Seismic Design of Steel Staggered Truss Systems

Seismology Committee, Structural Engineers Association of California

This is the first in a series of STRUCTURE® articles that have been condensed and adapted from the Structural Engineers Association of California (SEAOC) online series called the SEAOC Blue Book: Seismic Design Recommendations. Beginning in 1959 and extending to 1996, the SEAOC Seismology Committee published updated printed editions of Recommended Lateral Force Requirements and Commentary, which was commonly called the Blue Book. The "Requirements" portion of those publications was in large part adopted verbatim by the International Council of Building Officials as the seismic regulations of the Uniform Building Code. With the transition to the unification of the three major model building code organizations into the International Code Council, and the nationwide use of the NEHRP seismic design provisions that are developed under the auspices of FEMA and the Building Seismic Safety Council, SEAOC decided the "Requirements" portion of the Blue Book no longer served a purpose, but that there was a still a need for statements of position and guidance for practicing engineers and code officials to help them to resolve ambiguities among various codes and standards and to interpret research. A number of Blue Book articles are in development and are being published one-by-one, after each has passed through an extensive SEAOC Seismology Committee review process.

The staggered truss system was developed at MIT in the 1960s (Scalzi 1971). Its arrangement of story-deep trusses in a staggered pattern allows large column-free areas and low floor-to-floor heights. With fewer columns than other steel framing systems, staggered truss frames can also offer faster fabrication and erection schedules, and reduced foundation costs (Wexler and Lin 2003).

Most staggered truss systems are in areas of low seismic hazard. Because of the apparent benefits of the system, AISC, structural steel contractors and others have expressed interest in using the system in high-seismic regions of the USA. The American Institute of Steel Construction (AISC) has published a design guide with a chapter on seismic applications (Wexler and Lin 2003). The following statement appears in its introduction:

One added benefit of the staggered-truss framing system is that it is highly efficient for resistance to the lateral loading caused by wind and earthquake. The stiffness of the system provides the desired drift control for wind and earthquake loadings. Moreover, the system can provide a significant amount of energy absorption capacity and ductile deformation capability for high-seismic applications.

The staggered truss system is not a recognized seismic force-resisting system in ASCE 7-02 Table 9.5.2.2 or in ASCE 7-05 Table 12.2-1, equivalent to an "undefined structural system" per 2001 CBC section 1629.9.2. Therefore, pending review of substantiating cyclic test data and analytical studies, or project specific peer review in combination with analytical studies, the Committee recommends against use of the staggered truss system as a seismic force-resisting system per ASCE 7-02/05 Seismic Design Categories (SDCs) C through F and in 2001 CBC Seismic Zones 3 and 4. While SDCs C-F effectively covers all of California, the "substantiating test data" requirements of ASCE 7 and the 1997 UBC are applicable to all SDCs and Seismic Zones.

Description of the System

The staggered truss system is contemplated for buildings from 6 to over 20 stories tall (Wexler and Lin 2003). Its benefits are most apparent in regular buildings with rectangular floor plans. The system consists of full story-deep trusses spanning the transverse direction of the building; truss spans are typically 60 feet. From one story to the next, the trusses are horizontally offset by one column bay (typically 20 to 30 feet) so that the truss locations are staggered up the height of the building (*Figure 1*). The stagger is typically of a uniform dimension and symmetric in plan. Floor diaphragms are typically precast planks spanning from the bottom chord of one truss to the top chord of the adjacent truss. Exterior columns support the ends of the truss and provide frame columns for the lateral force-resisting system in the longitudinal direction of the building. To maximize the architectural benefits of the system, there are frequently no continuous interior columns.

Each truss acts as a braced frame in the transverse direction. A Vierendeel panel is often provided at the midspan of the truss to accommodate passageways. Under transverse seismic loads, the Vierendeel panel would be subject to high deformations (much like the similar panel in a special truss moment frame), and would therefore have to be designed to dissipate energy through flexural yielding. The trusses resist transverse shear, overturning forces, and interstory drift, and the floor diaphragm acts as a load path element between adjacent trusses. The longitudinal lateral force-resisting system is typically a perimeter moment frame or braced frame.

Response to Earthquake Loads

Acceptable earthquake performance of a staggered truss system will be limited by the following attributes:

- The lateral and gravity force-resisting systems of the building are one and the same. Every gravity-resisting truss and column is also integral to the transverse lateral force resisting system.
- Long transverse spans limit the ability of the system to redistribute gravity loads in the event of a column failure.
- The ground story is usually much more flexible than the floors above. Customarily, moment frames replace the staggered truss elements at the ground story.
- Diaphragms are critical to the lateral load path of this structural system, transferring relatively high forces between vertical elements. This is especially true at lower stories, where the diaphragm and diaphragm-to-truss connections must transfer nearly the entire base shear from one story to the next.

This last point about the diaphragms might be unique to the staggered truss system. The floor diaphragms are required to participate in the lateral system as fully as the trusses and columns. Model earthquake design codes, however, assign seismic design factors (i.e. *R*, C_d, and Ω_0) without thorough consideration of

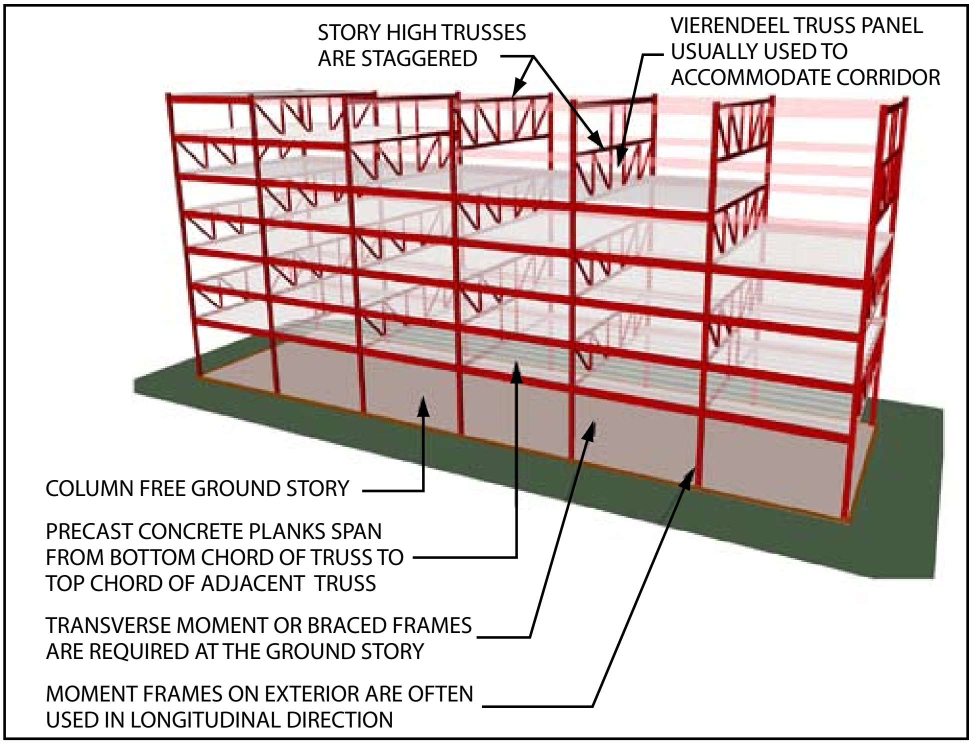

Figure 1: Typical Staggered Truss Frame Layout.

diaphragm ductility and modes of inelasticity within the diaphragm. Use of seismic design factors from moment-resisting frames, braced frames, or special truss moment frames for a staggered truss system would be inappropriate.

The assertions by Wexler and Lin quoted above are apparently based on elastic analysis results and theoretical response estimates by Goel et al. (1973) and perhaps by an inappropriate extrapolation of inelastic behavior modes expected in special truss moment frames (Basha and Goel 1994). Additional information may be found in Scalzi (1971), Goel et al. (1973), Gupta and Goel (1972), and Hanson and Berg (1974).

Recommended Research

The Seismology Committee is not aware of any recent testing of the staggered truss system for use as a seismic force-resisting system. AISC and others are investigating the feasibility of the staggered truss system for areas of high seismicity. Testing and analysis are expected to focus on sources of inelasticity, diaphragms, and diaphragm-to-truss connections.

The development of eccentrically braced frames and special moment-resisting frames perhaps offers examples for proponents of the staggered truss to follow. Specifically, ASCE 7-02 section 9.5.2.2 and ASCE 7-05 section 12.2.1 give requirements for qualifying an "undefined" seismic-force-resisting system. The Seismology Committee expects that adequate testing and/or analysis will be required to adequately address at least the following design and performance issues:

- Identification of predictable inelastic mechanisms
- Design forces and deformations in yielding Vierendeel panels and adjacent truss members
- Design forces related to diaphragm-truss interaction, considering expected strength, stiffness, and ductility
- Force distribution and inelasticity in precast diaphragms and topping slabs under high in-plane forces
- Force distribution and inelasticity in diaphragms under vertical displacements related to truss deflections and link deformation
- Design of diaphragm-to-truss connections, considering cyclic loading and diaphragm or truss overstrength
- Column design forces and ductility demands, considering dynamic truss-column interaction and sharing of columns by lateral and transverse systems
- Vulnerability of the gravity system to failure of seismic-force-resisting members
- Effects of openings and discontinuities in highly loaded diaphragms
- Disproportionate effects of atypical and irregular building configuration
- Axial and flexural interaction in truss chords, diagonals, and connectors

In addition, because the system load path involves an out-of-plane offset at every floor level, testing must consider the interaction of yielding (and possibly degrading) diaphragms, trusses, and connections, as opposed to just the behavior of individual components. Even the testing of an entire truss frame would not capture the essential aspect of shear transfer between adjacent frames.▪

The complete SEAOC Blue Book series of on-line Seismic Design Recommendations articles is available at: **www.seaoc.org/bluebook/index.html**.

References

ASCE (American Society of Civil Engineers) (2002). ASCE 7-02, *Minimum Design Loads for Buildings and Other Structures*. ASCE, Reston, VA.

ASCE (American Society of Civil Engineers) (2006). ASCE 7-05, *Minimum Design Loads for Buildings and Other Structures*, Including Supplement No. 1, ASCE, Reston, VA.

Basha, H.S., and Goel, S. C. (1994). *Seismic Resistant Truss Moment Frames with Ductile Vierendeel Segment*, Report #UMCEE94-29, University of Michigan Department of Civil and Environmental Engineering, Ann Arbor, MI.

California Building Standards Commission (2001). *2001 California Building Code* (California Code of Regulations, Title 24). California Building Standards Commission, Sacramento, CA.

Goel, S. C., Berg, G. V., and Hanson, R. D. (1973). *Seismic Behavior of Staggered Truss Framing System - Design Procedure for Earthquake Loading*, Report UMEE 73R2 for AISI Project 175, University of Michigan, Ann Arbor, MI.

Gupta, R. P., and. Goel, S. C. (1972). "Dynamic analysis of staggered truss framing system," Proc. Paper 9038 in *Journal of the Structural Division*, ASCE, v. 98 n. ST7, July, 1475-1492.

Hanson, R. D., and Berg, G. V. (1974). "A seismic design of staggered truss building," Proc. Paper 10289 in *Journal of the Structural Division*, ASCE, v. 100, n. ST1, January, 175-193.

Scalzi, J. B. 1971. "The staggered truss system – Structural considerations," *AISC Engineering Journal*, October.

Wexler, N. and Lin, F.-B. 2003. *Staggered Truss Framing Systems* (AISC Steel Design Guide Series No. 14), American Institute of Steel Construction, Chicago, IL.