The World Trade Center

For decades, industry professionals have debated the performance characteristics and benefits between steel frame structures and concrete frame structures in mid- and high-rise buildings. Until the tragic events of September 11, 2001, specifically those involving the terrorist attack on the World Trade Center, such debates had revolved primarily around theories. As terrible and tragic as the destruction of the WTC is, we, as industry professionals, have the responsibility of looking deeply into the performance of our building structures to reasonably and responsively prevent such immediate destruction and catastrophic failure from happening in the future. The following discussion is not intended to capitalize on this tragedy but to analyze several key factors surrounding the structural failure of the WTC and consider whether a concrete frame would have performed differently.

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This discussion is between Bill Klorman, president of W.M. Klorman Construction Corp., El Monte, Calif., and Ken Bondy, a consulting structural engineer in West Hills, Calif. Both Klorman and Bondy are members of the ACI Responsibility Committee, Klorman its chairman. Bondy is one of the country's leading designers and authorities on post-tensioned concrete structures.

Klorman: In the films of the attack, the buildings appear to take the impact itself quite well. But that seems inconsistent with the complete collapse that follows shortly thereafter. From an engineering standpoint, how do you interpret the performance?

Bondy: It seems to me that the buildings did resist the initial impact well. A redundant load path clearly allowed the loads above the impact area (about 15 floors for the North Tower, 30 floors for the South Tower) to be transferred around the damaged area. There is a strong possibility that the buildings would have remained standing had there been little or no fire. In my opinion, however, the buildings did not perform well in resisting the fire. That is not a criticism of the design because the impact and fire appear to have substantially exceeded the original design criteria, both in the impact force and the intensity of the fire. The major structural elements (columns, primary beams, and girders) in modern fire-resistive buildings are supposed to resist the most severe anticipated fire for at least 3 hours without failure (that's essentially what is meant by a "3-hour rating"). The time between impact and collapse in these buildings was only about an hour for the South Tower, about 1¾ hours for the North Tower. Obviously many people owe their lives to those survival times; however, many more surely could have been saved had the buildings lasted the full 3 hours. Now that we know that these types of events are possible, we need to design for them.

Klorman: What do you think finally triggered the collapse?

Bondy: Ongoing investigations, including a major effort by ASCE, will tell us eventually much about the actual collapse mechanism. But like many others, I feel the fire ultimately caused the collapse. The fire protection in the building consisted of a vermiculite plaster wrap for the steel box columns and a suspended ceiling for the bar joists in the floor system. It is likely that the impact damaged large portions of this nonstructural fireproofing and allowed a direct path for the flames to the unprotected steel, eventually weakening it to the point of failure. Based on the fact that the collapse was so sudden, it seems that the failure mechanism must have been either a compression failure in the columns or a massive shear failure in the connection between the floor bar joists and their support at either the perimeter or the core. Since the floor bar joists were "secondary" members (they don't individually carry a lot of floor area) and the columns were "primary" members (individually they carry a much larger portion of the floor area), column compression failure, either in the core or at the perimeter, is most likely to have been the initial event that started the complete collapse.

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build systems, I am especially concerned with the fireproofing issues that have been raised here. After the success of a 32-story concrete frame high-rise in southern California, we have tried to promote not only the cost and time advantages of concrete but also the inherent fire resistance and added life safety of concrete buildings. Do you think concrete would have improved the performance of the WTC buildings?

Bondy: Yes. Tall concrete buildings have significant advantages in the area of fire resistance. Perhaps most important is the fact that the fire protection is an integral part of a structural concrete member rather than a nonstructural addition. Impact damage in a concrete member can expose the reinforcing steel locally, but it does not provide a direct path to steel in other parts of the frame.

Second, in concrete columns, the load is shared between concrete and reinforcing steel, unlike in a steel column where the entire load is carried by steel. In most concrete columns the reinforcing steel carries less than 50% of the total column load, even less with higher concrete strengths and lighter loads, as in the upper floors of multistory buildings. The concrete, a naturally fire-resistant material, carries most of the load.

Finally, concrete buildings, particularly cast-in-place concrete buildings, are inherently resistant to progressive collapse because of continuity of the floor members and the frame action between the floors and the columns, which is present to some degree even if you don't design for it. This provides redundancy and

a "path" for loads to travel around a local area of damage. Also, the ACI Building Code now incorporates requirements for "integrity steel," reinforcement specifically intended to enhance the resistance of concrete buildings to progressive collapse. I would anticipate that ACI Committee 318 will focus now even more on measures to prevent progressive collapse, including criteria for at least some minimum level of "ductile frame" detailing in all buildings, not just those in seismic zones.

I think the 1995 behavior of the Murrah building in Oklahoma City demonstrates how concrete buildings can limit the spread of a progressive collapse. About half of the Murrah building, outside the impact footprint, did not collapse after the bomb exploded, undoubtedly saving many lives.

Klorman: From a construction standpoint, I am aware of an additional advantage of concrete in tall buildings. In concrete buildings the perimeter beams and columns can be exposed architecturally, and the windows and the rest of the curtain wall can be recessed inside the structural edge of the floor. This eliminates the gap between the structural floor and the curtain wall often found in structural steel buildings, a gap which can and has allowed the upward passage of fire from floor to floor in a multistory building. This was known to happen in the First Interstate Building, a 62-story structural steel office building in downtown Los Angeles during a severe fire that damaged four floors in the late 1980s.

There are some obvious practical problems, primarily weight, involved in building tall concrete buildings; however, they are not insurmountable when we use existing tools like high-strength concrete and post-tensioned floor systems. Now that we know that some people are willing to intentionally fly large commercial airplanes into our tall buildings, I think we need to develop ways, to the greatest degree possible, to mitigate the effects of such terrible actions. I feel the use of concrete framing in tall buildings can help to make them safer and that many owners of tall buildings will be looking to concrete in the future.