structural
PERFORMANCE

Seismic Design of Aluminum Structures

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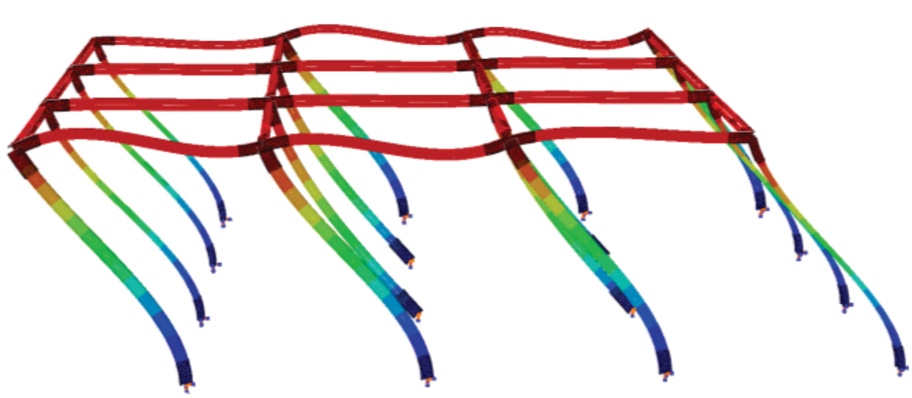

Aluminum building first dynamic mode shape.

Earthquakes impose such large and infrequent forces on structures that building codes permit seismic damage if the structures do not collapse. This damage often takes the form of inelastic, permanent deformation of members and connections. The idea is that the occupants can safely exit the building after a significant seismic event; the structure may be a total economic loss when subjected to the maximum considered earthquake, but collapse prevention is the primary goal.

The *R*-Factor

In designing for other loads, such as wind and snow, engineers realize that permanent deformations can be expected at strength limit states. But what makes modern seismic design interesting is that this inelasticity is actually advantageous to the performance of the structure during an earthquake. A partially yielded structure has less stiffness and consequently attracts smaller inertia forces – that is, less demand on strength as long as adequate ductility is present. To use elastic analysis for determining internal forces from an earthquake while simultaneously allowing inelastic behavior, building codes permit designers to divide such forces by a seismic response modification factor *R*. The *R*-factor is greater than 1, and its value depends on the seismic force resisting system (SFRS) of the structure – such as a braced frame or a moment frame – and the ductility of the structural material and components. For instance, the *R*-factor for a steel ordinary moment frame is 3.5. The bigger the *R*-factor, the smaller the seismic forces that must be resisted.

Before the 1994 Northridge earthquake, *R*-factors were estimated for various structural systems and materials and listed in ASCE 7, *Design Loads for Buildings and Other Structures*, which is referenced by most building codes. Northridge, however, revealed that some of these estimates were overly optimistic because unexpected fractures occurred. Consequently, code writers became much more cautious in assigning *R*-factors and systems that have not been grandfathered into the code now face a considerably higher hurdle to establish their *R*-factors. Because aluminum seismic force resisting systems did not have *R*-factors assigned before Northridge, aluminum lateral force resisting systems now fall in the "show me" category.

Part of the reason for this omission is that lateral force resisting systems are rarely designed and constructed of aluminum. In many buildings, the lateral force resisting system is either a steel or reinforced concrete frame, and aluminum and glass are used for the building envelope to transmit the wind pressure on the face of the building to the steel or concrete frame. When the earthquake hits, the aluminum is just along for the ride.

There are exceptions, however, including greenhouses and space frames such as domes. But it is hard to say today whether aluminum systems do not have *R*-factors because they are not used as SRFSs, or if aluminum systems are not used as SRFSs because they do not have *R*-factors.

In the absence of code-defined *R*-factors, designers either have to estimate a factor and provide justification so that the building official agrees, or set *R* equal to one, which means not accounting for the beneficial effects of inelasticity that may occur during an earthquake. While conservative, resisting earthquakes elastically is neither efficient nor competitive with other materials, unless, of course, wind loads govern the design of the lateral force resisting system. Wind can often govern the design of aluminum structures because aluminum has a high strength-to-weight ratio, so aluminum structures are light, resulting in less resistance to wind overturning while experiencing less inertial forces in an earthquake.

Aluminum and Steel

While it is tempting to think that aluminum SFRSs should have about the same *R*-factor as equivalent steel SFRSs, that is not necessarily a slam-dunk. Steel and aluminum are both ductile metals, but aluminum has less elongation at rupture than steel. For example, the most commonly used aluminum structural alloy is 6061-T6, which has a minimum strain elongation of 8%, while A992 steel has an elongation of 21%. Also, the ratio of yield to ultimate strength for 6061-T6 is not limited and is 0.92 for minimum strengths, whereas this ratio is limited to 0.85 for A992 steel. Lastly, aluminum strengthened by heat treatment loses that strength when welded, unlike steel. So where to go from here?

In 2009, the Federal Emergency Management Agency (FEMA) developed a rigorous protocol, P695 *Quantification of Building Seismic Performance Factors*, for determining *R*-factors for building systems. In the P695 procedure, an *R*-factor is assumed in a structure's analysis and design. The structure is then subjected to a suite of 44 ground motions and, based on advanced inelastic analyses of the structure for these motions, the probability of collapse is determined. If that probability is below FEMA's specified threshold, the *R*-factor assumed at the beginning of the process is good to go. Because there is a significant amount of work involved in inelastically analyzing structures for all those ground motions, you are well advised to pick your initial *R*-factor wisely.

Studying Differences

In 2013, the Aluminum Association, a trade association of aluminum producers, initiated a series of studies conducted by NBM Technologies to investigate aluminum SFRSs. NBM's work culminated in a paper by Meimand et al. (2016), *Incremental Dynamic Analysis and Seismic Performance Evaluation of an Aluminum Framed Building Compared with Steel*. They started by designing a one-story, three-span ordinary moment frame as the lateral force resisting system. This initial system was constructed of 6061-T6 extruded aluminum members in accordance with the *Specification for Aluminum Structures*, the design code for aluminum structures specified by the *International Building Code*. The bays of the system were 10 feet in both directions, giving an overall grid of 30 feet by 30 feet, with a 10-foot height. In addition to the dead load, a roof live load of 50 psf was assumed.

Using the FEMA P695 procedure and ABAQUS for the non-linear inelastic analyses, NBM determined a seismic response modification *R*-factor of 3 for this aluminum frame based on a 10% probability of collapse (see *Figure*). That alone would have been interesting, but not necessarily conclusive, because the P695 procedure is computational and complicated. To demonstrate the validity of the analysis, NBM next designed a steel frame of the same dimensions, using the AISC *Specification for Structural Steel Buildings* to size the members. Using the same method of seismic analyses, they found that the steel structure also satisfied the P695 criteria but with *R* = 3.5, a very happy outcome since ASCE 7 says that *R* is 3.5 for such steel SFRSs. Of course, this is good news for the steel design profession too, because it helps to validate the steel seismic factor estimates of the past.

Because codes allow steel SFRSs to be designed without special ductility details for low seismic applications if an R-factor of 3 is used, the study suggests that aluminum SFRSs using an R-factor of 2.5 (3 times 3/3.5) might also not require special ductility details. However, it would be premature to establish this from a limited investigation.

While the study examined only one frame and ignored fracture limit states, the models included local buckling, local-global buckling interaction, and yielding. Perhaps the results are not surprising because aluminum's ductility is an attribute that contributes to its extensive use, but hindsight rarely fails. Not only aluminum designers, but those working with hot-rolled steel, cold-formed steel, and stainless steel can gain confidence from this study.▪