Nonlinear dynamic analysis capabilities and limitations

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Nonlinear dynamic analysis is feasible for tall buildings, and can be done for reasonable cost. This paper looks briefly at the following questions:

- How does nonlinear dynamic analysis differ from linear?
- What are the steps?
- How are the analysis results used to assess structural performance?
- What skills are needed?
- Does nonlinear analysis lead to better design?
- Is it necessary to use capacity design?
- Is it necessary to consider geometric nonlinearity (large displacement) effects?
- How much computer time does it take?
- What are some other limitations?
- Can static push-over analysis be used instead of dynamic analysis?

Introduction

Many structural engineers are using nonlinear dynamic analysis for earthquake resistant design, especially for retrofit. This paper is directed mainly at engineers who are not yet using nonlinear analysis.

How Does Nonlinear Dynamic Analysis Differ From Linear?

1. Response spectrum analysis can be used for linear dynamic analysis of tall buildings, but not for nonlinear. The main reason is that response spectrum analysis depends on superposition, which does not apply for nonlinear behavior. It is necessary to use step-by-step integration, also known as time history or response history analysis.
2. For linear analysis all structural components are elastic, and only elastic properties are needed for analysis. For nonlinear analysis, some components can yield, and additional inelastic properties are needed for these components. These properties are more complicated than the elastic properties.
3. In linear analysis, the forces in the structural components are computed, and the performance is assessed using strength demand/capacity (D/C) ratios. In nonlinear analysis, inelastic deformations are also calculated, and the performance is assessed using both deformation and strength D/C ratios. An example of an inelastic deformation is the rotation at a plastic hinge.
4. Formulas for strength capacities have been developed and refined over a long period of time, and are well understood. Formulas for deformation capacities are more recent, less refined, and less well understood.
5. A linear analysis model typically requires only a few component types (bar, beam, column, shell). For a nonlinear model the choice of component types is larger, because there are many different types of nonlinear behavior.
6. For elastic components the important properties are elastic stiffnesses such as EI and EA, which are usually simple and fairly well standardized. For inelastic components the important properties include such things as yield strength, post-yield behavior, and stiffnesses degradation under cyclic loading, in addition to the initial elastic stiffness.
7. Inelastic (nonlinear) modeling is more complex than elastic (linear) modeling. It requires more judgment and a deeper understanding of structural behavior.
8. Nonlinear analysis requires much more computer time.

What Are The Steps?

1. Define the structure geometry (mainly nodes and elements), in the same way as for linear analysis.
2. Define gravity loads, in the same way as for linear analysis.
3. Define the properties of the structural components. This more complex than for linear analysis, and often makes up most of the modeling effort.
4. Define the deformation capacities. For linear analysis, strength capacity formulas from design codes are commonly built into computer programs. This is reasonable even though it transfers substantial control from the engineer to the computer programmer. Deformation capacities are less standardized, and in the author's opinion would be a mistake to build them into computer programs at this time. Requiring the engineer to specify the capacities means more input data to the computer program, but it keeps the engineer in closer control of this new technology.
5. Select one or more (usually more) earthquake ground motions. This is a bit of a black art, but methods are available.
6. Analyze the structure for gravity load. Then run a nonlinear dynamic analysis for each of the ground motions. This is a routine task, but may require substantial computer time.
7. Evaluate the performance, using both deformation and strength D/C ratios.
8. If necessary revise the design and re-analyze.

How Are The Analysis Results Used To Assess Structural Performance?

1. Some components and modes of behavior are ductile, and inelastic behavior is allowed. In these cases performance is assessed using deformation D/C ratios. An example is plastic hinge rotation in a steel beam.
2. Other components and/or modes of action may be brittle, and inelastic behavior is not allowed. In these cases performance is assessed using strength D/C ratios. An example is shear in a reinforced concrete beam.
3. Other performance measures, such as story drift, may also be used.
4. In general, the more D/C calculations that are done by the computer program during the analysis, the better. If a computer program does only nonlinear analysis, and does not calculate D/C ratios, the performance assessment must be done by exporting the results and calculating the D/C ratios in spreadsheet or other programs. This can add substantially to the analysis effort.

What Skills Are Needed?

1. The key skills are a good engineering grasp of inelastic behavior and an understanding of the performance based design process. Formal academic knowledge of nonlinear analysis theory and methods is not necessarily an advantage.
2. The most important skill for nonlinear modeling is an understanding of the behavior of components of various types. Beams tend to be fairly straightforward, although such aspects as axial growth and shear in concrete beams can be complex. Columns are inherently more complex, mainly because of PMM interaction. For tall shear walls, complications include shift of the neutral axis as the cross section cracks and yields, shear behavior, and the effects of coupling beams or panels. Squat walls can have very complex behavior, especially if they have irregular window and door openings. Under cyclic loading many structural components progressively degrade in strength, ductility and energy dissipation. Conversely, some components, notably buckling restrained braces, progressively increase in strength.
3. For a plastic hinge in a beam, the force-deformation (F-D) relationship is bending moment vs. hinge rotation. The F-D relationship for this type of component can be drawn as a simple F-D graph. A plastic hinge in a column is more complex, since both its yield strength and its subsequent inelastic behavior are affected by PMM interaction, and its force-deformation relationship cannot be drawn as a simple F-D graph. To model the behavior with interaction it is necessary to use as theory such as plasticity theory. An engineer needs a basic understanding of the assumptions and limitations of the interaction theory. A detailed understanding of the mathematics is not needed.
4. There are several other types of interaction that need to be understood. For example, if there is a yielding zone (in effect, a plastic hinge) at the end of a concrete beam, the shear strength can depend on the amount of hinge rotation, with larger rotations corresponding to smaller shear strengths. Recognizing and accounting for interaction may be the most challenging aspect of nonlinear modeling.
5. It is not necessary to have a detailed understanding of finite element theory or nonlinear analysis strategies. The documentation of a computer program should describe the nonlinear components in a form that can be understood by a typical engineer. The nonlinear analysis should, and can, be a black box that requires little or no knowledge of the underlying numerical techniques.
7. Always keep in mind that the goal of structural analysis is to get useful results to help in making design decisions. The goal is not to predict "exact" behavior for a structure. Getting useful results for design is feasible. Predicting "exact" behavior for a real structure is literally impossible.

Does Nonlinear Analysis Lead To Better Design?

1. As noted, the goal of structural analysis is to get useful information for design. If there is significant nonlinear behavior in a structure, it is reasonable to expect that a nonlinear analysis will give better information than a linear analysis, simply because it is more rational.
2. Nonlinear analysis is currently used mostly for retrofit, where the behavior can be complex, and the cost savings realized by allowing nonlinear behavior can justify the added analysis costs. For new design, methods based on linear analysis may be sufficient.
3. Nonlinear analysis has the potential to provide much better information for predicting the amount of damage, and hence for assessing earthquake risk.

Is It Necessary To Use Capacity Design?

1. In the basic form of Capacity Design, certain components in a structure are permitted to yield. These components are designed to be ductile, and the deformation demands can be calculated using 4 nonlinear analysis (i.e., their performance can be assessed using deformation D/C ratios). Alternatively, these components can be designed to provide generous ductile capacities that the designer believes will exceed any foreseeable demand, in which case nonlinear analysis may not be needed. The remaining components need not be ductile, and they are designed for strength. The strength demands on these components depend on the strengths of the yielding components, so the strength demands are best calculated by nonlinear analysis. However, in simple cases the strength demands can be estimated with sufficient accuracy by other methods.
2. When capacity design principles are used, it greatly reduces the uncertainty, and greatly simplifies the task of creating a reliable nonlinear analysis model.
3. If capacity design principles are not used, the engineer may have to allow for inelastic behavior in many or all of the structural components, and is essentially asking the computer analysis to predict the behavior of the structure. This may be unrealistic.

Is It Necessary To Consider Geometric Nonlinearity (Large Displacement) Effects?

1. For tall buildings it is usually necessary to consider the P- effect. This accounts for the fact that equilibrium should be considered in the deformed shape of the structure, not the original undeformed shape. Consideration of the P- effect adds little or nothing to the computer time required for analysis. P- theory is fairly simple, and is sufficiently accurate for drift ratios up to about 10%.
2. It is usually not necessary to consider the P- effect. This accounts for equilibrium in the deformed shape for individual columns, allowing for deformations within the column length. Except for very slender columns these displacements are so small that they have negligible effect. P- theory is complex. If P- effects are likely to be significant in any column, the simplest approach is to add nodes along the column length, dividing the column into a number of elements. This converts the P- effect in the column to a P- effect in the overall structure.
3. For earthquake design it is rarely, if ever, necessary to consider true large displacement effects, which are significant only at impractically large drifts. Considering these effects can lead to substantial, and unnecessary, increases in computer time.

How Much Computer Time Does It Take?
The computer time required for a dynamic analysis depends on the size of the structure and the strength of the ground motion (stronger motions cause more nonlinear behavior, which usually increases the computer time). It is generally not possible to estimate the computer time accurately in advance.

Table 1 shows some analysis times, using a PC with a 3 GHz processor and the PERFORM-3D computer program. The times are for a single nonlinear dynamic analysis, with two components of horizontal ground motion, and 1000 time steps at 0.02 seconds per step (earthquake duration = 20 seconds). Gravity load analysis must also be carried out, which typically takes little time.

The time required for post-processing the results and assessing performance must also be considered. As Table 1 shows, the time for a dynamic analysis increases substantially as the size of the structure increases. However, the time required for post-processing is not dramatically greater for a large structure than for a small one. For a large structure the post-processing adds relatively little to the total computer time.

<table>
<thead>
<tr>
<th>Structure Description</th>
<th>Analysis Time</th>
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<tbody>
<tr>
<td>11 stories, steel frame, 3 bays by 7 bays, some shear walls in lower stories. 720 nodes, 640 inelastic beam elements, 320 inelastic column elements, 320 inelastic panel zone elements, 160 elastic wall elements, 2100 degrees of freedom.</td>
<td>Approximately 10 minutes.</td>
</tr>
<tr>
<td>61 stories, RC core wall plus columns and braces. 2250 nodes, 1200 elastic wall elements, 120 inelastic wall elements, 320 elastic beam and column elements, 16 buckling restrained braces, 6200 degrees of freedom.</td>
<td>Approximately 2 hours.</td>
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<tr>
<td>50 stories, very complex RC shear wall system. 16,700 nodes, 12,500 inelastic wall elements, 9,400 inelastic coupling beams, 48,000 degrees of freedom.</td>
<td>Approximately 3 days.</td>
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Table 1 Some Computer Times for Nonlinear Dynamic Analysis

What Are Some Other Limitations?

1. If analyses are carried out for several ground motions, there can be substantial variation in the results. Partly this is because nonlinear behavior is inherently sensitive to relatively small changes in the ground motion. Partly it is because of the methods used to select the ground motions.
2. A computer program analyzes the nonlinear analysis model, not the actual structure. Different engineers can make different modeling assumptions, and may get different results for the same structure. Also, the response of a structure may be sensitive to the strengths and stiffnesses of its components, and the actual properties may not be known accurately. Capacity design can greatly reduce the uncertainty.
3. For strength-based design using linear analysis, if the strength D/C ratios for some components are larger than 1.0, redesign can often be done by increasing the component strengths. This may also increase the stiffness, requiring re-analysis, but the process usually converges quickly. For deformation-based design using nonlinear analysis, the choices can be to increase the strength, or the ductility, or to change other properties. It can be more difficult to choose a re-design strategy, and a larger number of re-analyses may be required.
4. These limitations may seem serious, but the fact remains that if inelastic behavior is present, a nonlinear analysis is more likely to give reliable design information than a linear analysis. There may be less variability in the results of linear analyses, but this is illusory because linear analysis is inherently uncertain. A important goal of research and code development should be to reduce the variability in nonlinear analysis.

Can Static Push-Over Analysis Be Used Instead Of Dynamic Analysis?

1. Nonlinear static push-over analysis has the advantage that it uses a response spectrum rather than a suite of earthquake ground motions. Also, a push-over analysis takes substantially less time than a dynamic analysis. However, push-over analysis can be used for performance assessment only if the behavior of the structure is dominated by its first vibration mode. It does not work well if a structure has a number of significant modes. This is the case for most tall buildings.
2. In the author's opinion, if a structure is small enough that push-over analysis applies, it takes only a short time to run a dynamic analysis, and push-over analysis does not save much time. An exception may be certain hospital buildings that have large numbers of complex shear walls, where dynamic analysis can take too long.
3. For any structure, push-over analysis can still be useful for checking nonlinear analysis models and for gaining insight into the nonlinear behavior.

Conclusion

1. Nonlinear dynamic analysis can lead to better design.
2. The modeling and analysis tasks are challenging but feasible. They require understanding of structural behavior and the design process rather than academic skills.
3. ASCE 41 provides some very useful guidelines.
4. Computer software is available.
5. The goal of structural analysis is to get information for making design decisions, not to predict the "exact" behavior of a structure.
References