Severe Events

Facing the Challenge

By Joe Kallaby, P.E., S.E.

Recent events pose a challenge for structural engineers. How safe are our structures against such severe events as hurricanes, earthquakes, tornados and blast? This article proposes that structures be investigated for such events, using their "reserve strength" which derives from their ductility and post elastic strength.

The pushover procedure is used to evaluate this reserve strength and identify a structure's primary weak links, to strengthen them for compliance with statutory requirements for severe events, as they are further developed. This article re-visits the pushover procedure, to clarify its essential elements that may not have been properly applied.

*Alaska Earthquake March 27, 1964. Wreckage of the J.C. Penney Department Store at Fifth Avenue and D Street in Anchorage. The building failed after sustained seismic shaking. Most of the rubble has been cleared from the streets. Courtesy of **http://libraryphoto.cr.usgs.gov**.*

We have traditionally designed structures to meet requirements of codes, standards, and guidelines, using good practice. This standard practice, we will call "Design Strength Level" or DSL, maintains structures in the elastic range, where material stresses are below yield, buckling or ultimate strength, by a comfort margin (safety factor), recognizing reliability of materials, design process, and acceptable risk. It is based on providing adequate stiffness to limit deflections and provide for operating requirements, cladding compatibility and comfort. It has served us well and continues to be the basis for design.

Recent events have focused attention of policy makers and the public on safety of structures. They have prompted us to look beyond this standard practice, to find ways to address "severe" events. These may be natural disasters caused by the environment (hurricanes, tornados, tsunamis and earthquakes) or by people (blast and terrorism).

Severe events are not amenable to strength design, mainly because of prohibitive cost. They demand a higher level, which we will call "Reserve Strength Level" or RSL, which capitalizes on the inherent reserve strength of structures in the post elastic range, up to collapse. A rational approach, commonly referred to as the "Pushover" procedure, allows us to not only evaluate reserve capacity but, more importantly, to make changes to substantially increase it to meet severe events demands.

This article proposes that structures, designed for DSL, be investigated for their reserve strength, ductility, energy absorption capacity and stability in the post elastic range, to meet the demands of RSL, using the Pushover procedure. It will revisit this procedure, to highlight its basic elements and focus on correctly interpreting them.

For a moment, let us put all codes, standards, and books aside to answer two basic questions.

A Structure Is Intended To:

A) Remain functional, under loadings consistent with its intended use and that of the environment, with no damage, throughout its useful life.
B) Provide a safety net for its occupants under severe, uncommon demands placed on it by the environment or other events. In this condition, the only requirement is that the structure will not collapse. It can buckle, yield and undergo large deformations, but must remain stable.

Structural Engineers Can Provide:

A) Strength designs for A above, having been "weaned" on elastic design, whether it is Allowable Stress Design (ASD) or Load and Resistance Factor Design (LRFD).
B) Safety assessment, using the structure's reserve strength.

But what is reserve strength, how to measure it, how to increase it?

Before we proceed, let's clarify the following, as they pertain to this discussion:

Structure: A building, a bridge, an offshore platform, a silo, or any configuration that requires structural engineering to bring it to form. A structure can resist gravity and lateral loads through frame action, shear walls, or a combination of both.

Foundation: An essential part of the structural system. Coupling structure-soil system is necessary for simulating true performance, even more so under severe event loading.

Cladding, Mechanical & Electrical Systems: are essential, but are beyond the scope of this article.

Reserve Strength: is simply a measure of the ability of a structure to sustain additional loading, past the DSL, up to collapse.

How to Measure Reserve Strength:

Three approaches have been used:

A) The ratio of the base shear at collapse to that at DSL. This has been used to gauge the base shears due to earth quakes or storms.

B) The ratio of the energy absorbed up to collapse to that at DSL. (Hardly used.)

C) The ratio of the target displacement at a point of interest (roof is commonly used) at collapse to that at DSL.

Pushover Defined

Pushover is simply a step-by-step procedure, intended to "mimic" the progression of post elastic deformation of a structure until collapse. For dynamic loading, it "mimics" the changes of the inertial loading pattern, recognizing all significant mode shapes, as it progresses to collapse. It is a series of snap-shots of the deformed structure, at progressive stages, up to collapse.

The pushover procedure was originally used to evaluate the reserve strength of offshore platforms for severe earthquakes. Developed by this author and implemented by the co-author, it was presented in an Offshore Technology Conference paper in 1975. It was adopted by the American Petroleum Institute in 1977, as its design standard for offshore platforms, which led to extensive post-elastic behavior research and testing of plane and space frames. The paper won the Inaugural Hall of Fame Award in May, 2006.

The concept of evaluating the inherent post elastic strength of a structure up to collapse, as a measure of its reserve strength to resist major seismic events, is at the heart of the pushover procedure. The 1975 paper also proposed two levels of earthquake events: a "Strength Level", with a high probability of occurring during the life of the platform, to insure adequate stiffness to remain fully elastic; and, a "Safety Level", the most severe that regional tectonics can be reasonably expected to generate, to have adequate ductility and reserve energy absorption capacity to maintain stability, without collapse.

Pushover is applicable to almost all events in which either lateral, vertical or a combination of both forces act in an increased and sustained manner to cause structural collapse. Its essential elements are re-visited here. For purposes of this article, the discussion is limited to braced, space frames under severe earthquake events.

Basic Requirements of Pushover

Software Model: A 3-D model of the structure is essential to allow for effects of higher modes and torsion. It should be able to:

A) Allow coupling of the foundation system to the structure, either linear or non-linear.

B) Process a large number of members and joints.

C) Automatically allow for P-Delta effects, which are critical to stability, and may trigger collapse.

D) Allow for increase in critical damping ratios, especially for large deformations prior to collapse.

E) Perform dynamic (modal) analysis and summation (SRSS, CQC, others).

F) Have reliable routines for post elastic performance of yielded joints and buckled members, to analyze a structure in its "deformed shape".

Many simpler models can be used, if justified by their demonstrated, or intuitively arrived at, post elastic performance of the structure-foundation system. Offshore structures have had the good fortune of ample funding for such software.

DSL response spectrum with lateral and vertical components, preferably site specific, otherwise from statutory requirements. The vertical component can be critical, to avoid collapse due to columns punching through slabs or beams.

RSL requirements in the form of minimum reserve strength ratio, or a specified target deflection and location. Roofs are commonly used as acceptable locations. The 1975 paper proposed the ratio of the platform deck deflection at collapse to that at DSL be a measure of reserve strength. It also proposed that this ratio be based on the ratio of the effective ground acceleration at RSL to that at DSL.

Pushover Analysis Procedure

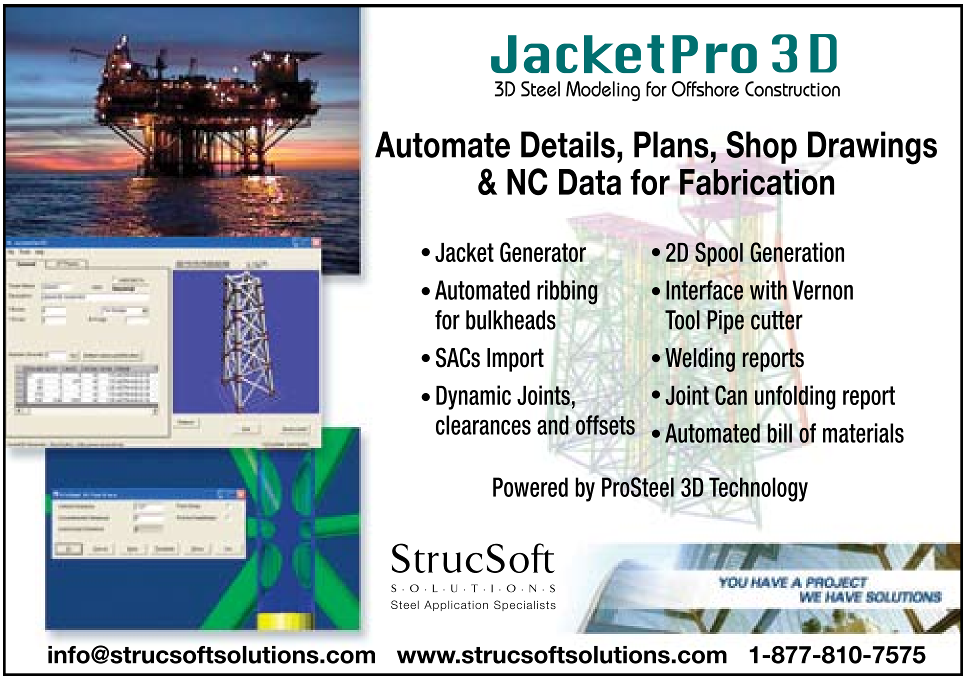
1) Select appropriate software capable of providing for the needs of the procedure.

2) Perform modal analysis to determine the characteristics of the structure-foundation system.

3) Perform response spectrum analysis using an appropriate damping factor, to determine DSL inertial joint loads. The lateral and vertical components of these inertial joint loads, along with dead and appropriate live loads, become the initial loads to start the pushover analysis. The lateral load distribution (shear diagram) is instructive, but not necessary for pushover analysis.

4) Check that the P-Delta option of the software is active. Increase both the horizontal and vertical inertial loads monotonically until either a member buckles or a joint yields. Buckled members will now have a reduced capacity, which may still be a substantial portion of its buckling capacity, because it is prevented from total collapse by constraints of the overall deflection of the structure. Yielded joints will now either have reduced capacity, or full Mp for compact sections.

5) Perform a new modal analysis using the deformed model, to revise the inertia loads. As the structure becomes less stiff, inertia loads decrease. When and how often to perform such analysis is an important call by the engineer, based on experience and/or intuitive



forecasting of the structure's performance. Increasing loads monotonically up to collapse, without re-visiting inertia loads, may lead to significant errors for ductile structures with significant higher modes, and is not recommended.

6) Continue incremental increases of inertia loads, monitoring reduction in stiffness, for another round of inertia loading revision. Dead and live loads are unchanged.
7) As the structure moves towards collapse, its stiffness tends to diminish, while its damping tends to increase. Here again the engineer is called upon to revisit the damping ratio when up dating the inertia loads. This is important in tracking performance.
8) At collapse, RSL displacement is determined and compared with statutory or target requirements. If it meets these, analysis is terminated. It is best to continue the analysis up to collapse, to gain insight into the behavior of structures.
9) If RSL displacement at collapse does not meet requirements, the analyst can bring it to compliance by :
   a. Upgrading critical joints to compact sections
   b. Reducing kl/r values of critical bracing members. A high Kl/r value provides little reserve strength compared to a lower one.
   c. Adding alternate load paths to allow for improved re-distribution of loads.
   d. Applying all above remedies.

Using Pushover for Other Severe Events

Understanding how loading generated by other severe events incrementally increases is essential, because it is event dependent. Let us look at a couple of common examples.

Hurricanes

These may have lateral and vertical components from waves, currents and wind. For offshore platforms, for example, it is critical to recognize that this loading increases with higher waves, stronger currents and faster winds, rather than monotonically, as many erroneously assume.

Storm Surge

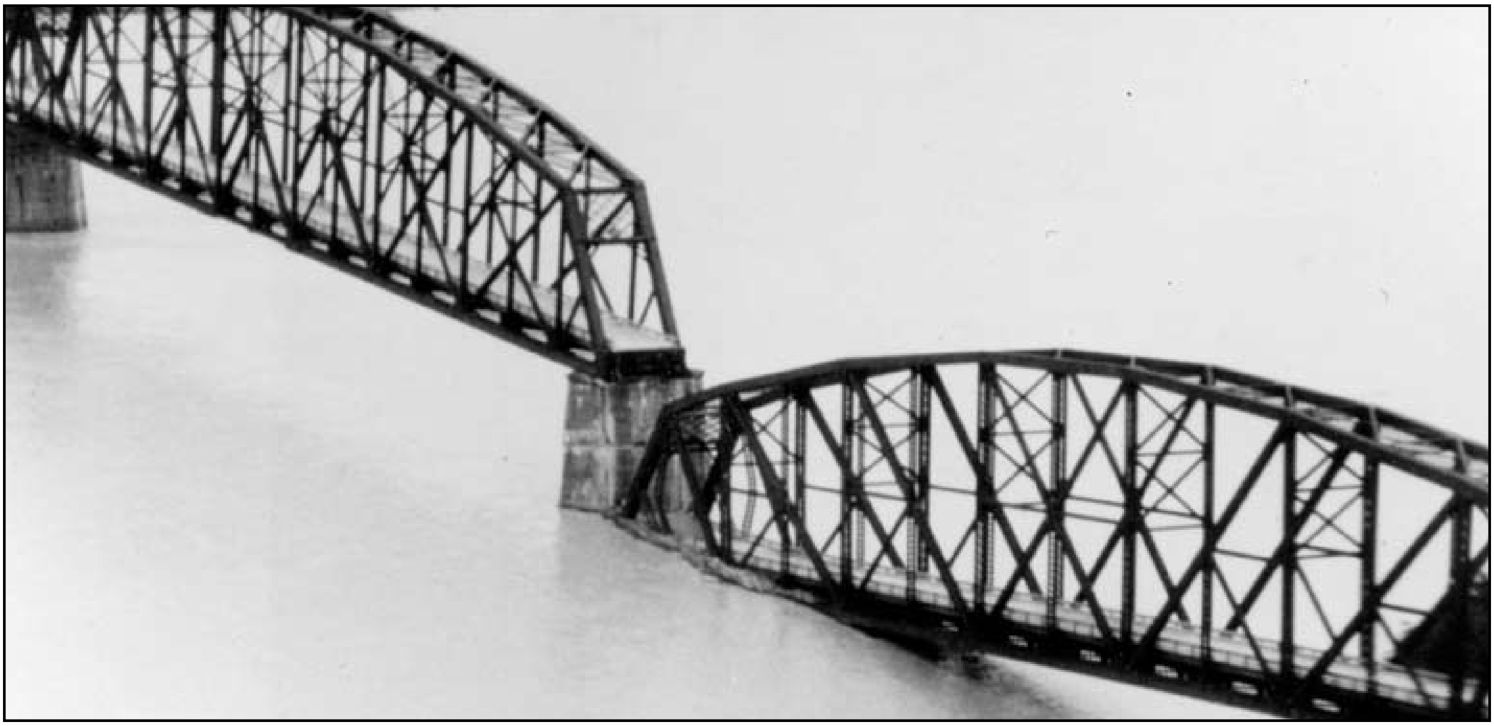
Effects of hurricanes on near-shore buildings or other structures require a different approach. In this case, the actual position of the building is defined by its latitude and longitude, and the maximum surge, with its accompanying wind, is determined for each of the Hurricane Categories. The owners, in the absence of statutory requirements, select the level of risk appropriate for their needs, based on the cost of upgrading to each next level of hurricane category. In each case the building is checked for its ability to survive, using Pushover.

A Glimpse at A Structure As It Approaches Collapse

Essential to designing structures with a good chance of survival under severe events is the ability of the structural engineer to clearly visualize how it "musters" all its strength to do so. Using earthquake as an example, as the structure deforms it softens, reducing its stiffness, and therefore the inertia loads trying to force it down. As deformation continues, structural as well as soil damping increases, and so does the structure's resistance. Mass, of course, remains unchanged. A structure, well designed for post elastic ductility and strength, stands a good chance of survival.

Fundamentals Of Well Designed Structures

1) Critical joints should have high ductility, as in compact sections. This allows the joint to undergo large post elastic deformations and still maintain full plastic moment (Mp) capability. Concrete columns can provide much ductility, as demonstrated by the Olive View Medical Center ground floor columns with lateral deflections of 2-feet in story height of 12-feet, during the 1971 San Fernando Earthquake.
2) Critical bracing members should have lower Kl/r values, preferably between 50 and 70, to increase lateral load resistance and provide significant increase in ductility and reserve strength.



Alaska Earthquake March 27, 1964. Million Dollar Bridge on the Copper River Highway; no. 4 span off no. 4 pier. View is southwest. Courtesy of ***http://libraryphoto.cr.usgs.gov.***

3) Alternate load paths are essential to avoiding the "chain link syndrome" where a structure collapses because loading can not be transferred to the next "less injured" members.

The above can be monitored using Pushover, where critical joints and bracing members are monitored and enhanced, as needed, to comply with requirements. To illustrate, assume a mid-rise building with a large number of joints and members, entirely supported by three columns, which make up 2% of its total steel tonnage. If one of these columns buckles first, the structure will collapse. The balance of the steel, almost all of it, is worthless, unable to help. This would be easily remedied.

The ideal structure is one designed such that every major component will "give its all" before collapse.

Future Needs (Wish List)

To perform meaningful and realistic pushover analysis, it is critical that software be made available which can integrate all elements needed for such analysis. The offshore industry had the means and the will to climb this mountain, with both software and testing of planar and 3-D braced frames, to investigate their performance, and to try and emulate it with the software.

Buildings and onshore structures are more complex and diverse. However, they do have the resources to climb their mountain, if one were to consider the tragic human and material loss that natural disasters impose. FEMA, NIST and NSF through ATC, EERI, universities, and similar organizations may hopefully see the need and come forth with the resources. They have done much for earthquake research and are progressing on wind and blast, but have yet to commit to address severe events, using reserve strength. Software vendors would follow, having the incentive to develop the software needed. Simplifications and rules of thumb in applying Pushover for diverse small and medium sized structures, classified by their types, may continue to be the effective way to evaluate them. However, these should be based on investigations and testing of the performance of such structures.

Here are several areas requiring attention, to better understand and evaluate structural performance:

- Software capability to properly model large or complex structures in full 3-D, with sufficient accuracy to reasonably predict performance. This would allow for inclusion of significant higher modes, torsion, P-Delta effects and coupling of foundation to structure. Efficient software with extensive graphical displays is essential for review and understanding of the strengths and weaknesses of the structure.
- Good routines for representing column and joint post elastic behavior are critical.
- Software ability to "snap-shot" a deformed structure to perform modal analysis and revise inertia loads, as pushover progresses.
- Determining soil properties that are consistent with the level of loading that the structure will be subjected to, especially as it approaches collapse. For earthquake events, dynamic soil properties can be critical to stability.
- Providing realistic critical damping ratios for structure and foundation, as they undergo significant post elastic deformation.
- Establishing free field site dependant response spectra for groups of foundation soils that might be expected, to be evaluated for near field.
- Establishing "safety" demands for "severe events," appropriate for evaluating reserve strength. For example, for earthquakes, this can be a roof target drift or displacement, an RSR value, or simply the ratio of the RSL effective acceleration to that of the DSL.
- Performing full scale tests on small, representative structural systems to correlate actual with modeled behavior.
- Providing simplified procedures for diverse, complex framing systems, many with bracing and shear walls, which make up a major inventory of structures but have no reasonable expectation of sufficient owner funds to perform the required analysis for reserve strength.

Conclusion

This article proposes going beyond standard design practice by evaluating structures for "Severe Events", using their reserve strength. It uses the Pushover procedure to evaluate and enhance reserve capacity to achieve compliance with requirements to be formulated.

Key elements of this procedure are revisited to underscore their importance for realistic representation of structural performance up to collapse.

A "wish list" of future needs is proposed, with emphasis on buildings and other onshore structures.▪

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REFERENCES

Ref. 1: "Inelastic Analysis of Fixed offshore Platforms for Earthquake Loading" by Joseph Kallaby and David N. Millman, Proceedings of the Offshore Technology Conference, Paper No. OTC 2357, May 1975.

Ref. 2: "Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms", American Petroleum Institute, Recommended Practice 2A, 7th. Ed., January 1978, Dallas, Texas.