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REAL-TIME PHYSICS-BASED REGIONAL EARTHQUAKE DISASTER SIMULATION USING STRUCTURAL MONITORING DATA

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Abstract

Cities, particularly in the high-speed urbanization regions, have become more and more vulnerable to earthquakes due to their high concentration of people and wealth, ageing or densely-located buildings, overloaded infrastructures, and poor quality of materials. These cities, especially in the earthquake-prone zones, are at very high risk of severe earthquake disasters. What is worse, limited experience and knowledge have been accumulated on how the rapidly developing cities will behave subjected to the potential devastating earthquakes. Despite of limited historical damage data, physics-based simulation can be made full use of to study the seismic responses of the city and minimize the risk of the earthquake disaster. In this study, a new version of a simulation tool, called YouSimulator, is presented to achieve the real-time physics-based regional earthquake disaster simulation. The real-time ground motions from the accelerometers of the structural health monitoring system are used for computing. The numerical simulation system is developed based on a C++ code, which includes four basic modules: (a) the automatic modeling module; (b) the online response computing module; (c) the results analyses module; and (d) the 3-D visualization module. The real-time ground motion data is stored on the cloud, and will be sent to the simulation system automatically when the amplitude of the ground motion reach a given warning value. Driven by the received ground motion data, nonlinear time-history analyses for each of the buildings in the region are started. Typically, the simulation system is able to present the following products within 30 seconds: (1) a figure to present the damage state of each building; (2) a video to show the damage evolution of the region during the earthquake; and (3) a text file to list the damage data for each of the buildings as well as the global damage data of the entire region. The immediate post-earthquake damage evaluation of the affected area has a great potential to provide essential information support on the decision-making for the emergency responses and regional disaster mitigation. Finally, the application of the proposed simulation system to part of a city is exhibited.

Keywords: Regional earthquake disaster simulation; Real-time; Physics-based; Monitoring data; Rapid evaluation

1. Introduction

Urban areas are vulnerable to earthquake disasters due to high and unplanned concentration of people, aging and overloaded buildings and infrastructures. City is such a sophisticated and dynamic system that each city has unique seismic behavior. A small accident may cause serious problems which affect the effective operation of a city. Besides, the lessons learned from one city may not work well for other cities. Present knowledge is usually not sufficient to understand and deal with the potential threatening from the future severe earthquakes. Particularly in China, two thirds of the cities, which have over one million people, are located in the earthquake-prone areas with a seismic intensity degree of 7 or above. Due to the continuous rapid urbanization in the past forty years, the major cities have undergone tremendous changes and become very large and complex. Work has to be done to prepare for the potential devastating earthquakes.

Although it is impossible to test the seismic performance of the cities by physical tests, the physics-based numerical simulation methods can be made full use of to explore the weakness of the city and provide a quick damage evaluation for the emergency rescue. Recently, as the advancement of new technologies, such as the high-performance computing, Geographic Information System (GIS), big data and artificial intelligence (AI), various numerical tools for the city-level detailed earthquake disaster simulations have been developed. A lot of research efforts have been made for the continuous improvement of the simulation methods. Goto et al. [1] developed an earthquake disaster simulation systems based on GIS by integrating the models of the ground responses, building collapse, road blockage and fire spread. Hori et al. [2] proposed the integrated earthquake simulation (IES) based on the full computation of the earthquake hazards and disasters. Sahin et al. [3] built a Turkey version of IES, which was built on the MATLAB environment. Lu et al. [4] presented a solution for earthquake disaster simulation of urban areas using nonlinear multiple degree-of-freedom (MDOF) model and time-history analysis. The authors [5] developed a simulation platform (called YouSimulator) to model, assess and visualize the earthquake disasters in city level, and the nonlinear time history responses of about one million buildings can be achieved within 10 minutes by scalable parallel computing.

Recently, a new version of the city-scale simulation platform YouSimulator has been developed by combining the techniques of structural health monitoring and online high-performance regional simulation. One of the main objective is to realize real-time earthquake disaster monitoring and dynamic risk evaluation for a region by the health monitoring system of a single building. In this study, the framework and workflow of the updated YouSimulator with the online computing module is introduced. An application of the real-time physics-based regional earthquake disaster simulation using structural monitoring data is presented.

2. Current version of simulation platform YouSimulator

The real-time physics-based regional earthquake disaster simulation is carried out based on the simulation platform called YouSimulator, which was originally developed to model, assess and visualize the seismic behavior of the cities based on the automatic physics-based nonlinear modeling and modern scalable simulation techniques. The platform was made primarily by C++ code, which helps make the program portable for different computer operation systems.

The previous version of YouSimulator is Version 1.0, which was developed in 2016 primarily for the automatic modeling and nonlinear time history analyses of a large area of buildings subjected to earthquakes. As introduced in Ref. [5], the platform has four basic modules, the automatic modeling module, the response computing module, results analyses module and the 3-D visualization module. Fig. 1 shows the basic modules and workflow of the newest version (V2.0), which is able to perform real-time regional simulation based on the structural health monitoring data. Fig. 2 shows the details of the automatic modeling and time history analyses.

The polygon data and the corresponding property data of buildings, which are stored in the GIS, are used as the input of the automatic modeling. The information on the plan view, floor area and location of the building can be obtained from the polygon data. The minimum property data required for the simulation includes the building height (or the number of stories) and type of structure. Other property data, such as the built year and type of usage, can be optional but better to be available. The seismic fortification intensity and site information, which are used to design the buildings, were obtained directly from the seismic design code.

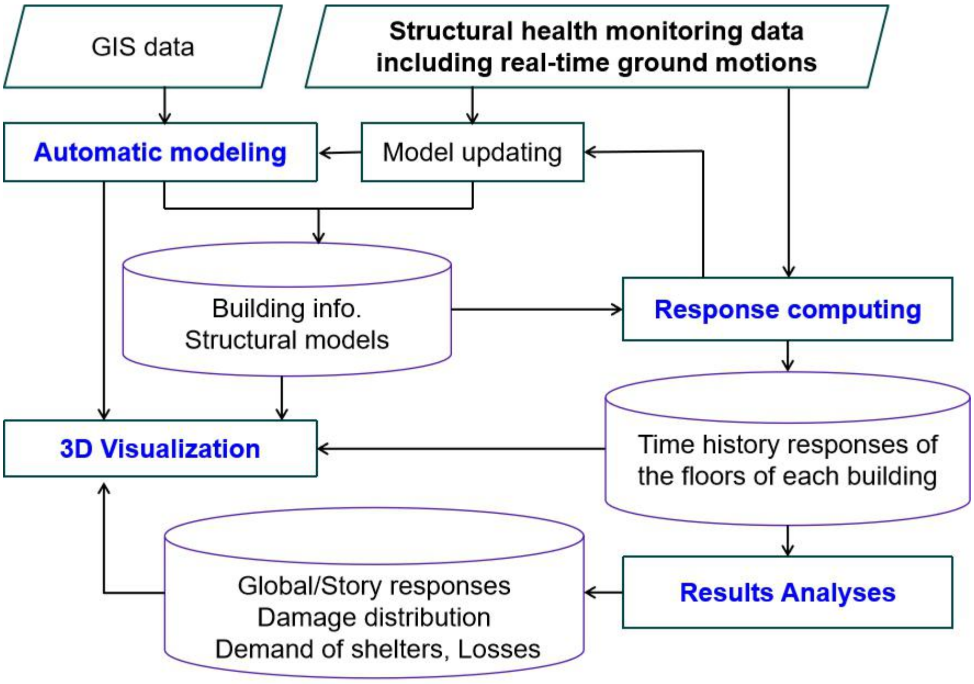

Fig. 1 – Basic modules of the updated YouSimulator V2.0

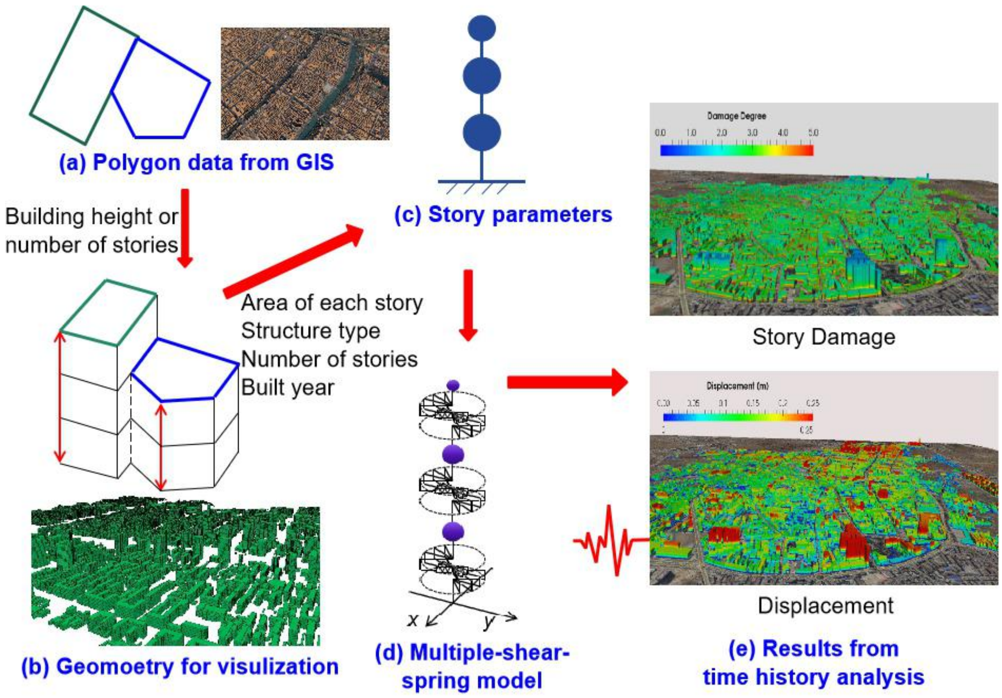

Fig. 2 – Automatic modeling and time history analysis

The three-dimensional geometry information of a building (see Fig. 2(b)) is formed from the data of one or multiple polygons (Fig. 2(a)) through the topological relations operations. An algorithm is designed to determine the mass and the shear force-drift relationship curve of each story. Typically, the tri-linear skeleton curve is used for the relationship curve.

Multiple shear spring (MSS) models [6, 7] were adopted as the default model for the nonlinear time history analyses of the buildings, as shown in Fig. 2(d). The MSS model can capture the building behavior subjected to two directional shear deformation. The skeleton curve of each spring is determined by the story shear force-drift relationship curve. The modeling from the polygon data to the nonlinear computing models is implemented by the code automatically.

The responses computing module perform the nonlinear seismic responses of a large number of buildings. Scalable parallel computing is designed based on the message passing interface (MPI). The results analyses module is designed to provide further data processing based on the computed results of the time history analyses. The time history responses of a million buildings can be computed within 10 minutes. Indices related with the structural responses, damage, economic loss, risk of casualties, the damage of the nonstructural components, risk of the road blockage and resilience, are integrated in the results analyses module and can be visualized in the visualization module.

Particularly, in this study, the structural health monitoring data are used as the input of the real-time regional simulation in the following two ways. First, the floor acceleration data can be simply used to obtain the fundamental frequency of the monitored building. The measured frequency can be used to update the model of the correspondent building. Second, the acceleration waves recorded at the ground floor or free site can be used as the input ground motions of the simulation. The recorded ground motions are applied to the entire regions or community around the monitored structure.

3. Real-time regional disaster simulation based on structural monitoring data

The real-time regional earthquake disaster simulation was realized by introducing the cloud-based health monitoring system, as shown in Fig. 3. YouSimulator platform is set online or in a client computer with internet access. The simulation platform checks the real-time monitoring data in every 5 seconds, which is just the default value of the program and can be modified. As long as the recorded ground acceleration reaches a certain threshold, the data will be sent to YouSimulator by the cloud-based heath monitoring system, and the regional earthquake disaster simulation will be initiated. The computing is usually accomplished in seconds.

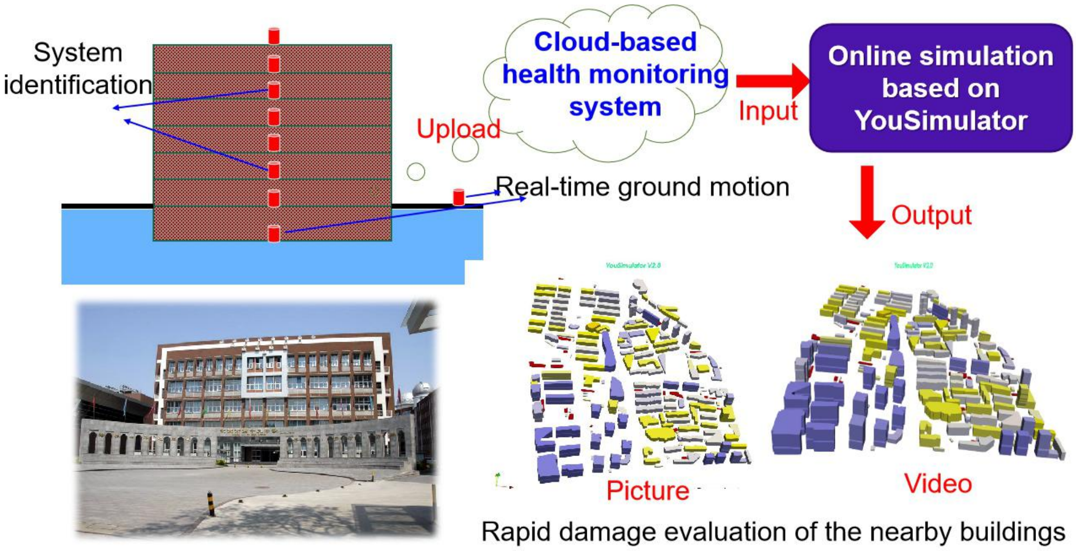

Fig. 3 – The real-time regional earthquake disaster simulation

Typically, the simulation system is able to present the following products within 30 seconds after the initiation of the computing: (1) a figure to present the damage states of all building in the designated region; (2) a video to show the damage evolution of the region during the earthquake; and (3) a text file to list the damage data for each of the buildings. The picture and video are generated by calling the python commands of the open-source scientific visualization toolkit ParaView.

As one of the application examples, the proposed real-time simulation platform was deployed to a six-story teaching building of a middle school, as shown in Fig.3. Three-dimensional accelerometers were arranged to each of the floors (including the basement) as well as the ground of the free site outside the building. The real-time data from the sensors located at the basement and free site are selected as the input ground motions of the online regional simulation. 216 Buildings in the region near the school buildings were modeled in advance by using the automatic modeling module. A Magnitude-4.5 earthquake occurred in Tangshan at 8:02 AM, December 5, 2019. Its epicenter was about 150 km away from the monitored school building. Although the magnitude of the earthquake was small. The ground accelerations were recorded by the monitor system. The PGA of the recorded ground motion was about 1.2 cm/s^2. The damage states of all the buildings are obtained shown in Fig. 5. Most buildings were damage free (indicated by grey or green colors). Only two buildings which were modeled as unreinforced poor-quality masonry buildings present minor damage (indicated by the blue color). The simulated results on the region were obtained immediately (within 30 seconds) after obtaining the real-time data by the local earthquake administration agency, which helped estimate the damage of the region before more information is available.

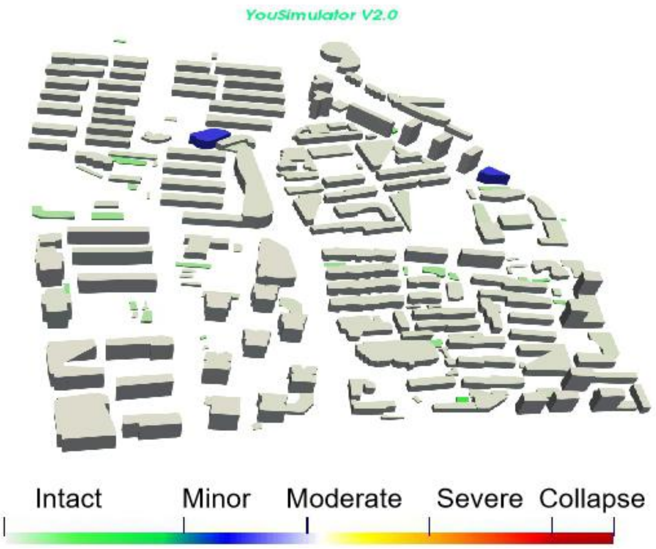

Fig. 4 – Damage distribution of buildings in the monitored region

4. Conclusions

The new version of the simulation platform called YouSimulator is developed to achieve the real-time physics-based regional earthquake disaster simulation based on the structural health monitoring data.

The platform could automatically construct the nonlinear models of the buildings from GIS data, and the time history responses of a million buildings can be computed within 10 minutes. With this tool, the earthquake disaster monitoring and dynamic risk evaluation for a region can be achieved based on the health monitoring system of a single building. The real-time regional simulation was successfully deployed to make the online regional earthquake disaster estimation of an downtown area based on the cloud-based health monitoring system of a school building. The simulation platform was confirmed to work smoothly in an real earthquake, and could help estimate the damage of the region and make decisions before more information is available.

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