Could the World Trade Center have been modified to prevent its collapse?

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Abstract
The feasibility of protecting tall buildings against progressive downwards collapse following catastrophic structural failure at high level is explored and various design suggestions made.

Introduction

There has been considerable discussion about the mechanism by which the World Trade Center's twin towers collapsed. After the intense fires that followed impact, either the floor supports in the impact zone gave way, or vertical columns in the impact zone buckled. Whichever happened first, in each case at least one floor collapsed onto the floor below, leading eventually to more column buckling so that the whole of the undamaged superstructure above the impact zone fell downwards onto the rest of the building below it.

The resulting impact load, when the falling superstructure collided with the structure below, caused previously undamaged columns to buckle. The falling mass then increased, transmitting a higher impact load to the next floor below, and a huge stress wave propagated downwards, destroying previously undamaged structure, and eventually destroying the whole building. Simplified calculations support this explanation of the collapse (Bazant and Zhou, 2001), which accords with the evidence of eye-witnesses.

A recent article (New York Times, 11 Nov, 2001) has examined the collapse scenarios and commented that "No building could be expected to survive such an onslaught." However the article also says that "It is possible that skyscrapers with a different structure would not have ultimately collapsed." If that is to be the case, the design must meet one or other of two conditions. Either the structure in the impact zone (wherever that occurs) must be strong enough and sufficiently protected against fire to continue to carry the weight of the building above it whatever happens. Or, alternatively, if the impact zone can be destroyed so that the building above it falls, there must be a sufficient means of energy absorption in the undamaged storeys below the impact zone to stop the structural avalanche that otherwise occurs. Kinetic energy would have to be removed fast enough to decelerate the falling superstructure without generating high enough loads to cripple otherwise undamaged structure.

This paper considers what would be needed to meet the second condition, by exploring the introduction of intentionally energy-absorbing floors or "collapse barriers" within a building. Each energy-absorbing floor might accommodate a reduced number of people (to allow space for the energy-absorbing material), but would serve as a means of arresting a downwards traveling stress wave thereby preventing the progressive collapse of otherwise undamaged structure below.

Collapse barrier thickness

Two properties are required for collapse barriers. The first is to provide a massive amount of energy absorption when crushed. The second is to introduce cushioning so that the peak dynamic forces which occur during crushing can be resisted by undamaged structure (of conventional design) below. In principle, if the collapse barrier is big enough to provide enough energy absorption and cushioning, then a collapsing stress wave like that experienced at the WTC can be arrested. But how big is "big"?

We consider first how thick a collapse barrier would have to be to arrest the vertical fall of the (undamaged) top of a building when several intermediate storeys fail. We assume that the top of the building falls freely before

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impacting an undamaged storey which incorporates an energy-absorbing collapse barrier. This barrier is intended to remove energy to bring the top of the building to rest before damage has progressed far into otherwise undamaged structure below.

There is a fundamental relationship between the thickness of a collapse barrier and the vertical distance between adjacent barriers. It arises because the deceleration distance of falling structure (and therefore the thickness of the barrier) must be sufficiently long to ensure that the dynamic load caused by its deceleration does not cripple sound structure below. It is independent of the material used for the collapse barrier.

Suppose that the top part of a building has mass m and falls n floors of spacing h before encountering a collapse barrier. Locally there are high impact loads when contact occurs with undamaged structure around the collapse barrier. These loads buckle or knock out structural columns so that the collapse barrier comes into operation and starts crushing, supported by the sound structure below it. Let the collapse barrier crush at load νmg and the sound structure below be able to resist a vertical load of ηmg before it starts collapsing ($\eta > \nu$). Pessimistically, assume that collapse of the conventional structure involves no energy absorption. Assume also that the collapse barrier crushes at constant load through distance H. Then, by equating the loss of potential energy of the falling mass to the energy dissipated by the collapse barrier,

$$mg(nh + H) = \upsilon\, mgH \qquad (1)$$

giving

$$H = nh/(\upsilon - 1). \qquad (2)$$

Consider the case when $\nu = 2$ so that the collapse barrier crushes at $2mg$ (this assumes that the conventional structure can resist more than $2mg$). The crushing distance will have to be $H = nh$. So putting $n = 1$ gives $H = h$. Assuming that a collapse barrier could crush to half its initial thickness, the collapse barrier would have to be $2h$ thick, so that it would occupy two storeys of the building. If $n=3$ storeys collapsed, so that the undamaged structure fell $3h$ before impacting with a collapse barrier, its crushing distance would have to be $H = nh = 3h$, and the collapse barrier would have to be $6h$ in thickness.

These considerations lead us to conclude that if energy-absorbing material is to be introduced to prevent progressive downwards collapse, it would be necessary for this to be located at every floor of the building and should extend from floor to ceiling at each storey.

Our analysis assumes that the undamaged superstructure moves downwards without collapsing and that damage propagates progressively into the initially undamaged structure below the collapsed zone. This is likely to be the case because the lower structure is more heavily loaded than that above it. However if the opposite obtains, the same process of progressive collapse will occur but with the collapse wave-front moving upwards instead of downwards.

Selection of energy-absorbing material

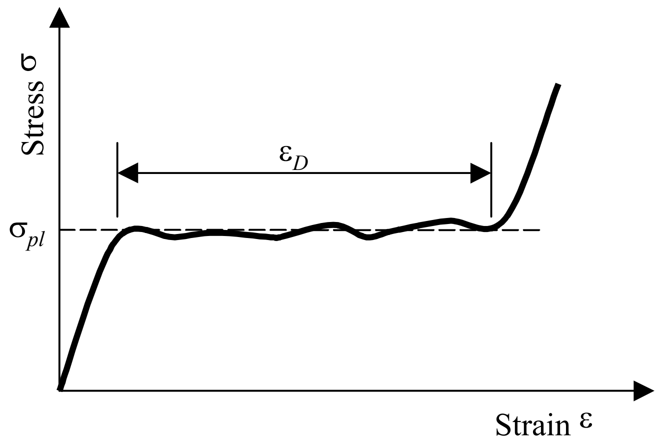

Fig. 1 Schematic stress-strain curve for a metal foam or honeycomb.

How much space would the energy-absorbing structure in a collapse barrier take up? To answer this question requires specific information on the energy absorbing properties of suitable materials.

Good materials for absorbing energy through plastic deformation are foams and honeycombs (Ashby et al, 2000). The stress-strain curve of such a material is shown schematically in figure 1. At low strains (0.5% to 5%) there is an initial elastic region. The material then yields at approximately constant stress (the 'plateau stress' σ_{pl}), until the cell walls are forced into contact with each other, when the stress-strain curve rises steeply. The 'densification strain' ε_D is typically around 50%, although for lower density foams it can be significantly more than this figure. The area under the stress strain curve up to densification is the useful energy that can be absorbed per unit volume. It is given approximately by

$$W_v = \sigma_{pl}\,\varepsilon_D. \qquad (3)$$

Figure 2 shows energy per unit volume absorbed up to densification, W_v, plotted against 'plateau stress', σ_{pl}, for various metal and polymer foams and metal honeycombs. (The plateau stress is taken to be the compressive stress at 25% strain, $\sigma_{25\%}$). Each 'bubble' represents a material, the size of the bubble indicating typical variation of its properties. Numbers in parenthesis on each label indicate the density in Mg/m^3.

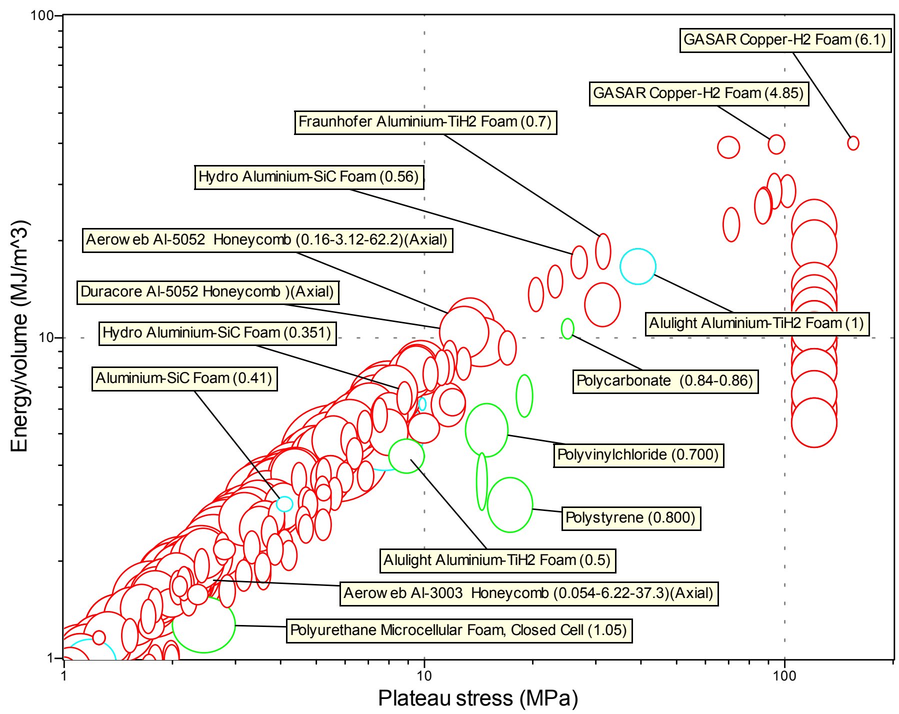

Fig. 2 Energy absorbed per unit volume up to densification, plotted as a function of plateau stress, for metal and polymer foams and honeycombs. Each material is labelled with its density in Mg/m^3. Chart generated by the Cambridge Engineering Selector (CES, 2001).

The best energy absorbers are copper foams (near the top right corner of the chart), with energy absorption capabilities up to $40MJ/m^3$. However, these are very expensive and consequently are probably not viable in this application. Higher density aluminium foams like 'Fraunhoffer (0.7)', ($\sigma_{25\%} = 30$MPa; $\varepsilon_D = 60\%$); and 'Alulight (1)' ($\sigma_{25\%} = 40$ MPa; $\varepsilon_D = 40\%$) are more practical. These have energy absorption capabilities around 16-20 MJ/m^3. The best performing honeycomb, 'Aeroweb Al-5052', has considerably lower energy absorption, around 12 MJ/m^3.

An alternative analysis taking *cost* into account is shown in Fig. 3. This chart plots the energy absorption per unit cost, calculated using

$$W_c = \sigma_{pl}\, \varepsilon_D /(\rho\, C_m), \qquad (4)$$

where ρ is the density and C_m is the cost of material per kg. It indicates that aluminum honeycombs, such as 'Aeroweb Al-5052', have the highest energy absorption per unit cost, followed by polymer foams, such as polypropylene structural foam, with a density of approx 0.6 Mg/m^3. However, from Fig 2 these materials have energy absorption per unit volume that is considerably less than that of the aluminum foam, so larger amounts of them would be needed. Note also that polypropylene has a much lower melting point (around 100°C, compared with approx 550°C for aluminum). Being a thermoplastic polymer, strictly polypropylene does not melt. Its viscosity decreases progressively at temperatures above its glass transition temperature (-20 °C). It can usefully carry loads up to its maximum working temperature of around 100°C.

So aluminum foam or possibly aluminum honeycomb are thought to be good candidate materials for effective energy absorption. The final choice would depend on the trade-off between the cost and weight of the raw material, the value of the space the barrier occupies, and the need for headroom after collapse. There are formal methods for optimising such a trade-off (see, for example, Ashby 1999).

In the following analysis, we shall consider what can be achieved with an aluminum foam with a density of around $1Mg/m^3$ (the number in brackets on each label on the chart is the specific gravity). This has a densification

strain of approx 40%, and a plateau stress (at 25% strain) of approx 40MPa. The energy absorbed per unit volume is about $16MJ/m^3$. For comparison, the yield stress at room temperature of hot rolled steel used in structural columns is typically 355MPa.

Barrier design considerations

Suppose that energy absorption material is added to every floor (we consider in the next section how this might be done) so that every storey has its own collapse barrier and that aluminum foam with the above properties is used as the cushioning material. Let the energy-absorbing crush force of the foam be represented by P and assume that the maximum crushing length is 40% of the collapse barrier's original length. If the floor spacing is h=4m, the foam collapse barrier for this floor may then crush H= 0.4 x 4 = 1.6 m, leaving head-room of 2.2m less the thickness of the floor.

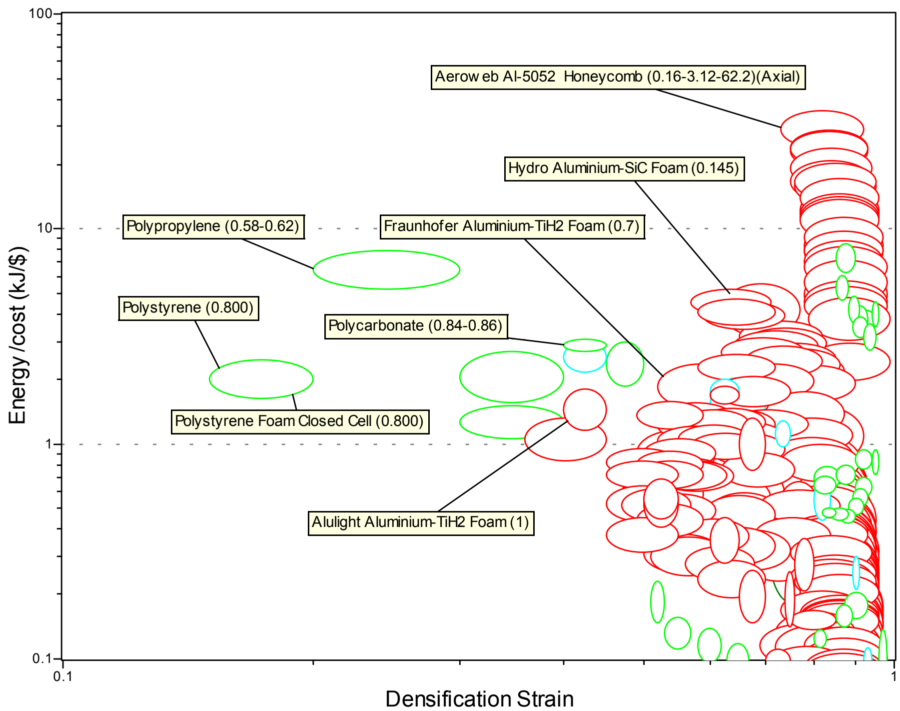

Fig. 3 Energy absorbed per unit cost up to densification, plotted against densification strain. Chart generated by the Cambridge Engineering Selector (CES, 2001).

If we assume initially that one floor (only) is completely destroyed, so that the undamaged super-structure falls freely distance h and then decelerates over H, the absorption system has to absorb $mg(h+H)$ where m is the total mass falling. Energy absorption by the collapsing conventional structure is again ignored. Hence $PH=mg(h+H)$ where $m = 5.8x10^7$ kg (Bazant and Zhou's figure for the top third of the WTC). If we allow two storeys to be crushed, the deceleration length is H = 0.4x2x4 = 3.2 m, giving $P = 1.3x10^9$ N (130,000 tonnes).

For the crushing damage to be localised around the collapsed storey, the remaining undamaged structure below (and above) the destroyed floor must be able to withstand a short-time dynamic force of peak magnitude $P = 1.3x10^9$ N. Expressed as a multiple of the falling weight mg (part only of the building), this is $P/mg = (h + H)/H = 7.2/3.2 = 2.3$. If the undamaged structure below the collapsed section cannot support 2.3 mg without failure, this peak dynamic force can be reduced by making the crushing resistance of the aluminum foam less and allowing more structure to collapse, thereby giving a lower rate of deceleration.

For a crushing stress of 40 MPa for aluminum foam (from the above data), the required load-carrying area is $1.3x10^9/40x10^6 = 33\ m^2$ (about 6m x 6m). For a building the size of the WTC, with a gross floor area per tower of about $4,000\ m^2$, this is a loss of about 1% of the floor space, which is probably negligible given the advantage.

Even for an aluminum honeycomb with a 12 MPa crushing stress, the load-carrying area required is only 110 m^2 (about 11 m x 11 m), about 3%, which is also not excessive.

Consider now what happens if three storeys are destroyed so that the superstructure falls 3*h* before impacting undamaged structure below which then collapses, crushing the aluminum foam collapse barrier. Again assume that the crippled structural columns collapse without absorbing energy so that all the kinetic energy must be removed by crushing aluminium foam with the same properties as above.

Now the undamaged superstructure falls freely distance *3h* and then decelerates over *H*, so that this time the absorption system has to absorb $mg(3h+H)$ where *m* and *P* are as before. Putting $P=1.3\times10^9$ N for the same energy absorbing system as before, and solving for the crushing distance *H* gives $H = 9.3$ m which means that a vertical height of $H/.4 = 23$ m would be affected. Therefore the aluminium foam in the storey immediately below the collapsed region would be fully compressed and deformation would continue into the storey next below that until this aluminium foam is completely compressed, and so on downwards. As a rough guide, if *n* storeys are destroyed, we may expect the 2*n* storeys immediately below to be crushed to their full extent (about 40% compression) while structure below that height should be spared major structural collapse. As noted already, since more weight is carried by the structure below the collapsed sections, we expect that to be crushed more than structure above the collapsed sections. However local crushing damage may occur both above and below the collapsed sections with the total crushing length being unaltered.

Assuming a density of 1 Mg/m^3, the added weight of aluminium foam (per floor) is $33\times4\times10^3$ kg = 130 tonnes compared with a superstructure weight of 58,000 tonnes for about 30 floors, or say 2000 tonnes per floor, which is a weight increase of 6.5%.

Lower down the same building the added mass of foam would have to be more to achieve the same collapse lengths (i.e. deceleration distances) because more energy has to be absorbed by a larger mass falling the same distance, or, alternatively, more storeys would be crushed in bringing the falling superstructure to rest. It will obviously be necessary to explore the strength margin on existing buildings when determining how much energy absorbing material to use and where to place it. If the undamaged structure can survive an impact load greater than the level assumed above (2.3*mg* where *m* is the falling mass), the deceleration distance (and therefore collapse length) can be less than calculated here.

Possible constructional features

The embodiment of an energy-absorbing system depends on the detailed constructional features of the building concerned. The location of the collapse barriers is extremely important. They must engage the main downwards load path while not being close enough to existing structural members to be displaced when column collapse occurs.

One constructional arrangement has the energy-absorbing material enclosed in a cylindrical telescopic housing. This functions as a collapsible energy-absorbing strut. It is attached at its upper and lower ends to the building. Two conceptual models in fig. 4 show possible embodiments. In fig. 4(a), the collapsible column is attached to the floor structure at its upper end and to a vertical load-bearing column at its lower end. In fig. 4(b) the possibility that outwards displacement of the lower end of the collapsible column may occur is prevented by an additional lateral attachment to the lower floor span.

(a) (b)

Fig. 4 Schematic embodiments showing attachment of energy-absorbing columns.

These embodiments assume that failure occurs due to column buckling. Referring to fig. 4(b), when the load-bearing column shown buckles, the energy-absorbing column collapses with its two ends moving together until their full travel is taken up. Then an impulsive load is transferred to the load-bearing column next below, which in turn buckles and the process continues until all the energy has been absorbed. In the worked example referred to above, column buckling is assumed not to begin until the transient downwards impulsive load exceeds 2.3 *mg*, where *mg* is the static load. If less than that, the energy-absorbing struts must be designed to collapse at a lower load than 2.3 *mg*, and then their total collapse length will be proportionately more before motion is stopped.

An alternative arrangement might be to install vertical foam-filled tubes which are not telescopic but which collapse by buckling of the tube walls and simultaneous crushing of their aluminum foam filler. This provides two means of absorbing energy, by crumpling the tube walls and by crushing the foam filler. Since the tube walls are supported by the foam they contain, their buckling wavelength is shorter than for empty tubes, creating more plastic folds per unit length and increasing the energy absorption. A possible approach for *new* buildings might be to use tubular load-carrying columns, filled with foam cores, and designed to collapse axially in a controlled fashion when subjected to excessive downwards force, rather than to buckle sideways.

A further design possibility is to combine energy dissipation by hydraulic (water-filled) dampers with energy dissipation due to crushing structural foam. This can be done in various ways and the water would serve both to slow down the deleterious effects of fire and to increase energy absorption on collapse. One construction would be to incorporate an annular water jacket outside the aluminum foam with pressure relief valves to give a controlled rate of water release on collapsing. Another would be to use hydraulic water-filled dampers alongside crushable foam structures. The practical feasibility of these constructional features can of course only be decided after detailed calculations and tests have been made.

Cost considerations

How much would the installation of collapse barriers cost? For 'Alulight (1)', from figure 2, the energy-absorption achievable per unit volume is W_v = 16 MJ/m^3, and from figure 3, the energy-absorption per unit cost is W_c = 1.6

kJ/\$ approximately. For the volume of foam per storey that we have calculated above, 33 m^2 cross-sectional area and 4 m thickness, the total energy-absorption capability per storey is 33x4x16 = 2,100 MJ. These figures indicate that the cost of energy-absorbing foam would be about $2.1x10^9/1.6x10^3$ = \$1.3 million per storey. But since foam is currently manufactured only in small quantities, probably the unit cost would be greatly reduced for large quantities, although this reduction would be offset by the cost of the associated steelwork.

Assuming that the cost per storey is half the above figure, that is \$ 0.65 million, the cost of an aluminum foam energy-absorbing system to protect a 110 storey building the size of one of the towers of the WTC would be in the order of \$72 million. If 20,000 people work in the building, this translates to a minimum extra cost of \$3,600 per person, or say \$120 per person per year when amortized over 30 years. The cost of installation and loss of income from the space occupied by energy-absorbing material would of course have to be added.

For comparison, the cost of the two towers of the WTC (which were constructed during the period 1966 to 1977) is recorded as \$350 million (World Trade Center, 2001). Assuming an inflation factor of 3.6 (Source: GDP Deflator, reference below), the current cost would be \$1.26 billion, or say $\$1.26x10^9/(2x110) = \$5.7x10^6$, nearly \$6 million per storey per tower. Therefore the installation of an energy absorption system will add significantly (\$0.65 million is 11% of \$6 million) to the total cost of some existing buildings. The challenge is to design a system which achieves the required protection at minimum cost so that it is considered economically justifiable.

Conclusion

Our conclusion is that it is possible, in principle, to design collapse barriers consisting of columns of foam impact-absorbing material which, if fitted in every storey close to the main load-carrying structure of a building like the WTC, will arrest the downwards traveling stress wave that caused its structural collapse. A full feasibility study will have to include comprehensive computer modeling of the dynamics of collapsing structures with energy absorption arranged in the manner suggested. Of course there are many design questions to be answered, including how heat protection can be provided to ensure that a partially collapsed building survives for as long as possible if fire in the building cannot be extinguished. However the advantages of a successful system are so huge and the psychological benefits so great that we believe that such a further study is warranted and urgently required.

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