Structural Analysis: Are We Relying Too Much On Computers

Part 2: A Solution

By Graham H. Powell, Ph.D., P.E.

In Part 1 of this series of articles, I expressed the opinion that there is a serious problem in the way that we teach structural analysis in our universities. The main problem, as I see it, is that far too much time is spent teaching the "number crunching" phase of analysis, and far too little time teaching the more important "modeling" and "interpretation" phases. As a consequence, students are poorly educated in the proper use of computers. The fault lies not with the computer, but with the way that structural analysis is taught.

Basic Education for a Structural Engineer (April 2007 STRUCTURE®) proposed a course content for structural analysis. The proposed content emphasizes hand calculation methods such as Moment Distribution and Slope Deflection, and mentions computers only once. In my opinion it is outdated, and it perpetuates the problem noted above.

This article proposes a solution, in the form of an outline for a much different course content with a different set of outcomes. This course content places much greater emphasis on the effective use of computers.

Outcomes

Consider, first, some desirable outcomes, and for the moment consider only undergraduate education.

Before a student takes a course in structural analysis, I would expect that he or she would first take a course in mechanics of materials, and would also have had some instruction in statics and kinematics. I assume that only one semester-length course in structural analysis is required, with one additional course available as an elective. Beyond that, a student would take graduate courses.

At the end of the first course, I believe that a student should be able to do the following:

1) Develop a linear elastic model of a fairly realistic 3D structure composed of frame, wall and connection components. Run computer analyses for static gravity and lateral loads. Present and interpret the results. Given beam and column strengths, calculate strength Demand/Capacity ratios.
2) Develop a nonlinear model of a 2D frame with simple plastic hinges. Run computer analyses for static gravity and lateral loads, with and without P-Δ effects. Explain the behavior. Given beam and column strengths and hinge rotation capacities, calculate strength and deformation D/C ratios.
3) Given the results of a computer analysis, check the equilibrium of various components and connections, using free bodies and equilibrium equations.
4) Given the results of a computer analysis, check that compatibility is satisfied (i.e., check that element deformations are consistent with nodal displacements).
5) Explain stiffness and flexibility coefficients, and stiffness and flexibility matrices. Calculate stiffness and flexibility matrices for bar and beam elements.
6) Explain the Direct Stiffness Method of structural analysis. Explain how numerical sensitivity can cause this method to give incorrect results.

At the end of a second course, a student should be able to model, analyze and check more complex structures with a wider variety of element types (including simple finite elements), consider dynamic loads (with a basic understanding of inertia and damping forces, mode shapes and modal superposition), and have a deeper understanding of the underlying theory.

Broad Skills

To satisfy the above outcomes, a student must develop skills in modeling and interpretation, be able to run an analysis, and have a basic understanding of the underlying theory.

Modeling requires an understanding of the behavior of the various components that can make up a structure, an understanding of stiffness and flexibility, the ability to distinguish important and unimportant aspects of behavior, and the ability to create an analysis model given a "toolbox" of structural elements.

Interpretation requires a number of skills, for checking whether the analysis results are reasonable, for identifying the cause when the results do not look reasonable, and for organizing the results in a way that supports decision making for design.

Specific Skills for Modeling and Interpretation

Some specific skills are as follows:

1) The ability to set up free bodies of a wide variety of types, and to apply equilibrium equations to these free bodies to check that equilibrium is satisfied. It should be emphasized to students that errors in setting up free bodies and applying equilibrium equations are inexcusable.
2) The ability to use virtual work to solve simple statically determinate structures (i.e. to apply the Virtual Displacements Principle for rigid bodies and mechanisms) as an alternative to free bodies and equilibrium equations.
3) The ability to calculate internal actions (P, M, V) in statically determinate structures, and to draw P, M, V diagrams.
4) The ability to sketch deflected shapes for structures and structural components of a variety of types, in order to show, qualitatively, how a structure or structural component is likely to deform.
5) The ability to do simple deflection calculations for frames and trusses, using tools such as Moment-Area and Williot diagrams. These tools require a clear understanding of the relationships between internal deformations (beam curvatures,

bar extensions, etc.) and external displacements. In my opinion, the ability to calculate deflections using virtual work (i.e., using the Virtual Forces Principle) is not an essential skill – it requires a lot of effort to learn, it does not help a student to develop a "feel" for structural behavior, and I have not found it to be particularly useful.

6) The ability to calculate stiffnesses and flexibilities for structural components of a variety of types, and to understand the importance of stiffness and flexibility. This can be done for most components using the above skills. It should include the ability to calculate stiffnesses and flexibilities for simple components in series and in parallel (i.e. adding stiffnesses for components in parallel, and adding flexibilities for components in series).
7) The ability to apply common sense, for example by recognizing when a calculated deflection is obviously too large or too small, or that the proportions of a structural member are obviously unrealistic.

These skills are needed mainly to understand structural behavior (for example, how forces are transmitted through connections), and to check that computer results are reasonable. These skills may occasionally be used to analyze simple structures by hand, but a structure must be very simple before hand analysis is more efficient than computer analysis.

I have not included the ability to analyze a statically indeterminate structure by hand. In my opinion this is something that an engineer will never be required to do, so it is not a useful skill. In my practice, I use equilibrium equations all the time; I sketch deflected shapes often, and I frequently do simple deflection calculations. I never use moment distribution or other classical methods to analyze a statically indeterminate structure. These methods are of interest to a historian, but to teach them is, I believe, a waste of a student's valuable time and energy. There are much more useful, and more interesting, things to teach.

Skills for Number Crunching

The number crunching phase, as I have defined it, includes both theory and computation. In the present era, the method that is used for virtually all analyses is the Direct Stiffness Method, and the computation is always done by computer The engineer defines the model, but a computer program forms the element stiffnesses, assembles them, sets up the loads, solves the equations, etc. This process can be treated largely as a black box – we can assume that it is done correctly, and we do not need to worry about the details.

Obviously, however, when an engineer uses an analysis method, he or she should have an understanding of the theoretical and computational basis of that method. The question is: how much detail do we need to teach?

In my opinion, we do not need to go into a lot of detail for undergraduate students. A student needs to understand the concepts of stiffness and flexibility, to know about stiffness coefficients and stiffness matrices, to understand the process for assembling element stiffnesses into a structure stiffness, to know that a large set of equations must be solved, and a few other things. These can be explained using physical reasoning, with no need for elaborate mathematics. Compared with the complexities of modeling and interpretation, the Direct Stiffness Method is not difficult to understand. The full details can be left to advanced graduate courses.

It is also important for students to recognize that the Direct Stiffness Method is not foolproof. A common problem occurs when an element in a structure is assumed to be extremely stiff, and an inexperienced engineer makes that element astronomically stiff (for

Example Exercise – Source of Deflections in a Moment Frame

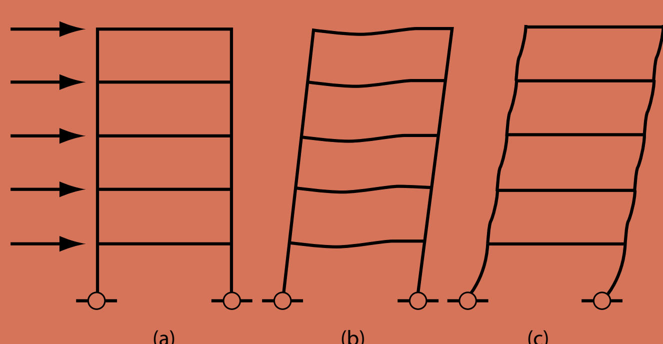
Consider a simple moment frame as shown.

Basic Studies

1) Analyze the frame, by computer, with very stiff columns and deformable beams (*Figure b*). Look at the roof drift and explain the deflected shape.
2) Analyze with very stiff beams and deformable columns (*Figure c*). Again look at the roof drift and explain the deflected shape.
3) Compare the roof drifts to get an idea of how much of the frame deflection originates in the columns and how much in the beams.
4) Analyze with deformable beams and deformable columns. Look at the roof drift and the deflected shape. See if the roof drift is the sum of drifts from the previous analyses. There is no reason why it should be equal to the sum, but it should be close.
5) Perform equilibrium checks on the results. For example, given the column shear forces get the story shears and compare with the shears from the lateral loads.
6) For the cases in *Figures b* and *c*, check the deflections by hand. This can easily be done using direct geometry and standard cantilever and beam flexibilities (deflection = $PL^3/3EI$ for a cantilever with an end load, deflection = $PL^3/12EI$ for sway of a column fixed top and bottom, end rotation = $ML/6EI$ for a beam).
7) For the case in *Figure b*, given the roof drift, calculate the beam end rotations, and use the beam stiffnesses to calculate the end moments. Confirm that they agree with the computer results.

Some Additional Studies

1) For the case with stiff beams, consider both pinned and fixed supports for the bottom story columns. Show that the first story with pinned supports is four times more flexible than with fixed supports. Look at the bending moment diagrams and use Moment Area to see why. Discuss how pinned and fixed (moment-resisting) supports might be provided in an actual frame. Discuss whether such fixed supports might really be rotationally rigid.
2) Vary the beam and column sizes within practical ranges. Discuss practical span-to-depth ratios.
3) For the case with deformable beams, add stiff end zones to the beams, to account for increased stiffness in the connection region. See how much this increases the stiffness. Compare the bending moments at the column face and column centerline.
4) For typical steel member sizes, analyze with very stiff beams and columns and deformable panel zones in the connections. See how much of the deflection originates in the panel zones.
5) Make the stiff columns astronomically stiff. The results will be garbage. Show that if the stiffness ratio between beams and columns exceeds the precision of the computer, accuracy is lost. Progressively reduce the column stiffness and show that correct results are ultimately obtained. Show that if the column stiffness is 100 or more times the beam stiffness, there is not much difference in the results.
6) Instead of very stiff columns, use rigid link constraints to make the columns truly rigid. Note that there are no numerical sensitivity issues. Note that when the columns are very stiff the computer calculates P,M,V values for the columns, but that when rigid link constraints are used the computer calculates zero P,M,V values.



example, by specifying an area of 10^{20} units for a very stiff bar). Such errors can cause numerical inaccuracy in the equation solving part of the Direct Stiffness Method. Students need to understand the basics of the numerical procedure, to avoid making such elementary mistakes.

Computer Programming Skills

In my opinion, most courses in structural analysis spend too much time on the number crunching phase. Among other things, it is not uncommon to require students to write computer programs to implement the Direct Stiffness Method (and possibly other methods). The programming effort can be substantial and at the undergraduate level I do not believe that this is a good use of a student's time – there are more important things to teach.

This does not mean, however, that undergraduate students should not be encouraged to use computers. Many tasks in the modeling and interpretation phases involve equilibrium, compatibility and other calculations. Usually the calculations can be done quickly by hand, but sometimes it can be more efficient to develop solutions in computer programs such as Mathcad and Matlab. I believe that students should be encouraged to use such programs when it is appropriate.

Instructional Method

I believe that the best and quickest way for a student to learn structural analysis is to do structural analysis.

On the first day of the first course, give every student a computer program and begin assigning analysis exercises along the lines of those listed in Part 1 of this article. Using such exercises, teach how to model structures and how to check the analysis results. Explain the behavior of frame and wall components under bending and shear, and how to model this behavior. Show how to use the virtual displacements principle, and tools such as Moment-Area and Williot diagrams. Show how stiffness and flexibility matrices can be formed for simple elements, and how stiffness and flexibility can be calculated for components in series and parallel. Explain the physical basis of the Direct Stiffness Method, explain the P-Δ effect (equilibrium in the deformed configuration), and introduce simple inelastic behavior (e.g. plastic hinge concepts). Do this within the framework of a series of exercises that require skills in modeling, analysis and interpretation.

With this approach, a student can progressively develop the required skills, and also develop a "feel" for structural behavior. The hands-on approach also helps to keep students interested.

An Example Exercise

An example exercise is provided (see page 22), which could be the first exercise to be assigned in a first undergraduate course. This exercise can be used to introduce stiffness concepts and the Direct Stiffness Method, show how simple equilibrium and compatibility tools can be used to check the analysis results, and get a student thinking about structural behavior.

There are many other exercises that can be assigned, illustrating different aspects of structural behavior and serving as a framework for developing a variety of skills. A semester course might cover a half dozen exercises.

Graduate Courses

At the graduate level, there are likely to be a number of analysis courses. I believe that there should be two basic courses, with roughly the same aims as the above two undergraduate courses, but at a higher level. These courses should include dynamic loads, nonlinear behavior, some basic finite elements, and comparison of P-Δ and true large displacement effects.

In my opinion, both dynamic loads and nonlinear behavior should be included in these basic courses. In most graduate programs, dynamics is taught as a separate discipline and nonlinear behavior is usually considered only in advanced courses. I believe this is a mistake.

Beyond these basic graduate courses there can, and should, be a number of advanced courses, including finite element theory, advanced dynamics, advanced nonlinear analysis, and computer programming for structural analysis. These should be PhD level courses, for the relatively small number of students who need a deeper theoretical understanding.

Matrix Methods

In the April 2007 article *Basic Education for a Structural Engineer*, the course content included a "Matrix Methods" course. This implies that the earlier courses do not use matrices, and/or that matrix methods are somehow distinct from other methods. I think this is a mistake. There is really no such thing as a "matrix method" – only matrix notation, which applies to all methods and should be used whenever it is appropriate.

Licensing Examinations

Currently, the structural analysis sections of professional licensing examinations require analysis of statically indeterminate structures by hand. Why? To get a driver's license do you have to show that you can ride a horse?

Conclusion

The goal of courses in structural analysis should be to educate young engineers to analyze complex structures using modern methods, and to understand what they are doing and why they are doing it. I believe that most structural analysis courses in our universities fail to achieve this goal. The first part of this article describes the problem, and this second part proposes a solution.

We are doing a disservice to both our students and the profession. It is time to modernize our courses, and provide our students with truly useful skills.▪

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