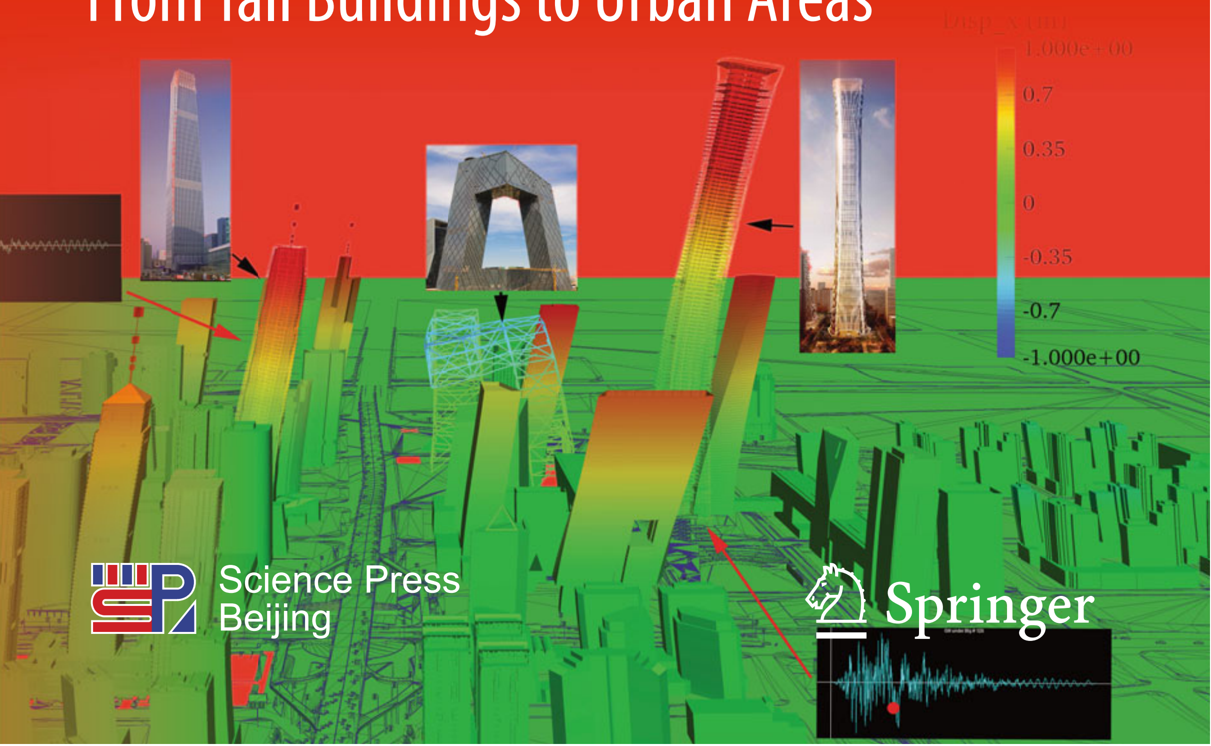
Xinzheng Lu
Hong Guan

Earthquake Disaster Simulation of Civil Infrastructures

From Tall Buildings to Urban Areas



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Preface

Earthquake is a natural disaster that severely threatens the safety of people. In consequence, increasing the seismic resistance and resilience of civil infrastructures and cities through in-depth research of earthquake engineering has significant value for safeguarding life and property. Note that since the devastating Tangshan Earthquake in 1976, no severe earthquake has taken place for more than 40 years in the eastern and central cities of China. Experiences gained from the previous earthquakes obviously cannot satisfy the latest development of structures and urbanizations. Considering the capacity limitations of physical testing facilities, an accurate, efficient, and realistic numerical simulation of seismic damage to structures and cities is critically needed for developing rational and practical engineering solutions and mitigation strategies to reduce the impacts of earthquakes.

The authors of this monograph have systematically studied the earthquake disaster simulation of civil infrastructures for more than 12 years. The outcomes of their work are summarized in this monograph, covering the novel computational models, high-performance computing methods, and realistic visualization of tall buildings and urban areas, with particular emphasize on collapse prevention and mitigation in extreme earthquakes, earthquake loss evaluation, and seismic resilience. Typical engineering applications to several tallest buildings in the world and selected large cities in China are also introduced to demonstrate the advantages of the proposed computational models and techniques. It should be recognized that extensive studies related to earthquake disaster simulation have been conducted by many other researchers. This monograph is intended to present the work completed by the authors and their coworkers only.

The contents covered in this monograph include the research outcomes of many important research projects sponsored by various research agencies, including the Excellent Young Scientist Fund of the National Natural Science Foundation of China (NSFC) (No. 51222804), the Key Research Plan of NSFC (No. 90815025, 91315301), the NSFC-NSF US Major International (Regional) Joint Research Project (No. 51261120377), the General Projects of NSFC (No. 51178249, 51378299, 51578320), the National Key Technology R&D Program of the Ministry of Science and Technology (MOST) of China (No. 2006BAJ03A02,

2009BAJ28B01, 2012BAJ07B012, 2013BAJ08B02, 2014BAL05B04, 2015BAK17B03, 2015BAK14B02), the Beijing Natural Science Foundation (No. 8142024), the Program for New Century Excellent Talents in University (No. NCET-10-0528), the Fok Ying Dong Education Foundation (No. 131071), the Tsinghua University Initiative Scientific Research Program (No. 2010THZ02-1), and the National Non-Profit Institute Research Grant of IGP-CEA (No. DQJB14C01).

The work presented in this monograph is completed by the authors and their co-workers, including Professors Lieping Ye, Aizhu Ren, Song Cen, and Peng Pan of Tsinghua University, Professor Muneo Hori of the University of Tokyo; Professor Kincho H. Law of Stanford University; Dr. Xuchuan Lin of the Institute of Engineering Mechanics of China Earthquake Administration; Professors Wuhui Qi, Weibiao Yang, and Wei Zhen of the Beijing Institute of Architectural Design; Dr. Yuli Huang of Arup Ltd.; Professor Halil Sezen of the Ohio State University; Professor Tony Yang of the University of British Columbia; and Professor Cheng Yu of the University of North Texas. Many graduate students of Tsinghua University also contributed extensively to the development, analysis, and simulation work presented in this monograph. They include doctoral graduates: Drs. Xunliu Wang, Zhiwei Miao, Qianli Ma, Yi Li, Zhe Qu, Zhen Xu, Xiao Lu, Wei Shi, Chen Xiong, and Linlin Xie; master graduates: Wankai Zhang, Bo Han, Mengke Li, Bin Liu, and Lisha Wang; and current graduate students: Xiang Zeng, Kaiqi Lin, Yuan Tian, Zhebiao Yang, Qingle Cheng, and Donglian Gu. In addition, Professors Jiaru Qian, Jingbo Liu, Linhai Han, Zuozhou Zhao, Xiaodong Ji, and Peng Feng of Tsinghua University also provided many valuable advices to this work. The China Academy of Building Research, the Beijing Institute of Architectural Design, the Institute of Engineering Mechanics, the Institute of Geophysics of China Earthquake Administration, Xi'an University of Architecture and Technology, and the THUPDI Ltd also provided generous support to this research.

Support provided by the Key Laboratory of Civil Engineering Safety and Durability of Ministry of Education of China and the Laboratory of the Mechanical Computing and Simulation of Tsinghua University for undertaking extensive computer simulations and experimental studies is greatly acknowledged.

During the writing up stage, Drs. Xiao Lu, Zhen Xu, Linlin Xie, Chen Xiong, Mr. Kaiqi Lin, Xiang Zeng, Qingle Cheng, and Ms. Yaning Zhu helped to finalize all the figures and proofread the entire manuscript. Their contributions are also gratefully acknowledged.

Given a significant amount of research being conducted in the related areas, the work presented in this monograph is just a small contribution. There must be some limitations and errors in the contents of this monograph. Any comments and suggestions from the readers are warmly welcomed.

Beijing, China
September 2016

Xinzheng Lu
Hong Guan

Contents

Abbreviations

ACI	American Concrete Institute
AEBM	Advanced Engineering Building Module
ASCE	American Society of Civil Engineers
ATC	Applied Technology Council
BIM	Building information model
CBD	Central business district
CEA	China Earthquake Administration
CFST	Concrete-filled steel tube
CMR	Collapse margin ratio
CPU	Central processing unit
DBE	Design basis earthquake
DM	Demand measure
DOF	Degree of freedom
EDP	Engineering demand parameter
ELF	Equivalent lateral force
FE	Finite element
FEMA	Federal Emergency Management Agency
GIS	Geographic information system
GPU	Graphics processing unit
IBC	International Building Code
IDA	Incremental dynamic analysis
IDR	Inter-story drift ratio
IM	Intensity measure
MCE	Maximum considered earthquake
MDOF	Multiple degree-of-freedom
NMFS	Nonlinear MDOF flexural-shear
NMS	Nonlinear MDOF shear
PEER	Pacific Earthquake Engineering Research Center
PFA	Peak floor acceleration
PFV	Peak floor velocity

PG	Performance group
PGA	Peak ground acceleration
PGD	Peak ground displacement
PGV	Peak ground velocity
RC	Reinforced concrete
RM	Reinforced masonry
RSA	Response spectrum analysis
SDOF	Single degree-of-freedom
SLE	Service level earthquake
SOE	System of equations
SSI	Soil-structure interaction
TBI	Tall Building Initiative
THA	Time-history analysis
URM	Unreinforced masonry

Chapter 1
Introduction

1.1 Research Background

China, being located in an earthquake-prone region, is one of the countries in the world that suffers the most from earthquake disasters (Chen et al. 1999; Jiang 2005). Spanning over a long history, China has experienced a significant number of devastating earthquakes, resulting in enormous casualties and property losses. Past earthquake events have repeatedly proven that damage to civil infrastructures is the major contributor to earthquake disasters. Building collapses in particular are responsible for a large percentage of deaths and property losses in earthquakes. Therefore, one of the important research pursuits is to develop rational and practical engineering solutions and mitigation strategies to reduce the impacts of earthquakes, through an in-depth understanding of the mechanisms of earthquake damage to civil infrastructures.

Much progress has been made in earthquake engineering research and applications following more than 100 years of scientific endeavor. Recent earthquakes have signified that if the ground motion does not overly exceed the maximum considered intensity, building collapses and casualties can be largely prevented should the structures be engineered in strict accordance with the seismic design code specifications. Such a finding marks a notable achievement and contribution to the entire earthquake engineering community. Despite these remarkable research and application efforts, a range of new challenges are yet to be faced due to rapid societal growth and increasing complexities of earthquakes. To address these challenges, further research efforts must be made in the following areas:

1. **Seismic design of new types of structures**

Many international seismic design codes and specifications are largely based on the lessons learnt from historic earthquakes. Given rapid development of civil engineering technology and randomness of earthquakes, many new types of structures are being constructed without having gathered adequate earthquake experience

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data. For instance, in recent years, there is a boom of supertall building construction worldwide (http://ctbuh.org/). However, most of these supertall buildings have not experienced any major earthquake. The actual safety and performance of the supertall buildings of 400–600 m tall and beyond still remain unknown when they are subjected to severe earthquakes. An in-depth study is indeed urgently needed to ensure safety and robustness of the new types of structural systems.

2. **Disaster prevention and mitigation of urban areas**

Advances in earthquake engineering for new structures, while contributing to the improvement of the community safety, are still limited to comprehensively solve earthquake disaster prevention and mitigation problems in urban areas. Using an analogous statement of "Rome wasn't built in a day," every city has a long history in which the buildings were constructed over different periods. Many outdated buildings lack adequate seismic resistance, a problem that is particularly critical for countries like China. The underlying reason lies in the fact that a large percentage of the urban buildings were constructed well before the modern earthquake engineering design methodology was widely implemented. This situation has become the "Achilles' heel" of contemporary Chinese cities. When a powerful earthquake struck an urban area of China with a dense population, it often caused massive losses to human life and property. Although the economic and social consequences can be mitigated by rebuilding or strengthening all the non-seismic resistant buildings, this may not be easily accomplished in the near future due to a substantial financial burden imposed. Thus, an accurate prediction of the potential seismic damage to urban areas is of practical importance for effective pre-earthquake planning and post-earthquake emergency management.

3. **Earthquakes beyond the range of maximum considered earthquake**

Although the understanding of earthquake risks in China has been increasingly improved owing to the latest revisions of the earthquake hazard zoning map of China, the probability of occurrence of extreme earthquakes that beyond the maximum considered earthquake must not be considered lightly in structural design due to the complicated nature of earthquakes. Critically, important buildings and civil infrastructures are so functional important which are deemed "too big to fail." How to enhance the collapse resistance of such structures subjected to extreme earthquakes remains a significant challenge when aiming for the right balance between safety and construction costs. This requires damage control of the entire structural system in the collapse prevention design against extreme earthquakes, instead of merely designing for strength or ductility of individual components as commonly suggested by most existing design codes (Ye et al. 2010; Tang et al. 2011; Wang et al. 2010).

4. **Resilience of buildings and communities**

In traditional seismic design, great emphasis has been placed on safety and collapse prevention of structures. However, lessons learnt from recent earthquakes reveal that: In addition to the damage control of structural components, loss control of non-structural components and contents in the buildings, as well as post-earthquake recovery of buildings and communities, are also vastly important for disaster risk reduction. Accordingly, the seismic design concept of "resilience" has drawn an increasing attention worldwide (Bruneau et al. 2003; UNDP 2015; Cimellaro 2016). Much in-depth work is thus required to achieve disaster-resilient buildings and communities.

1.2 Significance and Implication of Earthquake Disaster Simulation of Civil Infrastructures

Given the large dimensions and complicated configurations of civil infrastructures, and their likelihood to be destroyed by sudden, devastating, and regional earthquakes, investigation and evaluation of earthquake damage through costly experiments face many challenges. For seismic damage assessment of an urban area, in particular, computer-based simulation has become the most feasible and efficient methodology for scientific research and engineering application.

Computer simulation of earthquake disasters covers the following three components:

1. Mathematical models that can reproduce the behavior of structures;
2. Numerical methods that can provide solutions to a system of mathematical equations; and
3. Computer hardware for implementing numerical simulation.

In light of the above, earthquake disaster simulation falls within a typical multi-disciplinary field of research. From the structural engineering viewpoint, the major task is to continuously develop accurate and reliable mathematical models to mimic the actual behavior of real structures. In addition to this, efficient computer hardware and numerical solvers are also critical issues to be addressed due to excessive computational workload required for an earthquake disaster simulation of a complicated structure or a large urban area.

Numerical simulation using 3D solid elements has many advantages in reproducing the true behavior of 3D structural components. However, their application to real-world structures is both costly and impractical. For example, Yamashita et al. (2011) modeled a 129.7-m-high regularly shaped steel frame with 16 million solid elements. Such a simulation is a huge challenge even for the fastest computer in the world. For this reason, efficient computational models and numerical solvers remain attractive development goals, so does the high-performance/low-cost hardware platform.

It is worth noting that there always exists a major conflict between scientific research/engineering demand and the capabilities and limitations of the physical/experimental and virtual/numerical simulations. Comparing to the slow progression of the experimental capacities, the computing power of numerical simulation has increased rapidly in the past several decades. The list of top 500 fastest computers is updating monthly, and today's desktop computers are almost as fast as the world's fastest supercomputer some 15 years ago. Thus, current earthquake engineering research can largely benefit from full utilization of the capabilities of modern computers.

1.3 Research Framework and Contents

In view of the four critical challenges outlined in Sect. 1.1, this monograph thus focuses on earthquake disaster simulation of tall/supertall buildings and urban areas, with particular emphasize on collapse prevention and mitigation in extreme earthquakes, earthquake loss evaluation, and seismic resilience. The research framework and contents of this monograph are as follows:

Earthquake disaster simulation of tall buildings is covered in Chaps. 2–7.

Given large-scale and complicated structural systems, a computational model with balanced accuracy and efficiency is critical for earthquake disaster simulation of tall buildings. In consequence, Chap. 2 proposes a suite of high-fidelity computational models for tall building simulation (covering fiber-beam element model, multilayer shell element model, and so forth), followed by model validation against published experimental results.

The high-fidelity computational models introduced in Chap. 2 bring new challenges to effective implementation of computer simulation and visualization. Consequently, Chap. 3 proposes graphics processing unit (GPU)-based high-performance matrix solvers in conjunction with physics engine-based high-performance visualization technique, with which the simulation and visualization can be greatly accelerated.

Using the above techniques, earthquake-induced collapse simulation of two real-world landmark supertall buildings, i.e., the Shanghai Tower (H = 632 m) and the Z15 Tower (H = 528 m), is presented in Chap. 4. In-depth discussions are also provided with respect to the collapse process and failure mechanisms of these supertall buildings.

Despite the improved accuracy of the high-fidelity computational models, excessive computational workload limits their application at the preliminary design phase. Therefore, simplified models are proposed in Chap. 5 which can greatly reduce the modeling and computational cost without compromising required accuracy. The simplified models can be used for preliminary design and selection of the most appropriate structural scheme for a given building.

Based on the high-fidelity computational models and simplified models, Chap. 6 discusses, in some detail, several issues pertaining to supertall buildings that have received much attention from wide engineering community. These issues include but not limited to ground motion intensity measure and minimum base shear force for supertall buildings, and optimal design of an actual supertall building based on collapse analysis.

Discussions on tall buildings presented in Chaps. 2–6 are primarily focused on the overall structural performance. Given increased demand on seismically resilient tall buildings, Chap. 7 details the structural performance and seismic resilience of typical tall buildings designed based on the Chinese and US codes, using the computational models developed in previous chapters and the new-generation performance-based design method.

Earthquake disaster simulation of urban areas is presented in Chaps. 8–12 of this monograph.

To overcome the limitations of existing urban building seismic simulations, Chap. 8 proposes nonlinear multiple degree-of-freedom (MDOF) models in conjunction with time-history analysis to predict seismic damage to buildings in large urban areas. The computational models and the corresponding parameter determination methods are proposed for multi-story masonry buildings, reinforced concrete frames, and tall buildings.

A realistic visualization is highly important for users of urban building seismic simulation who are not professional civil engineers. With this in mind, 2.5D and 3D

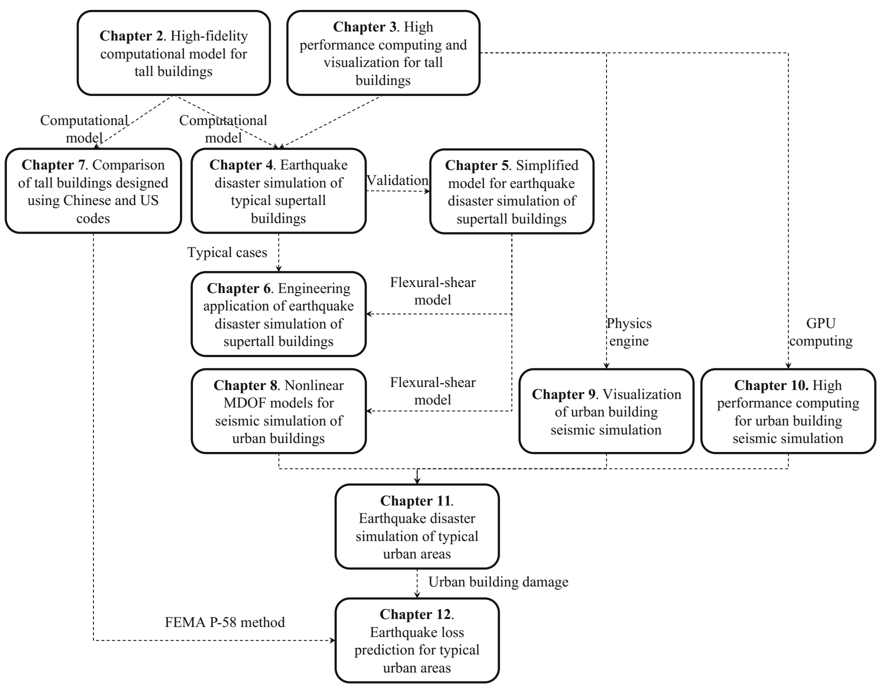

Fig. 1.1 Contents and interrelationships of all chapters

visualization models are proposed in Chap. 9 to enhance visualization capabilities of urban building seismic simulation. In addition, collapse simulation of urban buildings is achieved through physics engines.

Earthquake disaster simulation of an urban area based on nonlinear MDOF models or high-fidelity computational models brings more challenges to computational workload. A coarse-grained CPU/GPU collaborative parallel computing and a distributed computing framework for multi-fidelity models are therefore proposed in Chap. 10 which impressively accelerated the earthquake disaster simulation of an urban area.

Using the method proposed in Chaps. 8–10, Chap. 11 presents six typical examples of urban building seismic simulation. The number of buildings simulated is up to hundreds of thousands, demonstrating the advantages and applicability of the proposed method.

While the urban building seismic simulation technique developed in Chaps. 8–11 focuses mainly on the structural damage, Chap. 12 makes use of detailed structural responses to predict the earthquake loss of an urban area based on the new-generation performance-based design method. A secondary disaster simulation of falling debris of buildings is also presented which in turn helps to select a rational and safer site for emergency shelter construction. The outcome of this simulation is expected to provide a useful reference for improving community resilience.

Last but not least, Chap. 13 summarizes the major achievements and contributions reported in this monograph, based on which the future research directions are given.

A schematic of the contents and interrelationships of various chapters are illustrated in Fig. 1.1.

Chapter 2
High-Fidelity Computational Models for Earthquake Disaster Simulation of Tall Buildings

2.1 Introduction

Since the completion of Taipei 101 Tower in 2004, the first supertall building exceeding 500 m, construction of supertall buildings is booming all around the world, especially in China. Data from the Council on Tall Buildings and Urban Habitat (CTBUH, http://ctbuh.org/) in 2012 indicates that before 2000, the average height of the first 20 tallest buildings in the world was approximately 375 m; yet by 2010, the average height had increased to 439 m. Amazingly, the average height of the first 20 tallest buildings is projected to reach 598 m by 2020.

Earthquakes are serious threats to tall buildings, particularly to many newly constructed supertall buildings located in the high seismic region. Due to their comprehensive functions, high residential densities, and long service life requirements, earthquake-induced collapse of supertall buildings would result in unacceptable economic losses and casualties. Therefore, collapse of supertall buildings due to extreme earthquakes must be prevented through a rational and effective seismic design.

The structural system of a supertall building is rather complex. A large number of novel structural systems and high-performance structural components are adopted in newly constructed supertall buildings. Unfortunately, the seismic performance of these new systems and components has not yet been sufficiently studied. In consequence, the matching design philosophies and methodologies are yet to be comprehensively specified in the building codes. In addition, due to the much longer fundamental periods of supertall buildings than the other ordinary structures, the applicability of the current ground motion intensity measures (*IM*) and code-specified design requirements (e.g., the minimum base shear force) has not been verified for supertall buildings. Therefore, how to develop a rational seismic design method to ensure structural seismic safety is the primary objective of the seismic design for supertall buildings.

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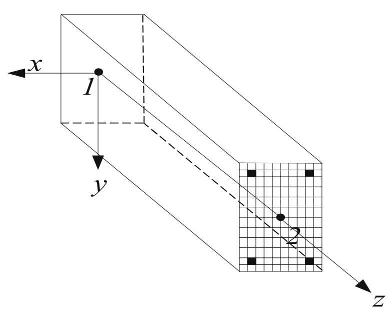
Given numerous structural components and complexities of the structural systems in tall buildings, an accurate and efficient computational model is critical for the disaster simulation of such structures. A high-fidelity finite element (FE) model of supertall buildings, composed of fiber-beam element model for beams/columns and multilayer shell element model for shear walls, is proposed herein. Relevant work on the fiber-beam element and multilayer shell element models is presented in Sects. 2.2 and 2.3. To cater for non-conventional structural components that fiber-beam element and multilayer shell element cannot provide a satisfactory solution, a special hysteretic hinge model is developed, as elaborated in Sect. 2.4. In addition, for some special regions (e.g., the joints), using the fiber-beam or multilayer shell elements cannot satisfactorily predict the actual structural behavior. While solid elements can be adopted, simulating the entire structure with solid elements would require excessive computational workload which is considered unacceptable. For this reason, the multi-scale modeling method can be an ideal alternative, as discussed in Sect. 2.5. During the process of collapse, the fragmented structural components can be simulated by elemental deactivation technique and visualized by a physics engine, as introduced in Sect. 2.6.

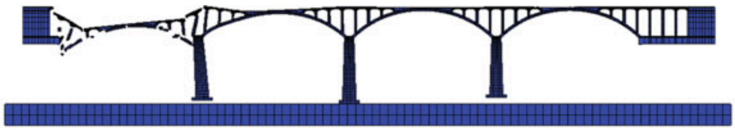
2.2 Fiber-Beam Element Model

2.2.1 Fundamental Principals

The fiber-beam element model has been widely accepted to model reinforced concrete (RC) frames predominately failed in flexural (Taucer et al. 1991; Spacone et al. 1996). In this model, the structural frames (beams and columns) are modeled with beam elements, and their cross sections are divided into a number of fibers (Fig. 2.1). Each fiber has its own uniaxial constitutive law, and different fibers on the same section follow the “plane section” assumption. The model is capable of simulating the axial–flexural coupling behavior of RC frames and is adaptive to different sectional shapes. The confinement effect of the stirrups to the concrete can also be considered by using confined uniaxial constitutive relationship for core

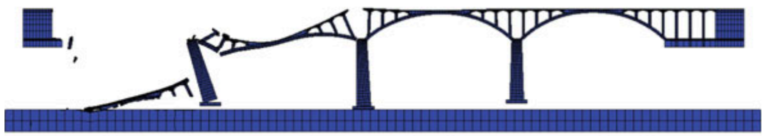
Fig. 2.1 Fiber-beam element





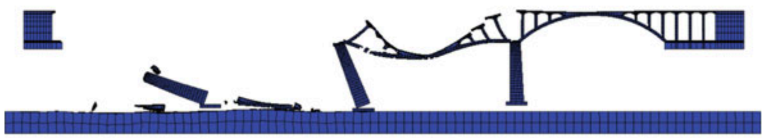
(a) Conventional FE result (t=1.68s)

(b) Visual simulation with fragment details (t=1.68s)



(c) Conventional FE result (t=3.36s)

(d) Visual simulation with fragment details (t=3.36s)



(e) Conventional FE result (t=5.52s)

(f) Visual simulation with fragment details (t=5.52s)

Fig. 2.50 Comparison of collapse process between the conventional FE results and visual simulation with fragment details graphics. This looping process forms animation of the fragments, as illustrated in Fig. 2.49.

An efficient and integrated OSG and PhysX platform is thus established, based on the class *Fragments* and the class *Move-callback*, to achieve a real-time simulation of fragments. More importantly, independent features of PhysX and OSG are maintained in relation to their modeling processes. This helps to lay a solid foundation for solving the rendering problems in fragment simulation.

2.6.2.3 Case Study

Based on the above technology, as well as the fragment clustering algorithm (Xu et al. 2013b), the collapse process of a bridge is simulated as shown in Fig. 2.50. It is evident that the deactivated elements are well displayed by the fragment simulation, which provides much more completed and realistic details than the post-process of many other conventional FE analyses.

2.7 Summary

An accurate and efficient computational model is critical for earthquake disaster simulation of tall and supertall buildings. With this in mind, a high-fidelity computational model, composed of fiber-beam element model for conventional beams/columns and multilayer shell element model for conventional shear walls, is proposed. The corresponding material laws, cross-sectional model, and element model of fiber-beam elements and multilayer shell elements are discussed in some detail. The accuracy and reliability of the material and element models is validated through comparison with various experimental results. To simulate the complicated pinching and deterioration behavior of structural components, a special hysteretic hinge model is proposed and validated against various steel and concrete specimens. Further, in order to achieve an optimal balance between computational accuracy and workload, a multi-scale modeling approach is also proposed conjoining the microscale and macroscale models. Moreover, an elemental deactivation technique is introduced to simulate the collapse process of structural components. Finally an integrated approach for fragment simulation is developed to realistically simulate and visualize the movements of fragmented structural components.

The numerical models and simulation techniques proposed in this chapter lay a foundation for earthquake disaster simulation of tall and supertall buildings. The models developed will be applied in collapse simulation and performance evaluation of various tall and supertall buildings, to be presented in the subsequent chapters (Chaps. 4, 6, and 7). The proposed high-fidelity model will also be used as the benchmark model to validate the accuracy of various simplified models for earthquake disaster simulation of tall/supertall and urban buildings (Chaps. 5 and 8).

Chapter 3
High-Performance Computing and Visualization for Earthquake Disaster Simulation of Tall Buildings

3.1 Introduction

High-fidelity computational models proposed in Chap. 2 for earthquake disaster simulation brings new challenges to high-speed computing and visualization. Despite the rapid progression of computer hardware, novel computational algorithms that can make full utilization of the latest hardware capacity are critically demanding for an efficient high-fidelity simulation. This chapter is driven by such demands to develop graphics processing unit (GPU)-based high-performance matrix solvers in conjunction with GPU-based high-performance visualization of massive time-varying data resulted from large-scale structural dynamic analysis, with which the process of simulation and visualization can be greatly accelerated.

3.2 GPU-Based High-Performance Matrix Solvers for OpenSees

3.2.1 Fundamental Conception of General-Purpose Computing on GPU (GPGPU)

Graphics processing unit (GPU) was originally designed for high-performance visualization of computer graphics. Due to the outstanding parallel and float computing capability of GPU, general-purpose computing on GPU (GPGPU) was subsequently proposed to perform high-performance computing tasks in addition to visualization. In 2006, NVIDIA Corporation released a new GPGPU platform, i.e., CUDA (Compute Unified Device Architecture), which greatly reduced the programming difficulties and enhanced the performance of GPGPU (NVIDIA 2012). A typical processing flow on CUDA is show in Fig. 3.1 (https://en.wikipedia.org/wiki/CUDA). The central processing unit (CPU) controls the task processing and

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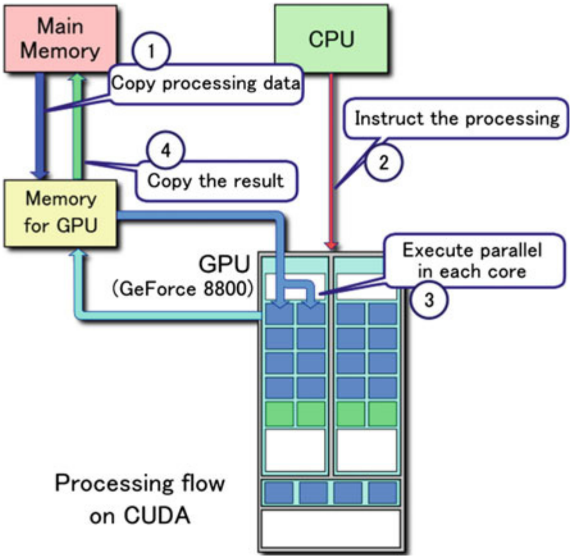

Fig. 3.1 Typical processing flow on CUDA (https://en.wikipedia.org/wiki/CUDA)

assignment. The tasks that demand a large number of parallel computing are copied to the graphics memory and then executed by GPU. The output is copied back from the graphics memory to the main memory. To further reduce the programming workload of GPGPU, numerous mathematics libraries, and algorithm packages have been developed based on CUDA. In consequence, GPGPU has been widely used in the fastest computers worldwide.

3.2.2 High-Performance Solver for Sparse System of Equations (SOE) in OpenSees

Although OpenSees (McKenna et al. 2009) has been widely used in earthquake engineering research, its computational efficiency still remains a critical challenge (Elgamal et al. 2008). For large structures having hundreds of thousands of degrees of freedom (DOFs), a nonlinear time-history analysis in OpenSees may take several weeks to complete. Most computational time is consumed on solving the system of equations (SOE). In consequence, a high-performance solver for SOE is desirable for the application of OpenSees to tall and supertall buildings. To fulfill this demand, GPU-based high-performance matrix solvers have been developed and implemented in the open-source FE code of OpenSees by Xu et al. (2016b) and are introduced as below.

The storage and solution methods for SOE are determined by the two basic classes in OpenSees: the Linear System of Equation (*LinearSOE*) class and the Linear System of Equation Solver (*LinearSOESolver*) class, respectively.

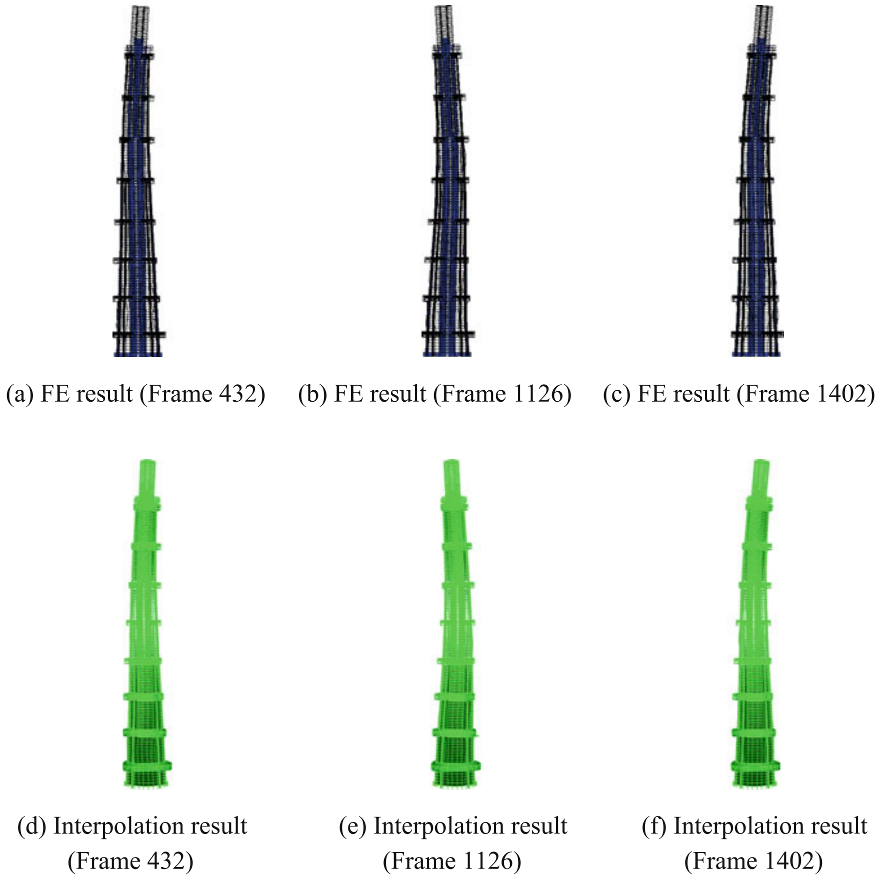

Fig. 3.11 Comparison between the original FE results and the interpolation outcomes for the supertall building

resulted from the original FE analysis and the proposed frame interpolation is also compared in Fig. 3.12. The similarity coefficient between the two sets of results is found to be 0.9996, which again validates the rationality of the proposed interpolation method.

Using MSC.Marc, the rendering time is found to be approximately 2 s for a time step in the FE analysis of the same supertall building, and the entire rendering process (2001 time steps) takes one hour. Using the proposed interpolation method, on the other hand, the rendering efficiency reaches 30 FPS (frames per second) and the entire rendering process requires only 66.7 s; this is equivalent to 0.03 s per time step and approximately 67 times improvement. Such an improvement once again confirms that high-performance visualization can be successfully achieved by the proposed method for a large-scale structural dynamic analysis. The optimized data access model plays an important role in improving the interpolation efficiency,

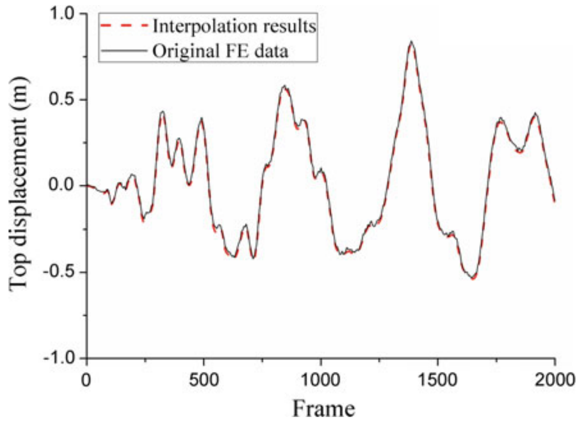

Fig. 3.12 Top displacements between the original FE results and the interpolation outcomes for the supertall building

by which the time for one interpolation of all vertices (54,542 vertices and 163,626 coordinate components) ranges from 0.0032 to 0.0016 s, with a speedup ratio of 2.0. It is worthwhile noting that the larger the amount of data is, the more significant the advantage of the optimized access model is.

3.4 Summary

To fulfill the demand of high-speed computing and visualization of high-fidelity computational models proposed in Chap. 2, GPU-based high-performance matrix solvers are developed and implemented in the open-source FE code of OpenSees. A maximum speedup ratio of up to 15 times is achieved with the GPU-based matrix solvers compared to the existing solvers in OpenSees. Further, a complete GPU-based solution for high-speed visualization of massive time-varying data resulted from large-scale structural dynamic analyses is also developed. The rendering efficiency is improved by 67 times compared to the post-processor of MSC. Marc. Using the improved techniques presented in this chapter, the process of computing and visualization of high-fidelity computational models is remarkably accelerated. This offers a promising opportunity for the proposed high-fidelity computational models to be widely applied in earthquake disaster simulation of real supertall building projects.

Chapter 4
Earthquake Disaster Simulation of Typical Supertall Buildings

4.1 Introduction

The earthquake disaster simulation of tall buildings can be implemented based on the proposed high-fidelity computational models, high-performance computing algorithms, and visualization techniques developed in Chaps. 2 and 3. In this chapter, two typical supertall buildings are taken as examples to study the earthquake-induced failure modes, collapse processes, and the corresponding collapse mechanisms. The first example is the Shanghai Tower, being the tallest building in Shanghai with a height of 632 m. The collapse simulation of the Shanghai Tower was performed by Lu et al. (2011), and the influence of the soil-structure interaction on the collapse resistance was discussed in Li et al. (2014). The second example is the Z15 Tower, being the tallest building in Beijing with a height of 528 m. The collapse simulation of the Z15 Tower was performed by the authors (Lu et al. 2013d), and the comparison of different structural design schemes was reported in Lu et al. (2016a). The abovementioned work is expected to provide a useful reference for the collapse prevention and the seismic design of supertall buildings.

4.2 Earthquake Disaster Simulation of the Shanghai Tower

4.2.1 Overview of the Shanghai Tower

The Shanghai Tower, located in Lujiazui, Shanghai, is a multi-functional office building (as shown in Fig. 4.1). The total height of the main tower is 632 m, and the structural height is 580 m. This building contains 124 stories. The seismic design intensity of the Shanghai Tower is 7-degree as specified in the Chinese

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seismic design code (GB50011-2010). The corresponding peak ground acceleration (PGA) value of the design earthquake (i.e., exceedance probability of 10 % in 50 years) is 100 cm/s^2. A hybrid lateral force-resisting system (as shown in Fig. 4.2), referred to as the “mega-column/core tube/outrigger,” was constructed for the main tower. Details of this system are described briefly as follows:

1. The main component of the core tube (see Fig. 4.2) is a 30 m × 30 m square reinforced concrete (RC) tube. At the bottom of the building, the thickness of the flange wall of the tube is 1.2 m, and the wall thickness decreases with the height of the tube and reduces to 0.5 m at the top of the building. Similarly, the thickness of the web wall decreases from 0.9 m at the bottom to 0.5 m at the top. According to the architectural functional requirements, the four corners of the core tube are gradually removed above Zone 5, resulting in an X-shaped configuration at the top (Ding et al. 2010; Jiang et al. 2011; Tian et al. 2011).
2. The mega-column system consists of 12 shaped steel reinforced concrete columns with a maximum cross-sectional dimension of 5300 mm × 3700 mm. A total of eight mega-columns extend from the bottom to the top of the building, and their sectional sizes gradually reduce to 2400 mm × 1900 mm at the

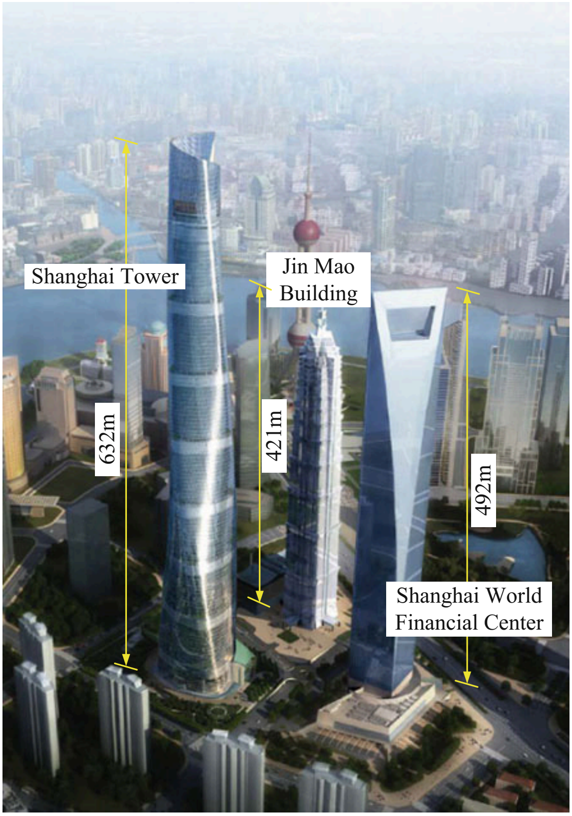

Fig. 4.1 The location of the three supertall buildings in Shanghai (from www.eastday.com)

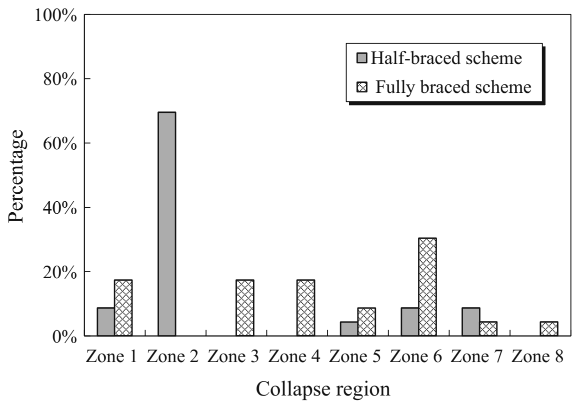

Fig. 4.61 Collapse regions of the two design schemes

said, having the smallest planar layout, Zone 6 has a higher possibility to become the initial collapse region than the other zones. Such initial collapse regions can also be treated as the weakest areas of the building when performing design optimization of the structural components.

The collapse fragility curves for these two schemes are compared in Fig. 4.62. Due to the complicated nature of the ground motion records, the choice of various intensity measures (IMs) may affect the shape of the fragility curves. The authors have discussed the rationality of different IMs for supertall buildings and proposed a more efficient IM$(\overline{S})$ (Lu et al. 2013c). Further details are given in Sect. 6.2 of this monograph.

The collapse fragility curves obtained for the two design schemes using PGA and $\overline{S}$ as IMs are shown in Fig. 4.62. Generally, the collapse probability of the half-braced scheme is higher than that of the fully braced scheme subjected to the same ground motion intensity. The dispersions of the fragility curves based on $\overline{S}$ (Fig. 4.62b) are significantly smaller than those based on PGA (Fig. 4.62a). For

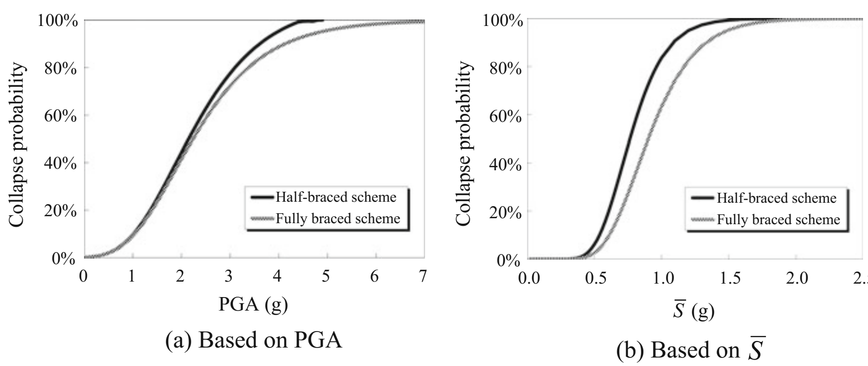

Fig. 4.62 The collapse fragility curves for the two design schemes

example, the IM of each ground motion that triggers a collapse is recorded, which is referred to as "$IM_{collapse}$" (e.g., "$PGA_{collapse}$ " or "$\overline{S}_{collapse}$"). The coefficient of variation (COV) of $PGA_{collapse}$ for the half-braced scheme is 0.426. In contrast, the corresponding COV of $\overline{S}_{collapse}$ is only 0.282. Thus, the application of $\overline{S}$ is able to significantly reduce the dispersion in collapse resistances due to different ground motions.

The CMR proposed in FEMA P695 (FEMA 2009) is adopted herein to quantify the structural collapse-resistant capacity. When using PGA as the intensity measure, the CMRs of the half-braced and fully braced schemes are 5.88 and 6.75, respectively. This evidently demonstrates that the fully braced scheme has a relatively higher collapse resistance than the half-braced scheme.

Furthermore, the collapse probabilities of the building at the MCE level earthquake are approximately 1.34 and 1.29 %, respectively, for the half-braced and fully braced schemes. Clearly, the resulting collapse probabilities, being considerably low, satisfy the safety requirements set by both ASCE 7–10 (i.e., <6 % at the MCE level for Risk Category III) (ASCE 2010) and *the Code for Anti-collapse Design of Building Structures* of China (i.e., <5 % at the MCE level) (CECS392:2014).

To summarize, the fully braced scheme exhibits a higher collapse resistance, having a CMR 14.8 % higher than that of the half-braced scheme. Furthermore, the total material consumption of the fully braced scheme is 11.2 % lower than that of the half-braced scheme. In view of these, the fully braced scheme is recommended as the lateral force resisting system for the Z15 Tower.

4.4 Summary

In this chapter, the earthquake-induced collapse of two real-world supertall buildings, i.e., the Shanghai Tower with a height of 632 m (the tallest building in Shanghai) and the Z15 Tower with a height of 528 m (the tallest building in Beijing), are simulated. Specifically, the influence of the soil-structure interaction on the collapse resistance of the Shanghai Tower is discussed. The material consumption, seismic performance and fragility due to different structural design schemes of the Z15 Tower are compared. A better design with higher collapse margin and lower material consumption is identified as a result of the comparison. The earthquake disaster simulation of the two supertall buildings presented in this chapter not only demonstrates the capability of the proposed high-fidelity computational model, but will also be used as the typical cases for validating the proposed simplified models and undertaking performance assessment and design optimizations in the following chapters.

Chapter 5
Simplified Models for Earthquake Disaster Simulation of Supertall Buildings

5.1 Introduction

A high-fidelity finite element (FE) model integrating the fiber-beam element for beams/columns and multilayer shell element for shear walls/core tubes has been introduced in Chap. 2. This model enables an accurate simulation of the entire collapse process of tall and supertall buildings with sufficient adaptability. Nevertheless, this model has certain limitations pertinent to the computational efficiency. The workload required to establish a high-fidelity FE model as well as associated analyses is overwhelming, especially for parametric analyses or incremental dynamic analysis. Moreover, for real engineering projects, a number of different design schemes are often proposed at the preliminary design stage. Comparison between various design schemes cannot be easily performed using the high-fidelity FE models due to the high computational cost required. To address this issue, a simplified model that can represent the key nonlinear and dynamic characteristics of supertall buildings while being computationally effective has potential to facilitate academic research and application for real engineering practice.

Inspired from the above consideration, this chapter presents two simplified models with different degrees of simplification for supertall buildings (Lu et al. 2013b, c, 2014a, 2016c). The application of the flexural-shear coupling continuum model (referred to as "flexural-shear model" hereafter for brevity), proposed by Miranda and Taghavi (2005) for supertall buildings, is discussed in Sect. 5.2. This model can well represent the elastic behavior of supertall buildings with fewer degrees of freedom (DOFs) involved. The model is subsequently used in Sect. 6.2 to evaluate the applicability of different ground motion intensity measures for supertall buildings. A novel fishbone model, being able to represent the nonlinear characteristics of supertall buildings with only thousands of DOFs, is proposed

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(Lu et al. 2014a, 2016c) and introduced in Sect. 5.3. The application of the fishbone model in the selection between different design schemes for a real engineering practice is also illustrated in detail, emphasizing on the damage control and seismic resilience.

5.2 The Flexural-Shear Model

5.2.1 Fundamental Concepts of the Flexural-Shear Model

Most modern supertall buildings are constructed in the form of the following two types of hybrid lateral load-resisting systems: mega-column/core-tube/outrigger system, and mega-braced frame-core-tube system. The deformation modes of these structural systems are typically a combination of flexural deformation and shear deformation. As mentioned above, although the proposed high-fidelity FE model is capable of predicting the seismic responses of supertall buildings, the associated modeling and computational workload is excessively high. Therefore, a simplified model is required that can represent the key nonlinear and dynamic characteristics of supertall buildings while being computationally effective. One such simplified model was proposed by Miranda and Taghavi (2005), referred to as the flexural-shear coupling continuum model ("flexural-shear model" for short hereafter) shown in Fig. 5.1. This model has been proven to be able to accurately represent the flexural-shear deformation mode of building structures. The application of this model to supertall buildings is discussed as follows.

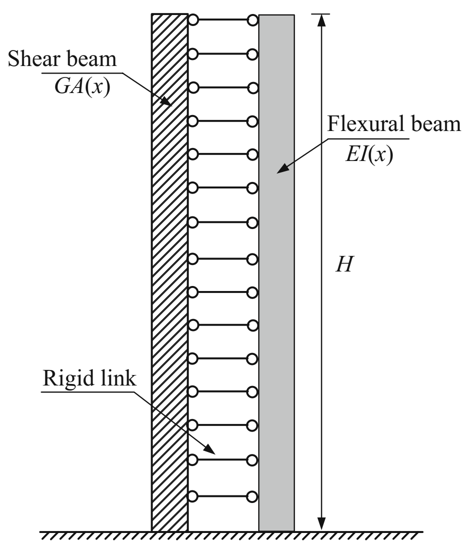
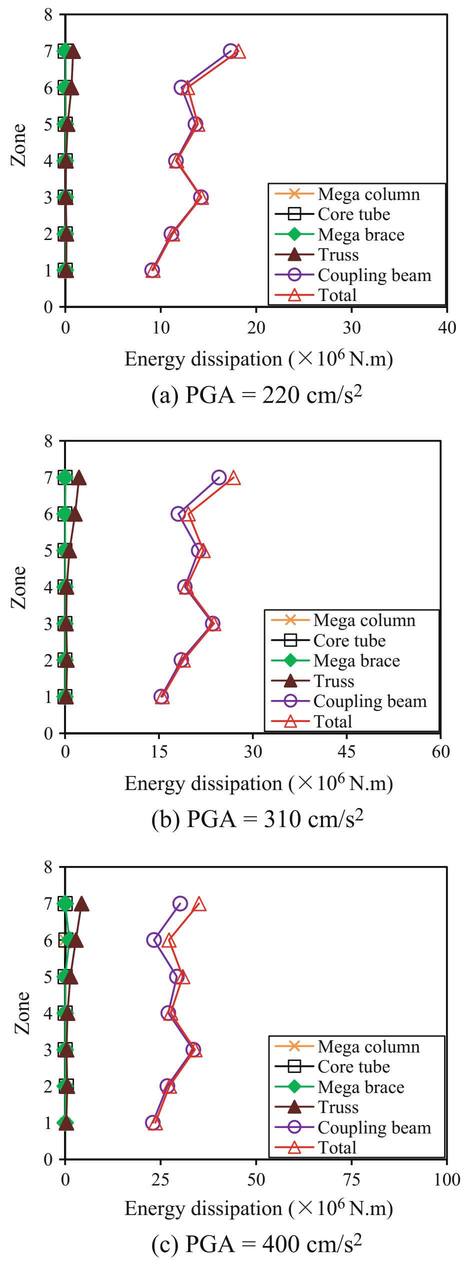


Fig. 5.1 Schematic diagram of the flexural-shear model (Miranda and Taghavi 2005)

Fig. 5.36 Plastic energy dissipation along the building height in the fully braced scheme under different seismic intensities



with height. The continuous arrangement of the mega braces can effectively control the higher-order modes, thus preventing the coupling beams from damage concentration.

As described above, the fully braced scheme is found to induce a uniform plastic energy dissipation distribution and effectively enables the energy dissipation to be located in readily replaceable components. Conversely, significant plastic energy dissipation concentration is observed at the upper four zones of the half-braced scheme, and the core tubes are found to suffer significant damage; as a result, the functional recovery of the building will be delayed. Overall, the fully braced scheme provides a better seismic resilient performance compared to the half-braced scheme.

5.4 Summary

Two simplified models (i.e., the flexural-shear model and fishbone model) are developed and applied to investigate the seismic performance of two real-world supertall buildings. Both models offer notable computational efficiency. The flexural-shear model can well represent the elastic dynamic properties of supertall buildings. This model is subsequently used in Sect. 6.2 to evaluate the applicability of different ground motion intensity measures for supertall buildings. Furthermore, a nonlinear MDOF flexural-shear model is developed in Sect. 8.3 for the seismic simulation of regional tall buildings. The fishbone model is capable of (1) capturing the basic dynamic properties, (2) approximately reflecting the internal force distribution characteristics under static loads, and (3) simulating the nonlinear responses and capturing macro-damage characteristics when subjected to earthquakes. The high efficiency and accuracy of the fishbone model lay a foundation for detailed evaluation of energy dissipation characteristics of supertall buildings, which will assist in (1) identifying primary plastic energy dissipation components, (2) understanding damage mechanisms, (3) guiding seismic damage–control designs, (4) assessing seismic resilience performances, and (5) comparing seismic performances between different design schemes.

Chapter 6
Engineering Application of Earthquake Disaster Simulation of Supertall Buildings

6.1 Introduction

One of the major purposes of earthquake disaster simulation is to discover the mechanisms of structural collapse, so as to validate the design methods, optimize the structural designs, and take effective measures to avoid collapse. Real-world applications of earthquake disaster simulation techniques have been introduced in Chaps. 4 and 5. This chapter will further discuss the application of earthquake disaster simulation of supertall buildings with respect to the ground motion intensity measure (IM) selections, base shear force adjustments, and optimal designs of components in the seismic design of this type of buildings.

6.2 Ground Motion IM for Supertall Buildings

6.2.1 Background

Performance-based seismic design has been widely adopted since the Loma Prieta earthquake in 1989 and the Northridge Earthquake in 1994 (Hamburger et al. 2004). The IM is an important component of performance-based seismic design, which connects the seismic response of structures to the seismic hazard. A reasonable IM can effectively reduce the deviations in the prediction of structural responses. Many studies on IMs for conventional structures have been conducted in recent decades (Shome et al. 1998; Cordova et al. 2001; Baker and Cornell 2005; Luco and Cornell 2007; Tothong and Luco 2007; Ye et al. 2013; Lu et al. 2013b).

The fundamental periods of supertall buildings are much longer than those of ordinary frame structures or shear wall structures. For example, the fundamental periods of the Shanghai Tower (Jiang et al. 2011) and the Ping-An Finance Center (Yang et al. 2011), two supertall buildings in China currently under construction,

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will be larger than 9 s, which is far beyond the limit of 6 s specified in the design acceleration spectrum in *the Chinese Code for Seismic Design of Buildings* (GB50011-2010). Although great progress has been made on reducing the deviation of the predictions of structural seismic responses with reasonable IMs, it should be noted that most of the existing intensity measures are based on the ordinary structures with periods in the range of 0–4 s. Given the large number of supertall buildings that have been and will be constructed, the suitability of these IMs must be validated, and if necessary, a suitable and practical IM for supertall buildings must be developed.

Therefore, based on the dynamic characteristics of the supertall buildings, as well as the advantages of the existing IMs, a practical and efficient intensity measure is proposed by Lu et al. (2013c) and presented in this section using the flexural-shear coupling continuum model (Miranda and Taghavi 2005) introduced in Sect. 5.2. The key parameter of the proposed intensity measure is calibrated by a series of time-history analyses (THA), and a reasonable value is suggested. Collapse simulations of two supertall buildings are used to discuss the suitability of the proposed IM and other existing IMs for supertall buildings.

6.2.2 A Brief Review of the Existing IMs

Published literatures (Tothong and Luco 2007; Cordova et al. 2001; Luco and Cornell 2007; Baker and Cornell 2005; Vamvatsikos and Cornell 2005; Ye et al. 2013) indicate that the existing IMs can be classified into two types: scalar and vector valued. Scalar IMs can be further categorized into single-parameter and multi-parameter IMs according to the number of parameters required.

The traditional peak values of ground motion records such as PGA, PGV, and PGD are typical single-parameter scalar IMs. These IMs are still widely used in many national design codes because of their simplicity (GB50011-2010; Building Centre of Japan 2000).

Some recent literature indicates that PGA or PGV, which only consider the characteristics of ground motions, does not perform well in predicting structural responses within short-to-medium periods. For this reason, the 5 %-damped elastic spectral acceleration $S_a(T_1)$ at fundamental period T_1 (Shome et al. 1998) has been widely used for these periods. $S_a(T_1)$ covers not only the characteristics of the ground motions, but also the dynamic features of the structures. Compared to PGA, the dispersion of the predicted structural responses based on $S_a(T_1)$ is remarkably reduced (Ye et al. 2013), particularly for the first-mode-dominated, moderate period structures. Despite these advancements, $S_a(T_1)$ only deals with the characteristics of the elastic fundamental period of the structure. When progressing into the nonlinear stage, the fundamental period of a structure elongates gradually, leading to changes in the structural dynamic characteristics. Furthermore, for tall buildings, higher-order vibration modes greatly influence the structural responses. All these

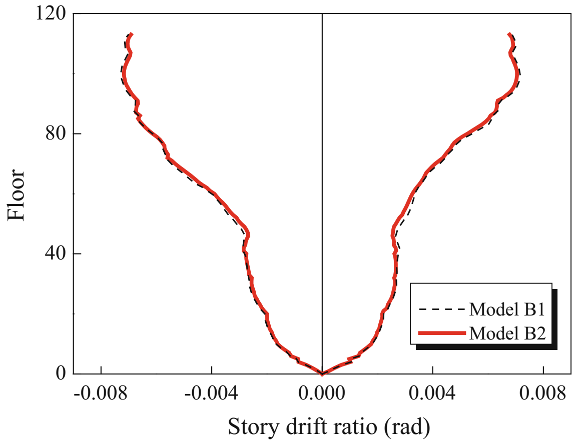

Fig. 6.39 Displacement responses of Models B1 and B2

(JGJ3-2010; GB50011-2010). Not being able to distinguish the advantages and disadvantages between these two designs, further collapse analysis is thus needed to quantify the collapse resistances of Models B1 and B2.

The same seven ground motion records are also used for the collapse analysis, through which the typical collapse modes of Models B1 and B2 are compared in Fig. 6.40. It indicates that the collapse of Model B1 is initiated from the 85th story, which is the story without the brace-embedded shear walls. In contrast, the collapse region of Model B2 is located at the mid-height of the building (i.e., 56th story). It

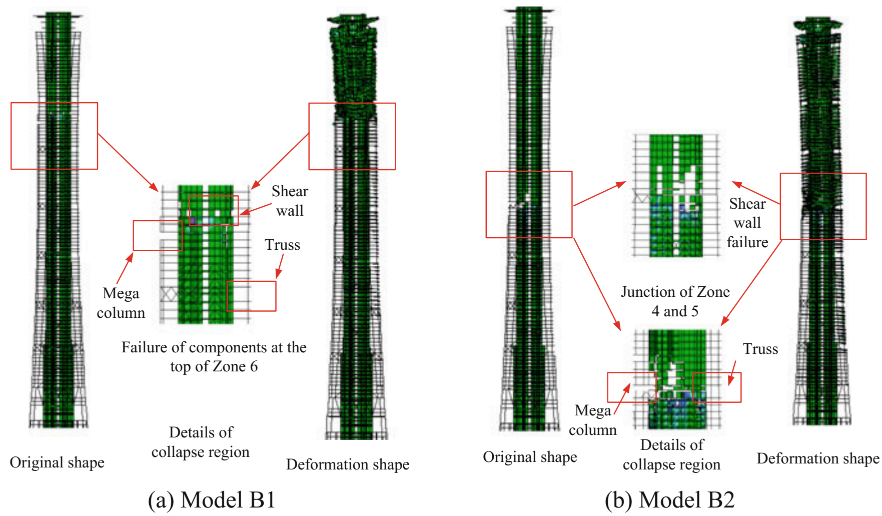

Fig. 6.40 Typical collapse modes of Models B1 and B2 subjected to extreme earthquake

can be concluded that after enhancing the shear walls by embedded braces, Zone 6 is no longer the typically weak region in this building and the global collapse resistance (i.e., CMR) of Model B2 has been increased by 12.7 % comparing to Model B1. Therefore, enhancing the shear walls in 78th and 95th stories by embedded braces is an effective means to increase the collapse resistance of this supertall building. Note that the increased amount of steel due to the embedded braces is less than 0.1 % of total steel consumption, which means that such an enhancement method is very cost-effective. In the final design, brace-embedded shear walls have indeed been used in 78th and 95th stories in the supertall building concerned.

6.5 Summary

The proposed earthquake disaster simulation techniques have been successfully applied to the design of real-world supertall buildings and the development of the design codes or guidelines. In this chapter, several typical applications are discussed, including the IM selections, base shear force adjustments, and optimal designs of supertall buildings. Given limited experiences drawn from the seismic performance of supertall buildings under strong earthquakes, the proposed earthquake disaster simulation techniques are considered as a useful tool for feasible and effective design of this type of structures.

Chapter 7
Comparison of Seismic Design and Performance of Tall Buildings Based on Chinese and US Design Codes

7.1 Introduction

7.1.1 From Performance-Based Design to Resilience-Based Design

The main objective of the conventional seismic design is to prevent human losses during an earthquake. However, the Northridge (1994), Kobe (1995), and Chichi (1999) earthquakes have led to extreme property losses and incurred enormous recovery cost, which is far beyond the acceptable level of the stakeholders (Ghobarah 2001). To reduce the impacts of earthquakes, the performance-based seismic design philosophy has received a lot of interest during the recent two decades.

The performance-based seismic design has many advantages over the conventional seismic design method (Bozorgnia and Bertero 2004). It sets more adaptive objectives, results in less life cycle cost, and is friendly to new structural system and construction materials. Many important documents on performance-based seismic design have been published, including Vision 2000 (SEAOC 1995), ATC 40 (ATC 1996), FEMA 273/274/356 (FEMA 1997a, b, 2000), ASCE 41-06 (ASCE 2006), TBI (PEER 2010), and LATBSDC 2011 (LATBSDC 2011).

With ongoing development of earthquake engineering research and the lessons learnt from recent strong earthquakes, the seismic design concept of "resilience" has drawn increasing attentions worldwide (Mieler et al. 2013, Jacques et al. 2014). The term "resilience" has been used in many disciplines (Chang and Shinozuka 2004; Rose 2004, Decò et al. 2013). "Resilience" was defined in PPD-8 (2011) as "the ability to adapt to changing conditions and withstand and rapidly recover from disruption due to emergencies." This concept was further expanded in PPD-21 (2013) to include "the ability to prepare for and adapt to changing conditions and to withstand and recover rapidly from disruptions." Bruneau et al. (2003) defined the seismic resilience as "the ability of social units (e.g., organizations, communities) to

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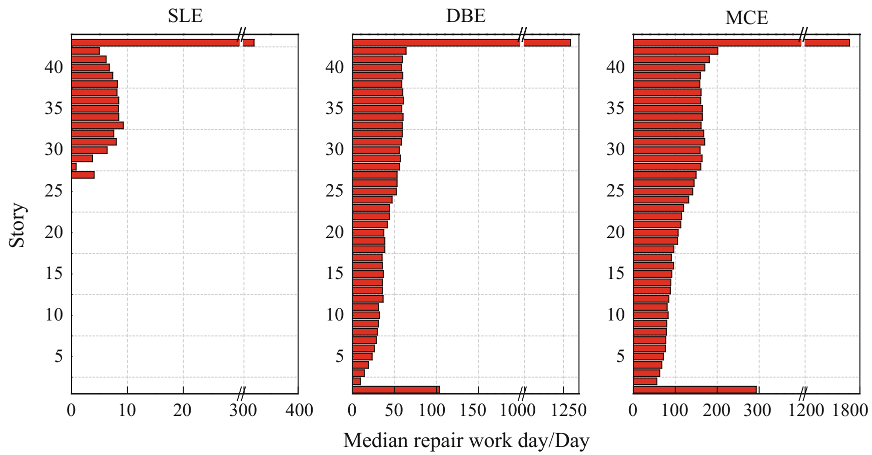
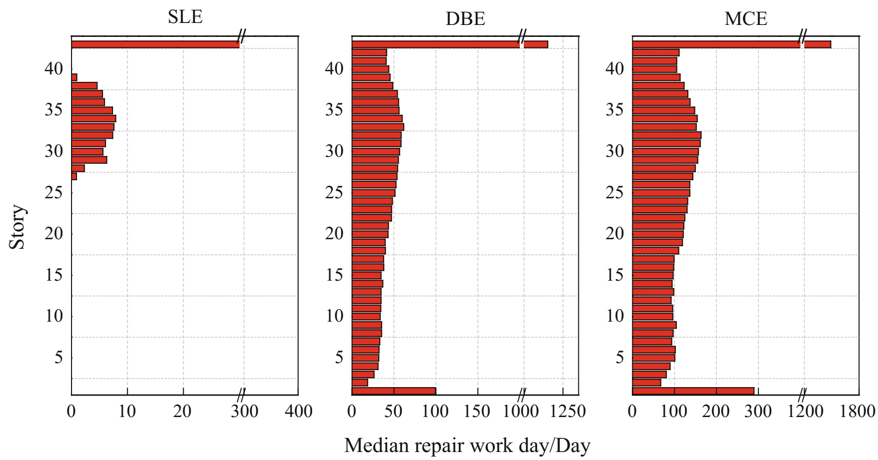
mitigate hazards, contain the effects of disasters when they occur, and carry out recovery activities in ways that minimize social disruption and mitigate the effects of future earthquakes."

Tall buildings, housing a large population and performing complex functionalities, are critical infrastructures of modern cities. After Christchurch was devastated by earthquake in 2011, none of the 51 tallest buildings in the city collapsed owing to the rigorous seismic standards developed in New Zealand. Nonetheless, 37 of these tall buildings had to be demolished due to their severe damage and potentially high costs associated with repair, thereby leading to enormous economic loss and negative social impact (Wikipedia Contributors 2015). In consequence, the seismic design concept of "resilience" for tall buildings has become vitally important for modern scientific community. In this regard, many studies have been conducted in relation to the seismic resilience of buildings and healthcare systems (Cimellaro et al. 2010; Biondini et al. 2015). At the UN World Conference on Disaster Risk Reduction in 2015, the UN Development Program (UNDP) announced a new 10-year global program to support the national efforts in reducing the risks of disasters. The program, named "5–10–50," is expected to provide a strong support to 50 countries and communities over 10 years in delivering better risk-informed development. The "resilient recovery" was also listed as one of the five strategic areas on which the program will focus (UNDP 2015).

To achieve the objective of resilience, the structures are required not only to sustain a state of safety in earthquakes but also to be prepared for post-earthquake recovery to ensure continued operation and functionality immediately thereafter (Almufti and Willford 2013). Therefore, it is important to gather accurate information on the repair costs and repair time of the buildings under earthquakes. In the existing performance-based seismic design, the seismic performance of the structural components is normally considered in detail, but that of the non-structural components is often neglected. Note that earthquake-induced repair costs of non-structural components and contents of modern tall buildings usually account for more than 50 % of the total cost, due to the increasing expenses of these components. For example, during the 1994 Northridge earthquake, non-structural damage accounted for 50 % of the total loss (i.e., approximately $18.5 billion of building damage) (Kircher 2003). For this reason, to better predict the seismic losses of buildings in earthquakes, all structural components and non-structural contents of buildings should be considered. To achieve this, the next-generation performance-based seismic design method (i.e., FEMA P-58 Seismic Performance Assessment of Buildings, Methodology and Implementation) (referred to as "FEMA P-58 method" hereafter) has been proposed by the Federal Emergency Management Agency (FEMA) and the Applied Technology Council (ATC) of the United States (US) (FEMA 2012a, b). An associated software (i.e., Performance Assessment Calculation Tool (PACT)) has also been provided to facilitate the implementation of the FEMA P-58 method. The flowchart of the FEMA P-58 method is shown in Fig. 7.1. Compared with the existing performance-based seismic design method, the FEMA P-58 method directly correlates the structural seismic performance with the seismic loss, repair time, and human casualties, and



(a) Building 2A



(b) Building 2N

Fig. 7.15 Distribution of median repair workdays in Buildings 2A and 2N

stories, whereas Building 2N has a larger median repair workload at the lower stories and more uniform distribution of the repair time along the height. The underlying causes of these phenomena are similar to those at the DBE level.

7.5 Summary

Based on a benchmark study of a RC frame–core-tube tall building, Building 2A, provided by PEER (Moehle et al. 2011), Building 2N is generated through a redesign process according to the Chinese seismic design code. The design procedures of these two buildings and their seismic performances under different earthquake intensities are compared and evaluated in detail. The study indicates that the seismic design forces determined by the Chinese response spectrum are larger than the US counterparts at the same seismic hazard level. In addition, a higher requirement for the inter-story drift ratio is specified by the Chinese code, thereby resulting in larger seismic design forces. These two aspects together have led to a higher level of material consumption for Building 2N than Building 2A. Nonetheless, the global level performance assessment, including the story drift ratio and plastic hinge distribution, indicates that the two designs exhibit approximately similar structural performances under different levels of earthquake intensities. The comparison at the component level indicates that Building 2N has stronger columns and core walls, but weaker beams and coupling beams.

The seismic resilience of the two tall buildings is also systematically quantified and compared using the FEMA P-58 procedure and the associated software PACT. Both Buildings 2A and 2N display sufficient collapse resistance and seismic safety. Building 2N performs slightly better in terms of the failure probabilities. At the three earthquake intensities, the repair costs of Building 2N are smaller than those of Building 2A. Building 2N requires less repair time at the SLE and DBE levels. However, Building 2N necessitates a longer repair time at the MCE level because more structural components of Building 2N are damaged.

Note that at the three earthquake intensities, the repair time and repair costs of the non-structural components, such as the HVAC, partitions, and wall finishes, constitute the majority of the overall time and cost. When no building collapse occurs, the suspended ceilings and elevators may be the main cause of casualties. Thus, more attention must be paid to these non-structural components in the design. Further, more reliable design methods and construction detailing for the non-structural components are highly recommended to improve the seismic resilience of the entire structures.

The analysis results presented in this chapter offer a quantitative comparison of the seismic resilience of the two tall buildings and can be easily understood by the building owners and government authorities. Note that the application of the FEMA P-58 methods discussed in the chapter will be further extended to the seismic performance assessment of regional buildings in Chap. 12 of this monograph.

Chapter 8
Nonlinear MDOF Models for Earthquake Disaster Simulation of Urban Buildings

8.1 Introduction

The lessons learned from the previous earthquakes in the world prove that an accurate prediction of the seismic damage is critical to reduce the earthquake-induced losses. For a modern city associated with metropolitan and urban areas, a devastating earthquake may potentially cause damage to buildings, transportations, and lifelines. Of which, the vast majority of seismic losses are caused by the damage and collapse of building structures. For this reason, an accurate and efficient seismic simulation of buildings becomes an indispensable part of urban seismic prediction research worldwide.

Given the large number of buildings in a city, the seismic simulation of the buildings cannot be implemented through experimental means. Thus, various numerical models have been proposed to simulate the seismic damage to buildings in the recent three decades. These simulation models can be classified into two categories according to the fundamental methodologies being adopted, viz. the data-driven method and the physics-driven method.

The data-driven methods (e.g., the probability matrix method) are used to predict seismic damage based on the statistical data obtained from the previous earthquakes. For cities having suffered a number of destructive earthquakes, the data-driven methods are quite reliable given the actual seismic damage records. On the other hand, for many other cities in the world, particularly those in the eastern or central part of China, no severe earthquake has taken place for more than 40 years. The statistical data of the damaged buildings collected from those earthquakes occurred in the rural or western areas of China cannot be directly transformed for the buildings located in the eastern or central cities.

To overcome the limitations of the data-driven methods, the physics-driven methods for urban building seismic simulation have been proposed and progressed quickly in recent years. Using these methods, the building seismic damage can be simulated through structural analysis of individual buildings [e.g., the capacity

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spectrum method (MAE Center 2006; FEMA 2012c) or the time-history analysis (THA)-based method (Hori 2006; Lu et al. 2014c)]. Directly following the fundamentals of earthquake engineering, the physics-driven methods can better consider the special features of different earthquakes and buildings, which are more adaptive to various applications.

8.1.1 The Probability Matrix Method

As a representative data-driven method, the probability matrix method has been widely used since the twentieth century for urban seismic damage prediction (Onur et al. 2006). A typical example of using this method is documented in the ATC-13 report (Rojahn and Sharpe 1985), in which the damage states of buildings are classified into seven levels (i.e., none, slight, light, moderate, heavy, major, and destroyed). The probabilities of different types of buildings exceeding a damage states when subjected to different intensities of ground motions are statistically calculated and listed in a table, i.e., the probability matrix (e.g., Table 8.1). Thus, once the ground motion intensity of a site is given, the seismic loss of a certain type of buildings can be determined according to the number of buildings on that site and the probabilities of the buildings exceeding different damage states.

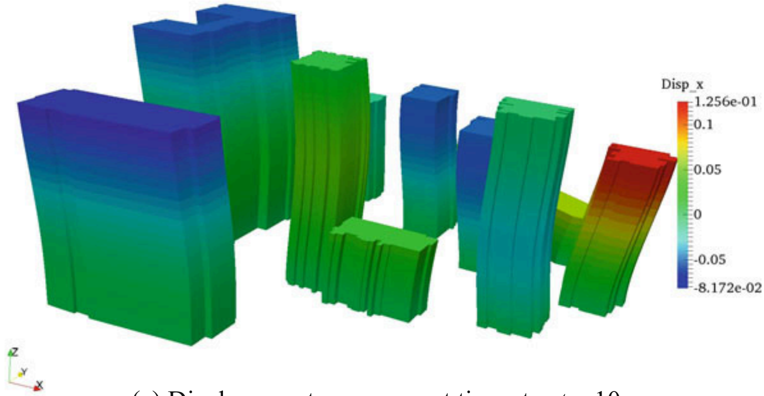
Although the probability matrix method is very convenient to use, it has several limitations: The earthquake hazard is represented by the ground motion intensity, which cannot fully represent the duration time and spectrum features of the ground motions. The seismic damage of buildings is predicted through the statistical data of the previous earthquakes, which does not take into consideration the characteristic features of a particular building or a specific earthquake. The accuracy of this method is also doubtful when it is used in a region without adequate statistical data of damaged buildings.

8.1.2 The Capacity Spectrum Method

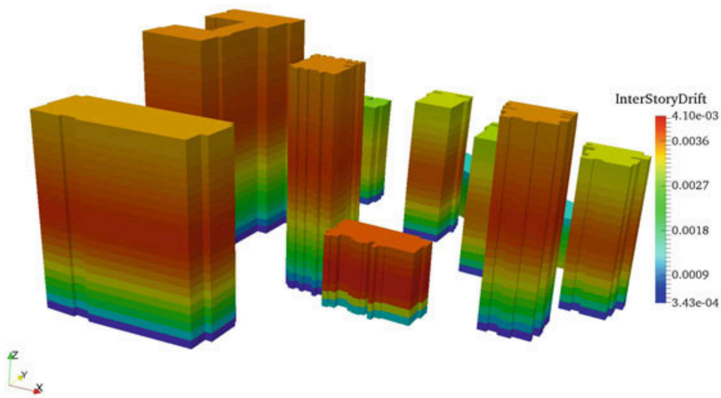
To overcome the limitations of the probability matrix method, the Federal Emergency Management Agency (FEMA) and National Institute of Building

Table 8.1 Damage states and loss ratio given by the ATC-13 report

Damage state	Loss ratio (%)	Medium of loss ratio (%)
1. None	0	0.0
2. Slight	0–1	0.5
3. Light	1–10	5.0
4. Moderate	10–30	20.0
5. Heavy	30–60	45.0
6. Major	60–100	80.0
7. Destroyed	100	100.0



(a) Displacement responses at time step $t = 10$ s



(b) Envelopes of inter-story drift ratios

Fig. 8.30 Seismic response results of buildings in a regional area

8.4 Summary

An accurate prediction of regional building seismic damage is highly valuable for mitigating the potential seismic risks of a modern city. Compared to the existing probability matrix method and capacity spectrum method, the proposed nonlinear MDOF shear model for multi-story buildings and the nonlinear MDOF flexural-shear model for tall buildings are proven to better represent the characteristics of individual buildings. The characteristic features of different ground motions can also be well considered through nonlinear THA. In principle, the simulation method based on the nonlinear MDOF models and THA is considered the most accurate method for seismic damage prediction of regional buildings. The challenging issue of determining the parameters of the nonlinear MDOF models for a large number of buildings is also addressed using a simulated design procedure and the statistics obtained from extensive experimental and analytical results. To this end, the proposed nonlinear MDOF models and relevant methods proposed in this chapter lay a solid foundation for the earthquake disaster simulation of urban areas, to be presented in the following chapters of this monograph. Specifically, Chap. 9 will discuss how to produce a more realistic visualization based on the nonlinear MDOF models; Chap. 10 will discuss the high-performance/low-cost computational platforms for practical implementation of the nonlinear MDOF models; Chap. 11 will demonstrate the application of the nonlinear MDOF models in the earthquake disaster simulation of real cities; and Chap. 12 will use the nonlinear MDOF models to predict the earthquake losses and secondary disasters induced by falling debris.

Chapter 9
Visualization for Earthquake Disaster Simulation of Urban Buildings

9.1 Introduction

A seismic simulation of a single building is often concerned by structural engineering experts. In contrast, the outcomes of seismic simulation of an urban area are often used by the planning, administration, and emergence agencies of a city in addition to the engineering experts. However, many of the non-professional users do not have adequate knowledge on structural dynamics or earthquake engineering. In consequence, a realistic visualization to vividly display the simulation results has become a critical issue for non-professional users.

The simplest approach to generate an urban seismic scenario is by extruding the buildings story-by-story according to their planar layout in a 2D-GIS (geographic information system) platform. Such is referred to as the “2.5D” building model in this work. Despite its simplicity, the 2.5D model makes the planar layout to be identical from the bottom to the top of the building, which cannot fully represent the building façade. To address this problem, the authors of this monograph have proposed a visualization method to generate the urban seismic scenario using the 3D polygon model of a city (e.g., the 3D city model in Google Earth) (Xiong et al. 2015), which will be introduced in Sect. 9.3.

Another challenge of urban seismic simulation is how to simulate the collapse of a large number of buildings. Collapsed buildings can make a great impact on the evacuation and rescue activities. To tackle this issue, a collapse simulation method based on physics engine was proposed by the authors (Xu et al. 2014a) and will be introduced in Sect. 9.4. The method has been proven to greatly improve the computation efficiency of the collapse simulation of urban buildings.

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9.2 2.5D Model for Visualization of Urban Building Seismic Simulation

The nonlinear multiple degree-of-freedom (MDOF) models discussed in Chap. 8 are regarded as structural models. In these models, the stories of each building are simplified as a series of mass points without considering their true three dimensions. As such, these MDOF models are not suitable for visualization purposes. To overcome this limitation, the planar outlines of the buildings in 2D-GIS are vertically extruded story-by-story to generate the 2.5D models of the buildings (Xu et al. 2008). The time-history displacements predicted by the nonlinear MDOF models are then mapped to the corresponding 2.5D model to display the deformations of the building. In addition, the surfaces of the 2.5D models can be covered by textures (Tsai and Lin 2007) to further improve the visualization effect (Fig. 9.1).

The creation and visualization of the 2.5D models are implemented in this work using the open-sourced platform of OSG (OSG Community 2012). The vertices of the building are firstly calculated to generate a vertex array. Then, the exterior walls of the building are created using rectangles covered by textures. Simultaneously, a polygon is generated to model the building roof. Note that OSG is based on OpenGL, and the concave polygons of the roof need to be divided into a group of triangles using the class *osgUtil::Tessellator* of OSG for display purpose (OSG Community 2012).

A 2.5D model of urban buildings is displayed in Fig. 9.2. The displacements and deformations of the buildings are explicitly shown in Fig. 9.3 by attaching the 2.5D model with the nonlinear time-history analysis (THA) results. This visualization approach is very convenient for implementation, thus making it a popular method for practical application.

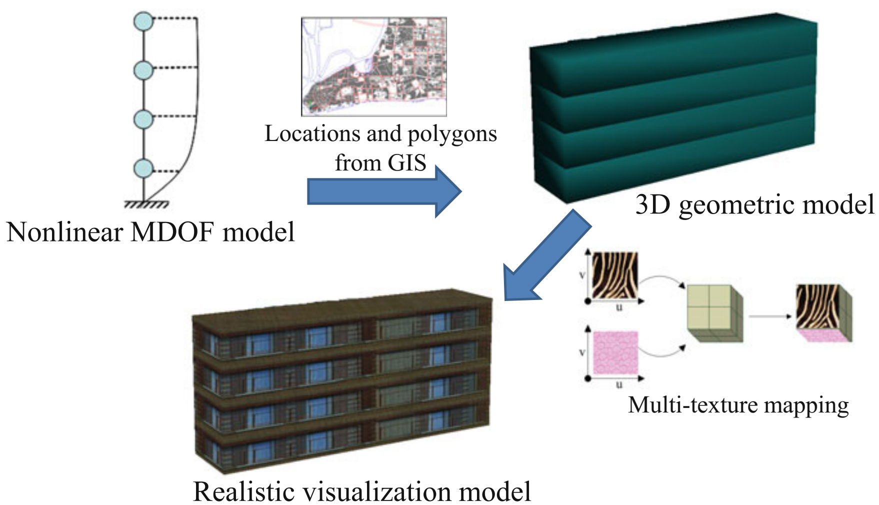

Fig. 9.1 Procedure for creating a 2.5D model of a building

Fig. 9.22 Stereo visualization of seismic damage

in virtual drills on escape and rescue in earthquakes. By using two digital light processing (DLP) projectors and double monitors, a stereo visualization of an earthquake disaster is performed for Shantou City, China, and the terrain and sky are added to the scenario of the earthquake disaster simulation (Fig. 9.22). The stereo visualization of the seismic damage creates a highly immersed and realistic earthquake scenario for emergency drilling.

9.5 Summary

Many non-professional users of earthquake disaster simulation of an urban area lack knowledge of earthquake engineering or structural dynamics. In consequence, a realistic visualization of seismic simulation is critical for these users. In this chapter, three techniques for realistically displaying the simulation outcomes acquired from Chap. 8 are introduced. Among them, the 2.5D model for visualization is the most convenient method to generate a spatial scenario of earthquake disaster. This method can be widely used in many cases, which will be demonstrated in Sects. 11.2, 11.4, and 11.5 through various sizes of urban regions. In contrast, the 3D-GIS model is much more realistic, however, incurs an increased modeling workload. The 3D-GIS model has a particular advantage for the regions with dense tall buildings, whose façades are quite unique from each other. Hence, this model is used for the earthquake disaster simulation of Beijing central business district (CBD) area to be presented in Sect. 11.3. This chapter also presents the collapse simulation of urban buildings performed using the physics engine, which greatly accelerates the simulation of the movement of collapsed stories. Note that the integration of the structural simulation approaches proposed in Chap. 8 and the visualization techniques proposed in this chapter are able to produce a realistic time-history scenario of dynamic responses and seismic damage to different stories of urban buildings at different times, which is much more convenient for non-professional stakeholders to grasp the earthquake-induced building damage in urban areas.

Chapter 10
High-Performance Computing for Earthquake Disaster Simulation of Urban Buildings

10.1 Introduction

Given the large number of buildings in an urban area, the computational efficiency becomes a big challenge for the time-history analysis (THA)-based urban building seismic simulation. Although such computational workload can be implemented on a supercomputer with thousands of CPUs, the incurred high procurement and maintenance costs are undesirable. The proposed high-performance/low-cost computing technologies are presented in this chapter, including a coarse-grained CPU/GPU collaborative parallel computing algorithm to accelerate the computing process of the nonlinear MDOF models (Lu et al. 2014c) and a computational framework using a network of distributed computers to accelerate the computing process of multi-fidelity models (Xu et al. 2016b).

10.2 Coarse-Grained CPU/GPU Collaborative Parallel Computing

10.2.1 Overview

In Chap. 8 of this monograph, the nonlinear multiple degree-of-freedom (MDOF) models and the corresponding parameter determination method are proposed to predict the seismic damage to urban buildings through the nonlinear THA. Despite the efforts made, the seismic simulation being presented has resulted in excessive computational workload. The conventional computational platform therefore cannot satisfy the high-performance/low-cost demand for such a simulation.

As outlined in Chap. 3 of this monograph, general-purpose computation on graphics processing units (GPGPU) has been widely used due to the outstanding parallel and float computing performance of GPU. Thus, a coarse-grained parallel

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approach for urban building seismic simulation based on GPU/CPU cooperative computing has been proposed (Lu et al. 2014c), with relevant details introduced herein.

10.2.2 Computing Program Architecture

It is well recognized that the GPU is efficient in parallel computing and float computing. However, despite these advantages, GPUs may not be flawless for all problems. The performance of a single core and the logic performance of a GPU are relatively weak. Thus, a GPU/CPU cooperative computing is desirable to make full use of the advantages of CPU and GPU, noting that a CPU has a powerful logical computing capacity.

For a parallelizable computing task, the most appropriate architecture of a GPU program should be based on fine-grained parallelism (Che et al. 2008), which means that each subtask is divided into many operations and the implementation of the operations is parallelized. This type of parallelism is widely used in neural networks and finite element (FE) analysis (Hung and Adeli 1994; Mackerle 2003). Carefully tuned algorithms are needed to manage large quantities of fine-grained parallelism on GPU platforms. In contrast, coarse-grained parallelism provides a much easier means to take advantage of GPUs. In coarse-grained parallelism, the parallelization is implemented for subtasks instead of operations. It is also implemented in analysis, optimization, and control (Adeli 2000). The performance of coarse-grained parallelism can be as high as that of fine-grained parallelism when it is implemented for tasks with the following features:

1. The quantity of subtasks is much greater than the number of cores on a GPU.
2. Each subtask has a moderate computing workload and can be individually implemented on a single GPU core.
3. The data exchange between different subtasks is limited, and no global synchronization is required.

Fortunately, urban building seismic simulations have all of these features. Although there are thousands of buildings in an urban area, if each building is treated as a subtask and a proper computing model is adopted, the computing workload of each subtask would be sufficiently small to be performed on a single GPU core. Furthermore, because the interactions between buildings (e.g., pounding) are limited and cannot be tracked at a large scale during an earthquake, the interactive effect can then be disregarded in the simulation for large urban areas, which results in little data exchange between different GPU cores. Note that there are hundreds of cores on a GPU and each GPU core can be used for the simulation of one building. This requires only several task assignment rounds to complete the simulation of a city with thousands of buildings using GPU computing. Thus, the computational efficiency is expected to be very high. Compared to fine-grained

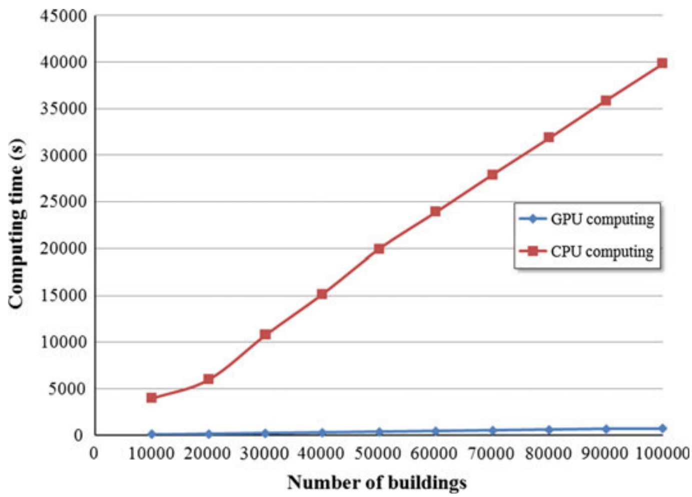

Fig. 10.14 Comparison between the proposed GPU computing and CPU computing

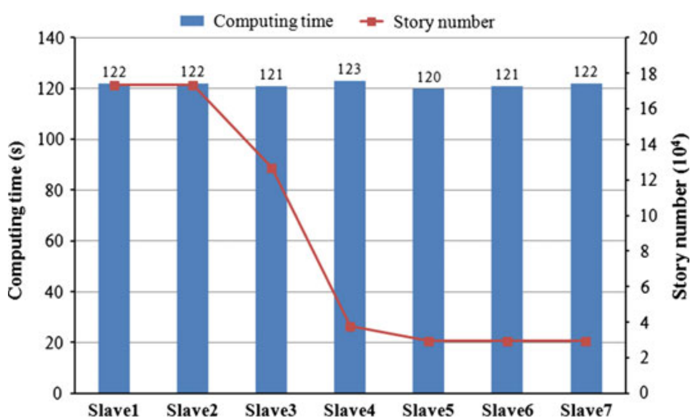

Fig. 10.15 Computing time for each slave in the moderate-fidelity simulation

10.3.4.3 Simulation Results

Using the computational framework as described, it is now possible to simulate the nonlinear THA of hundreds of thousands of building models within reasonable time. For example, a virtual city consisting of 50 important and special buildings and 100,000 regular buildings can be simulated in approximately 48 h. Without distributed computing and GPU computing, even using the most powerful slave computer 1, the total simulation time would have taken over 2500 h. The distributed GPU computing framework expedites the simulation of this case study of a relatively big city by 52 times. If additional hardware is incorporated for the multi-fidelity simulation, the computational time can be further reduced.

10.4 Summary

THAs of a number of nonlinear MDOF models for seismic simulation of urban buildings bring a big challenge to computing platform. Although such computational workload can be implemented on a supercomputer with thousands of CPUs, the incurred high procurement and maintenance costs are undesirable. As an alternative, a high-performance/low-cost computing platform would be quite attractive for wider applications of the proposed seismic simulation techniques. In this regard, the GPU-based computing has been proven to provide an efficient alternative solution comparing to the conventional supercomputers. Specifically, the computational workload of THAs of the nonlinear MDOF models can be shared by a large number of cores on a GPU, which can achieve an impressive speedup ratio with very limited additional cost. A coarse-grained CPU/GPU collaborative parallel computing algorithm is proposed to accelerate the computing process of the nonlinear MDOF models. A speedup ratio of 39 times is achieved with a GPU that is less than US$200.

Subsequently, a multi-fidelity modeling strategy is proposed for buildings in an urban area. It employs the moderate-fidelity nonlinear MDOF models for conventional buildings and the high-fidelity models for functionally important buildings or those with special structural arrangements. The use of the high-fidelity models improves the accuracy of the seismic damage prediction of the important or special buildings. The computational efficiency is further accelerated using a distributed GPU computing framework. The simulation of a relatively large virtual city is found to speed up by 52 times with the proposed computing framework and load balancing strategies. The outcomes presented in this chapter indicate an enhanced feasibility and applicability of the earthquake disaster simulation of urban areas.

Chapter 11
Earthquake Disaster Simulation of Typical Urban Areas

11.1 Introduction

Advanced earthquake disaster simulation techniques for urban buildings have been introduced in Chap. 8, 9, and 10 covering the nonlinear multiple degree-of-freedom (MDOF) computational models, the high-fidelity visualization method, and the high-performance computation approach. In this chapter, these techniques are applied to the earthquake disaster simulation of several typical urban areas of different sizes. Seismic damage simulation of 56 buildings in Longtoushan Town during the 2014 Ludian earthquake, China, is first performed to further validate the accuracy of the proposed techniques. Subsequently, damage simulation of 172 tall buildings in Beijing central business district (CBD) subjected to the Sanhe-Pinggu earthquake scenario is conducted to demonstrate the effectiveness of the multi-fidelity simulation and visualization methods. A medium-sized southern Chinese city with 4255 buildings is also simulated to compare the influence of different ground motions on the extent of seismic damage. Finally, several mega-cities with tens or hundreds of thousands of buildings are simulated to demonstrate the capability and advantage of the proposed techniques.

11.2 Earthquake Disaster Simulation of Ludian Earthquake

Seismic damage to Longtoushan Town during the 2014 Ludian earthquake is simulated using the nonlinear MDOF models and the corresponding parameter determination method proposed in Chap. 8 of this monograph. The numerical prediction is compared to the actual damage to validate the accuracy of the proposed methods.

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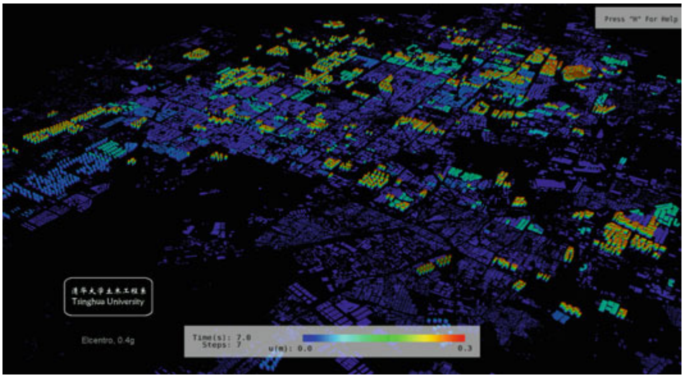
11.2.1 Seismic Damage to Buildings in Longtoushan Town

On August 3, 2014, a M6.5 earthquake struck Ludian County, China. The epicenter of this earthquake is close to Longtoushan Town of Ludian County, which caused severe damage to the buildings in the town. Figure 11.1 is the satellite photograph of the town from Google Earth before the earthquake hit. Figure 11.2 shows the actual damage to the town after the earthquake. The buildings within the solid lines marked in Fig. 11.1 were severely damaged. Fortunately, the ground motion of the main shock was recorded by the accelerograph located at the epicenter. In addition, detailed seismic damage and attribute data of the buildings in Longtoushan Town was also collected by the reconnaissance teams (Lin et al. 2015). Such useful data enable the seismic simulation of these buildings, so as to further validate the nonlinear MDOF building models.

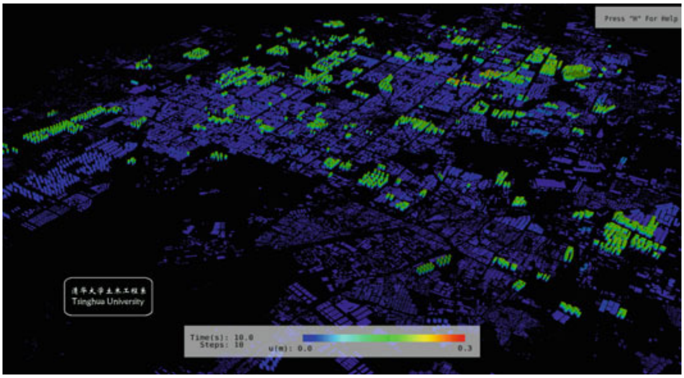
Most of the buildings in Longtoushan Town are unreinforced masonry (URM) structures. Some public buildings, such as schools, hospitals, and the city hall, are engineered structures. Due to the strong ground motion at the epicenter, a large number of engineered buildings also totally or partially collapsed, as shown in Fig. 11.3 (Lu et al. 2014d; Lin et al. 2015).

Necessary attribute data and damage information of 56 buildings were collected from the post-earthquake field investigation of Longtoushan Town. Seismic damage to the buildings in the town is studied to validate the proposed method for seismic simulation of regional buildings. Both the conventional damage probability matrix method and the nonlinear MDOF models are used for the validation.

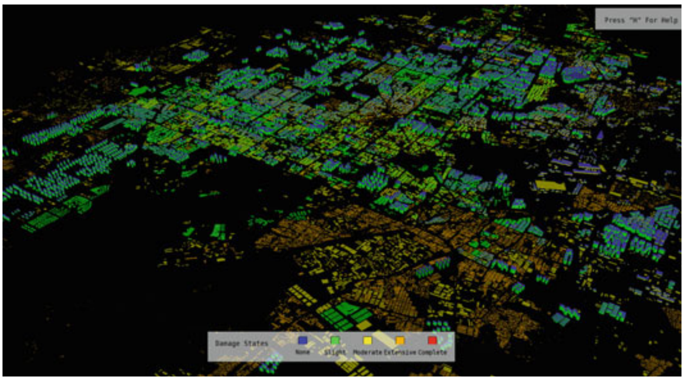
Fig. 11.1 Satellite photograph of Longtoushan Town from Google Earth before earthquake



(a) Building seismic response (displacement) $t = 7.0$ s



(b) Building seismic response (displacement) $t = 10.0$ s



(c) Building seismic damage states

Fig. 11.36 Urban building seismic simulation of Tangshan City (230,000 buildings)

11.6 Summary

This chapter presents the application of the nonlinear MDOF computational model, the high-fidelity visualization approach, and the high-performance computation method for urban building seismic simulation proposed in Chaps. 8, 9, and 10, respectively. Several typical urban areas with different sizes, covering from 56 to 230,000 buildings, are studied. Specifically, the accuracy of the proposed nonlinear MDOF computational model is validated through the seismic damage simulation of Longtoushan Town. The visualization effect of the multi-fidelity model is demonstrated through the seismic simulation of Beijing CBD subjected to a specific earthquake scenario. Finally, the capability and advantage of the proposed computational techniques in predicting the seismic damage to a large number of buildings are demonstrated through several examples of real-world mega-cities. The outcome of the study presented in this chapter will provide important references to disaster prevention and mitigation activities to be undertaken by modern cities. Furthermore, the predicted seismic damage and dynamic responses of the urban buildings will establish a solid foundation for conducting the earthquake loss and secondary disaster simulation to be presented in Chap. 12.

Chapter 12
Earthquake Loss Prediction for Typical Urban Areas

12.1 Introduction

Seismic damage to urban buildings can be simulated more rationally and accurately using the nonlinear multiple degree-of-freedom (MDOF) models and the high performance computing method introduced in Chaps. 8–11. Such simulations established a solid foundation for regional earthquake loss predictions. A regional earthquake loss prediction based on the new-generation performance-based design method has been proposed by Zeng et al. (2016) and will be introduced in Sect. 12.2. A secondary disaster simulation of falling debris and corresponding emergence shelter planning have also been conducted by Xu et al. (2016a) and will be introduced in Sect. 12.3. Outcomes of this work are expected to provide a useful reference for future development of sound earthquake mitigation strategies for urban areas.

12.2 Earthquake Loss Prediction for Urban Areas Based on FEMA P-58 Method

12.2.1 Overview

Earthquake is one of the most destructive natural disasters, especially when it strikes an urban area with dense population and high volume of buildings and other civil infrastructures. Seismic resistance of building structures has been significantly enhanced over the last three decades, due to the continuous advancement in earthquake engineering research. As a consequence, earthquake-induced building collapses and casualties on new constructions can be effectively controlled. Despite these advancements, the economic loss due to earthquake still remains very high. For instance, after the devastating 1960 M9.5 Valdivia earthquake, a strict building

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code was implemented in Chile (Guha-Sapir et al. 2011). As a result, during the 2010 M8.8 Maule earthquake in Chile, only four buildings constructed after 1985 collapsed (MAE Center 2010). However, this earthquake still caused a direct economic loss of US$ 30.9 billion[1] which represented 24.2 % of the global economic damage from all natural disasters in 2010 (US$ 127.8 billion) (Guha-Sapir et al. 2011). The economic loss could be even higher if the earthquake strikes other highly urbanized regions, as it has occurred in the 2011 M9.0 Tohoku earthquake which caused US$ 210 billion direct loss (Ponserre et al. 2012). Hence, it is crucial to develop a robust earthquake loss prediction model for urban areas, where the outcomes can be used by the relevant stakeholders to make informed risk management decisions.

HAZUS (FEMA 1999, 2012c) is one of the most widely used methods for regional earthquake loss prediction (e.g., Peterson and Small 2012; Remo and Pinter 2012; Chen et al. 2013). HAZUS calculates the building response using the capacity spectrum method (Kircher et al. 2006), in which buildings are treated as a single degree-of-freedom (SDOF) system when subjected to a pushover load. As a result, there exist three major limitations when using HAZUS to predict regional earthquake losses: (1) Because the SDOF model used within HAZUS cannot accurately differentiate the response at different stories and the financial loss may vary significantly at different stories, the economic loss cannot be accurately predicted using the HAZUS method; (2) as stated in the FEMA-445 report, the non-structural components in the HAZUS method are rather general (FEMA 2006). Financial losses from the non-structural components cannot be well characterized using the HAZUS method; and (3) the influence of the ground motion characteristics (e.g., near-field velocity pulses) on the building damage and economic loss cannot be easily considered using the capacity spectrum method (Lu et al. 2014c).

Since 2002, the Federal Emergency Management Agency (FEMA) funded a 10-year project to define the objective and procedure of the next-generation performance-based seismic design which eventually became the FEMA P-58 Report: "Seismic Performance Assessment of Buildings, Methodology and Implementation" (referred to as "the FEMA P-58 method" hereafter) (FEMA 2012a, b). This report provides a solution to the abovementioned limitations of the HAZUS method. The fragility of every structural and non-structural component in a building is directly considered in the FEMA P-58 method during the seismic assessment. Since its development, the FEMA P-58 method has been successfully applied to the seismic performance assessment of many individual buildings (Yang et al. 2012; Shoraka et al. 2013; Yang and Murphy 2015; Yang et al. 2015; Shome et al. 2015). The authors of this monograph have also used the FEMA P-58 method to compare the seismic performances of typical tall buildings in China and in the USA (Chap. 7). The Global Earthquake Model (GEM) vulnerability assessment

[1]In this work, the economic losses of different years are adjusted to 2011 US$ considering inflation. The adjustment factors are calculated according to the Consumer Price Index (CPI) statistics provided by the US Department of Labor Bureau of Labor Statistics or by referring to Coin News (2015). The adjustment factor from 2010 to 2011 is 1.03.

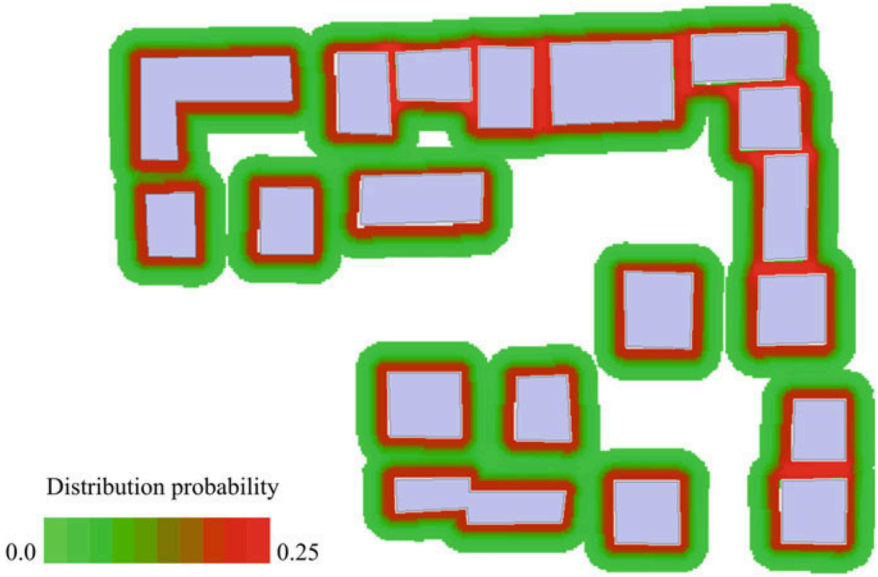

Fig. 12.17 Distribution probabilities of falling objects in the selected community area

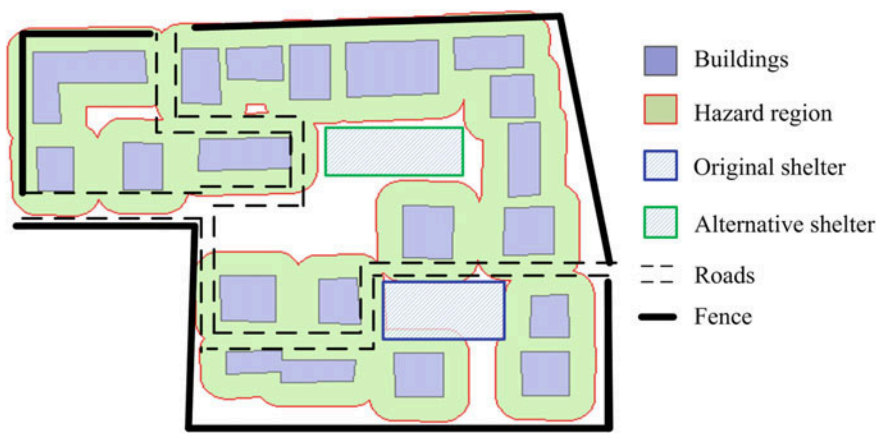

Fig. 12.18 Hazard regions of falling objects and site location for emergency shelter

nonlinear MDOF model. The distribution probabilities of the falling objects during the design life of a building are calculated via IDAs and a seismic hazard analysis. A residential community area is selected as a case study to evaluate the distribution probabilities of the falling objects, which in turn helps to select a suitable and safer site for an emergency shelter construction. Additional applications of the proposed simulation method, such as the selection of the excavation paths, will be conducted in the future. This study is expected to provide a useful reference for further development of efficient emergency and disaster management strategies.

12.4 Summary

This chapter demonstrates some typical applications of earthquake disaster simulation for urban areas, including the regional seismic loss prediction and the secondary disaster simulation of falling debris. The proposed regional building seismic simulation using the previously developed nonlinear MDOF models and THA is proven to provide more accurate and detailed dynamic responses of a large number of buildings (e.g., time history of displacement and velocity on each story of each building) in an urban area. The development of the novel simulation methods presented in this chapter helps to address the many restraints that limit the advancement of the disaster prevention and mitigation strategies for urban areas. It is worth noting that with continued progress in earthquake engineering research, the extent of collapse-induced building collapses and casualties will be further reduced. However, big challenges still remain as how to prevent enormous earthquake-induced property losses and personal injuries and deaths, due to various secondary hazards of earthquakes. The outcomes achieved in this chapter will provide useful references for future research in related areas.

Chapter 13
Conclusions

13.1 Major Achievements and Contributions

This monograph systematically introduced the technologies developed by the authors for earthquake disaster simulation of tall buildings and urban areas, with particular emphasize on collapse prevention and mitigation in extreme earthquakes, earthquake loss evaluation, and seismic resilience.

Chapters 2–7 present the earthquake disaster simulation techniques for tall buildings, including the proposed high-fidelity computational models and simplified models of tall buildings, high-performance GPU-based matrix solvers, physics engine-based high-performance visualization, and some typical engineering applications. Seismic safety and resilience of supertall buildings are new challenges to the earthquake engineering community. Therefore, many critical yet unknown problems are encountered by researchers and professional engineers, particularly on their seismic performances, collapse modes, and the corresponding design strategies. The high-fidelity computational model proposed in this work using fiber-beam elements and multilayer shell elements provides an efficient and reliable approach to discover the possible collapse modes and potential weak portions of the supertall buildings. This approach has also been successfully used in the design of some real-world supertall buildings (e.g., the Z15 Tower). The outcomes of the collapse simulation helped to save tens of thousands of tons of concrete and steel, while achieving a better seismic performance and safety of the supertall buildings. It is worth mentioning that such a high-fidelity computational model is the only feasible option to date for collapse simulation of supertall buildings that are higher than 500 m. In addition, the simplified models proposed are able to identify the nonlinear performance of supertall buildings subjected to different levels of earthquake hazards with remarkably reduced computational workload. Furthermore, the seismic performance and resilience of typical tall buildings designed using the Chinese and US design codes are evaluated and compared. All these developments and

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simulation outcomes are expected to provide important references for seismic design of tall buildings and future updating of relevant seismic design codes.

Chapters 8–12 describe the earthquake disaster simulation of urban areas, following many of the outcomes presented in the former chapters of this monograph (e.g., the simplified models of tall buildings, GPU-based high-performance computing, and resilience assessment method). A novel solution for earthquake disaster simulation of urban areas, using the proposed nonlinear multiple degree-of-freedom (MDOF) model and time-history analysis (THA), is systematically proposed, covering the nonlinear MDOF building models, parameter determination method, high-performance computing, and realistic visualization. The proposed earthquake disaster simulation technique delivers several unique advantages: Firstly, it can fully represent the characteristic features of individual buildings and ground motions. In consequence, it is more suitable for urban regions having many newly constructed buildings but with limited historic earthquake experience. Secondly, it can realistically display the earthquake scenarios, particularly the dynamic shaking of buildings subjected to an earthquake. Therefore, it is widely welcomed by the government and/or administration departments whose professional knowledge of earthquake engineering is lacking. Thirdly, the entire dynamic response on each story of every building can be predicted at any time period, which provides a solid foundation for the prediction of economic loss and secondary disasters of earthquakes. Given these advantages, the proposed earthquake disaster simulation technique has been successfully implemented in the seismic performance assessments and earthquake loss predictions of several central cities of China. The outcomes of the simulation as well as the feedback from the end users are encouraging, which confirms a promising application future of the proposed simulation technique.

13.2 A Future Perspective

Reitherman (2012) pointed out that there are three grant challenges in earthquake engineering: “risk, inelasticity, and dynamics.” Powered by the latest computational technology, some novel solutions for earthquake disaster simulation of tall buildings and urban areas targeting these three challenges have been proposed. Note that the real-world problems are far more complicated than those discussed in this work. Therefore, much more in-depth studies into the problems faced by the scientific community are necessary to be conducted. To this end, recommendations for future research directions are given below:

1. Uncertainty

In addition to the uncertainty of ground motions that has been discussed in this work through incremental dynamic analysis (IDA) using sufficient ground motion records, uncertainties in the design, analysis, and construction of the buildings (including but not limited to the uncertainties in the design information, computational model, and corresponding parameter values) can also influence the prediction outcomes (FEMA 2009; Ellingwood and Kinali 2009). Therefore, uncertainties in the earthquake disaster simulation of tall buildings and urban areas need to be systematically and thoroughly explored.

2. Soil-structure interaction, city-site interaction, and building-to-building interaction

The influence of the soil-structure interaction (SSI) on the seismic performance of a supertall building has been discussed in Sect. 4.2.4. However, the actual SSI behavior is far more complicated, especially when nonlinearity of soil is considered. The input ground motions adopted in this work are mostly generated or recorded from free fields, which may differ substantially from the actual ground motions in a dense city (i.e., city-site interaction) (Guidotti et al. 2012). In addition, neighborhood buildings may impact each other during an earthquake (i.e., building-to-building interaction), which may induce further damage. All these interaction behaviors require more attention for advanced earthquake disaster simulation.

3. Fire following earthquake and other secondary disasters

In addition to the direct damage of earthquakes, earthquake may also induce many secondary disasters. Fire following earthquake is one of the most severe secondary disasters of an earthquake for an urban area, which may incur an even greater loss than the earthquake itself (Lee et al. 2008). The earthquake scenario simulated in this work confirms the workability of the simulation of secondary disasters (e.g., simulating the falling debris as in Sect. 12.3). Further studies are required to develop a comprehensive earthquake disaster simulation methodology, taking into account various secondary disasters.

4. Virtual reality, augmented reality, and cloud computing

The visualization work presented in Chap. 9 can be further enhanced through virtual reality and augmented reality. The proposed high-fidelity models of visualization have established a solid foundation for the inclusion of virtual reality and augmented reality technologies into the scenario simulation of earthquake disasters. In addition, distributed computing technologies introduced in Sect. 10.3 can be further extended to cloud computing to make full use of the flexible capability of cloud computing platforms (Lu et al. 2015a). Note that the infrastructure as a service (IaaS) feature of cloud computing is particularly suited for earthquake disaster simulation: huge computational demand (due to a large number of buildings need to be simulated in a restricted time window) but occasional usage (due to low frequency of occurrence of strong earthquakes).

5. Bridges, lifelines, and other civil infrastructure

This study focuses on the earthquake disaster simulation of building structures. Many other civil infrastructure systems, such as bridges, electric, and water lifelines, are also critical for maintaining the functionality of a city. The simulation technologies proposed in this work provides useful information to guide future development of an integrated earthquake disaster simulation system for buildings and civil infrastructures.

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