Seismic details can help, but aren't necessary for resilience in steel buildings.

The Inherent Blast-Resistance of Steel Framing

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THE FEDERAL EMERGENCY MANAGEMENT AGENCY (FEMA) recently published FEMA P-439B *Blast-Resistant Benefits of Seismic Design*. Subtitled "Phase 2 Study: Performance Analysis of Structural Steel Strengthening Systems," this report is a follow-up to a study FEMA published on resilience of reinforced concrete buildings following the 1995 bombing of the Murrah Federal Building in Oklahoma City.

FEMA P-439B reports an analytical evaluation of a typical steel building and what would have happened if the Oklahoma City bomb had been parked in front of it. It also assesses how relevant seismic details are to the resilience of a steel building, and if the conclusions of the Phase 1 study for reinforced concrete—that seismic detailing is needed to improve its resilience—also apply to steel.

FEMA's Phase 1 study of the bombing of the Murrah Building concluded that the initial blast removed a single column and asserted that 15% of the lost floor area was proportional to this column; the other 85% of the lost floor area was removed by the progressive collapse that ensued after the initial blast damage. It also established that seismic detailing, had it been employed in the original design of the Murrah Building, would have improved the progressive collapse performance, and also might have reduced the blast damage area as well.

For Phase 2, a typical steel building and its actual details were used to assess performance. The building was intentionally selected to be similar in size and proportion to the Murrah Building. An older building of similar vintage to the Murrah Building, it had no special seismic detailing.

The author was privileged to participate in the work of the committee that undertook the development of FEMA P-439B. AISC also assisted the effort with supportive research when the group needed to confirm analytical results. When finite element analysis showed the Oklahoma City bomb scenario only damaged but did not remove the steel column, this needed experimental verification.

Figure 1 shows the column before its full-scale blast test. Cladding was installed to replicate the actual conditions of the study building column. Figure 2 shows the blast-damaged column, which is bent and deformed, but intact. A close-up view of the base where the damage is most severe is shown in Figure 3. Subsequent testing also assessed the residual strength the damaged column could provide for the evaluation of progressive collapse. The full blast test report is available on the AISC website at **http://bit.ly/pEIuQD**. A video of the blast test can be viewed at **www.modernsteel.com/blastvideo**.

When the column can be relied upon to remain and contribute strength after a blast event, it is obvious that the ensuing assess-

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ment of progressive collapse resistance is easier and more successful. When all of this can be done without seismic detailing, it also may cost less.

FEMA P-439B compares the baseline non-seismic design and several seismic strengthening schemes for their effect on the performance of the building when subject to the Oklahoma City bombing scenario. Did the seismic upgrade schemes help? Yes, but the baseline building fared very well without any seismic detailing. FEMA P-439B concludes that between 2% and 8% of the building floor area was damaged in the blast. The seismic upgrade schemes generally reduced this range to no more than 2% damage uniformly. These are very good results in all cases—even for the baseline building with no special seismic detailing.

Why did the baseline building perform so well? Simply stated, it was a well-detailed structural system with regular and redundant framing. Its 1970s details included moment connections at all beam-to-column connections, and its column splices were similarly robust. The designers of the subject building likely did not consider the event to which it was analytically subjected. Nonetheless, their design decisions offer insights and good guidance for resilient design today.

FEMA P-439B is worth reading because it provides much greater detail than this article about the study, characteristics of the baseline building, and other strategies investigated. To obtain a copy, call FEMA's publication distribution center at 800.480.2520.

Following are recommendations that, in the author's opinion will lead to resilient design and construction in today's steel structures.

Resilience Strategies for Today's Steel Structures

When considering the need for resilience, the solutions pursued should be coordinated and consistent with the level of the security plan. Avoid prescribed "solutions" or arbitrary choices—they might do nothing but add cost or result in a building that fails to meet the needs of the owner or its occupants. Also consider at what level the resilience is being assessed:

- At the basic level—the typical building being designed today—the designer may simply decide to configure a well-detailed, redundant and robust structure.

◄ Fig.1: Pre-test photograph of clad column with 4,000-lb TNT-equivalent charge placed at same distance (15.6 ft) and angle (26.5°) as for the Oklahoma City bombing.

▲ Fig. 2: Post-test photograph of the column.

▲ Fig. 3: Posttest photograph of the base of the column.

- Some buildings may require compliance with a prescriptive method for resilience.
- Occasional buildings are at the high end, where performance-based design follows from a complete building security plan that also identifies appropriate design criteria. Note that such a plan usually is both structural and non-structural in nature: blast threats, progressive collapse resistance, chemical and/or biological threats, alarm-system tampering, power disruption, arson, potable water-supply protection, protection of sensitive information, and computer network infiltration are all potential areas of need.

Strategies for Typical Buildings

The majority of buildings receive no special treatment other than judicious attention to the details with redundant configurations and robust connection designs that tie the structural (and non-structural) components together effectively. The typical details used in steel buildings inherently provide for redundancy and robustness, with the capability for load redistribution through alternative load paths. This fact has been demonstrated repeatedly when steel buildings have been subjected to abnormal loadings.

The following ideas can be beneficial in all steel buildings:

- Configure the building's lateral systems to provide multiple load paths from the roof to the foundations. Multiple lateral framing systems distributed throughout the building are generally better than fewer isolated systems.
- Provide complete horizontal floor and roof diaphragms to tie the gravity and lateral framing systems together.
- Minimize framing irregularities in both horizontal and vertical framing when possible. Horizontal and vertical offsets with copes and/or eccentricities can reduce the available strength at member ends—or require extensive reinforcement to maintain that strength.
- Use multiples of the same shape, rather than changing girder and column sizes. The additional strength in girders and columns that are heavier for convenience could cost less or be free. The use of a smaller number of different shapes in the building means a labor savings in fabrication and erection, and often more than offsets the cost of the additional steel weight.
- Remember that serviceability limit states indirectly add significant structural redundancy to steel framing. Usually, beams and girders are sized for deflection or floor-vibration criteria, and girders and columns are commonly sized for drift control. As a result, these elements have significant reserve strength.
- Use typical shear, moment and/or bracing connections judiciously. Reserve strength is gained at low cost if connection details are clean. It costs little to fill the web of a girder with bolts using a single-plate or double-angle connection.
- Recognize other sources of redundancy and robustness inherent in steel buildings, including: the common overstrength in the steel materials and connecting elements, membrane action in the floor and roof diaphragms, and the strength and stiffness contributions of nonstructural components.

With little—and sometimes no—modification, steel framing provides significant redundancy and robustness.

Strategies to Meet Prescriptive Requirements

Some buildings receive special treatment through the application of prescriptive criteria for design that go beyond those in the basic building code. While there are a variety of prescribed criteria, such as the removal of a building column, there usually is no attempt in these prescribed methods to characterize an exact effect of a threat, such as a blast. Instead, the goal could be to reduce the probability of progressive collapse in areas not directly affected by the blast. Several strategies can be employed:

- *The use of a perimeter moment frame.* This can result in a system that is significantly robust. In some cases, the framing will have enough redundancy to accept column removal without modification. If not, the column spacing can be reduced or the framing hardened by increasing size or switching to composite construction.
- *The use of a strong story or floor.* This solution can be a truss system with diagonals or a Vierendeel truss system, incorporated into a single story or multiple stories in the building. Alternatively, a single strong floor with heavier framing and moment connections throughout could carry or hang at least 10 floors. Nonetheless, exercise caution when considering hat-truss framing to create a strong story. Unless specifically designed for progressive-collapse resistance, hat trusses normally reduce the level of reserve strength and redundancy because of the efficiency they allow in the structural system.
- *Other innovative solutions.* One particularly innovative solution has been used with the building perimeter banded by steel cables to prevent progressive collapse should a column be lost.

Strategies for Performance-Based Building Designs

Performance-based criteria are used for a small number of buildings, normally ones that are government-related, high-risk or high-profile. Performance criteria vary, but generally require that the building withstand the effects of a threat such as a blast, protect the occupants of the building, and/or maintain a defined level of operability. The nature and characteristics of the threats are identified realistically and modeled in the design. Note that the performance criteria affect more than the structural frame, and often require special nonstructural elements, like blast-resistant windows, special site layouts, and site perimeter protection.

The key aspect of structural design for resilience is determining the nature and magnitude of the threat(s) and loading(s) for which resilience is required. In a blast threat application, this involves assessing the amount and type of explosive, as well as its distance from—or location within—the building. Another factor is the level of security that can be placed around and within the building.

- The means of transport for the explosives can be the limiting factor as to the amount of explosive that can be delivered. Does the threat include a package bomb, vehicle-borne bomb, both, or another means of delivery? Is there a security presence or feature that limits the distance or size at which the explosive can be delivered?
- The type of explosive is important because all explosives behave differently. Some types of explosives are easier to obtain than others.
- The distance from the building at which an explosive could be placed is perhaps the most critical factor. A large stand-off distance from the blast is essential to blast resistance. Can a defensible perimeter be used to ensure a certain stand-off distance? Equally important is to determine what level of design is required: typical, prescriptive or performance based.

Performance-based design for resilience often involves the use of a security consultant. MSC