

Nonlinear Dynamic Earthquake Analysis of Skyscrapers by ABAQUS

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Abstract: Due to the limitation of computer capacity and the soften of the material constitution, the nonlinear dynamic earthquake analyses of skyscrapers are not practical in engineer's desktop, and even in the research area they are still open problems. Utilizing ABAQUS's unique combination of implicit and explicit technologies and capable of solving large problem efficiently, the author solves the problem elegantly and practically. In the analysis model, all members and shear-walls are modeled by plastic zone model, and large deflection effects are taking into account. Especially, as the shear-walls are divided into element size around 0.7x0.7m, the material and geometry nonlinear buckling behaviors of the shear-walls are modeled almost numerical exact. The main analysis procedures and some key parameters are outlined. The analysis results of some prominent projects in China, such as Shanghai World Financial Center(492m in height), Jinta (330m in height) and Guangzhou West Tower(435m in height), are also presented. The analysis results are of great help for the design engineers to study the skyscrapers earthquake performance and therefore design the skyscrapers structure more safety and economically.

Keywords: Nonlinear, Dynamic, Skyscraper, ABAQUS.

1. Introduction

Seismic design is a very critical issue for skyscrapers built in the seismic area. In the earthquake engineering area, the earthquake loads are usually classified into three levels by their intensities (GB50011, 2001): ① frequently occur level; ② design intensity level; ③ severe level. For the first earthquake load level, the linear analysis is appropriate. However, the skyscrapers shall go into plastic range when subjected to the second and third earthquake intensity levels, therefore a more vigor analysis – nonlinear dynamic analysis should apply.

Nonlinear dynamic earthquake analysis is the most adequate and comprehensive analysis procedure to evaluate the nonlinear seismic response of structures, but currently available computer hardware and design software effectively limit the size and complexity of structures that may be analyzed by this technique. At present, there is no general-purpose nonlinear analysis software that will permit practical evaluation of large structures that include elements with the

wide range of inelastic constitutive relations actually present in the building inventory (FEMA274, 2001). As a matter of fact, most (if not all) current design engineering practices use the linear procedures only to do the structural design, and moreover, use the seismic concept design technique such as seismic fortification measures and details of seismic design to make the skyscrapers perform well under the design intensity and rare level earthquake load. It means that the design engineers don't know how the skyscrapers quantity response to the design intensity and rare level earthquakes. However, even in the research area, it is still an open problem.

In this paper, the author solves the problem by making use ABAQUS's unique combination of implicit and explicit technologies and capable of solving large problem efficiently. Nonlinear dynamic earthquake analysis become a practical analysis tool for structural design, and because of the technique, the skyscraper can be designed more safe and economical.

In the next section, the special features of nonlinear dynamic earthquake analysis for skyscrapers are outlined. Emphasizes are placed on how ABAQUS's built in functions and its development platform can fit in the special requirements, while other FEA packages can't fulfill the task. In section 3, a software package call BEPTA (Building elastic-plastic time history analysis) is introduced. The nonlinear dynamic earthquake analysis procedure carried out by running BEPTA and ABAQUS in tandem.

A couple of project examples are presented in section 4. These show that even the most complexity and largest projects in China can be analyzed in detail. Finally, some conclusions are drawn for nonlinear dynamic earthquake analysis by ABAQUS.

2. Why ABAQUS?

The nonlinear dynamic analyses of skyscrapers are consisted of two major steps that run in a tandem: ① gravity load analysis according to the construction sequence; ② seismic load analysis base on the stress statues obtained in the first step. Each step solves the highly nonlinear problems. In theory, both implicit and explicit solvers can solve these problems.

2.1 Gravity load analysis

The skyscrapers are built up one story by one story. The first analysis step should model this procedure by a couple of substeps, each substep represents a construction step (for example, one story) correspondingly. While the structural materials (steel and concrete) remain in the elastic range under the gravity load, the analysis step requires that the stiffness matrix of the model be updated for each substep.

The construction sequence analysis is a typical statues nonlinear analysis. ABAQUS/Standard nonlinear solver is the efficient solver to solve the problems. We can use the *remove and *add key (ABAQUS, v6.5) word with "stress free" option to model the structure status change during the construction. The "stress free" option can model the level plastering effect exactly. It should note that some structural design software such as ETABS, SAP2000 etc already have built-in function for the analysis procedure, but other FEA general purpose package are difficult to do such a kind analysis directly.

2.2 Seismic load analysis

The second analysis is a typical nonlinear dynamic problem. It is known that ABAQUS/Standard and ABAQUS/Explicit are capable of solving a wide variety of problems. However, under the design intensity and severe earthquake levels, the nonlinear dynamic analyses of skyscrapers has the following features:

- (1) The structures will go well into plastic range and may have very large deformations. Moreover, the steel and concrete materials may soften and lead to negative stiffness occurs in some components.
- (2) The degrees of freedom are very large (up to more than 1million). The computation cost is very high for each integration step. The cost-effective integration algorithm is mandatory.

Based on the above reasons, the implicit solver has difficulties in converging and the explicit solver must be chosen to solve the problem. However, ABAQUS is the only general purpose FEA package which provides both the high end implicit and explicit solvers. The same elements are used in the implicit and explicit solvers, and the implicit results can be transferred to explicit solver seamlessly by a *import key (ABAQUS, v6.5) world. Such a feature is perfect right for the nonlinear dynamic earthquake analysis of skyscraper. As far as the author's knowledge, no other general FEA software package can fulfill the task easier (if it can) than ABAQUS.

3. BEPTA Program

The scale of the nonlinear dynamic analysis of skyscrapers is very big. It is quite often that the degree of freedoms of the model are up to half million. To handle the large number of data correctly and smoothly, a strong and robust pre-post process program is mandatory for the analysis. BEPTA (Building elastic-plastic time history analysis) is a program developed on the ABAQUS platform, special for the nonlinear dynamic analysis of skyscrapers. It includes the following functions:

- (1) Suitable to do elastic or elastic-plastic analysis for all kinds of structures such as steel structure, steel-concrete mix structure and concrete structure.
- (2) Automatically transfer the structural data such as geometry, material elastic properties, member section and reinforcement into ABAQUS input deck.
- (3) Automatically set the nonlinear analysis control parameters.
- (4) Automatically set the nonlinear material parameters for steel and concrete.
- (5) Automatically set the analysis procedure special for nonlinear dynamic analysis of skyscraper.
- (6) Develop a concrete user subroutine for 3D beam element, which is not available in ABAQUS and other general purpose FEA code.

(7) Post process the super large analysis results, produce analysis report special for skyscraper nonlinear dynamic analysis.

The flowchart of the nonlinear dynamic analysis of skyscrapers, as illustrated in Fig.1, show the relationship of BEPTA with ABAQUS and some popular structural design program, such as SATWE and ETABS.

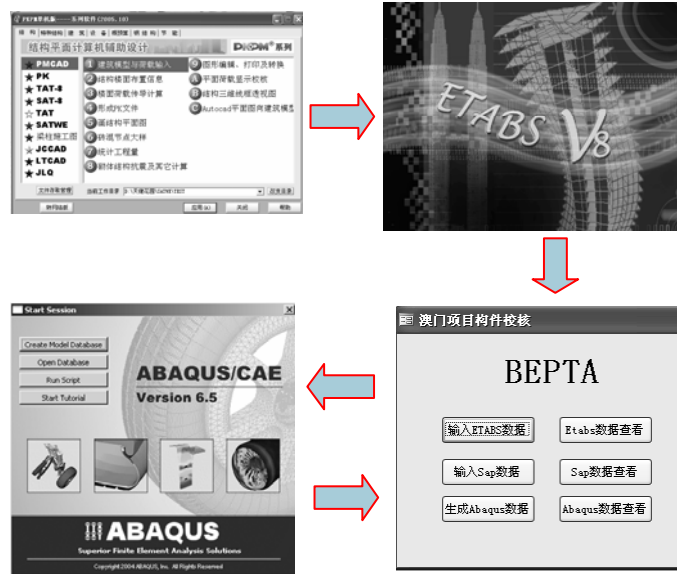


Figure 1. BEPTA+ABAQUS analysis procedure

4. Project examples

Making use of BEPTA+ABAQUS, the author has done the nonlinear dynamic analyses for more than 20 skyscrapers. Three prominent projects of them in China are shown as follow.

(1) Shanghai world financial center, Shanghai, PRC. The architect's perspective view is illustrated as Fig.2. The skyscraper is 492m tall at its roof, and has 101 floor plans in total. As show in Fig.3, the concrete core walls and the perimeter mega steel frames form the lateral system of the structure. Without simplification, all the structure members such as beams, columns, braces and shear walls have been modeled by the corresponding elements. The degrees of freedom of the model are 600K. The output file size is 6G with 200 steps results. The earthquake duration is 40s, while the cluster computer (6 CPUs) analysis time is 30 hours. Fig.4 shows the roof displacement time history.

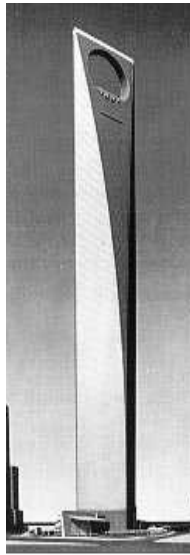


Figure 2. Perspective view



Figure 3. Analysis model

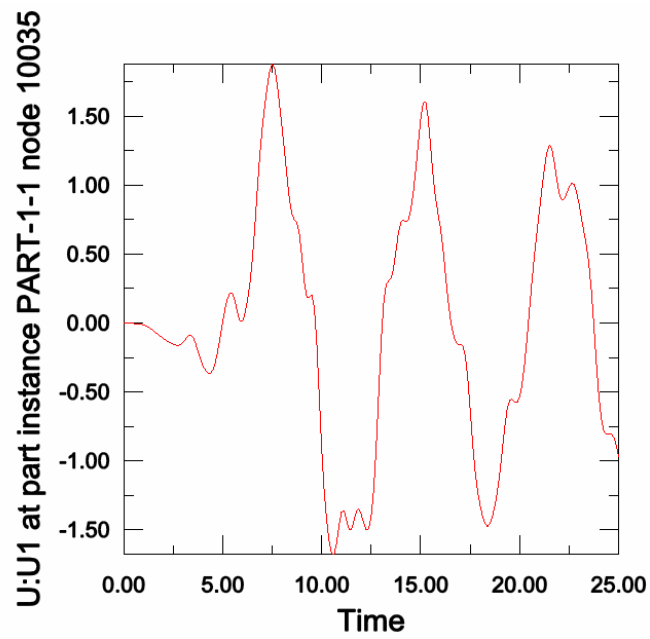


Figure 4. Roof displacement time history

(2) Jinta, Tinjin, PRC. The architect's perspective view is illustrated as Fig.5. The skyscraper is 350m tall at its roof, and has 75 floor plans in total. As show in Fig.6, the steel shear walls and the four outriggers form the lateral system of the structure. Without simplification, all the structure members such as beams, columns, braces and steel shear walls have been modeled by the corresponding elements. The degrees of freedom of the model are 500K. The output file size is 6G with 200 steps results. The earthquake duration is 40s, while the cluster computer (6 CPUs) analysis time is 25 hours. Fig.7 shows the max story drift during the earthquake.



Figure 5. Perspective view

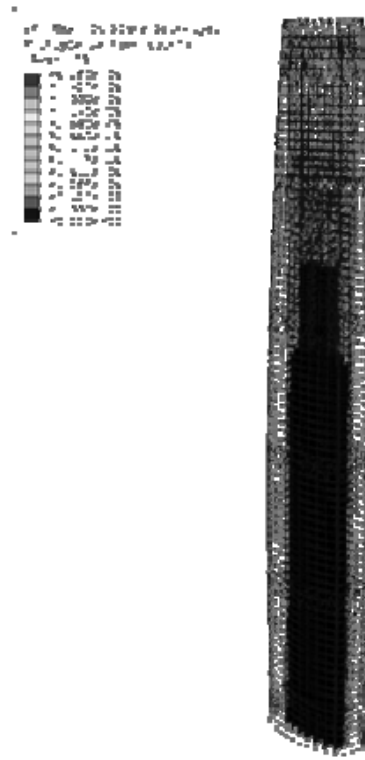


Figure 6. Member plastic strain contour

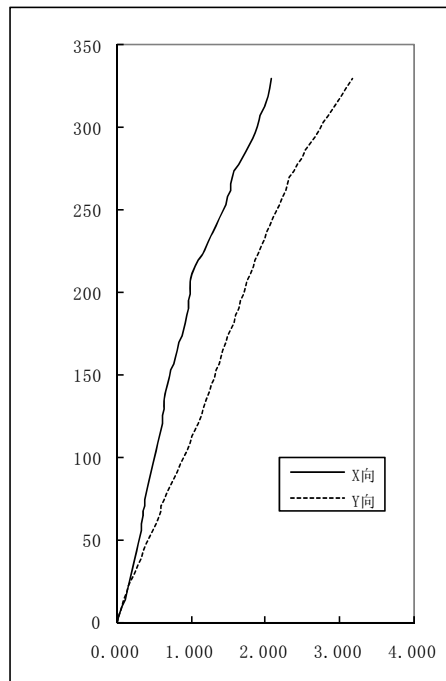


Figure 7. Maximum story drift

(3) Guangzhou West Tower. The architect's perspective view is illustrated as Fig.8. The skyscraper is 435m tall at its roof, and has 108 floor plans in total. As show in Fig.9, the concrete core walls and the perimeter slant concrete fill tube grids form the lateral system of the structure. Without simplification, all the structure members such as beams, columns, braces and shear walls have been modeled by the corresponding elements. The degrees of freedom of the model are 600K. The output file size is 10G with 200 steps results. The earthquake duration is 40s, while the cluster computer (6 CPUs) analysis time is 30 hours. Fig.10 shows the roof displacement time history.



Figure 8. Perspective view



Figure 9. Member plastic strain contour

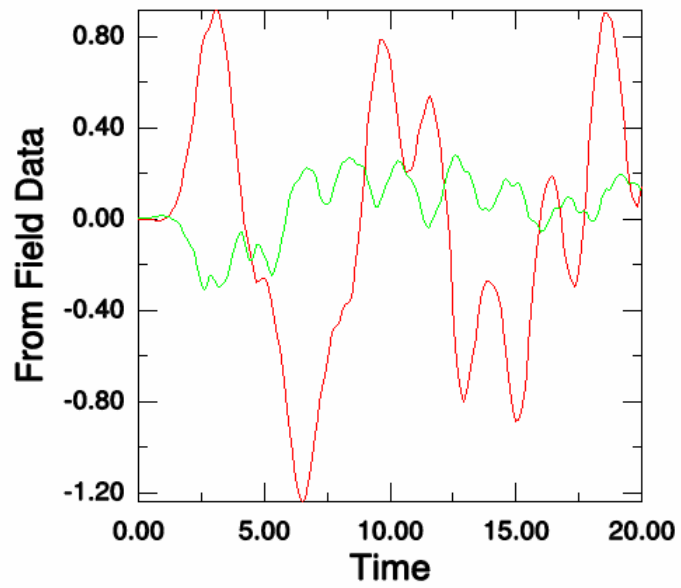


Figure 10. Roof displacement time history

5. Conclusion Remarks

- (1) Nonlinear dynamic earthquake analysis has become a practical tool for large and complexity structural design.
- (2) BEPTA+ABAQUS platform is the best solution for the skyscraper nonlinear dynamic earthquake analysis.

6. References

- 1. ABAQUS user manual v6.5.
- 2. GB 50011-2001 “Code for seismic design of buildings”, People’s republic of China.
- 3. FEMA274, Federal emergency management agency, USA.