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Efficient and automated method of collapse assessment

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Abstract. Seismic collapse analysis requires efficient and automated method to perform thousands of time history analyses. The paper introduced the advantages of speed and convergence property of explicit method, provided a few techniques to accelerate speed of calculation and developed an automated procedure for collapse assessment, which combines the strong capacity of commercial explicit finite element software and the flexible, intelligent specialties of control program written in FORTRAN language aiming at collapse analysis, so that tedious and heavy work of collapse analysis based on FEMAP695 can be easily implemented and resource of calculation can be made the best use of. All the key commands of control program are provided to help analyzers and engineers to cope with collapse assessment conveniently.

Key words: seismic collapse; earthquake wave; explicit method; time history analysis; IDA.

1. Introduction

Seismic collapse assessment of structures often includes lots of time history analyses, especially, FEMA P695 (2008) developed a collapse assessment system of building structures, in which enough archetype structures represent the structure system of interest and are subjected to 44 earthquake waves, carefully chosen among thousands of ground motions, to perform Incremental Dynamic Analysis (IDA). The methodology defines collapse level ground motions as the intensity that would result in median collapse of the seismic-force-resisting system. Median collapse occurs when one-half of the structures exposed to this intensity of ground motion would have some form of life-threatening collapse. As such, Maximum Collapse Earthquake (MCE) ground motions would result in a comparatively smaller probability of collapse. As defined in Eq. (1), the collapse margin ratio, *CMR*, is the ratio of the median 5%-damped spectral acceleration ($\hat{S}_{CT}$) of the collapse level ground motions to the 5%-damped spectral acceleration (S_{MT}) of the MCE ground motions, at the fundamental period of the seismic-force-resisting system

$$CMR = \hat{S}_{CT}/S_{MT} \tag{1}$$

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Then collapse risk level of the structure can be attained by comparing CMR with the acceptable value of CMR. An archetype space often includes dozens of structures, and each of 44 earthquake waves need to be scaled about 5 to 10 times to capture the collapse intensity. This means thousands of time history analyses are required, thus time consuming calculation, heavy burden of preprocessing and postprocessing work are the main difficulties, impeding the advanced collapse assessment to be used widely. High speed of calculation and automatic control of collapse assessment are the necessary conditions for the methodology.

Implicit finite element method is still the main method in seismic collapse analysis at present. Some researchers (Ibarra 2003, Haselton 2006, Liel 2008, Lignos 2008) adopted plastic hinge models for beam-columns in OpenSees (Open System for Earthquake Engineering Simulation) software to simulate collapse actions of structures, because plastic hinge model can greatly decrease calculation work and speed up the assessment process, and the model is calibrated by hundreds of experimental data. Lu *et al.* (2010) developed THUFIBER program on the base of MSC.MARC software, by which the whole collapse progress can be displayed, and researched seismic collapse resistance of RC frame structures. In highly nonlinear analysis of structure collapse, implicit method sometimes meets non-convergence problem, analyzers need intervene in the process to judge whether the collapse has occurred or any solution parameter should be adjusted to continue the analysis, thus the automation of collapse assessment can not be implemented smoothly and the efficiency should be improved.

Yang (2010) created an automated program in C++ language to use implicit software ANSYS to analyze bridge construction and provided the key commands. Vamvatsikos (2002) introduced DRAIN-2D software can be wrapped to automatically analyze seismic collapse, but the detailed method and commands has not be opened.

The paper researched the applications and advantages of explicit finite element method, pointed out that high speed and convergence property (no convergence problem exists) determine explicit method more suitable for collapse assessment based on FEMAP695 than implicit method. Subsequently, some techniques were introduced to save machine time, including adopting efficient load curve for gravity, taking advantage of scaling mass and sub-cycle functions provided by explicit software. At last, the paper develops an automated procedure for collapse assessment to combine the strong calculation capacity of commercial explicit software and the flexible and intelligent specialties of control program written in FORTRAN language aiming at collapse analysis.

2. The advantages of speed and convergence property of explicit method

Explicit finite element method is chosen for collapse analysis for its high speed and convergence property, which is compared with implicit method through a simple example, the concentrically braced steel frame shown in Fig. 1. The seismic precautionary intensity of the region is degree 8, and the cite class is II. The structural steel is Q235. The sections of the columns, beams and braces are H400 × 360 × 10 × 16, H400 × 300 × 8 × 14 and H220 × 220 × 6 × 9 respectively.

The mass of the structure is input at the joints by use of MASS element, and all members are simulated by 5 beam elements. The ground motion selects El Centro wave, the duration is 30 seconds, and the peak acceleration is scaled to 0.4 g. ANSYS and LS-DYNA software are chosen as the representation of implicit and explicit finite element software respectively.

The curves of interstory drift of roof versus time by implicit and explicit method are shown in Fig. 2, among which the first 10 seconds are used to attenuate vibration induced by gravity load. The graph

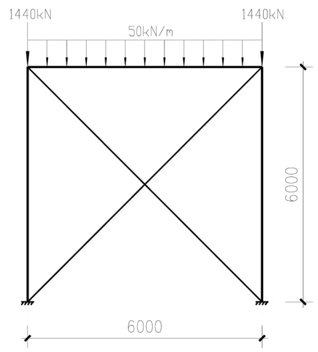
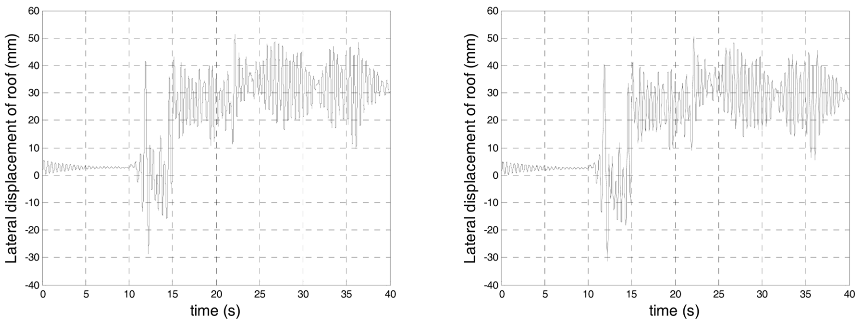


Fig. 1 Concentrically braced steel frame



(a) Result of implicit method (b) Result of explicit method

Fig. 2 Comparison of results from time history analysis

illustrates the satisfactory consistency between the results of the two methods. The maximum interstory drifts of roof are 50.4 mm and 51.1 mm respectively for explicit and implicit method, the relative error is only 1.3%. This is a highly acceptable result in strong ground motion. The example proves that the explicit finite element method can attain the same exactness as the implicit method in time history analysis.

The example is solved in a same platform (CPU: Inter(R) Core(TM)2 Duo P8700 @ 2.53GH, 4G memory, 32 bits winxp system) to compare the machine time required in a time history analysis by the two method. The explicit method cost 33 seconds, much less than 17 minutes required in implicit method, in another word, the speed of explicit method is approximately 30 times as fast as that of implicit method in the example.

Another advantage is that no convergence problem exists in explicit method. Explicit method is based on central difference algorithm; the stability of solution is assured by enough small time steps. This merit is extremely necessary in collapse analysis based IDA, without which analyzer must judge by himself that the cause of non-convergence is whether calculation problem or structure collapse when calculation is stopped in every curve of IDA and the automation of analysis can not be realized.

3. Techniques of speedup in explicit FEA

As a conditional stability method explicit method depends on enough small time steps to assure exactness of solution. The time step size is given by

$$\Delta t_e = L/c \tag{2}$$

where L is the length of the beam element or characteristic length of shell element, c is the wave speed, given by Eqs. (3), (4) for beam element and shell element respectively

$$c = \sqrt{E/\rho} \tag{3}$$

$$c = \sqrt{E/\rho(1-\upsilon^2)} \tag{4}$$

where, E is Young's Modulus, ρ is density, and υ is Possion's Ratio (Hallquist 2006).

In some finite element models, when more than one kind of elements are used in a model, for example, in eccentrically braced steel frame, beams, columns and braces are simulated by Hughes-Liu beam element, dissipating energy beam segment by shell element. Usually, the time step of shell elements is much less than that of beam elements. Under these circumstances, software takes the less time step of two kinds of element as the time step of the whole analysis procedure, thus the calculation speed will be very slow. To tackle this problem, analyzer can take advantages of two effective techniques to shorten solution process. One is Scaling Mass Method, by which much machine time can be saved at the cost of increase of some mass of the system. Another measure is Sub-cycle Function, by which elements are classified into different groups according to their time steps, and different time step is chosen in the different parts of the structure in calculation procedure.

The third effective method is the parallel computation technology. One modern person computer usually possesses more than one CPUs, at the present time 4 cores is the popular configuration. But the CPUs can not be fully taken advantaged of in traditonal serial computation technology, often only one CPU can be used, namely the efficiency of the machine is about 25%. One prominent advantage of explicit finite element method lies in that it supports parallel computation and the efficiency of CPUs can be improved to about 99%, by which solution time can be greatly decreased.

4. Highly efficient load curve of gravity

In pushover analysis, time history analysis and IDA, gravity loads are exerted at first, subsequently the horizontal forces or accelerations are input on the structure. Explicit dynamic analysis regards all mechanical phenomena as dynamic processes, thus the gravity load will induce vibrations in structure, which will gradually attenuate to zero in an enough long duration, because the damp of the structure can dissipate the kinetic energy imported by sudden gravity load. But when the load mode is stepped mode, vibration often attenuates to a negligible level in about 10 seconds. For example, the first 10 seconds of the time history analysis curves in Fig. 2 display the attenuation trends. Most of earthquake waves last 20 to 60 seconds. In this circumstance 10 seconds used to decrease vibration is a solution burden in time history analysis and IDA. To overcome this difficulty, illumined by the smooth step curve of ABAQUS , we put forwards a load curve of simple harmonic function used to exert gravity (as shown in Fig. 2). The first and second derivatives of load curve of simple harmonic function are smooth, by which gravity load can be steadily acted on structure in less than 0.5 second and the vibration induced by gravity can be successfully avoided, so that solution time can be saved significantly. An example in Fig. 4 is a 6-story, 6-span, V-type concentrically braced steel frame, with 6.5 kN/m^2 dead load of roof, 6.0 kN/m^2 dead load of floor, 2.0 kN/m^2 live load of roof and floor. The space between two frames is 6 m.

Gravity load is applied on the structure by the stepped mode and the load curve of simple harmonic function for comparison, and the vibrations of the reaction in y direction are illustrated in Fig. 5, which displays the load curve of simple harmonic function can decrease vibration of gravity load in 0.5 second to the negligible level, while stepped load require 16 seconds to reach to the same level. Clearly, the load curve of simple harmonic function can save machine time very much in time history analysis and IDA.

5. Fully automated method of collapse assessment

When the collapse assessment includes only a few ground motions, the simple batch method can be used to calculate continually. Simple batch method requires the analyzer to intervene in the analysis process to adjust the next action, namely, is not intelligent. But in collapse assessment system in FEMAP695, 44 earthquake waves are adopted and thousands of time history analysis required to be operated, the heavy burden of human intervene will become intorlerable. In this circumstance the fully automated collapse analysis must be developed to improve efficiency.

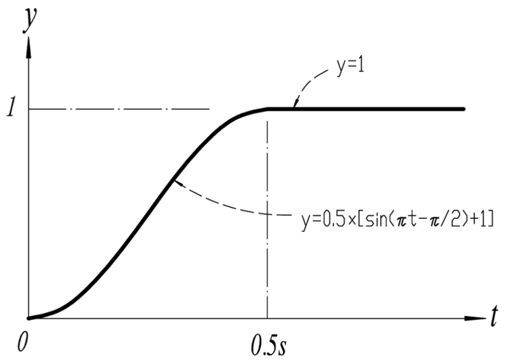


Fig. 3 Load curve of simple harmonic function

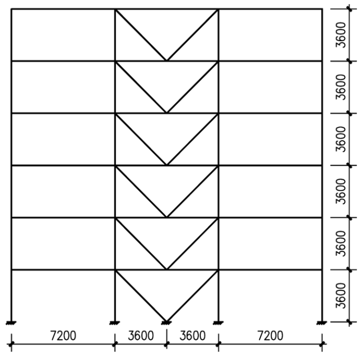
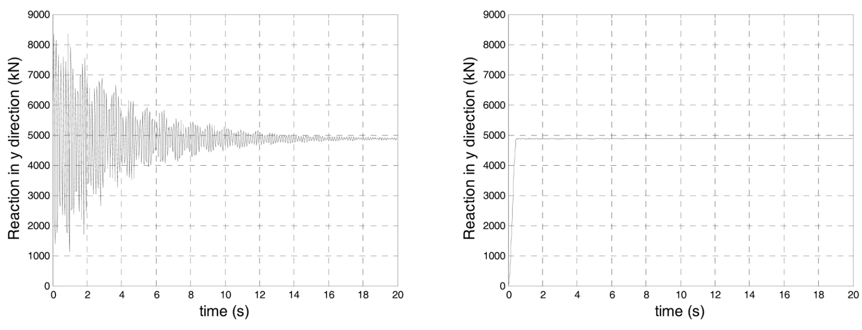


Fig. 4 Concentrically braced frame



(a) Attenuation by stepped mode (b) Attenuation by load curve of simple harmonic function

Fig. 5 Comparison of vibration attenuation of gravity load

The paper develops an automated procedure for collapse assessment based on software cooperation technique. The control program, control.for, written in FORTRAN, is the manager of the whole procedure, which uses a series of 'system' commands (a command in FORTRAN IMSL library, used to send DOS commands to execute operations) to run ANSYS and LS-DYNA software to perform modeling, solution, postprocessing work, and automatically select and scale ground motion to capture collapse intensity. The flow chart is shown in Fig. 6 and detailed explanation is as follows.

The 'system' command is the key function of the control program used to run commercial software. To call the 'system' command from FORTRAN math library, the sentence 'use msflib' should be added at the first line of control.for. Mod_1.dat, mod_2.dat and post.txt are APDL (ANSYS Parametric Design Language) files. Mod_1.dat contains all operations of parametric modeling, mod_2.dat includes all data of the structure system of interest, and post.txt is used to treat with the results of calculation.

In Control.for, Num is the sequence number of every earthquake wave, used to switch earthquake

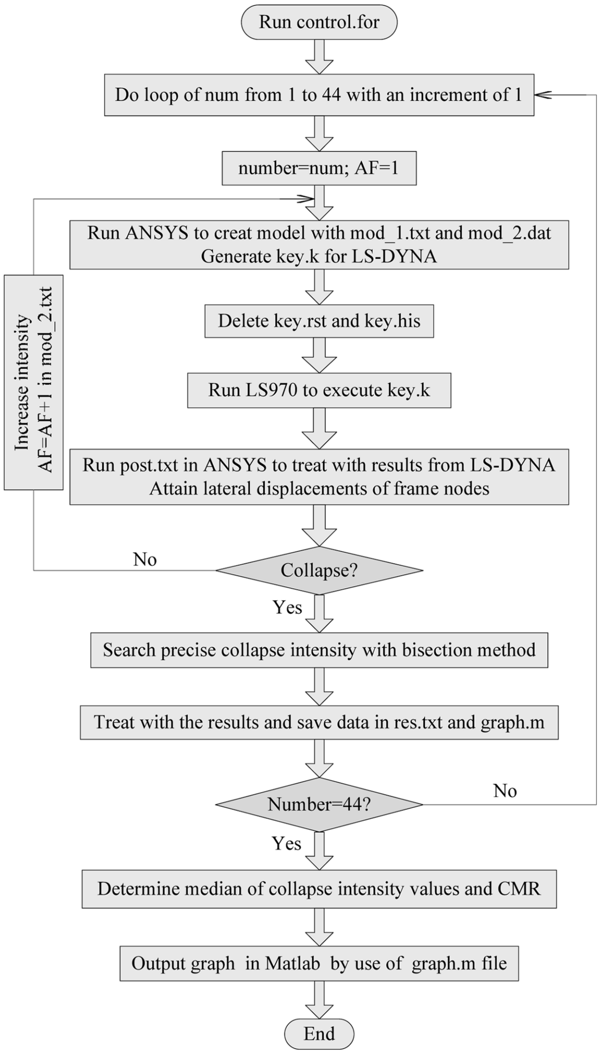


Fig. 6 Flow chart of automated collapse assessment

wave; AF is the amplification factor, used to scale ground motion to search collapse intensity.

1) Control.for uses a do loop to switch earthquake waves for IDA. Loop variable num changes from 1 to 44, the increment is 1.

2) Control.for opens mod_2.dat file, to write ‘number = num’ and ‘AF = 1’ sentences at the end of the file, by which every wave is input into numerical model and time history analysis is performed at the original intensity level at the first time.

3) Control.for starts up ANSYS to read mod_1.txt and mod_2.txt to create model for numerical analysis and generate the key file, key.k, for LS-DYNA. The command sentence is as follows, in which the string ‘-np x’ launches parallel computation function, *x* is the number of CPUs in the computer.

```
Value1 = system('c:\ansys\ANSYS90 -np 4 -b -p ane3flds* -i f:\collapse\mod_1.txt -o f:\collapse\result_a.txt')
```

In this step, each wave is input through next sentence in mod_1.txt by the forced substitution function (% %) of APDL:

```
/INPUT,%num%,TXT
```

Here, 1.txt, 2.txt, 3.txt, … , 44.txt (namely, num = 1, 2, 3, …, 44) are the earthquake wave files, located in the appointed directory.

4) Control.for deletes the key.rst and key.his generated in step 3, because the two files can not store the results more than 1000 records of time step, while more than 1000 records are required to be stored in time history analysis. The corresponding command sentences are:

```
B1 = system('del key.rst')
B2 = system('del key.his')
```

5) Control.for starts up LS970, the solver of LS-DYNA, to perform explicit dynamic analysis by key.k with the following command sentence, in which the string ‘ncpu = x’ launches parallel computation function, x is the number of CPUs in the computer.

```
Value2 = system('c:\ansys\ls970 i= f:\collapse\key.k ncpu = 4')
```

6) Control.for starts up ANSYS again to extract the lateral displacements of frame nodes and calculate the maximum interstory drift ratio with the post.txt written in APDL, and store the key data in output.txt in the form easily discerned and read by Fortran language. The sentence in Fortran environment used to launch ANSYS is:

```
Value3 = system('c:\ansys\ANSYS90 -np 4 -b –p ane3flds* -i f:\collapse\post.txt -o f:\collapse\result_b.txt')
```

7) Control.for reads output.txt to acquire the maximum interstory drift ratio and compare it with the collapse criterion. If the structure does not collapse (structure usually is safe in the original earthquake

wave intensity), then set AF = AF + 1.0 and the command at the end of mod_2.dat file, and return to step 4, repeat this operation until the structure collapses. This step gives the field of collapse intensity, between AF-1 times and AF times of original earthquake wave intensity.

8) In the collapse interval, Control.for takes advantages of bisection method to search more precise collapse intensity. Through 3 bisections, a rather exact collapse intensity value can be determined, with a relative error less than 1/8 of AF increment, which is a satisfactory result in IDA.

9) Control.for calculates the spectrum accelerations of every AF level and stores them with the corresponding maximum interstory ratios in res.txt and graph.m files. The former is the permanent file for storage, and the latter is used for matlab to output graph result, thus written in matlab form. The IDA of the first ground motion is finished.

10) Analysis returns to step 1, and Control.for selects the next earthquake wave to continue IDA until the collapse analysis of 44 waves are all implemented.

11) Control.for determines the median of collapse intensity values and CMR according to the data in res.txt.

12) Matlab software takes over the last task, takes charge of plotting the curves of IDA by use of graph.m, the m file, and adds necessary notations and notes.

13) Play music to inform the analyzer the task of collapse analysis has been finished (Storm software, the audio file player should be installed in responding directory in advance, and song.mp3, the audio file, is copied to the root directory of E disk).

```
Music = system('c:\Storm\ Storm e:\song.mp3')
```

14) Another choice is automatically closing the computer with the following command.

```
End = system('shutdown -s')
```

6. Example of seismic collapse analysis

The example in Fig. 2 is a 3-story, 3-span steel moment-frame. Table 1 shows the sections of the members. The loads are same as that of example in section 3. The structural steel is Q235. 44 earthquake waves used in IDA are taken from recommended far field waves in FEMAP695.

Collapse analysis is performed under the management of control.for. The collapse criteria are taken from FEMA350 (2000), namely, when one of the two phenomena happens, the structure is believed to

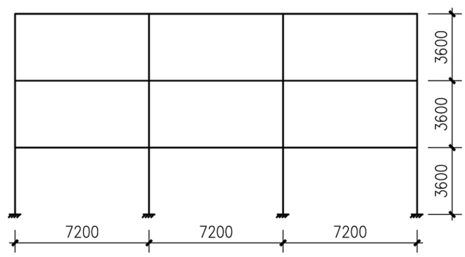


Fig. 7 Dimensions of steel moment-frame

Table 1 Sections of members

Story	Exterior column	Interior column	Beam
1~2	H450×250×10×12	H500×250×12×14	H450×240×8×12
3	H450×250×10×12	H500×250×12×14	H500×240×8×12

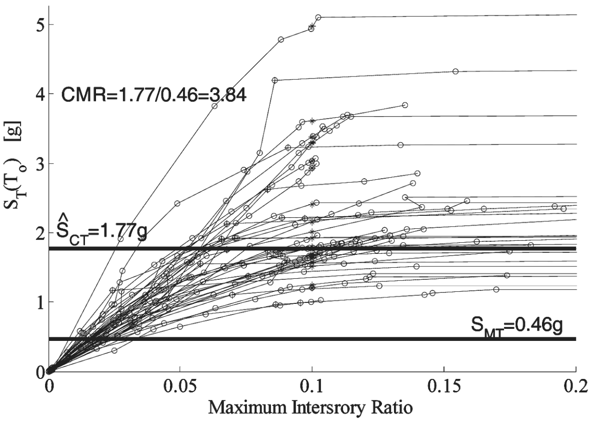


Fig. 8 Incremental dynamic analysis to collapse

reach to the critical state of collapse: 1) The maximum interstory drift ratio exceeds 0.1; 2) The slope of the IDA curve decreases to 20% of the elastic slope through the origin. The procedure spent 15.4 hours implementing the collapse analysis, and attained the CMR = 3.84, greater than the acceptable margin, 3.16, which means the structure is rather safe when earthquake occurs (by the way, the beneficial influence of spectrum shape is not considered here). The acceptable margin is from table 7-2d and table 7-3 in FEMAP695, considering that quality of model, design requirement, and experimental data are all categorized as 'B-Good'. Fig. 8 illustrates how to the IDA method is used to compute the CMR.

7. Conclusions

To effectively use the advanced methodology based on FEMAP695 to assess the seismic safety of structures, the numerical method with high speed and automated procedure must be provided.

The paper appointed out that the explicit finite element method can attain the same exactness as the implicit method in time history analysis, at the same time, explicit method possesses the advantage of speed and convergence property. High speed can save the absolute machine time greatly, convergence property provides the necessary condition for automation of collapse assessment. Some effective methods to accelerate calculation, such as load curves of gravity load, scaling mass method, sub-cycle method are introduced too.

By use of 'system' command in FORTRAN math library, the paper provided an automated procedure for collapse assessment. Firstly, the method develops the control program aiming at collapse assessment and realizes the automation of management; secondly, it makes use of strong and robust algorithm of LS-DYNA as calculation tool to speed up assessment progress; thirdly, it take advantages of the parametric modeling of APDL in ANSYS to conveniently build models for the structures in archetype space and treat with calculation results. As a result, the tedious and heavy work of collapse analysis based on FEMAP695 can be easily implemented and collapse assessment realizes full automation. All the key commands of control program were provided to help analyzers and engineers to treat with collapse assessment conveniently.

Acknowledgment

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