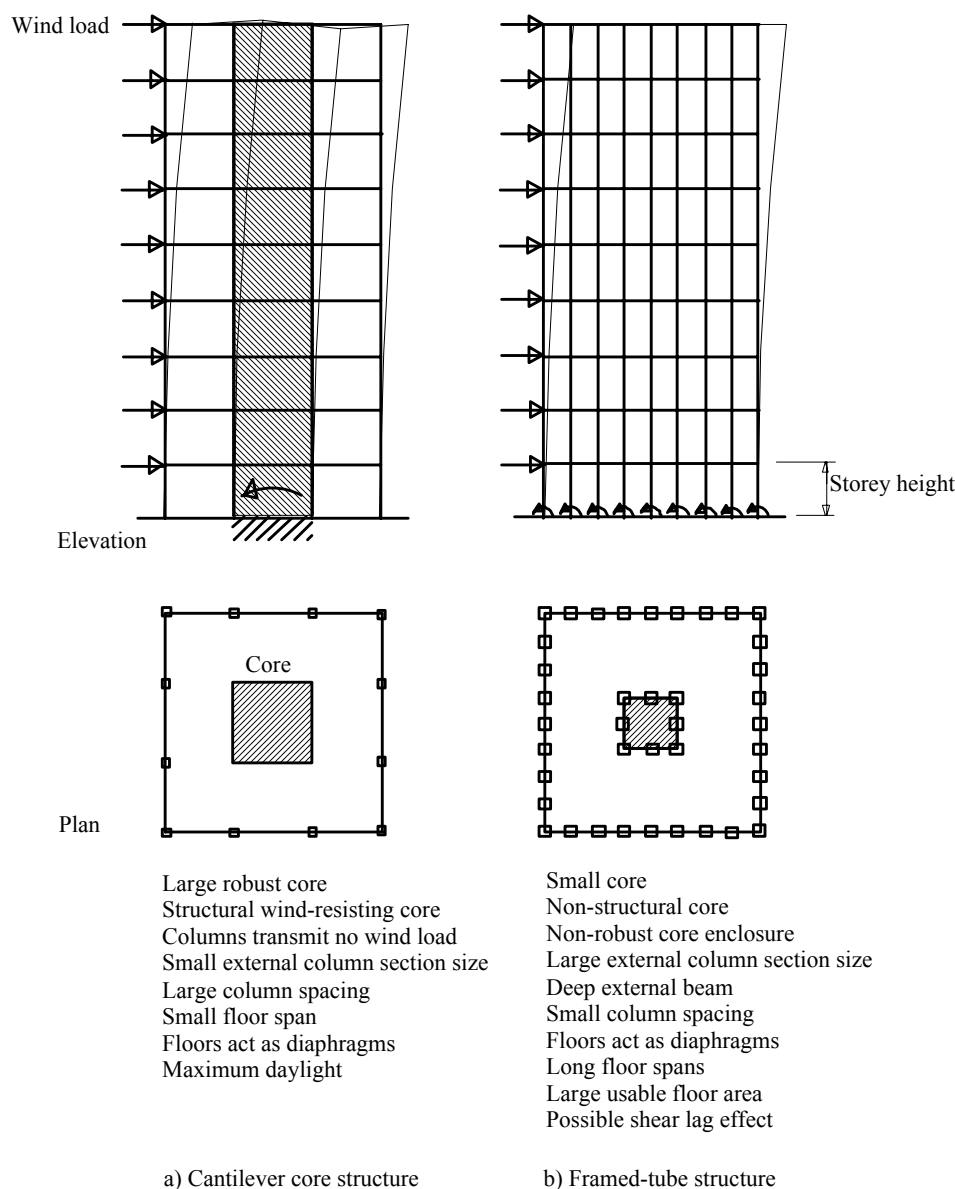


Figure 1 Comparison of cantilever core and framed-tube building

## INTRODUCTION

The demolition of the twin-towers of the World Trade Center (WTC) on 11 Sept 2001 by terrorist attack has led structural and fire engineers to consider what might be done to reduce the consequences of terrorist attack against heavily-populated tall buildings by large, fuel-laden aircraft. The combined effect of impact and fire led to collapse of both towers, the estimated loss of over 3000 lives including 350 firefighters, and estimated insurance losses of around \$30 billion. It triggered world war against terrorism and retaliatory bombing in Afghanistan.

This paper does not speculate on the sequence of structural element failures in the WTC tower collapse since several sequences are possible, besides, the author does not have access to all the video footage, map of debris location, or witness statements. One scenario is that floor beams outside the core may have weakened in the fire allowing the floor slab to drop onto the floor below pancake-fashion causing progressive collapse of that area of the floor for all floors below that level. At some point the external grillage of

columns, having lost the lateral support of the floors, would become unstable because of the greatly increased column buckling length, and the framed-tube, unable to sustain the load, would collapse. Another scenario is that several external columns were buckled outwards by a missile, e.g. an engine, exiting the façade. During the fire the out-of-plumb columns then deflected more away from the building stripping off the delicate floor-to-column connections allowing more gross deflections of the external grillage to occur and this may or may not have been compounded by later collapse of the floors pancake-fashion. A variety of comments have been made and scenarios proposed relating to the collapse of the WTC twin towers [1, 2, 3, 4].

This paper does, however, try to illustrate the main structural differences between the cantilever core structure and the framed-tube structure - forms mostly used in tall buildings - and describes, qualitatively, the vulnerability of these structures to missile attack. Figure 1 illustrates the main differences between the two types. Structural features (including external column sizes and floor depths) of actual buildings are described later so that the reader can get an intuitive feel for their vulnerability to missile and fire attack.

## **THE WTC TOWERS**

The twin towers of the WTC in New York, built in 1966/7, were roughly 60m apart and rose 420m and, in 1973, they were the tallest office towers in the world. The 110 stories contained almost 1million m<sup>2</sup> of office space and they were said to be capable of accommodating 50,000 people. Both towers were framed-tube structures in which the grillage of steel beams and columns forming the external wall carried all of the wind load.

The towers had external columns at nominally 1m centres and were prefabricated from steel plate in the form of a box with constant outside dimension, 450 mm square. The thickness and grade of steel plate were varied in successive steps in the upward direction [5,6]. In the Sept 11 impact zone the steel plate was 6 to 15 mm thick. External beams (spandrel panels) interconnecting the columns comprised steel plate, 1.2m deep. 12m below entrance level the external columns were combined, three in a group, to form single base columns spaced at 3m centres and having an overall cross section 800 mm square. Prefabricated lightweight steel open-web floor trusses were 900mm deep and spanned a maximum of 20m to the core. They were spaced 2m apart and laterally braced with secondary open-web joists. Floors comprised 100mm thick lightweight concrete on profiled steel sheet decking. The service core was nominally 50m by 20m and was supported by 450mm square steel box columns which carried only gravity loads.

### **1993 explosion**

On February 26, 1993, there was a terrorist-inspired explosion in the underground car park of the north tower which killed six people and left a crater 30m wide x 60m deep [7, 8]. There was immediate structural threat to seven columns, each nominally 450mm square, left unbraced for distances up to 18m in some areas. These columns had been

laterally braced by the car parking floor slabs which, in turn, were bracing the retaining wall.

To understand the possible consequence of the 1993 terrorist bomb in the North tower one must have an appreciation of the substructure. The WTC towers were founded on rock and involved the excavation of a massive volume of material and the construction of a 22m deep retaining wall around the site perimeter [9]. At the time the construction of a retaining wall of this depth in an area already well populated with buildings was a major feat and used the slurry-trench method for the 1m thick concrete wall. This involved excavating material while keeping the trench filled with Bentonite and then, when the full depth had been excavated down to bed rock, the trench was filled with concrete from the bottom up using the tremie method, and the Bentonite removed for reuse. In this way the walls of the trench were prevented from collapsing. As excavation for the towers proceeded, ground anchors (called tie-backs) were installed to provide lateral support to the exposed retaining wall. The anchors comprised steel tendons inserted into holes drilled at 45° and anchored in position by grouting them into 11m long drilled portions of the underlying rock, Figure 2. When the basement columns and floors of the towers were installed to the original ground surface, such that they provided lateral support to the retaining wall, the tie-backs were released.

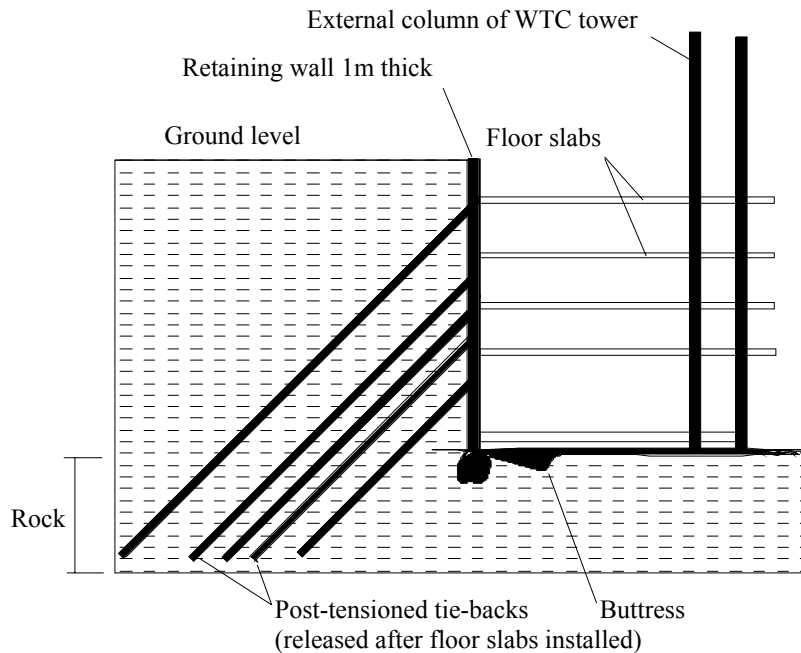


Figure 2 Section through retaining wall near WTC tower

Hence the subsequent removal of sub floors, as in an explosion, could remove the lateral support to the retaining wall which could collapse inwards putting the stability of the whole tower at risk. Fortunately this did not happen following the 1993 explosion. The explosion, however raised questions in some minds as to the wisdom of having towers so close to each other since collapse of one tower, from whatever cause, might destabilise

the retaining wall and thus affect the horizontal restraint of the columns in the other tower, leading in turn to collapse of that tower.

### Sept 11<sup>th</sup>, 2001

On 11 Sept 2001 the 92<sup>nd</sup> floor of the North tower was hit at 8.45 am by a hi-jacked Boeing 767 passenger jet loaded with fuel. At 9.03 am the South tower was hit by a hi-jacked Boeing 757 at the 83<sup>rd</sup> floor. Both impacts were accompanied by a fire ball. The South tower collapsed at 10.05 am and the North tower collapsed at 10.30 am. The plan configuration of towers and aircraft is shown in Figure 3.

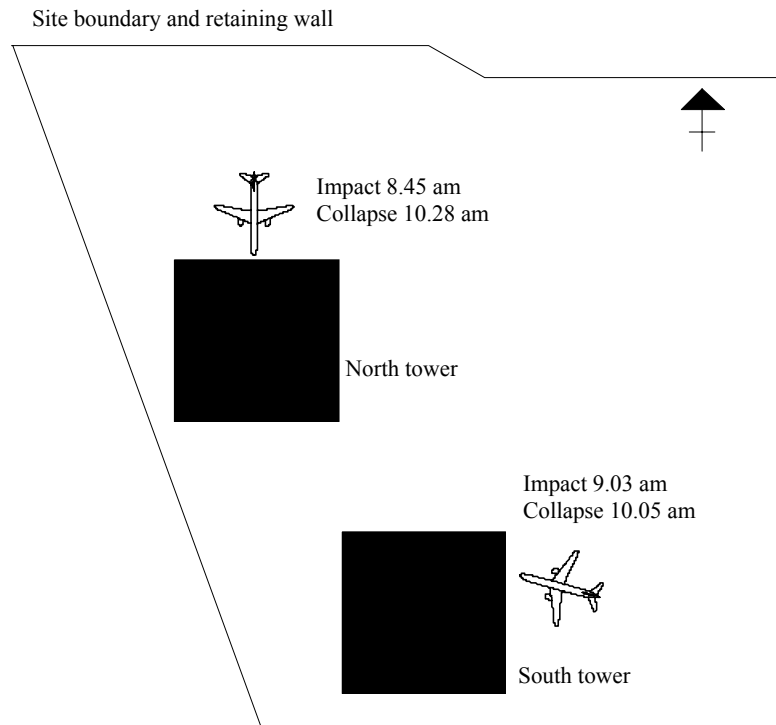


Figure 3 Location of towers and attacking aircraft

A nearby 47 storey building was also damaged, caught fire and collapsed later in the afternoon. The combined effect of impact and fire led to delayed collapse of both towers, the estimated loss of over 2800 lives including 350 firefighters, and estimated insurance losses of around \$30 billion [10]. At the time of writing (6 months after the event) removal of the debris continued. It is remarkable and fortunate that so few of the potential building occupants were killed.

We can say that the towers were able to resist collapse from the impact and that collapse was caused by the effects of fire on a severely distressed structure. It is difficult, however, to be sure about the mechanism of collapse or sequence of events because of the obscuring effect of the smoke and flames issuing from both towers, despite much external video footage. We believe that the floors of the WTC, like floors in most high-

rise buildings, were not designed to resist progressive vertical collapse caused by one floor dropping pancake-fashion onto the floor below. We also know that vertical load bearing members i.e. columns can only support the axial load if they are laterally restrained by the floors at (usually) each floor level. Structural engineers are aware that when the column buckling length is increased (as by the removal of lateral restraint provided by floor slabs), the Euler buckling load  $P$  reduces as the square of the effective length, assuming elastic behaviour:

$$P = \frac{\pi^2 EI}{L^2} = \frac{K}{L^2}$$

where  $E$  = modulus of elasticity  
 $I$  = 2nd moment of area of section  
 $L$  = effective length of column  
 $K$  = a constant

## **TWO TYPES OF BUILDING STRUCTURE**

Although there are hybrid forms, the structure of tall buildings can be divided into two main types: the cantilever core building and the framed-tube building. Figure 1 shows these structural forms. For a given building foot-print the objective is to minimise the area taken up by the core in order to maximise the usable floor area outside the core. To maximise daylighting and simplify services, all the services – stairs, elevators, toilets, and circulation routes – are normally placed within the core which is positioned centrally. Floors are usually simply-supported at their ends because of the large span and, for rectangular floor areas, half the dead and live floor loads are carried by the external columns and half by the core. Live floor loads are usually in the range 5 to 8kN/m<sup>2</sup> for office occupancies.

### **Cantilever core**

In the cantilever core building all of the overturning moment due to wind load is resisted by the central core; the external columns only transmit dead and live loads associated with the floors. The core is typically a heavily reinforced concrete ‘tube’ produced by slip-forming and penetrated by door openings at each storey level. Wind forces are transmitted by the cladding to the external beams and columns, then to floors, then, usually by diaphragm action, to the core, then by flexural action to the foundation raft and piles. The load path is reversed if there is an earthquake. The external columns can be widely spaced around the perimeter of the building and their spacing may be dictated by the spanning capabilities of the floor system used. Since the columns are not required to transmit large bending moments (as in the framed-tube) they can also be small in section size. As in all multi-storey framed buildings, the floors give lateral stability to the columns, and the columns support the floor edge – they are mutually dependent – and this has implications for progressive collapse (see below).

### **Framed-tube**

In the framed-tube building the external beams and columns are sized to transmit in-plane bending moments resulting from wind forces, and the columns additionally carry gravity

loads from the floors. The beam/column joints in the external wall have to be moment-resisting to resist wind loads and this, together with the need for rapid erection, normally means that off-site welded fabrications of ‘tree-columns’ have bolted connections at mid-column height where there is a point of contraflexure (position of zero bending moment). The nature of bending moments and shear forces for part of a framed-tube is shown in Figure 4, the bending moments, shear forces and section sizes diminishing with height above ground. Tree-columns of three-storey height were used in the WTC towers. The service core normally transmits only gravity loads (except in hybrid forms as in the Petronas towers, which are discussed later, in which the core is also a framed-tube). Hence the service core can be constructed on simple beam and post principles and, unlike the heavily reinforced cantilever core, can be clad in lightweight construction which could be very vulnerable to damage by any horizontal missiles which managed to penetrate the external framed-tube grillage. The framed-tube structure does have the ability to survive the removal of several external columns – it is now known from the FEMA report that approximately 30 columns on the north face of the North WTC tower were destroyed over a 4-storey zone and yet the building did not collapse, and this shows a remarkable level of redundancy and load sharing in the undamaged part of the structure.

### PROGRESSIVE COLLAPSE

The removal of a primary structural element such as a column, beam or load-bearing wall, can have a disproportionate effect on the rest of the structure.

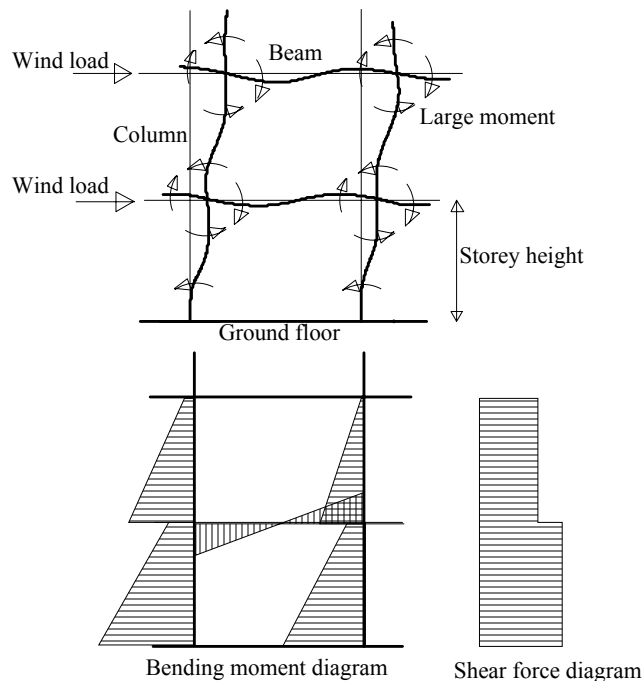


Figure 4 Nature of bending moments and shear forces in part of framed-tube

Progressive collapse is inevitable if floors collapse onto the floor below causing a dynamic load many times greater than the static load normally designed for. Once

collapse begins it cannot be stopped, unless strong floors are incorporated. Many office floors are designed to carry a vertical live load of only  $5\text{kN/m}^2$  plus a small additional load (e.g.  $1.5\text{kN/m}^2$ ) to allow for the weight of moveable partitions.

Progressive collapse was demonstrated in the UK by the collapse in 1968 of one corner of the 22-storey Ronan Point block of flats in London. Triggered by a gas explosion on the 18<sup>th</sup> floor, the corner of the building collapsed from roof to ground level killing four people. The building was formed from large precast wall and floor panels and the collapse revealed that the panel joints were designed to transmit wind pressure at  $12\text{ lb/ft}^2$  whereas explosion pressures were subsequently shown to be 30 to 100 times this pressure. The Report of the Inquiry [11] recommended that designs should take account of alternative load paths when a primary structural member was removed, and building regulations were changed to require design against progressive collapse in buildings more than 5 storeys high. These regulations mean that the designer must show that removal of a primary floor beam does not lead to collapse of the floor, and this means the floor has to be designed with a high level of reinforcing continuity steel in the concrete slab in order to span two bays instead of one. Currently (April 2002) there are UK government proposals [12] to extend the requirements so that they additionally apply to certain buildings, e.g. hospitals, irrespective of number of storeys. However the requirements are not intended to guard against collapse caused by one floor falling onto the floor below and so on – a scenario which seems likely in the WTC disaster - and it is, in the author's opinion, unlikely that a floor designed according to the Ronan Point recommendations would resist progressive collapse caused by one floor falling onto the floor below unless the upper floor sagged slowly onto the floor below, minimising the dynamic loading effect – a mechanism one would like to have, but is unpredictable since floors are not yet intentionally designed with this ductile failure mode in mind.

A missile such as the engine of a passenger jet would, the author believes, easily remove a column in a cantilever core building owing to its slender shape and size. According to UK codes, removal of one column should not lead to progressive collapse, but it seems likely that removal of two or three horizontally-adjacent columns could precipitate collapse unless there was a high degree of redundancy in the structure and negligible wind load acting at the time. Progressive collapse in such a building, however, would be confined to the floors outside the core, but the core, its floors, and its contents would remain standing since penetration of the core, such as to cause progressive collapse of floors within the core, is unlikely assuming the core floors are cast insitu and thus robust. Progressive and unconfined collapse of floors outside the core could be limited by the use of strong floors placed, say, every 10 storeys. These strong floors, perhaps constructed as storey-high vierendeel girders cantilevered from the core, might also be used as safe refuges for people. There are strong floors in the London NatWest office tower described later, though not designed as refuges.

## **IMPACT FROM AIRCRAFT**



To be realistic this paper considers the missiles used in the 11 Sept hi-jacking incident. The Boeing 757 and 767 passenger jets involved are very similar [13]. Both are low wing aircraft with one podded turbofan engine under each wing, and the following gives information essential to understand the missile-like properties of these aircraft. Engines are by Rolls Royce or Pratt and Whitney, weigh around 4400 kg each and are roughly 3m long by 2.2m diameter. The engines are spaced roughly 10m apart. The wing span is approximately 40m, the overall length and height of the aircraft is approximately 45m and 13m respectively. Maximum take-off weight is around 100,000 kg and approach speed with flaps down is in the range 150-250 mph. The 767-400ER for example can carry 300 passengers within a maximum range of about 6000 miles. A fuel capacity of approximately 40,000 litres is possible for a 757, which corresponds to about 25 tonnes. A plan view and front view of a Boeing 757 are shown in Figure 5

The force arising from an impact,  $F$ , can be calculated from Newton's Second Law of Motion: force = mass times deceleration,

$$F = ma \text{ (N)} \tag{1}$$

where  $m$  = mass (kg) and  $a$  = deceleration ( $m/s^2$ )

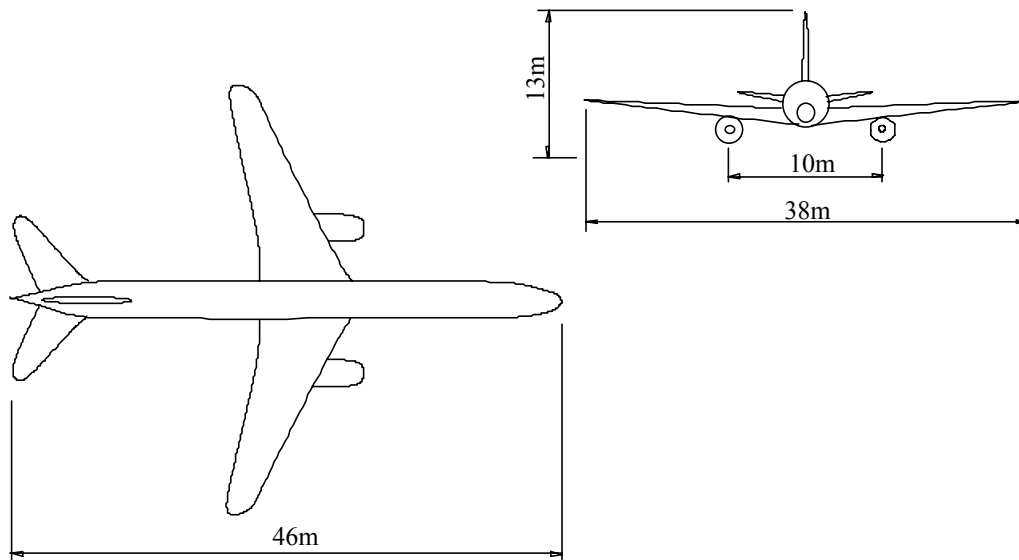


Figure 5 Main dimensions of a Boeing 757-200 twin turbofan passenger jet

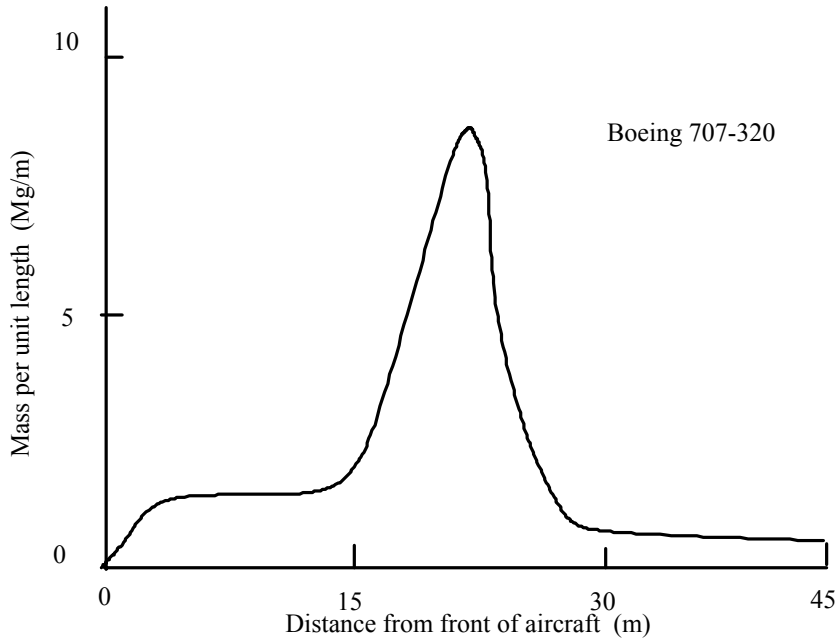
Consider just one jet engine weighing say 4000kg and moving at 250mph. Assume that all parts are decelerated over a period of 10 milliseconds, a big assumption. Then, as 1mile = 1609m:

$$F = \frac{4000 \times 250 \times 1609}{0.010 \times 3600} = 44.7MN$$

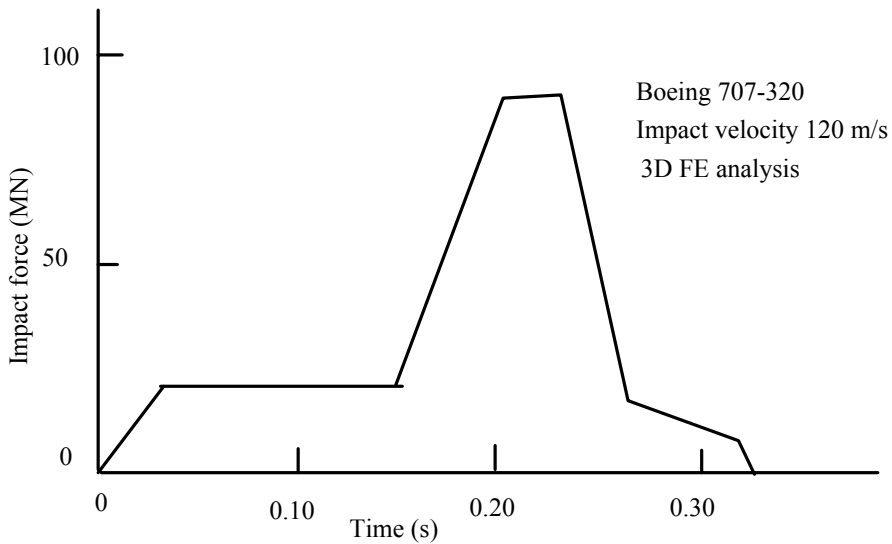
The impulse force is approximately 44.7MN (approx. 447 tonneforce). This is an enormous force. In a sense it is a theoretical force since the target would, arguably, have to be massive and unyielding to cause a deceleration of 10 milliseconds. The duration of impact is clearly important: the nose-to-tail crumpling time of a 43m long 757 aircraft fuselage travelling at 250mph perpendicular to the target is 0.384 seconds assuming the target does not move.

So we may know the mass of the missile (say an engine or a fuselage) but to quantify the force imparted by the missile we must know how the missile and target interact as this affects the deceleration of the missile. Unlike a bullet which may be designed to imbed itself in a target giving all its momentum to the target, a turbofan engine contains hundreds of fan blades moving at high speed and on impact the blades would be released radially due to centrifugal force and some of the concentrated mass would be lost. Thus on impact a turbofan engine would impart its linear momentum to the target and at the same time produce many lethal fan blade missiles travelling radially outwards. The fuselage on impact would crumple from front to back and could be regarded as a large area, soft body impact.

Figure 6a shows the longitudinal distribution of mass/unit length for a Boeing 707-320 from which it may be inferred that most mass resides in the wing area due to the engines, the fuel tanks and the wing construction itself: compare Figure 5 with Figure 6a.



**a) Variation of mass along 707 aircraft**



**b) Variation of impact force with length**

Figure 6 Mass and impact force data for a Boeing 707 passenger aircraft.

Since  $F = m.a$  it is not surprising to find that the curve of impact force with time, Figure 6b, approximately overlays the shape of the curve of mass with longitudinal position. Figure 6b is the impact force computed with a finite element computer program assuming the target is rigid [14]

To make accurate calculations of impact force is difficult. We may know the approach speed of the missile, say 250 mph for a hi-jacked 757 which, to gain accuracy of impact position, has been slowed down but is still above the stalling speed. But questions arise

over the time of deceleration. Is all the linear momentum of the missile imparted to the target as when the missile is embedded in the target, or does the missile or part of it pass through the target? Does the target or part of it behave elastically, instantaneously accelerating away with the missile so reducing the effective deceleration of the missile and the peak force imparted by it? The time period over which the impulse force acts is clearly important and depends on the crushing behaviour of the missile and target. Back-of-envelope calculations can give spurious answers because of the unknown impact duration time, and computer programs are normally used in such studies. In rare cases full size impact tests are carried out.



Figure 7. Silhouette of Boeing 757 against WTC external beam/column grid

Figure 7 gives the relative scale of the fuselage and two engines of a Boeing 757 and the array of beams and columns on the front face of a WTC tower. It will be recalled that the columns were at 1m centres and the storey height was approximately 3.75m. Without advance warning so that the building can be evacuated, it is clear that nothing can be done to avoid loss of life outside the service core within the two or three storey zone impacted by a passenger jet. There are however a large number of columns to resist penetration

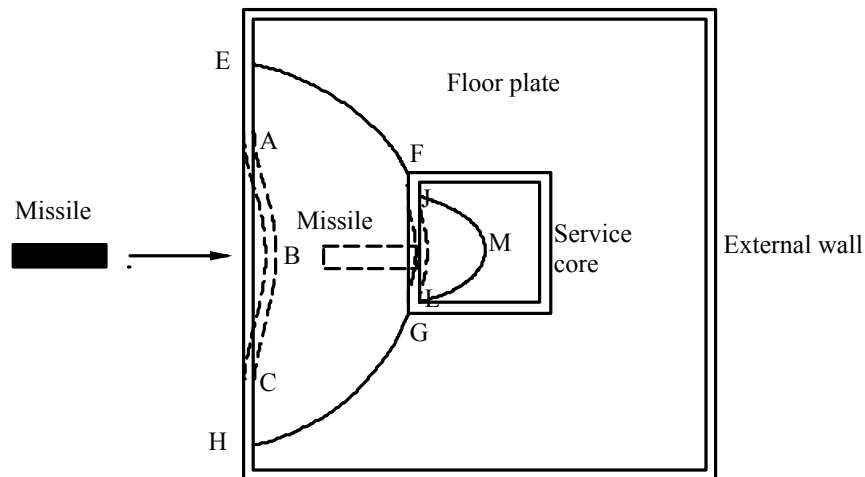


Figure 8. Missile penetrating to service core

A missile could rip through one façade and bury itself in the service core, as shown in Figure 8, or, depending on the robustness of the external columns and the trajectory of the missile (an engine or other heavy object), the missile could rip through one façade and emerge from the opposite façade having missed the service core, Figure 9.

In the case of a framed-tube structure, the missile on entering the façade will instantaneously make the façade framework behave as a tensile network involving catenary forces in the portion ABC in Figure 8. Any bolted joints in the external beam/column assembly (used at the junctions of the 3-storey tree-columns in the WTC towers) would fail since it is unlikely they would not have been designed to transmit large catenary forces. Instantaneously the floor slab (area EFGHE in Figure 8 and its support beams would also be placed in compression and would be expected to fail in buckling. In particular, light steel floor trusses, as used in the WTC towers, would suffer torsional instability. Assuming the missile penetrated the façade it is possible that the missile would damage the core, perhaps in the area FMGF in Figure 8, but such damage would be negligible within the reinforced concrete core of a cantilever core building.

The missile might not be in line with the service core and could enter and exit the façade, Figure 9, creating catenary forces in both facades.

The damage area will inevitably be large and in the case of the WTC façade many columns would be affected as shown in Figure 7. However a missile could more easily penetrate between widely spaced external columns in a cantilever core building resulting in a greater impact force on the core.

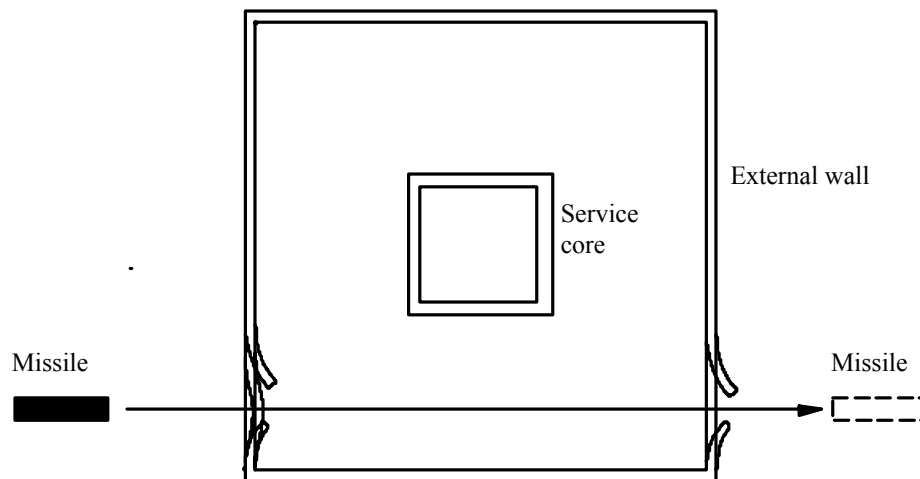


Figure 9 Missile penetrating both facades

## COMPARISON OF WIND AND IMPACT FORCE

It is interesting to compare the wind force acting on the WTC tower in a strong wind with the force produced by the impact of a passenger jet. The WTC tower is 420m high by 63.5 m wide. The wind pressure on a building 35m above ground level is nominally  $1\text{kN/m}^2$  for a wind speed of 40m/s (90mph) [15] and if we assume for simplicity that this acts uniformly over one face of the building, we have a wind force of 27,000kN (i.e.  $420 \times 63.5 \times 1.0$ ) or 27MN. Of course, the wind pressure varies with height and terrain, but the simplifying assumptions made are adequate to get a feel for the magnitude of the force acting. We saw from Figure 6b that the computed maximum impulse force generated on impact of a Boeing 707 was almost 100 MN for impact on a rigid target at 120m/s. A WTC tower could not be regarded as a rigid target and the impact force of a 707 would probably be less than the wind force calculated above. In the USA it is common for buildings to be designed to resist earthquakes and hurricanes with 100 mph wind gusts

## POST-IMPACT FIRE

Any passenger-carrying aircraft large enough to cause serious impact damage to a tall building will be carrying a substantial amount of aviation fuel, even near the end of its planned flight. It will also carry cargo which may be commercial in nature or passenger baggage. In a strictly fire safety engineered design, the design fire – the starting point of design – should take account of the total fire load (building contents plus combustible portions of the aircraft retained in the building), the different rates of heat release of the fuels (building and aircraft) and different ventilation factors. Generally, and this is clear from the well-known equations for compartment fire severity which express the time-

equivalent of fire exposure in terms of fire resistance [16], the larger the ventilation opening the lower the fire severity.

What can we say about the ventilation and fire load immediately after impact? We may assume that flying debris from aircraft impact removes most of the glazing except perhaps that shielded by the core structure, and that the fireball and the resulting thermal shock will remove the rest. It would be convenient for analysis purposes, and for peace of mind, to assume that in terms of fire severity the increased fire load imported into the building impact area by the aircraft would be compensated by the increased ventilation. However, whereas it is relatively easy to assume a ventilation factor for the external wall after impact (e.g. that all the glazing is absent in a storey), it is clearly much more difficult to estimate what the fire load density will be bearing in mind the fluid nature of aviation fuel and its ability to flow down lift shafts and staircases, if not by other routes, into lower floors. Hence fire will occur on several floors due to the flow of fuel to lower floors, and this complicates any analysis of fire severity and the effect upon the structure. What we can say with certainty is that the ventilation formed by the removal of glazing in the external wall will be much less in the framed-tube building than in the cantilever core building simply because in the former the massive beams and columns take up a larger portion of the façade area, and thus the fire severity would be greater, other things being equal.

What we can assume is that fire will only burn and produce heat if there is an adequate supply of air, and this commonplace has implications not only for fire severity but also duration of the fire. In a fire in a compartment of normal office storey height with conventional fuel such as office contents, a naturally developing fire will begin in the item first ignited in one area of a floor and gradually spread to other areas perhaps over a period of 20 or more minutes, accelerating after flashover to involve all the compartment contents. The import of aviation fuel, however, will mean that a large area fire will occur instantaneously when the fire ball inevitably occurs and all the compartment contents catch fire. However it does not follow that the whole area will continue to burn if there is insufficient air to feed the innermost areas of the fire, and this was shown in experiments that the author arranged in the UK Building Research Establishment's Fire Research Station large laboratory at Cardington. In these tests, which used 33 one metre square timber cribs as the fire load in a 23m long compartment 3m high and 6m wide with a ventilation opening at one end 6m wide, it was shown that, after flashover, the burning behaviour of the cribs was the same for the test when 3 cribs at the rear of the compartment were ignited as for the test when all 33 cribs were ignited simultaneously [17]. In the test in which the 33 cribs were ignited simultaneously (corresponding to a large area fire with limited air supply) it was observed that, after flashover, only the cribs near the ventilation opening appeared to be burning while the cribs behind stopped flaming because of oxygen starvation but continued to pyrolyse due to the heat. In other words burning remote from the air supply slowed down. In a building the size of the WTC tower (nominally 65m square) it is possible that fire near the core was not burning as severely as at the perimeter due to restricted air supply, unless the core was itself a source of air supply.

Modern tall buildings may have been designed to withstand a burnout of the contents with a hidden safety factor added to allow for the excessive height of the building, and it is common for such buildings to require a structural fire resistance of at least 90 minutes, with or without automatic sprinkler protection.

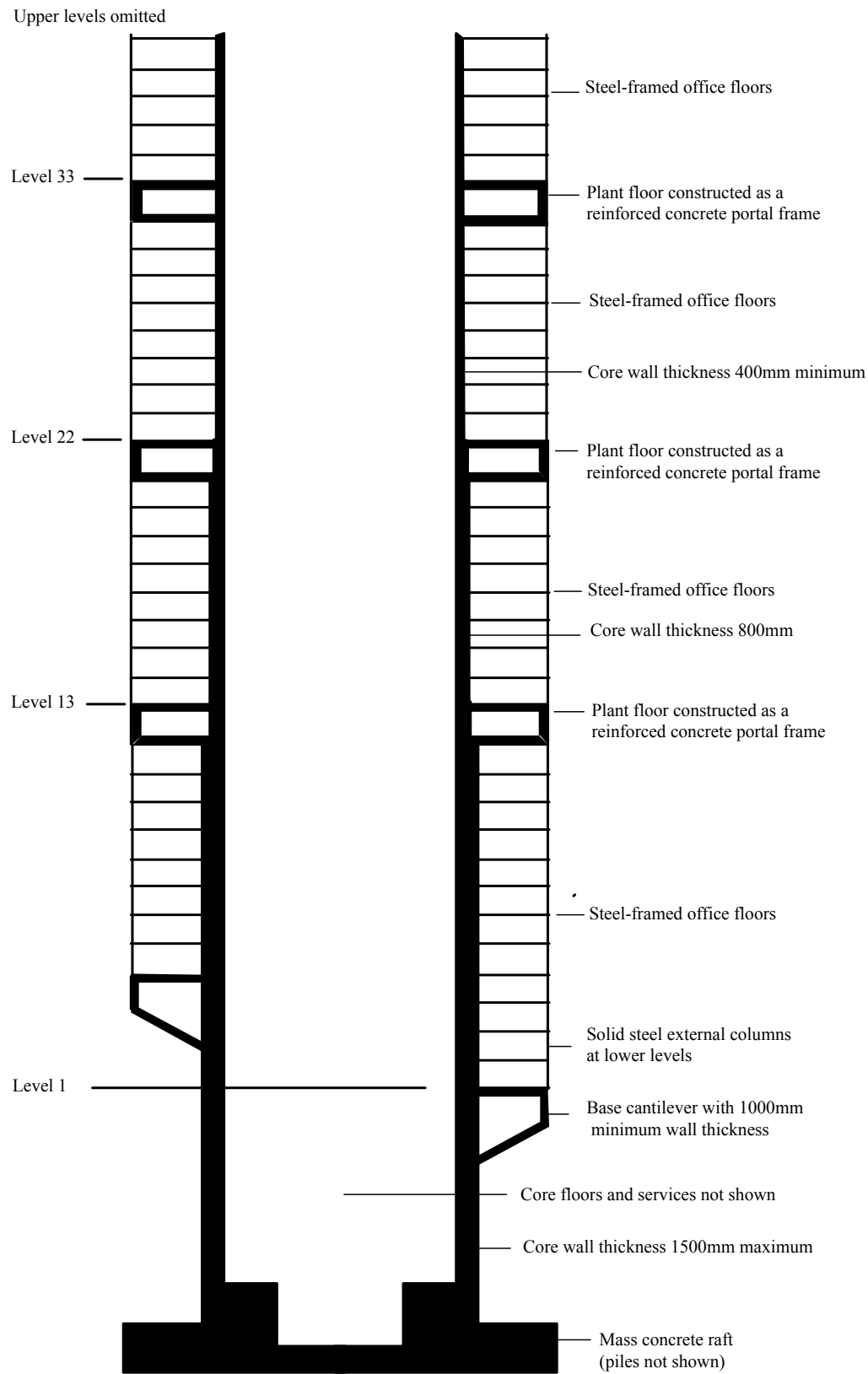
## **EXAMPLE OF UK CANTILEVER CORE BUILDING**

The 173m high NatWest office tower in the city of London is a good example of a cantilever core building and probably remains the tallest cantilever core office tower in the UK even though it was completed in the 1970's. It has an unusual external appearance as it has office floors in 3 distinct leaves springing from a central core at three levels [18]. As usual the central core houses lifts, staircases and toilets. The office floors are separated at levels 13, 22 and 31 by deep intermediate plant floors designed as portal frames which serve the floors above and below, Figure 10. The tower is designed as a cantilever to withstand wind forces and periodic vortex shedding and is founded on a concrete raft supported by 27m long 1.2m diameter piles.

The heavily reinforced concrete core wall varies in thickness from 1500mm at the base to 400mm at the top and can therefore be regarded as very robust against aircraft impact and, resulting from this, immune to progressive collapse of floors within the core. Again, the three base cantilevers are extremely robust, being 9m deep at root and 7m deep at tip. The office floors comprise 306mm deep I-section floor beams spanning a maximum of 10m with composite 117mm thick normal weight concrete incorporating continuity steel on profiled metal deck. The office floors are designed to support a live load of  $8\text{kN/m}^2$  and so that, in common with other buildings designed after the Ronan Point disaster, a floor beam could be removed without affecting the stability of the system. External stanchions are 250mm x 200mm solid laminated steel at lower levels and 203mm universal column sections at upper levels and are at 3m centres. Perimeter beams are 152 x 152 x 37kg UC sections

The incorporation of a robust cantilever service core, the incorporation of immensely robust base cantilevers, robust service floors at three levels (which would probably arrest the progressive collapse of floors in between), and the use of continuity steel in the composite floor slabs, all indicate that the building is, perhaps fortuitously, likely to be very robust against damage by large aircraft impact. Perhaps 2 or 3 floors would be demolished in the impact and fire but the building would remain standing and progressive collapse of floors minimised. It is difficult, however, to say if the stairs above the impact zone would remain usable, because of the unknown response of the fire doors to flying debris and fire.





**Figure 10** Cross section through core of NatWest cantilever tower.

## **EXAMPLES OF FRAMED TUBE BUILDINGS**

One Canada House, commonly called Canary Wharf, is now the best-known tall building in London, United Kingdom, and is a good example of a framed-tube building. The 244m high office tower with 50 floors can accommodate 11,600 people [19]. It was topped out in 1990. It employs the framed-tube concept so that the core is freed of any bracing function and is compact resulting in a high rentable-to-gross floor area ratio. This means the interior framing for the service core is designed solely for gravity loads. The tube is formed from I-section steel members in grade 50 steel. The columns are typically 700mm wide by 400mm deep while the spandrel beams are 1000mm deep by 250mm wide. Like the WTC towers these members were formed into 3-storey high column-trees off-site. A typical floor beam is 456mm deep with a 140mm semi-lightweight concrete topping on trapezoidal metal decking

Three further towers are being built at Canary Wharf. [20] One is tower DS5, the 45 storey office block to be known as 25 Canada Square, and the other two are to be 33 storeys high. Interestingly, all three will incorporate a cantilevered concrete core rising from a piled raft to carry all wind loading, and the external steel framing will carry only gravity loads, unlike One Canada House, the first Canary Wharf tower. The new towers will have almost clear façades because the external columns can be much smaller and are spaced 9m apart. Typical floor beams are 457mm deep UB sections spanning onto 610mm deep UB perimeter beams. The steelwork is spray fire protected. The floor slabs in the superstructure are formed with 130mm thick mesh-reinforced lightweight concrete on profiled metal deck to give 90 minute fire resistance. Although these buildings use cantilever cores, and in this respect are less vulnerable, in the author's opinion, to collapse from aircraft impact than their framed-tube counterparts, the cores are split-cores joined with link beams which may not be as robust as a single core of the same overall size. More importantly the 9m wide spacing of the external columns means that it will be more difficult to withstand missile damage to the external frame and this may have implications for progressive collapse of the floors.

## **EXAMPLE OF HYBRID FRAMED-TUBE BUILDING**

The twin 452m high Petronas towers in Kuala Lumpur city centre are hybrid framed-tube buildings in which the cantilever core carries half the wind load and the external framed-tube carries the other half [21]. At the time of writing (February 2002) the towers are the tallest in the world. Each tower rests on a concrete raft 4.5m deep supported by 104 bored piles some 60 to 115m deep. The towers are circular in cross section and employ 16 large diameter cast insitu circular-section, high strength reinforced concrete columns spaced 8 to 10m apart around the perimeter together with reinforced concrete ring beams to form the framed-tube. Each core has two web walls in a cruciform arrangement and heavily reinforced corners and provides a fire rated shaft. Floors comprise long span steel beams with metal deck topped with normal weight concrete of nominal thickness 110mm for the 90 minute fire resistance needed. The perimeter columns are massive, being 2400mm diameter in grade 80 concrete at the bottom and 1200mm diameter in grade 40 concrete

at the top of the towers (grade 80 means that the concrete has a cube compressive strength of 80Mpa – roughly three times the strength of concrete used in most low-rise projects). The close spacing and large diameter of the columns means that windows are narrow and this reduces solar heat gain and provides much-wanted shading. The size and structural continuity of the columns therefore present, in the author's opinion, an effective barrier to missiles and, provided there was not massive spalling following an aircraft strike, the behaviour in fire should also be good because of the slow heating rate of the massively-sized concrete members.

Each tower is fully sprinklered to NFPA 13 specification and has its own water reservoir in the basement which is mains-fed. The towers are linked by a sky bridge which serves as an egress route and refuge in case of fire. Using the sky bridge and shuttle elevators the building staff can evacuate occupants both vertically and horizontally. The strategy is to use phased evacuation of the fire floor, the floor above and the floor below. Perhaps this strategy will be reconsidered in the light of the WTC disaster.

### **RESEARCH NEEDED**

There seems to be a paucity of published research into the severity of fires involving the burning of aviation fuel in building compartments. As far as the author is aware, fire tests have been conducted with small trays of fuel in compartments but not for the purpose of assessing fully developed fire conditions in office-like scenarios. If this is so he believes it important to make experiments to determine the heat transfer properties of the combustion gases and flames and, importantly, the heating rates of concrete and steel members exposed to such fires. If it could be shown that the severity of burning aviation fuel can be simulated, with reasonable accuracy, using the standard hydrocarbon time-temperature relation used in fire resistance testing, this would be a useful step forward.

The WTC disaster, the author believes, has shown that conventionally designed floors can collapse progressively, pancake-fashion. Floors have to stay in place if lateral instability of loaded columns is to be avoided so that whole-building collapse does not occur. Research is needed to establish if it is technically and economically viable to design floors so that they fail safe when exposed to fire. The WTC floors only collapsed well after the impact i.e. as a result of fire.

### **SUGGESTIONS**

Every building is different. Missiles, or parts of them, are different depending on the particular aircraft design and the cargo and fuel it is carrying. It follows that it is impossible to give generic guidance that in all cases makes a building more resistant to missile damage. The following list is intended to give some ideas on what might be done, and it covers structural and non-structural measures.

- Limit the height of all tall buildings, especially icon buildings, and plan developments so that no single building rises prominently above its neighbour thus making it difficult to target an individual building.

- Perform a risk assessment for the building which includes extreme events such as accidental or malicious impact by large aircraft. This should allow for impact at any storey level and at any orientation in a horizontal plane. Arguably it should consider the worst case scenario for the additive effects of strong wind and missile impact.
- Ideally, design the building specifically to cope with large horizontal impacts. If not, at least check its vulnerability. Consider how the external wall and floors might behave as a missile enters the building and exits the building.
- Consider the effects of removing adjacent primary structural elements by a thorough understanding of alternative load paths and load effects.
- Design each tall building with a service core that acts as a laterally robust structural cantilever, e.g. as in the NatWest tower in London. Avoid designs using a delicate framed-tube construction.
- Where hybrid cantilever core/framed-tube construction is used, avoid the use of tree-columns which have stub-beam bolted connections unable to resist catenary forces arising from a horizontal impact from outside to inside and from inside to outside.
- Employ structurally robust external columns, e.g. as in the Petronas towers, so that a minimum number of columns are destroyed.
- For external columns consider the use of large diameter, high strength, reinforced concrete columns or, as practised in Australia, large welded-plate steel box columns filled with concrete[22].
- For reinforced concrete structural elements, consider including additional layers of anti-spalling steel mesh and/or the use of concrete-embedded fibres of steel or polypropylene to reduce spalling caused by impact and/or fire.
- Avoid using unprotected spray or board fire protection for structural steel beams and columns in which the protection can be easily removed by impact, flying debris or gross deformation. Consider the use of a fabricated stainless steel sheet cover to protect spray and board protection on critical members such as columns.
- Do not use intumescent fire protection for primary structural steel elements (i.e. columns and primary beams) unless it can be proved that the system is very robust.
- To avoid progressive collapse, design floors to behave as tension membranes in the fire limit state and check that floors are strongly connected to the external framework so that the catenary force can be carried and pancake collapse cannot occur.
- Avoid the use of lightweight structural steel members in floor construction which, stripped of their fire protection, heat up rapidly in fire.
- Avoid floor designs that have little in-plane resistance to compression caused by horizontal missile impact, e.g. avoid lightweight steel truss floors (as in the WTC towers) which have little resistance to local buckling and torsional instability.
- Avoid floor-to-wall connections that allow the external wall framing to be easily torn away from the floor construction when a missile exits the building.
- Develop design concepts for floors so that progressive vertical collapse cannot occur. This is of the utmost importance.
- Avoid building deep basements if progressive collapse of upper floors cannot be prevented, especially if there are tall buildings nearby. Basement retaining walls can collapse inwards if basement floors collapse so removing the diaphragm action, and this may make buildings nearby unstable.

- Avoid materials, such as plasterboard, for enclosing the central services core, especially escape stairs, which can be easily penetrated by missile debris.
- Review evacuation strategy – phased or simultaneous
- Include more staircase capacity but with vertically independent zones so that any smoke logging is confined in vertical extent.
- Include safe refuges in certain storeys.
- Maximise the person-holding capacity of the service core.
- Reconsider what appears to be a world-wide policy not to use elevators for escape from fire. In particular, consider greater use of elevators which serve a limited number of storeys so that some remain operational after the impact.
- Avoid placing sprinkler tanks at roof level if bursting of the tanks can lead to excessive loads applied to floors below causing progressive collapse of floors.
- Discount the effect of conventional sprinklers as they would be overwhelmed in a large area fire of the kind associated with burning aviation fuel, assuming the distribution pipework had not been disrupted in the impact. To include a foam fire suppressant would probably be considered unjustified when considering the low probability of a missile strike.
- Employ individual battery-powered emergency lighting luminaires throughout the building so that a missile strike would not leave occupants without light to escape. Avoid reliance on standby generators or central battery packs especially for emergency lighting systems in staircases since these are likely to be destroyed in an impact. It is noted that this is becoming common practice in the UK.
- Provide fire fighters with more education on structural aspects of building design
- Provide fire fighters with advance information on the structural form of the building and the likely resistance of the building to progressive collapse. This should be feasible for UK designers who have to prepare a fire risk assessment under the CDM regulations.
- Carry out large scale experiments in compartments to quantify the thermal severity of aviation fuel fires for a variety of ventilation conditions, for we should not assume they are simulated with the hydrocarbon fire used in standard fire resistance testing

## CONCLUSIONS

It is clear from the experience of the WTC disaster that a tall building can be designed to resist collapse immediately upon impact from a large aircraft and in the absence of fire. It is also clear that a tall building which has a severely distressed structure and a disabled fire suppression system can collapse due to the effect of widespread fire resulting from the burning of the building contents and the imported fuel.

The susceptibility to collapse has been considered for two forms of structure commonly used in tall buildings. It is suggested that total collapse is less likely for a cantilever core building than for its framed-tube counterpart. For cantilever core structures, progressive collapse of floors outside the service core appears to be the most difficult problem to overcome and this should be the subject of design studies and testing to quantify realistic options for preventing or limiting the extent of progressive collapse.

Some suggestions, not confined to structural measures, are made which could reduce the effects of aircraft impact and fire on tall buildings. Their adoption depends on the probability attached to the likelihood that accidental or malicious impact by large, fuel-laden aircraft will occur during the lifetime of the building – a difficult question to answer – and, of course, on the cost of the added safety measures.

## POSTSCRIPT

Shortly after preparing this paper the US Committee on Science, through the US Federal Emergency Management Agency (FEMA), published on the internet the first of its reports ‘World Trade Center Building Performance Study (Data collections, preliminary observations, and recommendations)’

Currently (September 2005) NIST have a draft 290 page report out for public comment. Details as follows:

Federal Building and Fire Safety Investigation of the  
World Trade Center Disaster

Final Report of the National Construction Safety Team on the Collapses of the World Trade Center Towers (Draft), September 2005

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