Quick Methods

Finding Errors in Structural Analysis and Design Results

By James Hanson, P.E., Ph.D.

You know they're in there somewhere. We make errors every day. The goal is to make sure that ultimately the design is safe and meets the needs of the client; therefore, many of the errors need to be corrected. But how do you find the errors? That was the focus of interviews recently conducted with 35 practicing structural engineers. The National Science Foundation has sponsored the project to find out how experienced engineers evaluate the reasonableness of their results, and to incorporate teaching those strategies into undergraduate structural engineering courses. This article summarizes the results of those interviews and identifies 10 quick checks that can be used to help identify the presence of errors in structural analysis and design results.

Types of Errors

For the purpose of this discussion, define "error" as anything causing our prediction to differ from reality or anything causing reality to differ from what we intended. From this definition, we can group errors into four categories.

1. *Idealization of the real structure.* This category includes all of the assumptions we intentionally make in order to model a structure. Some examples include assuming unrestrained rotation at every joint of a truss, exactly straight members, or perfectly rigid diaphragms. Fortunately, many of the errors induced by the idealization of the structure have a relatively small impact. The load and strength reduction factors used in design standards account for most of these errors. The exception is idealizing a structure that behaves between two extremes (e.g., semi-rigid connections, semi-flexible diaphragms). These exceptions, however, can be addressed by performing analysis on the two extremes and designing based on the most severe conditions.
2. *Assumptions inherent to the analysis method or design equations.* Every analysis method and design equation incorporates some assumptions. An example is the expression for shear capacity of a reinforced concrete beam without stirrups; that equation is an empirical lower bound based on laboratory tests. The load and strength reduction factors used in design standards account for these errors as well.
3. *Roundoff error*. Every calculation, hand or computer generated, is subjected to some roundoff. With 16-bit arithmetic being standard on desktop computers, these errors tend to be extremely small and are routinely ignored.
4. *Human error*. This broad category includes any error that is unintentional or unanticipated. These errors can occur at any time in the design process from design development to review of shop drawings.

Our current design standards account for the first three types of errors (with a few exceptions as indicated in the *Idealization* category). They do not, however, account for human errors. It is the responsibility of the designer to ensure that human errors do not reduce the safety or impair the performance of a structure. Therefore, it should not be a surprise that all of the information obtained from the interviews pertains to human errors.

Practitioners Interviewed

The 35 engineers interviewed in this study represent nine different design firms specializing in buildings. The group had an average of over 15 years of experience in structural engineering. Their individual experiences ranged from less than 1 year to 55 years, with a median of 8 years. Only six did not yet have their P.E. license. All of the engineers had college degrees. The distribution of highest degree was 8 Bachelors, 26 Masters, and 1 Doctorate. Each firm employed between 1 and 700 structural engineers world wide. The specific offices visited had up to 55 structural engineers.

You Too Can Participate!

It is not too late for you to participate in this study. If you would like to contribute, please contact Dr. Hanson to arrange for a time for the interview. The interview can be conducted over the phone and takes about 15 minutes. Also, please contact him if you would like more information on the teaching materials being developed. The materials can be used by faculty in their courses or by practitioners for in-house training.

Results of Interviews

During the interviews, each engineer was asked to describe instances when they found something unreasonable in the results of analysis or design. The interviews resulted in 67 specific instances. The engineers were also able to provide 20 examples of "common" problems and how they would find them. After reviewing the data, several category labels for the various strategies they described for identifying the presence of errors were developed:

Comparison (23 of 87). This category involves comparing two or more approaches or situations (e.g., hand calculations versus computer results, results from two different computer programs, results considering different conditions).

Rules of Thumb (7 of 87). This category involves use of simple formulas to predict member sizes or properties.

Visualization (5 of 87). This refers to visualizing the load path. Typically it involves making cuts and confirming that forces have a continuous path to the foundation.

Previous Experience (22 of 87). These strategies can only be developed through experience. They typically involve recognizing a situation as similar to previous projects.

Field (14 of 87). This is one of the least preferred strategies. It means that the problem is discovered during or after construction.

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The Pocket Guide

Ten Questions for Identifying Presence of Errors

1. Is the deflected shape consistent with what was expected?
2. Are the moment diagrams consistent with what was expected?
3. Does the building weigh what you anticipate?
4. Does total base shear equal total applied lateral load?
5. Do beams deflect more than permitted?
6. If most beams are the same size, why are the others not?
7. Is the beam depth consistent with standard rules-of-thumb?
8. For lateral load in any direction, do the connections and bracing provide a continuous load path to the foundation?
9. Do connection details match the assumptions used in the analysis?
10. Are the primary structural member sizes similar to members in similar projects?

Other (14 of 87). This category includes all of the other strategies used to discover a problem. Many of them are procedural (e.g., check model code used in the jurisdiction).

Not Reported (2 of 87). In just a few cases, the engineer was unable to recall how the problem was identified.

Of the 67 specific instances, 28 were instances where the engineer found the mistake in his or her own work. The other 39 were all instances where either the engineer found the mistake in someone else's work or someone else found the error in his or her work. The greater number of instances where the error was found in someone else's work might be due to the fact that those interviewed were mostly experienced engineers who spend more time reviewing other engineers' work. It might be due to human tendency to avoid sharing one's own mistakes. No matter the reason, the results clearly demonstrate the importance of a second set of eyes on any design.

Most engineers will agree that it is not practical to identify and fix all human errors in the design before construction begins. The number of problems discovered in the field was 14 out of 87. Whether that is an acceptable rate is a decision each firm must make independently. The argument can be made, however, that the number of problems discovered in the field can be reduced through formal education and training.

Comparisons, rules of thumb and visualization accounted for 35 out of the 87 instances and examples. Fortunately, all of these strategies can be taught. They can be incorporated in college courses, and they can be presented at in-house seminars within firms.

Strategies for Finding Errors

As a result of the information obtained in the interviews, the author compiled a list of ten questions that can help engineers discover the presence of human errors in their analysis and design results. More strategies were identified in the interviews, but this list includes the most frequently used.

1. *Is the deflected shape consistent with what was expected?*
   When reviewing displaced shape from analysis software, look for beams that rotate at beam-column connections; evaluate whether you intended for the connections to be rigid or not. Look for columns in lateral load resisting frames that do not start out vertical; evaluate whether the support should be pinned or not. Verify that the beams you expected to deflect most actually do. Verify that the frames you expected to deflect most under lateral load actually do.
2. *Are the moment diagrams consistent with what was expected?*
   When reviewing moment diagrams from analysis software, look for columns not part of the lateral load resisting system that have moment at the base; evaluate whether the support should be fixed or not. Look for torsion in girders; evaluate whether you intended for the beam-girder connections to cause torsion or not. Verify that the locations where you expected negative moment actually have negative moment. Verify that the locations of inflection points, points of zero moment, are where you expected them.
3. *Does the building weigh what you anticipate?*
   Add all vertical reactions from the analysis. Add all weight that you anticipate the structure will carry, and compare the two numbers.
4. *Does total base shear equal total applied lateral load?*
   Add all horizontal reactions from the analysis. Add all applied lateral loads, and compare the two numbers. Check this in two orthogonal directions.
5. *Do beams deflect more than permitted?*
   When reviewing deflections, compare the peak beam deflection with the allowable limit based on the design criteria for that project. For a live load deflection limit of L/360, this results in a limit of 1" per 30' length.
6. *If most beams are the same size, why are the others not?*
   When reviewing member sizes from design software or reviewing structural drawings, search for differences in beam sizes. Consider beams on the same floor and different floors. Evaluate whether you would expect the different beam to be bigger, smaller or the same.
7. *Is the beam depth consistent with standard rules of thumb?*
   A standard rule of thumb is that the depth of a steel beam in inches should be roughly ½ the span in feet (L/d = 24:1). The same rule can be used for prestressed concrete beams. For reinforced concrete beams, the depth of the beam in inches should be roughly ⅔ the span in feet (L/d = 18:1). The same rule can be used for timber beams.
8. *For lateral load in any direction, do the connections and bracing provide a continuous load path to the foundation?*
   Draw cross-sections through the entire structure. Apply lateral load and trace the load through the structure to the foundation. Evaluate whether the connections and bracing between structural components are sufficient to transfer the forces. Be sure to draw cross-sections in orthogonal directions and to consider lateral load from any direction.

9. *Do connection details match the assumptions used in the analysis?* Identify locations in the structure where you intended to have a rigid or semi-rigid connection. Verify that the associated connection details are consistent with the intended behavior.
10. *Are the primary structural member sizes similar to members in similar projects?* Check around the office for drawings of structures with similar size and use. If the members are significantly different, evaluate whether that should be expected due to differences between the projects. Ask other designers in the office to recommend projects with which to compare. If there is no similar experience in the office, call another designer who has experience with similar projects.

Conclusions

Not all errors are identified by previous experience. Strategies based on comparisons, rules of thumb and visualization are used routinely by experienced structural engineers to identify the presence of human errors. Even junior engineers can use those strategies because the can be taught. Several references provide rules of thumb such as *The Architect's Portable Handbook: First-Step Rules of Thumb for Building Design* and *Simplified Design: Reinforced Concrete Buildings of Moderate Size and Height*. There are fewer references for visualizing load path, but two examples are the *PCI Design Handbook: Precast and Prestressed Concrete* and *Loads and Load Paths in Buildings: Principles of Structural Design*. Some strategies for comparisons are scattered throughout textbooks, but no comprehensive resource yet exists. The author is working to develop such a resource as part of the NSF project. In the meantime, the questions provided here provide a starting point.

As you begin training your next new engineer, consider incorporating this list of questions. Although you cannot teach experience, you can teach comparisons, rules of thumb, and visualization. And those skills just might reduce the number of problems you discover in the field.▪

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