There was a time, which many readers may well remember, when elastic behavior of structures governed our thoughts when it came to their design. For seismic design, we understood that the response reduction factor (currently designated '*R*') was a reflection of system ductility and gave us the latitude of designing the system for much lower forces than standard elastic design might typically predict. Inherent within this was the understanding that actual displacements would be much higher than those calculated when using the response reduction factor. Likewise, forces would be at least marginally higher; the old (3/s)  $R_w$  multiplier comes to mind.

Advancements and widespread acceptance of nonlinear design methods, which more accurately predict actual conditions, coupled with verification in physical test models, continue to propel our understanding of how structural systems actually behave when moderate and major transient events occur. A previous Structure magazine article, How Big is that Beam? The 'X' Brace vs. 'V' Brace Conundrum (STRUCTURE, November 2014), presents an example. It prompted several worthwhile and meaningful comments from readers. Peers of the author have also presented other geometries for which actual nonlinear behavior varies widely from the behavior predicted using elastic methods. One of these is the "multi-tiered X" configuration. This article addresses differences between linear and nonlinear behavior for such a case, and the need to design members for forces that are dramatically different from those predicted by linear analyses.

Consider the multi-tiered 'X' frame of *Figure* 1. For this example, pseudo-static lateral forces of 100 kips and 75 kips have been applied at the diaphragm levels for illustrative purposes. *Figure* 2 shows the axial forces that develop in the frame members for these forces with a rigid diaphragm at each floor level, an assumption that makes only a minor difference in the overall outcome. Seems quite intuitive, right? Except for some small participation due to flexural rigidity of the members, most of the load is resisted by axial compression and tension (in equal shares) in the braces and columns.

What happens during an actual seismic event? By virtue of detailing prescribed in the AISC *Seismic Provisions for Structural Steel Buildings* (AISC 341-10), we may have to design the connections to accommodate, if not promote, out-of-plane buckling of the braces in compression. While the AISC Provision allows for a relatively small degree of post-buckled compression capacity, we

may conclude that once the braces have buckled, their contribution to the stiffness of the system is relatively small. This can certainly be demonstrated with nonlin-

ear analysis methods, such as pushover or response history. For the sake of this discussion, let us assume that the braces acting in compression no longer are contributing to system stiffness in their buckled state, at least for the instant of time represented by the pseudo-static transient load.

Now what is the load path? Suddenly the beams between floors, which had no load under the

## Engineer's Notebook

aids for the structural engineer's toolbox

By Jerod G. Johnson, Ph.D., S.E.

The Nonlinear Load Path



Figure 1. Multi-tiered braced frame with pseudo static forces.



*Figure 2. Development of linear elastic frame forces.* 

Jerod G. Johnson, Ph.D., S.E. (**jjohnson@reaveley.com**), is a principal with Reaveley Engineers + Associates in Salt Lake City, Utah.

THE STOCKED

A similar article was published in the Structural Engineers Association-Utah (SEAU) Monthly Newsletter (January 2012). Content is reprinted with permission.

elastic case, have significant axial force as demonstrated by the red members shown in *Figure*  $\beta$  and the forces shown in *Figure* 4. Note that this presumes an infinitely rigid diaphragm at the presumed floor levels where the loads were originally applied. This approach gives us a good handle on the nonlinear forces of the frame, right? Actually, no; but we do have a more realistic view of how alternate load paths develop as nonlinearity (in this case buckling) occurs.

Owing to the response reduction factor (R), we should understand that the distribution of forces in the system will likely be dictated by the maximum developed tensile forces in the braces - in other words, the yield forces adjusted with the appropriate over-strength factor  $(R_{\nu}F_{\nu}A_{e})$ , which for this case has a magnitude of approximately 384 kips. The intermediate beams are then acting in compression to resist this force, not unlike the alternating web members of a truss or open web joist. Hence, the compression capacity in the beams needs to be designed accordingly

(322 kips) to resist the aforementioned brace yield force, thereby developing a deliberate and reliable load path for the frame's nonlinear performance. Likewise, the connections must be designed for the full (adjusted) yield strength. Why are the design forces governed by the tensile yield strength of the brace, and not by the actual forces applied to the model? To answer this, we must examine a fundamental premise behind the equivalent lateral force methods



Figure 3. Development of nonlinear load path.

Figure 4. Nonlinear load path forces with pseudo static forces.

ADVERTISEMENT-For Advertiser Information, visit **www.STRUCTUREmag.org** 

prescribed by the building code. When utilizing the R factor, our design forces become much lower (artificially) and we are indirectly taking advantage of the inherent ductility of the system. Higher Rfactors mean higher ductility. Use of *R* means that we are presuming ductile behavior, which for most systems means that we are presuming that materials (probably steel) will yield. In fact, yielding will likely occur long before forces commensurate to the prescribed spectral acceleration will develop. Hence, actual yield strengths become the de-facto governing forces for the strength design of the system.

The author acknowledges Brent Maxfield for his conceptual contribution with respect to this article.

## **GT STRUDL**<sup>®</sup> Structural Modeling, Design & Analysis



STRUCTURE magazine 12

June 2015