

## Simulation for the Collapse of RC Frame Tall Buildings under Earthquake Disaster

Z. W. Miao<sup>1\*</sup>, X. Z. Lu<sup>1</sup>, L. P. Ye<sup>1</sup>, Q. L. Ma<sup>1</sup>

<sup>1</sup> *Department of Civil Engineerin, Tsinghua University, Beijing, 100084 China*

Email: zhiweim@gmail.com

**Abstract** China is a country that suffers a lot from the earthquake disaster. The major reason for the human death and property losses in earthquake is the collapse of the tall buildings. Hence, correct simulation for the failure modes and accurate prediction for the collapse of the tall buildings under earthquake disaster is very useful for studying the safety of buildings and evaluating losses during earthquakes. However, a lot of simplifications must be carried out in the existing simulations to overcome the numerical problems because the grave nonlinearity exists when collapse happens. This may lead to the results away from a real phenomenon. In this study, a fiber model for reinforced concrete (RC) structures (referred as THUFIBER) is developed, which is based on the general-purpose finite element package of MSC.MARC that carries significant capacity of solving nonlinear problems. In this model, the concrete and the reinforcement inside the structural elements are modeled respectively with different fibers so that the cyclic behavior of material can be properly simulated. Pushover and dynamic time-history analysis for a RC frame tall building are carried out to illustrate the capacity of the proposed model. And dynamic time-history analysis is emphasized in this paper to discuss the collapse modes of the structure. The results show that THUFIBER can simulate the collapse and failure process of the structure under the dynamic loads such as complicated seismic loads, including the softening and fracture behaviors of structural elements, and further the program shows good convergence in the non-linear cases. So THUFIBER has a strong and promising ability for nonlinear analysis including collapse numerical simulation.

**Key words:** fiber model, concrete, seismic, collapse, finite element, frame

### Introduction

China is a country that suffers a lot from the earthquake disaster. In recent 100 years, more than 27 earthquake disasters have happened in China, with a total human death of 0.7 million. So the simulation of the failure modes and to predict collapse of the tall buildings under seismic loads is very useful for studying the safety of buildings and evaluating losses during earthquakes<sup>[1]</sup>. However, a lot of simplifications must be carried out in the existing simulations to overcome the numerical problems because the grave nonlinearity exists when collapse happens<sup>[2]</sup>. This may lead to the results away from a real phenomenon. In this study, a fiber model for reinforced concrete (RC) structures (referred as THUFIBER) is developed, which is based on the general-purpose finite element package of MSC.MARC that carries significant capacity of solving nonlinear problems. In this model, the concrete and the reinforcement inside the structural elements are modeled respectively with different fibers so that the cyclic behavior of material can be properly simulated. Dynamic time-history analysis for a RC frame tall building is carried out to illustrate the capacity of the proposed model.

### Section Discretization and Constitutive Relation of Fibers

In the THUFIBER program, each section of the RC member is divided into 36 concrete and 4 reinforcement fibers as shown in figure 1. Users can define the position, area and constitutive model of each fiber. The program calculates the strain of each fiber by assuming plane remains plane and can insure that the stresses on the section are in equilibrium by iteration<sup>[3,4]</sup>.

In the program, the constitutive relation used for concrete fiber is shown as figure 2. The hysteresis relation of the concrete fiber follows the rule that unloading is directed to the origin and the constitutive relation doesn't take the tensile strength into account. The program can simulate confined and unconfined concrete behavior as well. The constitutive relation of reinforcement fiber is based on the perfect elasto-plasticity model and the reinforcement fiber is set to break at some very large tensile strain. The program with the above mentioned constitutive models for the concrete and the reinforcement fiber performs well in simulating the moment-curvature relation and the softening behavior under different axial forces applied at a RC column<sup>[5]</sup>.

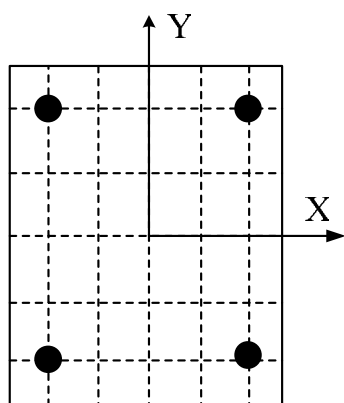


Figure 1: Section discretization

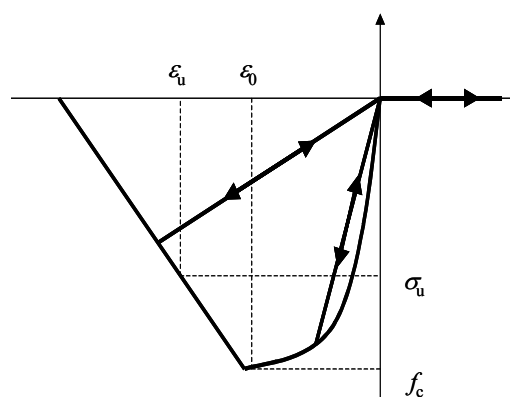


Figure 2: Constitutive relation of concrete fiber

### Computational Model for Collapse Simulation

In order to validate the capacity of THUFIBER, pushover and dynamic time-history analysis for a RC frame-tall building were carried out. A regularly-designed 10-storey RC frame structure was selected as the demonstration finite element model. The columns are spaced at 5m. The ground storey is 4.5m while all the other storeys are 3m in height. The columns have a fixed end on the ground. The serial number of each segment of the frame structure and the base of each column is shown in structure plane in figure 3.

The selected parameters for the materials are as follows. For concrete material, Young's Modulus  $E_0$  is 30GPa. Peak compressive strength  $f_c$  of is 30MPa with peak compressive strain  $\epsilon_0$  0.002. And ultimate compressive strength  $f_u$  is 20MPa with ultimate compressive strain  $\epsilon_u$  of 0.004. For the reinforcement, Young's Modulus  $E_s$  is 200GPa. Yield strength is 400MPa and the broken tensile strain is set as 0.02. With the consideration of the weight of the floors and live loads, the calculated period of the model corresponding to the first mode  $T_1$  was 0.72s. According to the empirical formula for the period of the frame structure in the existing resources<sup>[6]</sup>, the fundamental period for this frame is 0.6~0.8s. It can be seen that the result calculated through the finite element model is well within the empirical range. So the parameters for the finite element model are considered suitable.

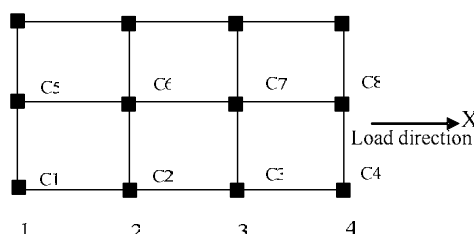


Figure 3: Serial number of each segment of the frame and base of each column

### Pushover Analysis

Pushover analysis was first carried out for the above frame structure model<sup>[5]</sup> and the following conclusions can be drawn from the analysis results:

(1) The finite element model based on THUFIBER embedded in MARC can simulate well the deformation and failure of the structure under the static load and especially the softening process of the column under the axial force and moment. Besides, the program has got good convergence in non-linear analysis.

(2) The failure mechanism of the frame structure was that the ductility of the columns in the compressive segment was low and the capacity of these columns descended rapidly after yielding because of the large axial load ratios, which caused failure of the whole structure.

### Seismic Collapse Analysis

Three different cases based on the above computational model were studied in the seismic collapse analysis.

Case 1:

Dynamic time-history analysis was carried out on the above structure model. The EL-Centro NS ground motion was applied to the structure as seismic input in the direction of X axis. In this case, the peak ground acceleration (PGA) was set as 1000gal to simulate the strong earthquake disaster.

The whole structure didn't collapse in this case, but there were already some plastic regions in some elements where the reinforcement fibers had yielded. The plastic regions at the maximal displacement state and the final state are shown in figure 4. The solid circles in figure 4 mean that some of the reinforcement fibers in these regions yielded. It can be seen that the plastic regions mainly located in column feet and beams in story 1~5.

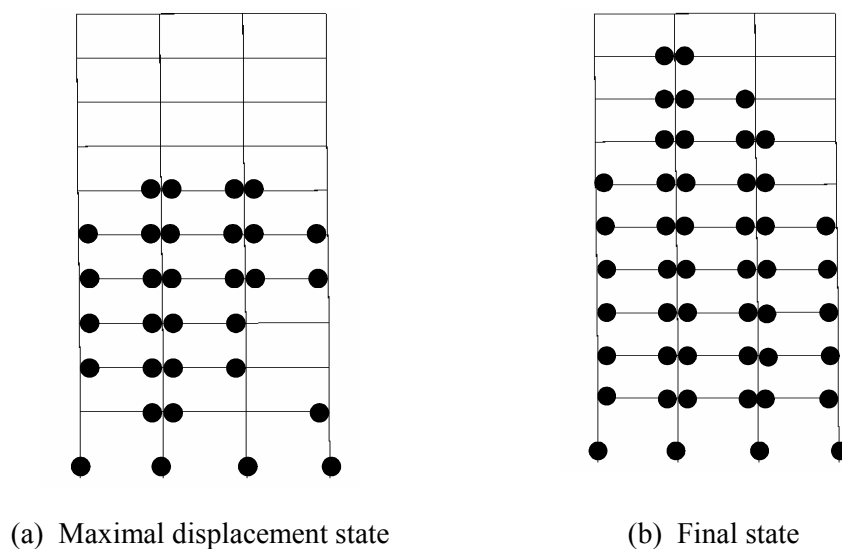


Figure 4 Plastic regions of initial structure(PGA=1000gal)

The bending moment-curvature curves for some columns in figure 5 show some more details about the characteristic of the structure under the seismic load. Here only some center columns are taken as an example. It is evident from figure 5 that the columns at the ground storey in the structure experienced complicated cyclic loading process during the strong earthquake. Under the conjunct load action of axial force and moment, all these columns yielded and some had entered the softening part. But none of these columns had completely failed and the whole structure could still stand during the earthquake with PGA of 1000gal.

It can also be inferred from figure 5(a) and figure 5(d) that the lateral load caused by the horizontal earthquake had a bending effect on the whole frame. When the large lateral load pointed to negative side of the X axis, the axial compressive forces on the columns in the 4th segment such as column 8 decreased, which caused the earlier yielding of these columns at smaller bending moments. But at the same time, the axial compressive force on the columns in the 1st segment such as column 5 increased, which resultantly increased the yield moment of these columns. So at the negative direction of the bending moment axis in figure 5, the yielding moment of column 5 is about 1700kN.m which is much bigger than that of column 8 (about 900kN.m). Similarly, when the direction of the horizontal load was reversed, the corresponding bending moment effect decreased the axial compressive force acting on the column 5 while increased the axial compressive force on column 8. So at the positive direction of the bending moment axis, the yielding moment of column 5 which is about 900kN.m is much smaller than that of column 8(about 1700kN.m).

Besides the effect of changing the yielding moment of the columns, the large axial compressive load ratios on the columns resulted in reduced ductility and the capacity of these columns descended rapidly after yielding. This can be illustrated clearly by the softening part of the exterior envelope of the bending moment-curvature curves of column 5 especially.

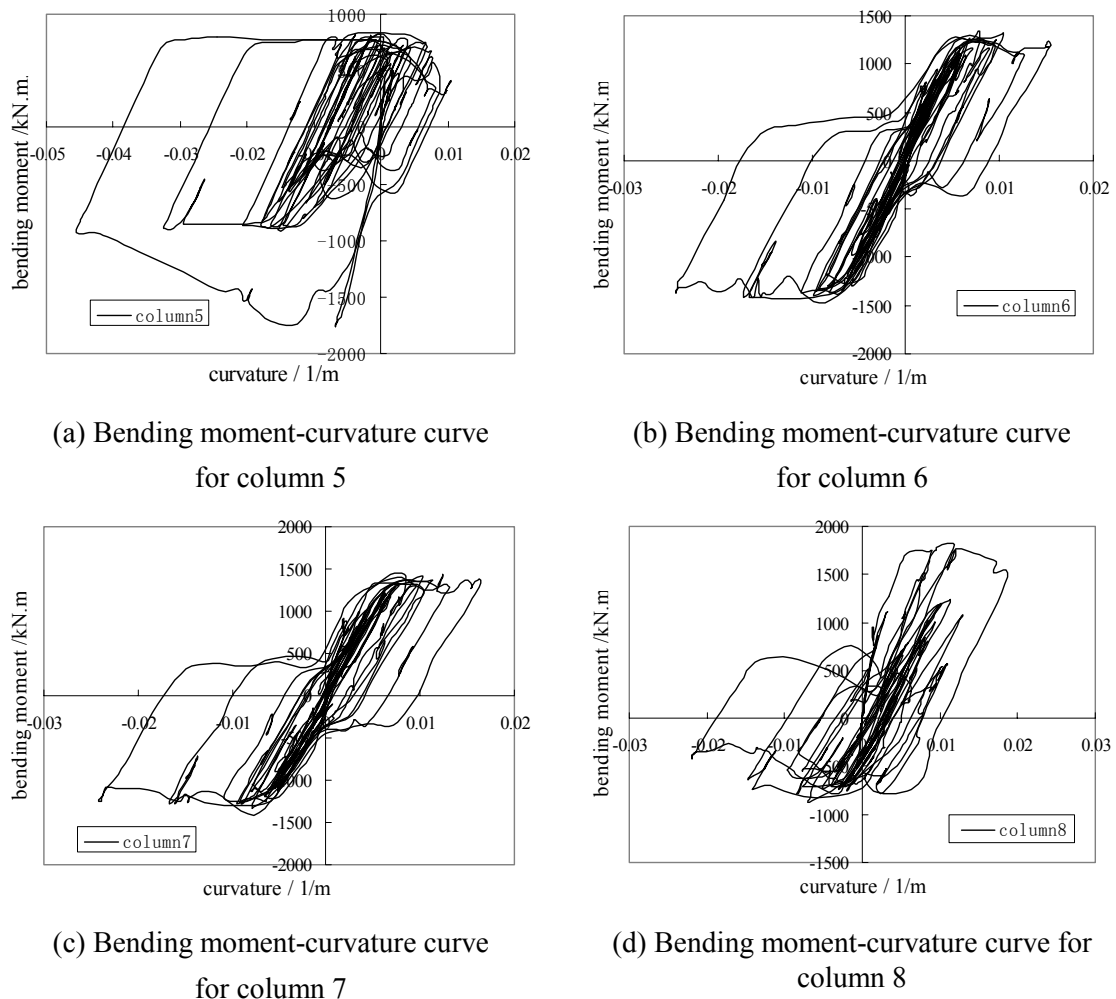


Figure 5 Bending moment-curvature curves for column feet in initial structure(PGA=1000gal)

Because the column 6 and column 7 located in the middle between column 5 and column 8, the above mentioned bending effect could hardly affect them. So their yielding moments in both directions are medium compared with that of column 5 and column 8. This can be easily concluded by comparing figure 5(a) and figure 5(d) with figure 5(b) and figure 5(c).

Case 2:

According to the analysis result that the structure model didn't collapse during the earthquake with PGA of 1000gal in the case 1, it can be concluded that the basic structure model designed initially was relatively stiff. So in the case 2, the same dynamic time-history analysis was carried out again on the same structure model, while the PGA was increased to 2000gal. This was to make the structure collapse and simulate the failure modes of the frame structure under strong seismic load. The results of the structural deformation at different time are shown in figure 6. It must be noted that the solid circles in figure 6 mean that some of the reinforcement fibers in these regions had broken up (not just yielded) and couldn't resist any load.

From the figure 6 it is evident that the damage of the basic structure started firstly at the columns in the 8th storey and the ground storey at about the 3rd second of the total simulation period of 20 seconds. Then very quickly, the 8th storey of the structure collapsed completely at about 1.4s later and also very large lateral displacement occurred at the ground storey. The above results show that weak storey of the structure was mainly at the 8th storey. As it is known, the earthquake always makes the weak storey fail firstly. As the damage originated at the columns of the 8th storey, the damage would localize into this storey. When the inter-storey displacement angle of the storey became too large, the P- $\Delta$  effect would speed up the collapse of this storey. So in this model, the 8th storey is the main weakest storey. The results of this case show a clear failure modes and collapse process under earthquake disaster. This will be very useful for studying the safety of buildings and evaluating losses during earthquakes.

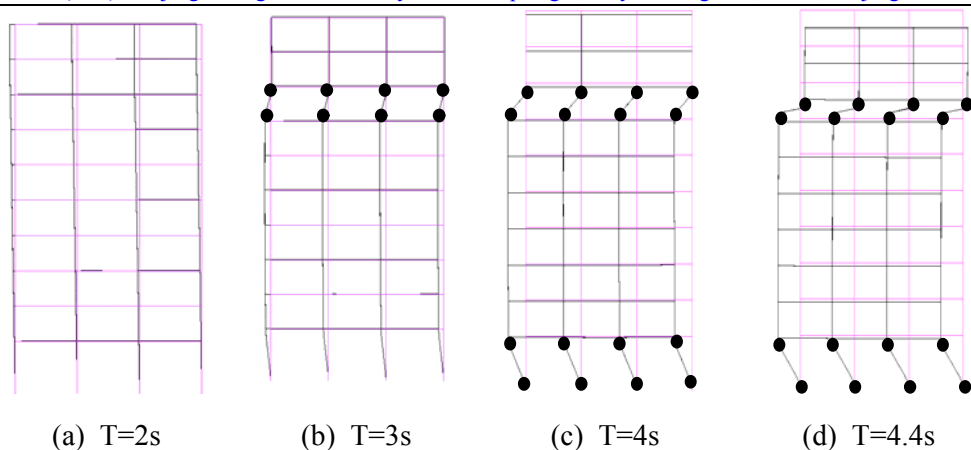


Figure 6 Deformation of the initial structure at different time(PGA=2000gal)

Case 3:

In the case 2, the 8th storey is found to be the main weak storey of the basic structure. To strengthen the weak storey, the amount of reinforcements in the columns at the 8th storey was then increased by 25% and the same dynamic time-history analysis with the PGA of 2000gal was carried out again in the case 3. And the results about the deformation of the strengthened structure at different times are shown in figure 7. The resultant displacements of the structure at different stages as shown in figure 8 also indicate the failure process. Besides, the top floor displacement time-history record is also shown in figure 9. As the structure collapsed to negative side of the X axis, the time-history curve diverges after the 8th second.

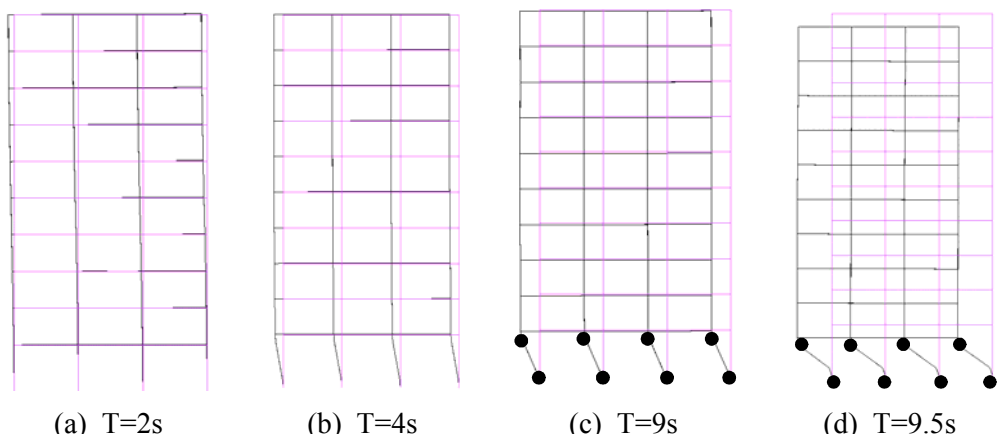


Figure 7 Deformation of the strengthened structure at different time(PGA=2000gal)

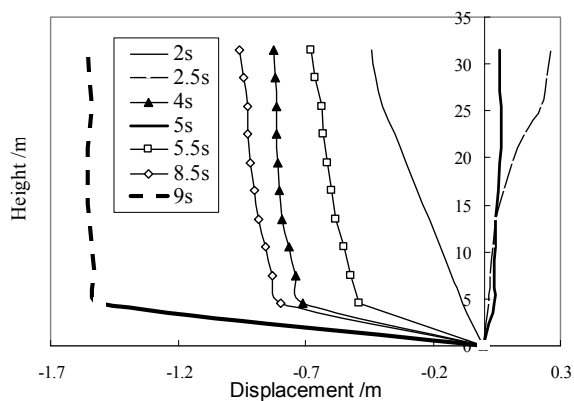


Figure 8 Displacement of each floor at different stages of strengthened structure

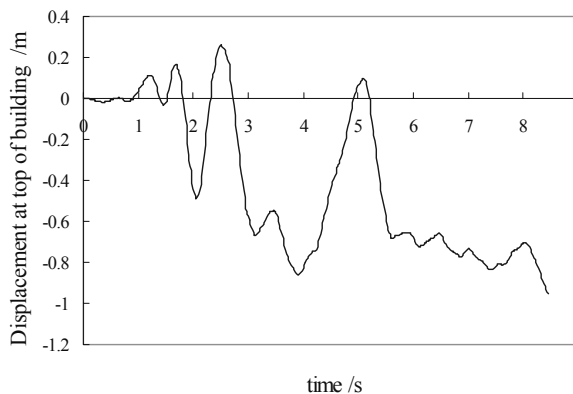


Figure 9 Displacement time-history record of strengthened structure

From figure 7~9, the collapse process can be predicted easily. As the 8th storey of the basic model was strengthened, the ground storey became the only weak storey of the structure and damage didn't occur at the other storey except the ground storey during the whole process of earthquake. The complete collapse of the whole structure happened at the time of 9.5s, which was delayed obviously compared with the initial model in case 2.

It must be pointed that during analysis the convergence criterion was set as 5% for the relative force and 0.5% for the relative displacement tolerance. The convergent results during the whole calculating process until the failure of the structure under the strict convergence criteria indicate the ability of the program in the region of nonlinear analysis.

## Conclusion

THUFIBER which is a developed program embedded in MARC can demonstrate the softening of the columns under the completed effect of axial force and moment and can present the failure mechanism of the frame structure clearly. Consequently it can perform well in simulating the deformation and failure stages of the structure under the dynamic load such as complicated earthquake disaster with a very good convergence during the calculation. The simulation of the failure modes and the prediction of the collapse of tall buildings under earthquake are very useful for studying the safety of buildings and evaluating losses during earthquake. So THUFIBER has a strong and promising ability for nonlinear analysis including collapse numerical simulation for studying the safety of buildings and evaluating losses during earthquakes.

## Acknowledgements

The authors are grateful for the financial support received from the Specialized Research Fund for the Doctoral Program of Higher Education, No.20040003095.

## REFERENCES

1. Lu XZ, Yang N, Jiang JJ. Application of computer simulation technology for structure analysis in disaster. *Automation in Construction*, 2004, 13(5): 597- 606.
2. Lu XZ, Jiang JJ. Simulation for the collapse of WTC after aeroplane impact. *Proc. International Conference on Protection of Structures Against Hazard*, Singapore, 2002. 57-60.
3. Jiang JJ, Lu XZ, Ye L.P. *Finite Element Analysis of Concrete Structures*. Beijing: Tsinghua University Press, 2005. 274(in Chinese)
4. Ye LP. *Concrete Structures*. Beijing: Tsinghua University Press, 2002. 19(in Chinese)
5. Lu XZ, Miao ZW., Qazi AU, Jiang JJ. Simulation for the Collapse of Concrete Tall Building under Static and Dynamic Load. *Proc. International Symposium on Innovation&Sustainability of Structures in Civil Engineering-including Seismic Engineering*, Nanjing, 2005.
6. Fang. EH, Qian JR, Ye LP. *Design for Tall Buildings*. Beijing: China Architecture & Building Press, 2003. 71 (in Chinese)