Elaboration on Aspects of The Postulated Collapse Of the World Trade Centre Twin Towers

Written by: G Charles Clifton
HERA Structural Engineer

Date: 13 December 2001

Scope of Paper

This paper provides elaboration on aspects of my paper [1] entitled *Collapse of the World Trade Centre Towers*, written 17 September 2001 and revised three times since then, with Revision 3 dated 11 December 2001.

Since that paper was written, there have been several minor errors noted in it. Of more importance, two important aspects of it have been queried; these being:

- The postulated structural load distribution in the North Tower (the first tower to be struck) following the impact and leading to the collapse; and

- The intensity of the fire being underestimated because of distance and scale effects.

These points of concern require a response. The principal purpose of this paper is to provide that response.

It also briefly details some of the known errors in revision 2 of [1], dated 8th of October, and which have been either corrected or noted in Revision 3 to [1]. These details are given below.

This is followed by a brief coverage of the structural load- carrying system before impact, listing the assumptions made which impact on the postulated collapse mechanism for the North Tower.

Elaboration on the material presented in [1] relating to this collapse mechanism is then given.

This is followed by further material that has come to hand, in the two months since the attack, relating to the likely structural fire severity of the fires in each tower before the collapses occurred.

The paper ends with brief conclusions and references.

As with the original paper [1], the details herein are of a general nature. They do not present calculations or detailed metallurgical or structural observations. In the former case, this is because there are too many unknown to make a “correct” set of calculations possible. In the latter case, I don’t have access to material / data from the wreckage of these buildings so I am not in a position to make detailed observations.

What I do have is a good general overview of the structural system and method of construction used in the Twin Towers, plus my knowledge from 17 years of research into and development of design guidance for the response of steel buildings to the extreme events of severe earthquake and severe fire.

The details presented in [1] and this paper are consistent with that knowledge and background, plus the material I have available on the attack and destruction of these two magnificent buildings.

Also, as with the original paper [1], the details presented herein are my opinions. It is for this reason that the paper and [1] have been written in the first person.

Inaccuracies Noted in The Original Paper.

These are as follows:

(1) The times given for impact and collapse of each tower in the original version of [1] were based on published details as of mid-September. Some variation in these details was noted at that time. The generally agreed times are now given in Revision 3 of [1]. These are based on seismological recordings of the impacts caused by, first the plane hitting the building and, secondly, the building collapsing.

(2) The directions shown on the site plan (Fig 2 of [1]) are approximately 40^o off the true directions. If one rotates the site plan 40^o clockwise, thus making the direction shown as North read N40E, then the map is correctly orientated.

(3) Some minor typographical errors have been corrected.

Structural Load Distribution Before Impact.

Overview

The section of [1] entitles “Details of the buildings “ and presented on pages 2-5 therein provide an overview of the structural system used.

In summary, this comprised:

- A closely spaced perimeter frame around the four external walls, providing lateral strength and stiffness and also providing vertical support to its tributary area of the floor slab.

- A cluster of compression load carrying columns in the core, forming the principal gravity load carrying system and supporting the vertical load from half the open plan floor system plus all the structural systems, services and components within the core.

- A light-weight, long spanning floor system running from perimeter frame to outside edge of core. This floor system comprised bar joists as girders (primary beams) supporting secondary joists which carried a 100 mm thick light-weight concrete slab on profiled steel deck. The presence of secondary joists connected into the bar joists and made integral with a composite slab (see Fig 6 from [1]) made for a light, stiff floor system with good capacity for two-way action under severe fire conditions.

Assumptions made about the structural system design

In postulating the collapse mechanisms for both towers (but especially relevant for the North Tower), I have made some assumptions about the structural system used.
These as follows:

(1) The bar joist/floor system is connected to the perimeter frame/gravity core using a top flange mounted seat system as roughly indicated in Fig.7 of [1]. This system is designed to support the applied dead load from half the floor joist clear span. The actual connection between each joist and the supporting girders at perimeter frame and core is a typical bar joist connection detail, designed to carry principally its tributary design vertical load and with some nominal lateral load transfer capacity.

(2) There is a shear stud or some form of physical connection of the slab into the perimeter frame girders, through eg. shear studs from girder into slab and slab reinforcement passing beyond the line of connectors or alternatively some type of starter bar arrangement from the perimeter frame into the slab. Some form of this is evidenced from photos of the still intact perimeter frame remnants at the site. This would presumably have been sized on the greater of diaphragm transfer forces from floor into perimeter frame at each level or code minimum requirements for the interconnection, as applying at the time of design

(3) The visco-elastic dampers added from the bottom chord of the bar joists back to the perimeter frame did not noticeably increase the shear or tension capacity between floor slab and perimeter frame.

(4) There was a network of beams interconnecting the 44 core columns, such that the core formed an effective moderately rigid box. Some details of these are given in [2].

(5) The perimeter frame assemblages were spliced by mid-span bolted web connections (this known) and columns spliced with bearing splices having some moment/tension capacity (this assumed).

(6) The gravity columns were spliced by slot and tab splices, with the ends prepared for compression bearing. That much is known; I have assumed that these column splices also had an integral connection capacity for shear (possibly 15% of design shear capacity, as would be stipulated by NZS 3404 [3]). If so, this could have been formed by blind bolting of the tabs of the supporting column through the walls of the supported column, or more likely, by incomplete penetration site butt welds between the abutting surfaces, with these welds of small size and formed using a ductile weld metal.

Prior to the impact, the applied vertical loads on the core would have been carried to ground through the core columns. The applied loads on the perimeter frame would have been carried to ground through the perimeter frame. The vertical loading on the floor system spanning between core and perimeter frame, including its self-weight, would have been carried effectively equally by the supports at core and perimeter frame.

Postulated Structural Load Distribution in the North Tower Following Impact

The plane hit the North-East face of the North Tower, flying near level, at around the 94th and 95th floors. It cut through the perimeter frame leaving a hole in this frame some 2-4 floors deep and impacted into the core, causing an unknown amount of damage there.

In my original paper [1], I stated that the impact on the core would have "removed 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". At that time (mid-September) I did not want to speculate in the paper on the number of core columns destroyed in the impact region. Since then I have been advised of estimates up to 40%.

This loss of core columns would have had the following immediate effects:

(1) The load from the still intact upper floors would have had to be carried by alternative load paths to the still intact core columns. This redistribution would have required vertical sagging of the core region to become effective, with this sagging occurring immediately on impact and to a very noticeable extent on the floors above, especially above the impact side of the core.

I believe that this immediate sagging offers a possible explanation as to why many people jumped from the North Tower upper floors before the effects of fire on those floors became very apparent. If this sagging hypothesis is correct, then it would have cut access to the stairs by jamming doors, etc. It would also have given a clear message of impending collapse, leaving the people trapped on these upper floors with a terrible choice; jump and die or stay in the building and die in the collapse.

(2) The compression load on the remaining core columns would have significantly increased.

(3) The vertical load being transmitted through the floor system into the perimeter frame would have increased , as the core region sagged immediately following the impact and in a progressive manner from then on to the final collapse.

(4) The gravity columns which had been severed by the impact would now act as tension ties between each of the floors above the impact region, through to the top floor. The amount of tension so transmitted upwards would have been limited by the strength of the column splices to transmit tension, and possibly by the amount of redistribution occurring within the core region.

(5) At the top floor, these "tension" columns would have exerted as additional unbalanced downward load on this floor, adding to the overload stress on the floor to perimeter frame connection.

Following the impact were the fires. Fires adjacent to the damaged core region would have impacted on core columns already suffering various extents of local and member buckling from the plane's impact and loss of insulation material. As these columns heated up, they would have been subject to additional compression forces from restrained thermal expansion. In the case of columns with member buckling, this would have increased their lateral deflections between points of effective lateral restraint, leading to increased P-delta (P-δ) actions and reduced compression capacity. The temperatures required for this effect to become significant, on already damaged columns, is not high - I would estimate no more than 400-500^{o}C would have been needed to cause significantly reduced compression capacity in the residual core columns.

In my opinion, based on the available evidence, there appears no indication that the fires were as severe as a fully developed multi-storey fire in an initially undamaged building would typically be. (More on this below). However, the observations show that fire temperatures of over 500^{o}C would have been probable over enough of the core to cause an ongoing loss of compression load carrying capacity in the remaining core columns.

This would have increased the pull-down action of the floors on the perimeter frame, with this effect greatest on the top floor. I believe that final failure would have been through detachment of the top floor from the perimeter frame, starting at one point and rapidly spreading around the top floor. This would have been followed by near instant tearing away of all floors above the impact region from the perimeter frame, with the pancaking effect then proceeding to the ground.

As detailed in [1], the above relates to the North Tower. The explanation of collapse for the South Tower is quite different, as given in that paper.

How Severe Were the Fires: Revisited

Having carefully studied all available material available to me and collected since the original version of [1] was written, there is nothing in points 1-5 of [1] under the section "How severe were the effects of the fires?" that I would amend on the basis of this new material.

In fact, the new material provides further support for the fires not being particularly severe. Additional points to 1-5 of [1] in this regard are:

(6) Almost every building occupant below the impact floors (including up to the 91th floor on the North Tower) survived. Given that the fire separating walls around the stairs & lifts over the impact region were destroyed, then there must have been negligible spread of burning fuel/debris down into the breached stairwells to allow them to remain tenable.

(7) There is a survivor account of a group trapped in a lift, which had the cables severed by the impact. They were able to stop the lift on the 53rd floor, open the doors/escapes hatch in the top & cut their way out through the drywall fire separation. Their account says little about the effects of any fire above; nor could these effects have been significant or they would not have survived.

(8) Close scrutiny of close-up views of the burning buildings that I have received since mid-September (i.e much more detailed pictures than Fig 9 from [1]) show little evidence of temperatures above 600^{o}C (i.e. fully developed fire conditions) within

the impact region. These same pictures also show that, on some of the upper floors where fully developed fire conditions are observed, the fire-rated suspended ceilings appear largely in place and so the likely effect of these fires on the structure is minor.

(9) A fire engineer (Martin Feeney from Holmes Fire and Safety, Auckland NZ) has advised that theoretical consideration of the fire severity based on the quantities of combustibles in the planes and impact region of the buildings give answers that are not supported by observation. The observed fire behaviour points to temperatures in the building not being particularly severe – say no more than about 600 to 700 Deg C. Possible reasons for this may involve the coating of combustible material in dust from pulverised concrete and wall linings and the volatility of the aviation fuel leading to large amounts of fuel being pyrolised but not burnt in the interior of the building.

Conclusions:

This paper, which should be read in conjunction with Revision 3 of [1], provides elaboration on aspects of the postulated collapse of the World Trade Centre Twin Towers that are given in [1] and which have been queried by readers.

The details presented in [1] & herein are my opinions and are put forward to stimulate discussion and consideration of all aspects of this tragedy, in order that we can learn as much as possible to make buildings safer & more resistant to deliberate or natural acts of an extreme nature.

References:

1. Clifton, GC; Collapse of the World Trade Centre Towers; HERA, Manukau City, New Zealand; written 17 September 2001; revised 19 September, 8 October and 11 December 2001.

2. Godfrey,GB (Editor); Multi-Storey Building in Steel, Second Edition; Collins, London, England, 1985, ISBN 0 00 38 3031 4.

3. NZS 3404:1997, Incorporating Amendment No.1: 2001, Steel Structures Standard; Standards New Zealand, Wellington, New Zealand.