PERSPECTIVE

Checking Our Work: Methods for Verifying Analyses of Structural Designs

by Dr. Thomas Murphy, Modjeski and Masters Inc.

For designers, there is often a strong incentive to keep things simple. Construction cost, design effort required, and the possibility of unforeseen problems push us to choose uncomplicated, easily understandable structural models for our designs. There are, however, other factors influencing design that can lead to more complex structural systems and behaviors. Aesthetics, geometric constraints, and the need to minimize material quantities are just some of the factors that can lead designers to select systems that are more difficult to analyze and more challenging to understand. The Bronco Bridge in Denver, Colo., is an example of a structure that required a complex analytical model (see photo).

Fortunately, our profession now has the tools to analyze and design virtually any structural system, no matter how complex. The challenge is making sure the analysis method and the corresponding results are adequately checked. This can be a daunting task, but there are methods that engineers can use to give them confidence that the complex behavior has been correctly captured in the results of the analysis.

The most direct approach is to perform an independent analysis and compare the results of the analyses. This can be time-consuming because you essentially perform the analysis twice and then attempt to resolve any differences in the results. There will almost always be differences between any two analyses due to differing assumptions and approaches, but this does not necessarily mean that one analysis is incorrect, or that a design based on the results of either would be deficient. The challenge for the designer in this situation is twofold: ensuring that the base assumptions made in both analyses are valid (that is, the same error was not made in both analyses), and resolving any differences in results until they are acceptably small.

The method of comparing analyses will vary depending on the details of

Designed to optimize the use of precast concrete, the Bronco Bridge in Denver, Colo., features a totally precast concrete rigid frame and is one example of a structural design that required a complex analytical model. Photo: Modjeski and Masters Inc.

the models (see "Element Modeling Options" for more information). If only beam- and frame-type elements are used, a comparison of deflections and key forces will likely suffice. However, if shell or solid elements are included, there is typically an additional step to go from the model output, typically stresses, to design values, typically forces and moments, with many opportunities for errors to creep into the process. A comparison of the final, integrated force and moment values would then be in order.

When performing an independent analysis, it is sometimes useful to intentionally vary the analytical approach from the base analysis as an additional check. For example, if the base analysis uses shell or solid elements, an independent analysis that uses beam elements can provide further assurances that the overall results are reasonable, even if the localized results may be less accurate due to the lower-order elements in the independent analysis.

When time and budget allow, the independent replication of results by a separate analysis is probably the best practice. However, it is not always appropriate, and other methods can be successfully and more efficiently applied.

Moving away from a full replication of the analysis, approximate methods of analysis can be used to provide what is often termed a "sanity check" on higher-order analytical results. Here, what is desired is a general check on the overall results without an independent evaluation of detailed results. In these cases, designers can take advantage of the rich library of approximate analysis techniques that were developed before the advent of the digital tools we heavily rely on today. There are many and varied examples of these techniques, including Pucher[1] and Homberg[2] charts used to determine moments in box-girder top flanges created by local loads and similar tables of moments in plates for a variety of fixity conditions from old U.S. Bureau of Reclamation publications, such as *Moments and Reactions for Rectangular Plates*,[3] or texts such as *Roark's Formulas for Stress and Strain*.[4] Concepts such as the elastic center method, historically used to simplify hand calculation of frames and arches, and the associated column analogy method of determining the location of the elastic center can still prove extremely useful in fashioning simpler models of complex behavior that can verify the solutions derived from far more involved and complicated numerical models.

There are few references that a bridge designer can consult to address the issue of verification of the results of complex models. One exception to this is the recently published Federal Highway Administration *Manual for Refined Analysis in Bridge Design and Evaluation*.[5] While primarily focused on typical structure types, the manual provides some guidance on the verification and validation of refined analyses, along with examples of how relatively complex models were verified by various methods.

The bridge design profession consists of multiple engineering generations with widely differing attitudes toward analysis.

Currently, the bridge design profession consists of multiple engineering generations with widely differing attitudes toward analysis. In a design office today, you might encounter engineers for whom a finite element analysis is considered something exotic, only to be used in the most extreme circumstances, as well as engineers who would create a shell element model to find the axial load in a member of a statically determinate truss. When developing an approach for the verification and validation of analytical models of complex structural behavior, it is often important to include multiple designers with a mix of engineering backgrounds. On the one hand, the engineers with the least experience may have the most expertise with finite element software packages and complex engineering issues. On the other hand, the engineers with the least numerical modeling expertise may be the most familiar with the shortcuts and approximate approaches that can be so valuable in providing a critical check on analytical results.

Element Modeling Options

Engineers have many different choices for how to model a structure. Simpler structures can be modeled using beam or frame elements, which idealize behavior as one-way bending, whereas more complex structures require elements that can capture bending in two directions, such as plate elements. Curved plate elements are sometimes referred to as shells.

References

1. Pucher, A. 1977. *Einflussfelder elastischer Platten/Influence Surfaces of Elastic Plates*, 5th ed. Vienna, Austria: SpringerVerlag Wien.
2. Homberg, H., and W. Ropers. 1965. *Fahrbahnplatten mit verändlicher Dicke*,1st ed. Berlin, Germany: Springer-Verlag Berlin Heidelberg GmbH.
3. Moody, W.T. 1990. *Moments and Reactions for Rectangular Plates*. Engineering Monograph No. 27. Washington, DC: U.S. Department of the Interior Bureau of Reclamation. https://www.usbr.gov/tsc/techreferences/hydraulics_lab/pubs/EM/EM27.pdf.
4. Young, W., G. Budynas, and A. Sadegh. 2012. *Roark's Formulas for Stress and Strain*, 8th ed. New York, NY: McGraw-Hill.
5. Adams, A., N. Galindez, T. Hopper, T. Murphy, P. Ritchie, V. Storlie, J. Weisman. 2019. *Manual for Refined Analysis in Bridge Design and Evaluation*. Federal Highway Administration Report FHWA-HIF-18-046. McLean, VA: FHWA. https://www.fhwa.dot.gov/bridge/pubs/hif18046.pdf.