On Thinking Inelastically

By M. Lee Marsh, Ph.D., P.E.

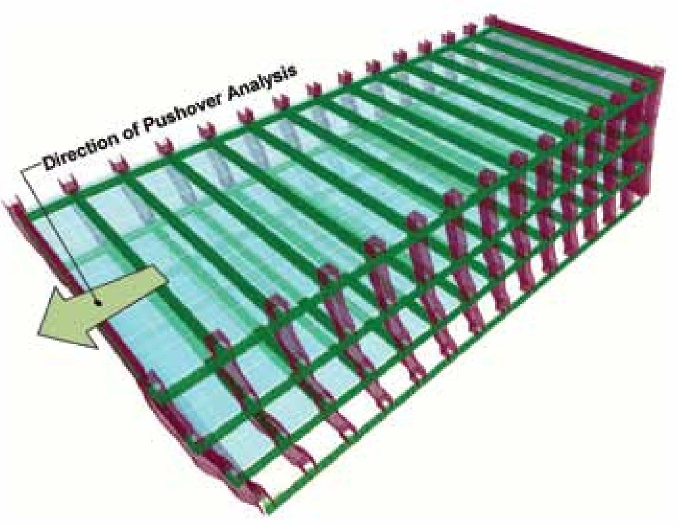

Figure 1: Analytical model of the Precast Building.

This article is about getting your head in the right place, about using the tools and techniques available today and about taking control of your design efforts.

All of us learned at one time or another that a little, and in some cases a lot, of ductility is a good thing. We cut our teeth on ductility of reinforced concrete beams, ensured by under reinforcing, which provides deformation capacity and warning time of impending problems should overloads occur. This practice, coupled with the suppression of unwanted failure modes, may have been the first inkling of "capacity design" that we knew as structural designers. Capacity design is the practice of setting a hierarchy of failure to control system behavior in the event of potential overloading. Nowhere is capacity design more important than engineering for extreme events, such as earthquake loading. At the risk of oversimplification, capacity design can be summarized in three steps:

1) Select the locations where yielding or inelastic deformation should occur,
2) Make these locations sufficiently ductile or deformable, and
3) Protect the remaining elements that do not need to be ductile by making them strong enough to resist the expected forces when yielding of the system occurs.

To be truly successful, the yielding must lead to a plastic mechanism that limits the forces in the system. It is the quest for such plastic mechanisms that is the focus of this article. Most folks who have opened a glass beverage bottle, sealed with a metal crimped-edge cap, intuitively understand capacity protection. The ductile cap yields and releases without breaking the glass when pried or twisted off, and life is good.

Enter seismic design. We often make a big fuss over performing seismic analyses and winding our way through a myriad of checks as prescribed by our design specifications. The process can be cryptic and unrevealing, but at the core we are only attempting to complete those three simple steps outlined above. Every provision of our seismic design specifications can be sorted into one of the three basic steps. This is where thinking inelastically comes in. When viewing the steps through the lens provided by elastic analysis and the seemingly unrelated checks of a force-based design, like those of our traditional building codes for new design, the designer can lose sight of what is being accomplished. However, when viewed through the lens of inelastic deformations, plastic mechanism, and capacity protection, the goal remains clear – develop a fusing mechanism that limits the internal forces and make sure that all the elements can resist the forces developed. And the designer, not the specification, should be in control of this process. What could be simpler?

In the last dozen or so years, techniques that were once used primarily for research have become more mainstream for everyday design. Key among these is the pushover technique or nonlinear static procedure (NSP). This analytic technique assists us in "thinking inelastically" and in quantitatively assuring that the ductile response we desire is in fact incorporated into our structures. The pushover technique is a direct check of deformability, where the force-based (R-factor) seismic design methodologies, with their associated prescriptive detailing requirements, simply attempt to indirectly achieve the three steps of capacity protection. Wouldn't a direct check be more satisfying than an indirect hope-for-the-best? Don't get me wrong, the R-factor methodology is not altogether inappropriate for regular structures, and it certainly is easy enough to execute, but for some of the more "creative" and complex structures we are building today, a direct check of deformability can often be a good thing.

The pushover technique has been variously codified in ASCE 41-06 *Seismic Rehabilitation for Existing Buildings*, the recent AASHTO *Guide Specifications for LRFD Seismic Bridge Design*, and in the forthcoming ASCE *Standard for Seismic Design of Piers and Wharves*. The pushover technique is not a design tool so much as it is a checking or assessment tool, to be used after a design has been assembled. But the approach is so much more revealing than the traditional force-based design approach, where force reduction factors are applied uniformly to the entire structure. Instead, with the pushover method, the actual path to plastic mechanism is tracked and internal deformations, whether plastic rotations, curvatures or strains, are quantified and these are compared against permissible capacities. The pushover process provides the analytic check of what our mind's eye conjures with respect to ensuring that a suitably ductile and capacity protected structure is designed. Such a tool certainly helps the designer control the design, something that often may not be a "given". And such analytic tools help designers hone their ability to "think inelastically".

Years ago, a professor of mine stressed thinking in terms of the deflected shape and identifying all the ways a structure could fail. In earthquake engineering, controlling "failure" to follow a ductile path and thinking in terms of plastic mechanism is the key to producing seismically successful and rugged designs. The tools and design procedures emerging today, across the various practice areas of structural engineering, are helping and encouraging engineers to "think inelastically" to ensure their designs will achieve the performance they desire should a severe overload such as a large earthquake occur. Remember, "there but for the grace of ductility go I". Think inelastically!

Once thinking inelastically, potential seismic performance can be better assessed. As an example, a pushover analysis was performed on 3-story concrete building constructed in the late-1960s. To expedite construction, precast concrete panels were erected as the primary structure and cast-in-place concrete was used to connect precast components and form the columns. The building layout was such that seismic resistance in one direction relied entirely on the shear and flexural behavior of the composite column, as shown in *Figure 1*. The pushover analysis, shown in *Figure 2*, exposed 3 important issues that may compromise seismic performance:

1) Hinging columns produce a soft-story with large deformation demand at the first level,
2) Hinges may be controlled by shear rather than flexure, resulting in less shear capacity and ductility, and
3) Shear demand on the composite column may separate the precast and cast-in-place components of the column and base shear capacity of the building may reduce dramatically.

In both the composite column and non-composite column cases, the target roof displacement exceeds the deformation capacity of the structure. The building is currently being designed for a seismic upgrade to correct known deficiencies.▪

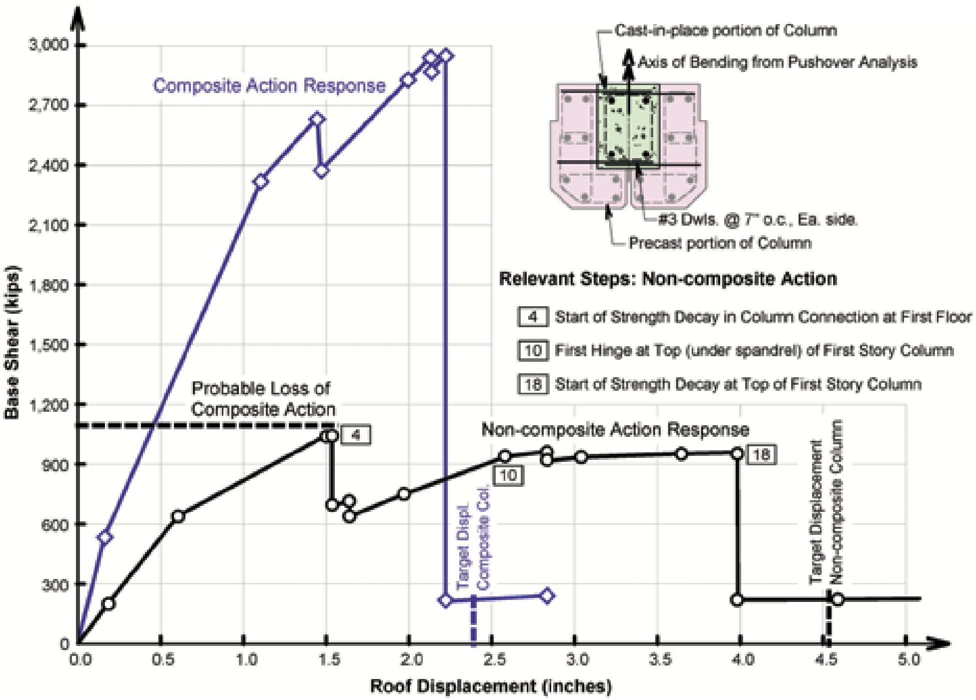

Figure 2: Pushover analysis of 3-story building showing the impact of composite vs. non-composite column behavior.

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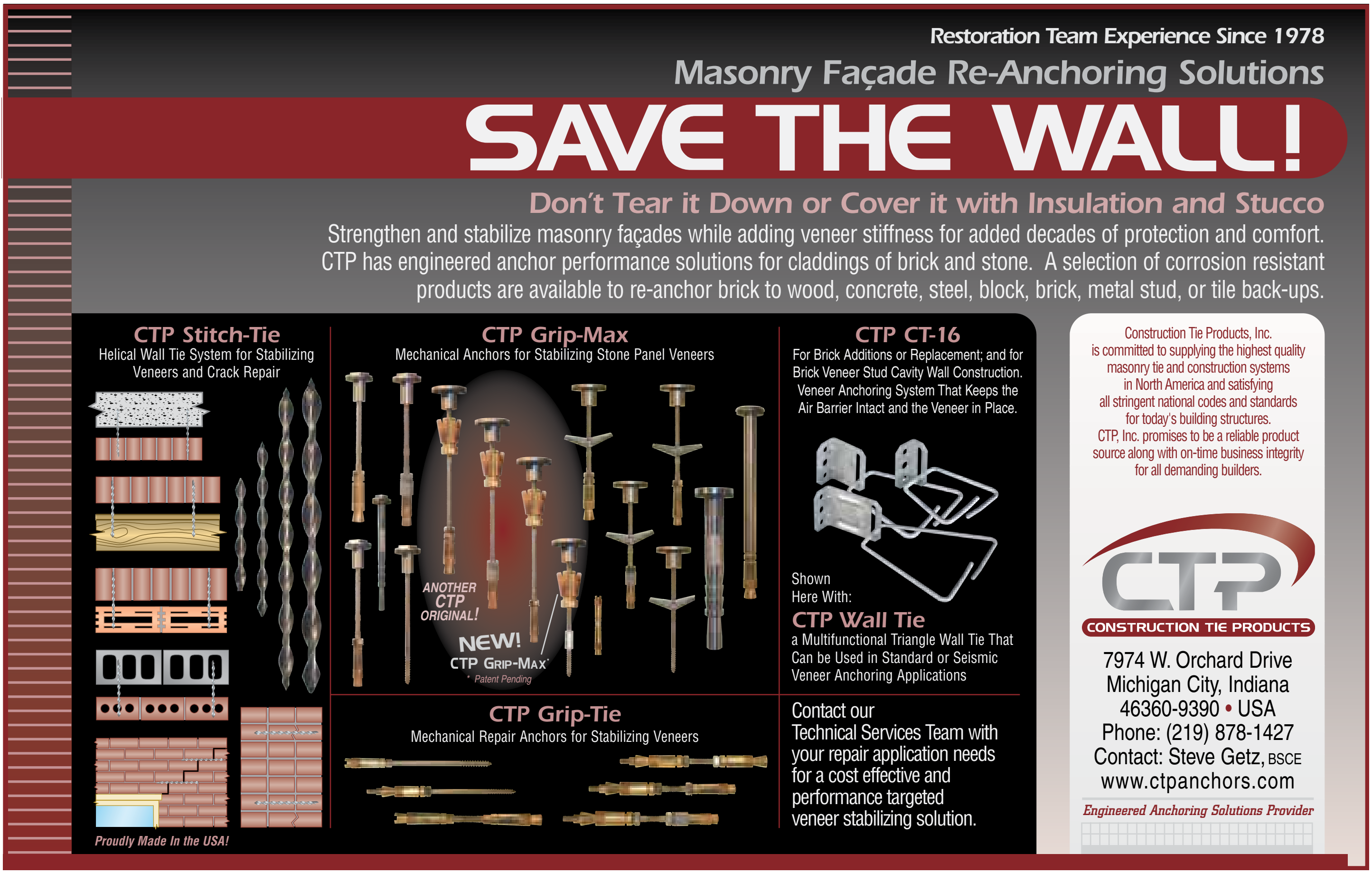
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