What Makes a Special Moment Frame SPECIAL?

BY BEHZAD RAFEZY, PHD

A look at the critical aspects of special moment frame systems and their connections that ensure ductile behavior and dissipation of energy.

THERE IS A SIGNIFICANT DIFFERENCE between designing a building for wind and gravity forces and designing for the effects of earthquakes.

In wind/gravity design, the building is subjected to pressure or force-type loading and is designed to respond elastically. The controlling life-safety limit state is strength. However, it is not economically feasible to design structures to respond elastically to earthquake excitations.

When considering seismic excitations, the building is designed based on the assumption that a significant amount of inelastic behavior will take place in order to provide large energy dissipation capacity in the system during the earthquake. The controlling life-safety limit state is deformability/ductility, and enough strength is provided to ensure that inelastic deformation demands do not exceed deformation capacity. It must be noted that while earthquake-resistant structures can be designed to remain fully elastic under design earthquakes, this necessitates using very large member sizes. On the other hand, any additional deformation capacity will increase the energy dissipation capacity of the system and help to reduce the structural member sizes further. (Figure 1 compares these two design philosophies.)

It is relatively simple and standard to design buildings to retain the required strength, but achieving required ductility is a relatively complex issue and requires extensive full-scale physical testing. Here, we'll review the special design requirements of steel moment resisting frames for seismic applications, as well as AISC's testing protocol. The focus will be on post-Northridge developments geared toward ensuring that steel special moment frames maintain a high level of ductility and energy dissipation mechanism.

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Stress State

Let's start with shear stresses. It has been established that plastic deformation can occur only in the presence of shear stresses. It can easily been understood from the Mohr circle that shear stresses are always present in a uniaxial or biaxial state-of-stress. However, in a triaxial stress condition, the maximum shear stress approaches zero as the principal stresses approach a common value (see Figure 2). Thus, under equal triaxial tensile stresses, failure occurs by cleavage fracture rather than by shear, which is considered brittle fracture. Consequently, triaxial tensile stresses tend to cause brittle fracture and should be avoided. A triaxial state-of-stress can result from a uniaxial loading when notches or geometrical discontinuities are present.

The tensile residual stresses resulting from welding can also increase the likelihood of brittle fracture. Residual stresses add to any applied tensile stress, and the actual stress in the member will be greater than applied stress. The high triaxial stress condition at the joint between the bottom beam flange and the column flange make it susceptible for brittle fracture. Also, the loading direction to the weld can play an important role on the brittle fracture of the welds. It is well understood that both the strength and the deformation performance in welds are dependent on the angle that the applied force makes with the axis of the weld (as shown in Figure 3). As you can see, the 90° angle between the weld and the force direction provides the least ductile behavior, making the weld susceptible for brittle fracture. These two phenomena can play an important role on the development of any special moment frame connections.

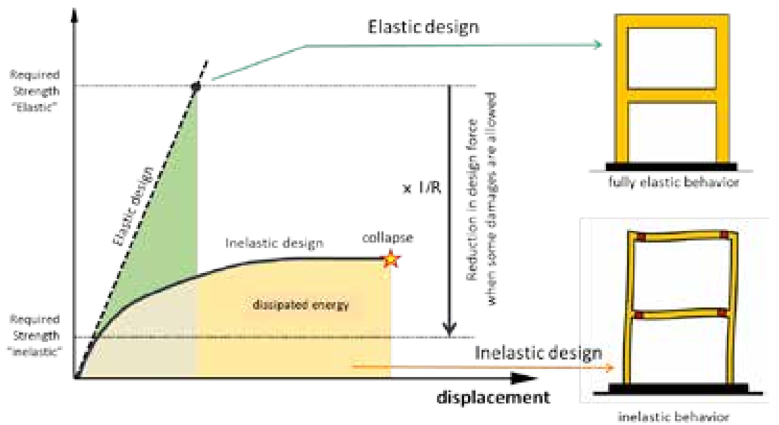


Figure 1. Different strategies of seismic design.

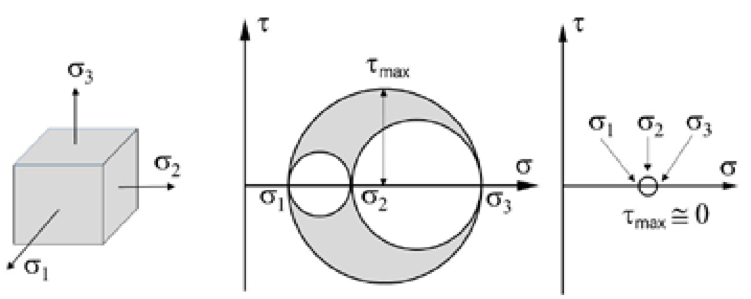


Figure 2. Uniaxial and triaxial stress states.

Prequalified Seismic Connections

Special moment frames (SMFs) are expected to withstand significant inelastic deformation during a design earthquake, so special proportioning and detailing requirements are therefore essential to resisting strong earthquake shaking. Experience from the Northridge earthquake significantly expanded knowledge regarding the seismic response of steel moment frames, and the design of SMFs—and their connections in particular—has undergone a significant change in the post-Northridge era.

Seismic Provisions for Structural Steel Buildings (ANSI/AISC 341-10, available at **www.aisc.org/publications**) provides detailed design requirements relating to materials, framing members, connections and construction quality assurance. It requires that moment connections used in special or intermediate steel moment frames be demonstrated, by testing, to be able to provide the necessary ductility. Two means of demonstration are acceptable. One consists of project-specific testing in which a limited number of full-scale specimens, representing the connections to be used in a structure, are constructed and tested in accordance with a protocol prescribed in Chapter K of the *Seismic Provisions*. Recognizing that it is costly and time-consuming to perform such tests, the *Seismic Provisions* also provide for prequalification of connections consisting of a rigorous program of testing, analytical evaluation and review by an independent body, the Connection Prequalification Review Panel. (Figure 4 on the following page shows typical test assemblage and loading protocol.)

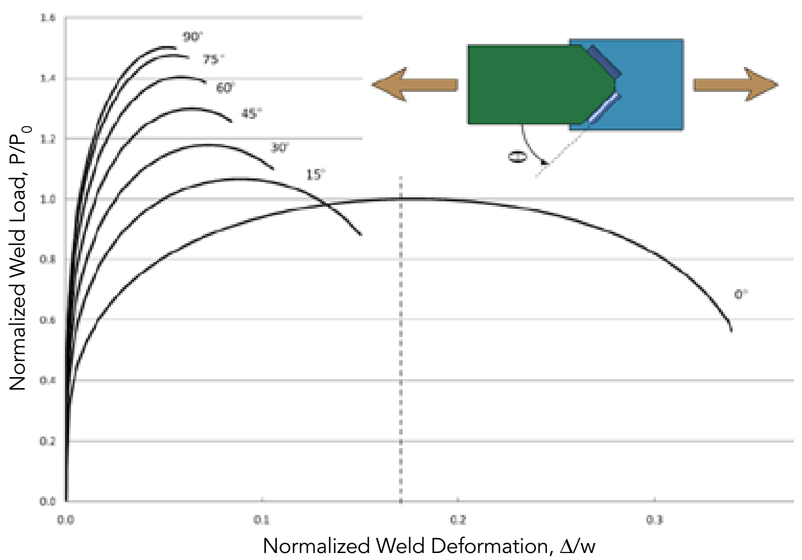
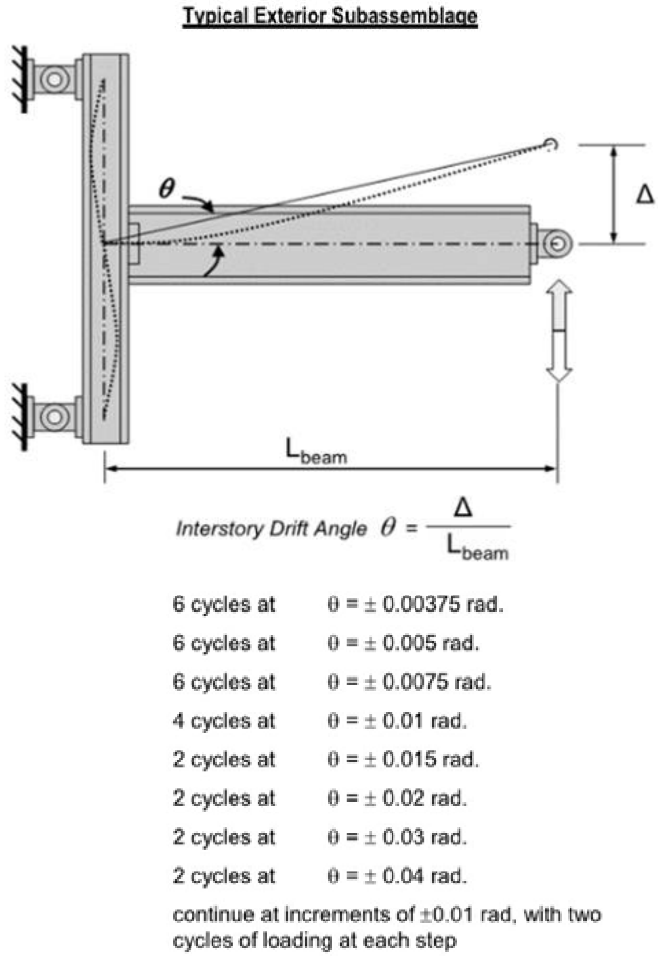


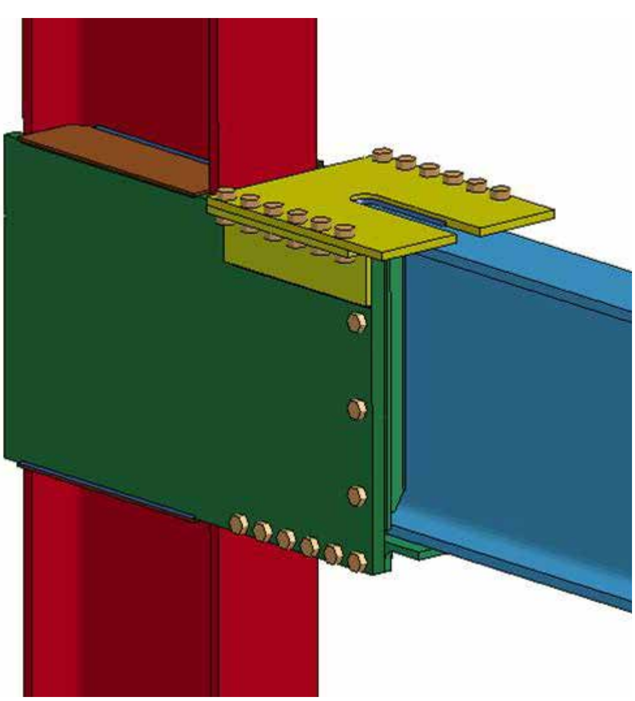
Figure 3. Load deformation relationship for welds.

According to the *Seismic Provisions*, the SMF connection should be capable of sustaining an inter-story drift angle of at least 0.04 radians, with the measured resistance of the connection being at least 80% of the connected beam's nominal plastic flexural strength.



▲ Figure 4. AISC 341 loading protocol.

▼ Figure 5. A SidePlate field-bolted SMF connection.



Prequalified Connections for Special and Intermediate Steel Moment Frames for Seismic Applications (ANSI/AISC 358-16, available at **www.aisc.org/standards**) is written to facilitate and standardize the design of steel special moment frame connections to allow their use without the need for project specific testing. It contains a series of connections that are prequalified to meet the requirements in the *Seismic Provisions* when designed and constructed in accordance the requirements of this standard.

Connections prequalified in this standard are intended to withstand inelastic deformation primarily through controlled yielding. The review of the prequalified connections shows that this goal is achieved either by strengthening the connection or weakening the beam so that the plastic hinge is forced to form in the beam region that has less complicated behavior and a low triaxial stress state. The reduced beam section (RBS) connection is a good example of "weakening the beam section" technique, and the SidePlate connection is a good representative of "strengthening the connection technique." Although the *Prequalified Connections* standard specifies design, detailing, fabrication and quality criteria for the prequalified connections, it does not provide any specific guidelines for refining existing connections or the successful development of new connections, and mainly relies on the results of full-scale testing.

Detailed Decisions

There are a wide variety of prequalified connections listed in the *Prequalified Connections* standard. Whichever prequalified connection is being employed, seemingly small but important decisions must be made when configuring them. One commonly known example is the SidePlate connection. This connection uses two interconnecting parallel plates that sandwich and connect the beam(s) to the column (as shown in Figure 5). The connection features a physical separation, or gap, between the face of the column flange and the end of the beam. The following techniques have been used to develop the connection:

1. The panel zone regions are substantially strengthened to force plastic hinging into the beam.
2. The additional SidePlate extensions cause the beam to hinge further out from the column face, which acts to effectively dissipate more energy without increasing the beam size.
3. The configuration requires only welds parallel to the direction of load providing maximum possible ductility in the welds.
4. Substantial finite element analyses were conducted to optimize weld hold-backs and weld-end profiles to reduce stress concentration at the points of load transfer from the beam to the connection. This results in a balanced and smooth load transfer according to the test results.
5. Only fillet welds are used in the configuration, ensuring that there is no notch effect in the root of the welds.
6. Every detail in every part of the connection was thoroughly studied to make sure that there is neither a high triaxial stress state nor notch effects.
7. Thorough finite element analysis is conducted if there are any changes or new features to the specification/construction of the connection.

In the end, properly designing any SMF connection, prequalified or otherwise, is as much of an art as it is engineering science. And using proven details will help ensure safe, effective connections. ■

This topic was featured in Session E15: "What Makes a Special Moment Frame Special?" at NASCC: The Steel Conference last month in San Antonio. Visit ***www.aisc.org/nascc*** *to view the presentation.*