Global Journal of Researches in Engineering: D
Aerospace Science
Volume 17 Issue 1 Version 1.0 Year 2017
Type: Double Blind Peer Reviewed International Research Journal
Publisher: Global Journals Inc. (USA)
Online ISSN:2249-4596 Print ISSN:0975-5861

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GJRE-D Classification: FOR Code: 090103

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A Study of Possible Explosion Effects in the New 1-WTC Tower

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Abstract- In the past analyses of aircraft impact against buildings the kinetic energy of fuel of the impacting aircraft was accounted for, but the chemical energy content was not. This paper addresses the explosion problem by means of analysis as well as well as Finite Element simulation. The effect of fuel detonation is evaluated with less than 1% of the aircraft fuel content acting in this manner. The fuel-air mix in the model was placed at one level, between the floor and ceiling of the worst affected impact area. The damage resulting from this is developed and presented herein. A comparison of resilience of the old WTC towers versus the new 1-WTC is made.

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I. Introduction

A historic example, which was a motivation for this work, was the collapse of the World Trade Center, which took place on the 11th of September 2000. Each of the two main towers was struck by an aircraft flying at large speed with the purpose of inflicting maximum damage.

Plenty of engineering work was done to explain the mechanism of WTC collapse,. The best known and the most extensive engineering investigation is presented in NIST reports, of which [1] could be the most relevant example. According to the reports, the reason for the collapses of the structures weakened by the aircraft impacts was the thermal effect caused by prolonged fires. Unfortunately, the simulations did not clearly demonstrate the mechanism of failure. In this sense, the effort was a failure of engineering science. More details can be found in Szuladziński [2].

Although those simulations took into account the impact of the fuel mass, they ignored the explosions of fuel, which were clearly visible and audible in the wide media coverage of the event. This problem was addressed by Szuladziński [2], who demonstrated how significant the damage can be even if only a fraction of available fuel detonates.

While the investigation of past collapses is valuable, sensitivity of new structures is of interest too. The "replacement" building for WTC towers is 1-WTC, a new tower somewhat resembling a tapered and twisted pyramid. This article is devoted to estimating an effect the fuel explosion might have on a possible collapse of 1-WTC building.

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A fairly extensive description of building geometry is provided by Szuladziński [3]. It is sufficient, for our purpose, to use only the top one-third height of the building proper, while retaining the spire. The mentioned segment is treated as built-in at the base. This is justified because the effect of a blast has a somewhat localized response. Besides, it is vertical effects are of main interest which makes a limited distance from the new base quite acceptable.

The explosive properties of the air-fuel mix and some of its effects in this type of event were presented in detail by Szuladziński [2]. To have a good picture of the structural effects some basic design features and static relationships must be considered first.

II. Floor Plate Design Loads

This follows the values used in the design of the old WTC towers. The mass per unit surface m is the total of the dead load (DL) and the design live load (LL) expressed in mass units. For a typical floor, one can expect DL = 300 kg/m^2 (61.44 psf) and LL = 205 kg/m^2 (42 psf) with a total of m = 505 kg/m^2 or the equivalent surface pressure of p_0 = 4,954 N/m^2. (The most likely LL for the building was used in place of the design load for a single floor, the latter being LL = 244 kg/m^2)

III. Material Properties

a) Steel

The peripheral column material is A514 steel. This is a quenched and tempered alloy steel, designated by its maker, Arcelor Mittal as T-1. Its nominal (minimum guaranteed) properties are

F_y = 690 MPa = 100 ksi (yield)
F_u = 759 MPa =110 ksi (ultimate)
ε_u = 0.081 (ultimate strain)

The above values hold for a thickness below 63.5 mm. The strength is somewhat smaller for thicker material.

The above data is used for design. When estimating the effect of accidental events, which are usually of dynamic nature, we are entitled to use two factors, which enhance strength. The first allows us to take advantage of the difference between the nominal and the expected average properties. [4] The second is the dynamic enhancement of strength, which can be calculated in several ways. We have multiplied the quoted values only by 1.1 to account for the two factors.

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(Dynamic strengthening is usually small for strong steel.) The same multiplier was used for the second steel involved, A588, employed for beams, which had the following nominal properties.

F_y = 529 MPa = 100 ksi (yield)
F_u = 634 MPa =110 ksi (ultimate)
ε_u = 0.103 (ultimate strain)

Finally, the reinforcing steel of the wall was characterized by

F_y = 451 MPa (yield)
F_u = 580 MPa (ultimate)
ε_u = 0.14 (ultimate strain)

b) Floor concrete slab

The slab is built using light-weight concrete poured over corrugated, galvanized steel sheet with a conventional reinforcement. This is in turn supported by metal beams, perpendicular to the corrugations. The directions of both change, as we go around the circumference of the building.

The lightweight (1602 kg/m^3) concrete has F'_c = 20.7 MPa and F_t = 2.7 MPa (tensile strength in flexure). The modulus is E_c = 12,500 MPa.

Supporting beams spacing imposed the strength requirement. For the 6m span of the beams, treating the slab as one-way type and assuming an intermediate condition at the supports the maximum bending moment induced by p_0 becomes 17,836 N-m/m. This, along with the factor of safety of 1.8 dictates the strength of the equivalent slab material. No dynamic enhancement of strength was used.

c) Reinforced concrete wall

The wall is cast with F_c = MPa concrete, whose estimated tensile strength is

$F_t = 0.6\sqrt{F_c} = 4.45$ MPa

and the Young's modulus, according to [4] is

$E_c = 3320\sqrt{F_c} + 6900 = 31{,}522$ MPa

The main design load for the core walls of the building is compression caused by gravity. Under a strong lateral pressure pulse, however, bending predominates. A simplified computational method will be employed, which states that a wall element fails if the net tension exceeds F_t' calculated using the limit bending capacity M_0:

$$F_t' = \frac{5\mathcal{M}_0}{BH^2} \tag{1}$$

The coefficient of 5 is mid-way between an elastic case of 6 and a perfectly plastic one of 4. We assume that the wall is reinforced with a square pattern of rebars giving an effective 1% of steel section in both horizontal and vertical directions. For a H = 160 mm thick wall, which is postulated here and a unit width B = 1 mm, a commonly used bending strength formula gives the yield moment as 56,015 N*mm/mm. When this is inserted into Eq. (1), the apparent strength on the tensile side becomes F_t' = 10.94 MPa. (This is a conservative approach, as it does not allow for a compressive failure and therefore it makes the wall appear stronger in the simulation to follow.)

IV. Estimate of slab Damage Caused by Explosion

We assume the detonating charge to have 200kg of aviation fuel mixed equally (by volume) with air. This gives a volume of 0.5m^3 and is equal to mass density of about of 400 kg/m^3 This corresponds to a cube with the side length of 794 mm. The fuel is treated as energetically equivalent to TNT (per unit of mass) in accordance with [2].

A simplified section of the space between floors is shown in Fig.1. The fuel-air mix, depicted as a centrally placed block is allowed to detonate. The approximate assessment will be coarse, just to find the extent of the threat. The first action is to replace the block of fuel by a concentrated mass at its geometrical center. This allows the use of such a popular code as CONWEP (a computerized version of [5]) to estimate the peak pressure and impulse reaching the floor slabs. The load imposed on the slab is found in a simplified way, as a pressure history based on the nominal distance of 2.21m. According to CONWEP, the charge of 200 kg placed at that distance should yield the following pressure p_0 and specific impulse i (reflected) values:

p'_o = 54.58 Mpa and i = 12.91 MPa-ms.

The fuel-air mix is likely to have the same or even larger impulse as the energetically equivalent solid explosive. However, pressure is significantly reduced in magnitude while lasting much longer [6]. Except for the immediate vicinity, impulse is the real measure of a structural damage to follow. For this reason, the Conwep value of the impulse is retained, while the pressure applied is samaller than mentioned above.

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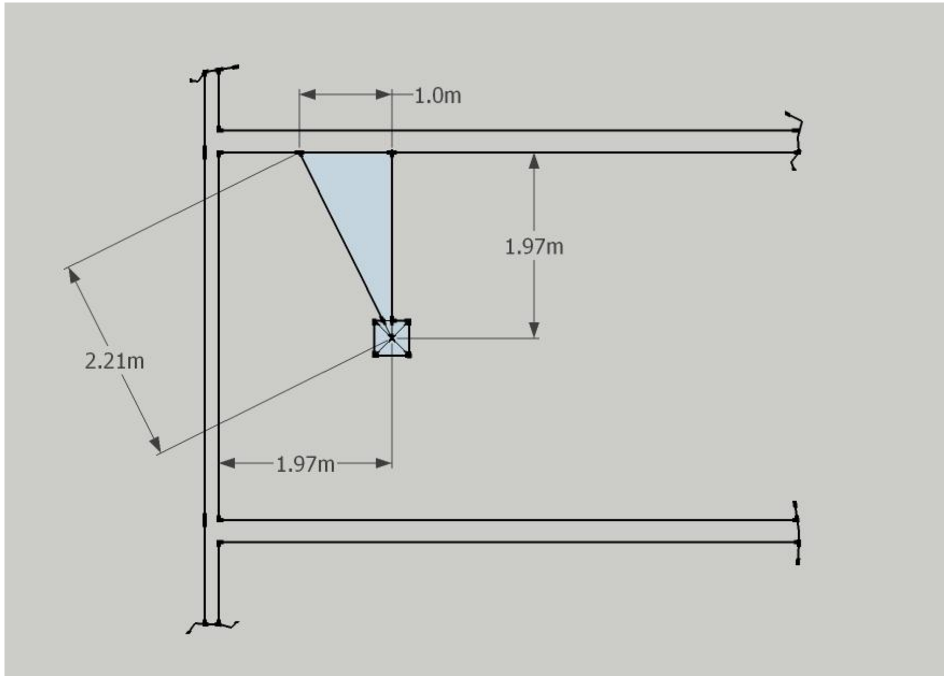

Fig.1: Section through a typical office floor, between two slabs and internal wall, with a block representing the fuel-air mix. The nominal distance from the center of the block to each of three surfaces is taken as 2.21m.

V. Dynamic Response of Floor and Wall Slabs

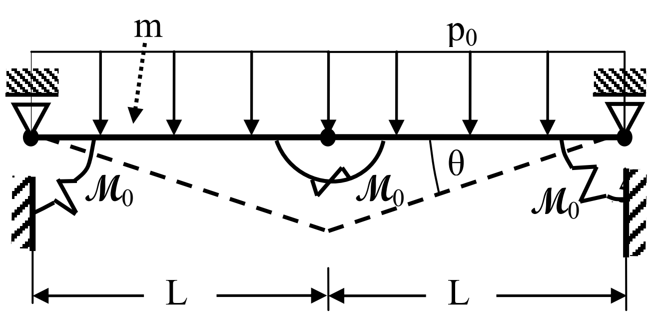

Fig.2: A beam with rigid supports subjected to a short impulse of pressure of magnitude p_o. (Szuladziński [7], Case 10.21)

A unit-width beam, acted upon by an impulse applied by distributed load p_0 is depicted in Fig.2. (The actual pressure distribution will not be uniform, but it is expected the nominal value used will provide the result with a minor error only. Also, if the beam is of width b, then p_0 in Fig.2 and the equation below must be replaced by $w_0 = bp_0$) Angular springs at ends and at the center have a rigid-plastic characteristic and their capacity is equal to that of the slab Mo. When the initial kinetic energy is equated to the energy absorption by the plastic springs, the maximum angle of permanent rotation is found as θ_m:

$$\theta_m = \frac{3L}{16}\frac{(p_0 t_0)^2}{m\mathcal{M}_0} \tag{2}$$

where L is the half-span, $p_o t_o$ is an impulse of pressure p_o applied over short time to, (poto stands for the impulse magnitude regardless of its shape. If the beam is b wide and not of unit width, then p_0 should be replaced by w_0, where $w_0 = bp_0$.) Finally, m is the mass per unit length of the beam. (One should remember that this is a small-deflection formula.) We have, for a beam 1 mm wide and 250 mm deep (A = 250 mm2):

L = 6000/2 = 3000 mm

$p_o t_o$ = 12.91 MPa-ms.

Density ρ = 2020 kg/m^3 = 0.00202 g/mm^3 (incl. steel)

m = ρA = 0.00202 x 250 = 0.505 g/mm

$\mathcal{M}_o$ = 17,836 N-mm/mm

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Substitution into (2) gives θ_m = 10.41 rad = 596°. This is an absurdly large response and the figure is merely due to the small-deflection limitation of (2). Indirectly, it tells us that the impulse will easily break the slab. Using the same procedure it is easy to check that the wall slab will also fail under dynamic loads Apart from the above there is a major threat in the pulverization mode caused by excessive pressure (spall). Even if we take pressure to be 4x smaller than calculated before (on account of the nature of our exploding material), which gives $p_0'/4$ = 13.6 MPa, which is more than the tensile strength of concrete, F_t = 4.45 MPa. (This is applicable to the wall. The situation is not any better for the floor, but somewhat different because of steel lining of the bottom.)

VI. Simulated Impact Zone Damage

The transient dynamic problem of the explosion effect was solved using LS-Dyna code [8]. The solid elements (concrete) were modeled with Type 2, fully integrated elements. Metal plates are represented by Type 2, Belytschko - Tsay shells. The slab reinforcement and truss diagonals are modeled using Type 1 beam, Hughes-Liu with section integration.

Figure 3 shows one-half of the building model. It is zoomed on the blast-affected zone, which is modeled in a greater detail than the rest of the structure. The long reinforcing beams run radially as well as along floor edges. Magnitude and duration of the pressure pulse was applied as described before. No secondary enhancements such as reflections were included.

As Fig.4 shows, soon after the explosion parts of the floor, ceiling and the wall are blown away. The ceiling falls on the floor in the impact zone, which helps the periphery columns to lose their stability. As a result the floor above loses its support and begins to descend. So do all floors above in a pattern known as 'progressive collapse'. This leads to a collapse of the entire structure, as shown in Figs. 5,6 and 7.

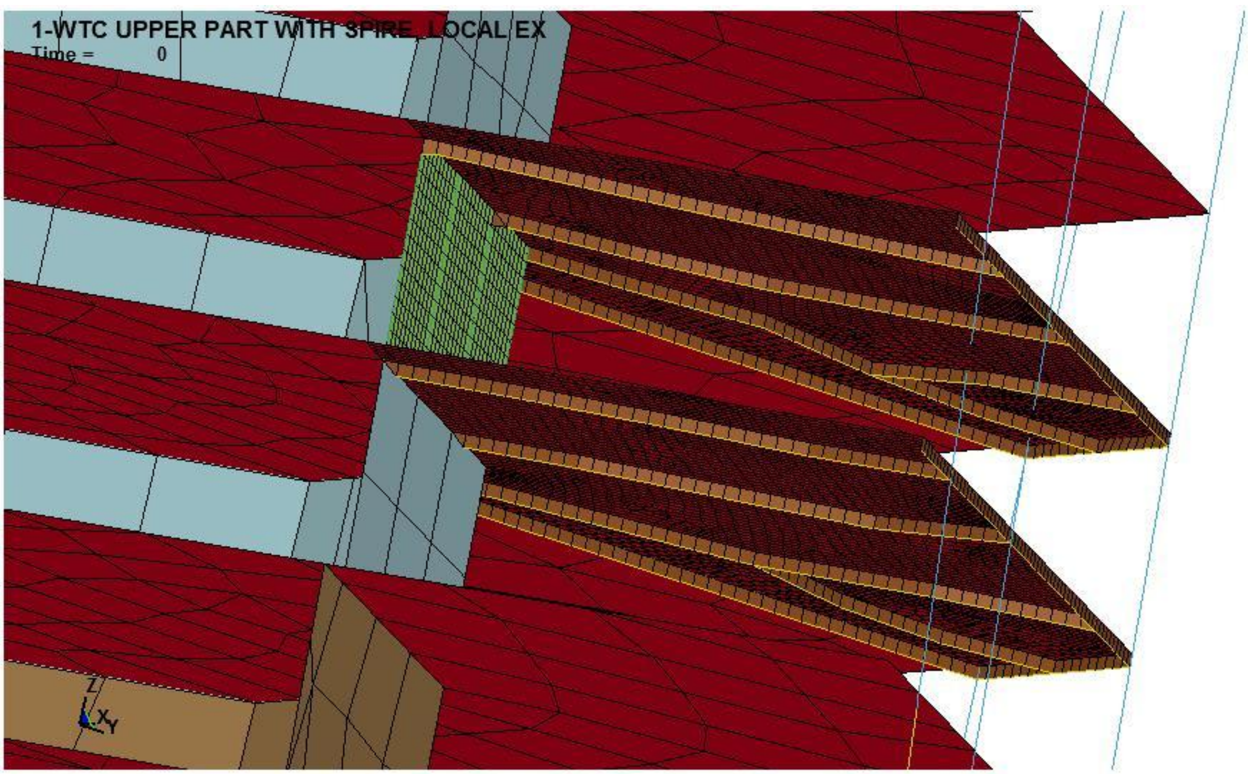

Fig. 3: Fragment of the tower showing the impact zone, where the floor and ceiling are modeled in detail. The view is from below, from the plane of symmetry

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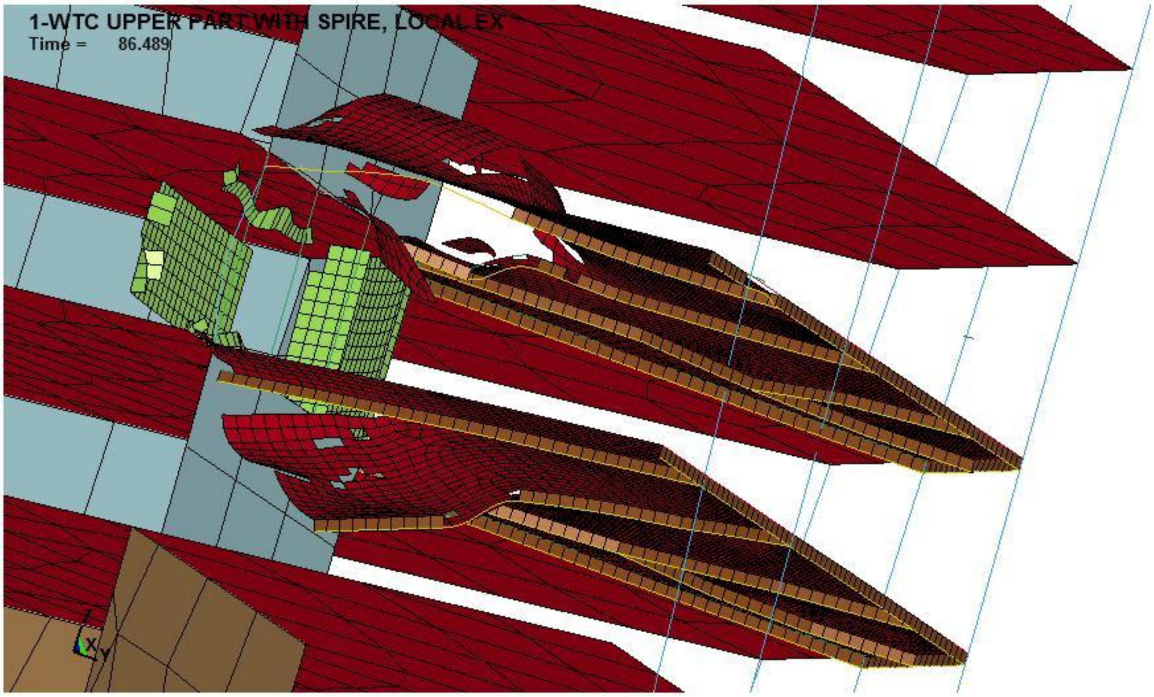

Fig.4: The status shortly after explosion. Both floor and ceiling are blown off the wall. Also, a part of the wall is separated from the rest.

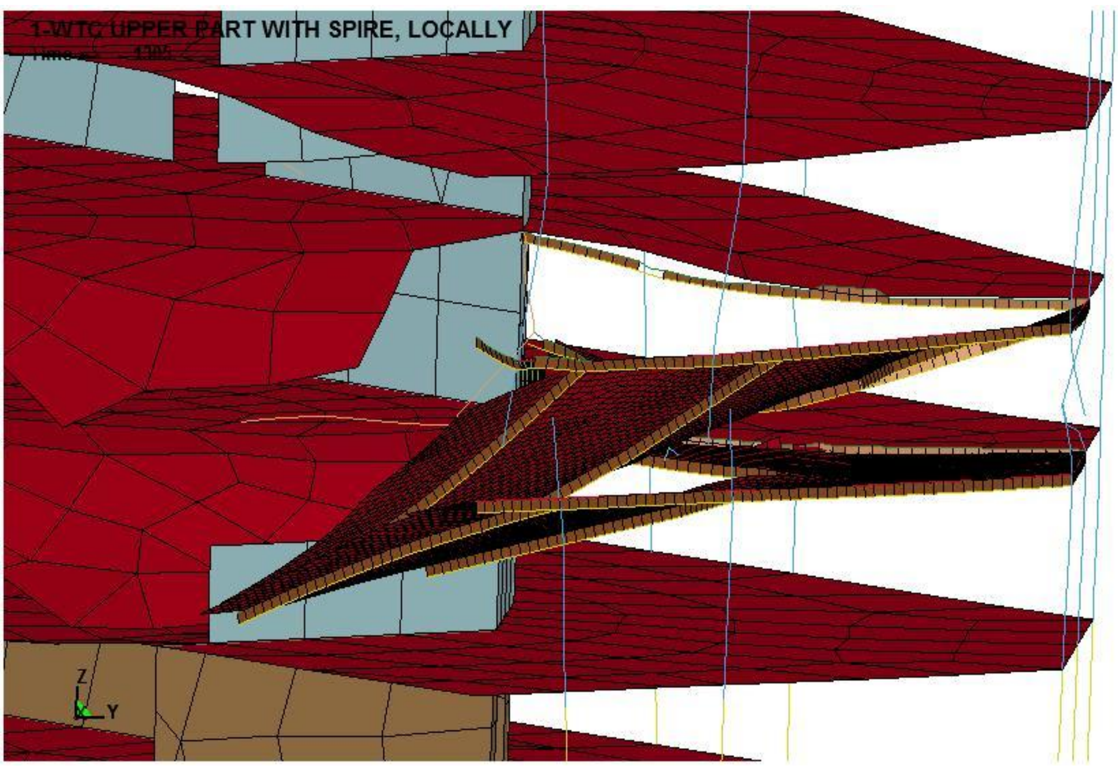

Fig. 5: The ceiling detaches and falls on the floor of the impact zone

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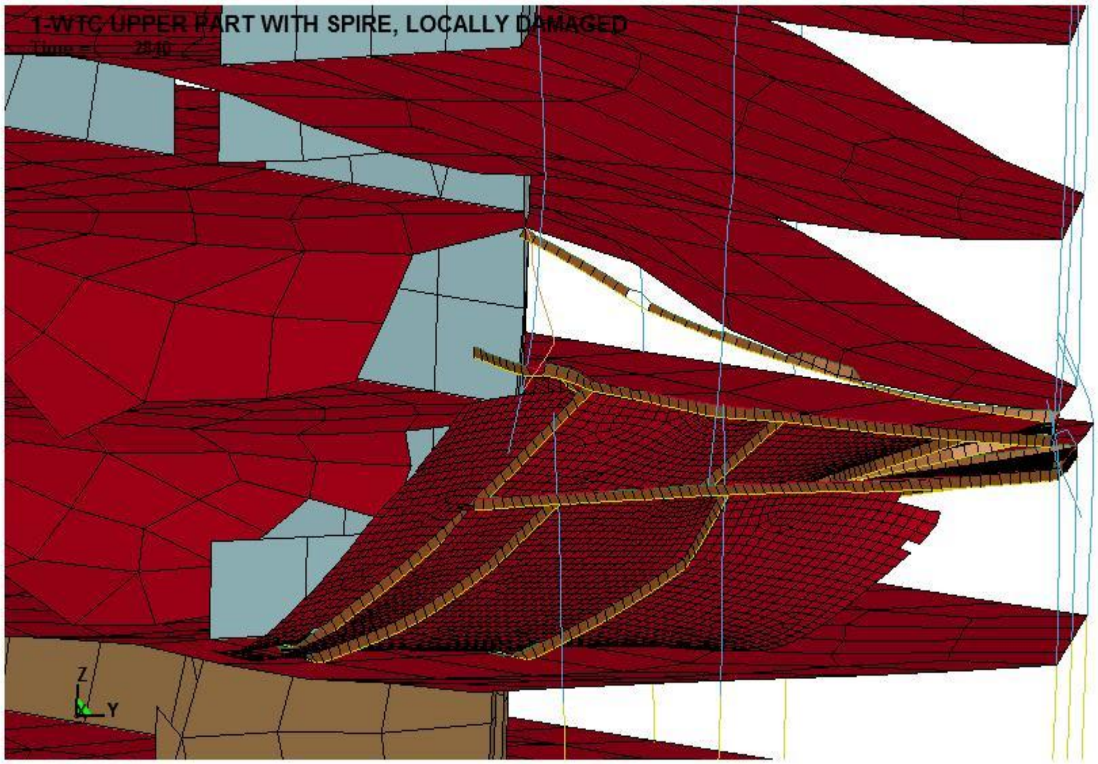

Fig.6: Both floor and ceiling impact the slab below.

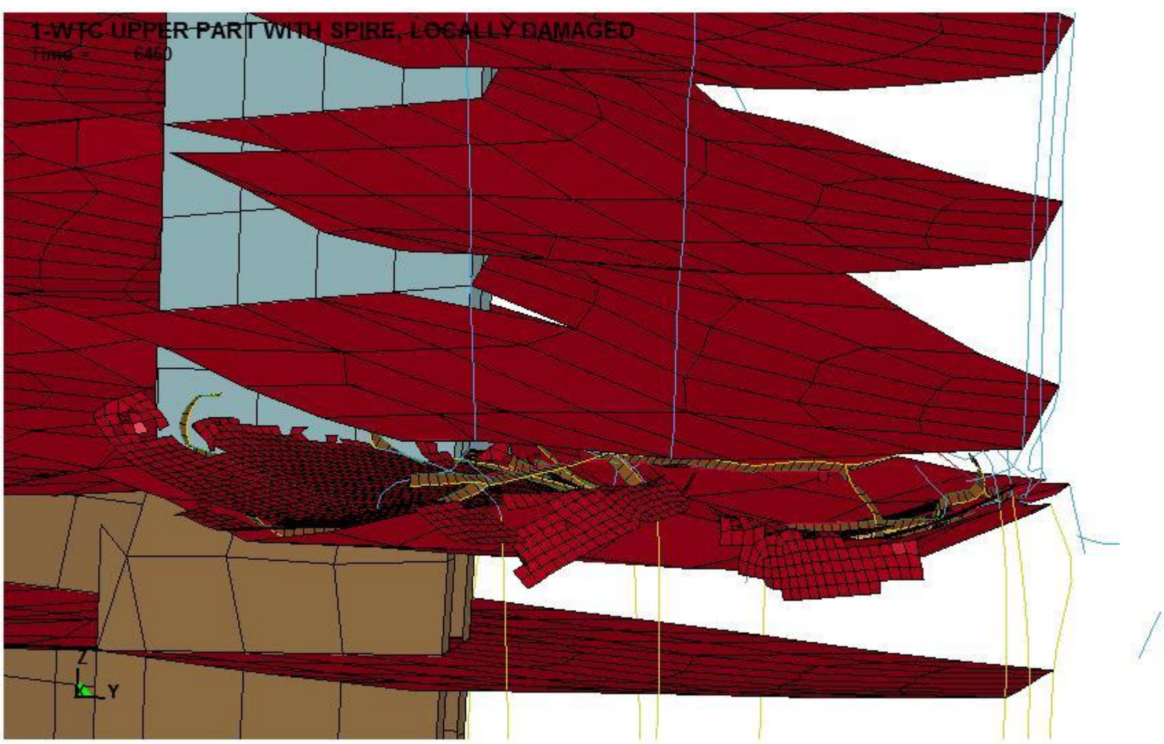

Fig. 7: The damage is deepening as the falling slabs pull down the floors above them.

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Fig. 8 As a result of wall damage the upper part of the building tilts and begins to fall. This motion can't be stopped

VII. Summary and Conclusions

After estimating the energy content of the 200 kg portion of fuel assumed to be detonating the pressure impulse created by said detonation was evaluated. A conventional check on flexural failure of the concrete wall demonstrated that this mode of failure is easily attainable. It is obvious, however, that in addition to general collapse the slabs not far from explosion sources will be subject to spalling.

The explosion at the critical floor level caused the wall, a part of the floor area as well as the ceiling to be blown off. This was the source of collapse, first taking place locally and then spreading throughout the entire structure. This lead to the whole building collapse, of which only the initial moments are simulated. (One should note that the overall speed of the downward movement was increasing.)

In the event mentioned before, the old WTC collapse, the amount of fuel carried by the aircraft was close to 30,000 kg. This means that in a similar event we are assuming less than 1% of the fuel content to be detonating. The amount is not inconsistent with the explosion seen after the attack on the old WTC.

Why is 1-WTC not as tolerant to such an attack than its predecessor? (a) Larger floor area in the latter (compared with the floor area at the impact level here) which imposes more damage on the moving craft. (b) More distributed manner of supporting the weight, with center columns placed rather far apart and not by a monolithic wall. (c) Only a minor fraction of the perimeter columns in the old WTC were destroyed in the attack. In our structure there are much fewer such columns so the influence of their demise has a lager over-all effect.

Many thanks are owed to Mr M. Soll for his careful study of this text, which made it a more comprehensive document.

The reader can watch the animations of this work on: http://www.youtube.com/user/gs98765432

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