A FRAMEWORK ON SEISMIC DESIGN OF STRUCTURES: ROBUST STRUCTURAL DESIGN AND LOSS ESTIMATION

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ABSTRACT

The study presents a framework on seismic resistant design issue for the structures, including the seismic design and seismic performance evaluation of structures. In the seismic design, a robust design method is proposed. The design method aims to enlarge the structural collapse resistant capacity by using a new lateral load pattern, while keeps the initial construction cost unchanged as compared to the current seismic design codes. Although the seismic design method can improve the structural performance significantly, the structure may still damage by the unpredictable large earthquake excitation due to the uncertainties inherent in earthquakes. Therefore, after the robust design, seismic performance evaluation on the designed structure needs to be conducted, which contains economic loss induced by structure damage and casualty. The casualty is predicted in a quantitative way by coupling the numerical simulation on the structural collapse and cellular automata based occupant evacuation simulation. The presented framework overcome the shortages of the strength-based seismic design methods used in most current seismic design codes, because of the robust design method fully uses the material performances and deformation verification is automatically satisfied; in addition, the economic loss verification is considered.

Keywords: framework; robust seismic design; collapse resistant capacity; loss estimation

1. INTRODUCTION

In order to grantee the structural safety, the seismic design of a structure with high-confidence intervals has become a major aim to the engineers. Past earthquakes reveal that the collapse of structures is the key reason leading to the seismic economic loss. Although it is a well-accepted idea that the collapse of structures in earthquakes normally occurs to old buildings whose designs are based on obsolete seismic codes, case observations from past and recent earthquake events reveal that sometimes collapses take place even for the structures were designed in accordance with contemporary design principles (Osteraas and Krawinkler 1988; Ger et al. 1993; Zhang and Jin 2008). The reason of this kind of unexpected structural collapse can be due to several aspects, e.g., the uncertainties of the ground shakings (Takewaki 2015), special ground motions with larger damage potentials (Ni et al. 2013; Raghunandan and Liel 2013; Wen et al. 2014; Ruiz-García et al. 2014), and deficiencies in our knowledge regarding the collapse resistant design. Therefore, the structural collapse resistant design is an ongoing topic and very important to the engineering community.

The paper discusses a series of research aspects relevant to the structural collapse resistant design. These research aspects are integrated into a framework that includes the structural response analysis, the seismic design, and the economic loss estimation. The design method in the presented framework tries to overcome the shortages of the seismic design methods used in most current seismic design codes, which are strength-based methods.

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2. FRAMEWORK ON SEISMIC DESIGN OF STRUCTURES

2.1 Overview of the framework

The framework shown in Figure 1 is given from a research viewpoint and also can be used in the practical structural design procedures. At the first, the designers need to understand the performance of the structure, which is a basis of the design and verification (i.e., evaluation procedure). The main work in this part is development of the methods for seismic response analyses. Numerical tools and experiments support the development of the analysis methods. The design method is used for initial structural design. Although the design method also belongs to the strength-based design methodology, it aims to let the structure having increasing collapse-resistant capacity. After the initial seismic design, evaluation procedure is performed to verify the initial design, the economic loss considered includes the structural itself and the casualty. The economic loss induced by the downtime is not considered. The evaluation is then feedback on the initial seismic design. In the following sections, the detail studies of each part by the authors are summarized.

![Figure 1. The framework of the seismic design of structures](image)

2.2 Analysis method: Numerical tool and Experiment

Nowadays, considering the wide possibility to use software and power computational tools, it is possible to use accurate models to perform dynamic analyses. The structural response analyses can be implemented by several commonly used software, such as OpenSees (2016) and Abaqus (2015). The numerical tools are expected to have the functions for analysis of all type of civil structures, such as steel, reinforced concrete (RC), and masonry. The steel structures are recognized that easy to simulate than the RC structures and can be performed by most finite element software. Simulation of nonlinear responses of RC beam-column members under seismic loads is a very fundamental requirement for design and safety assessment of RC frames during earthquake. High calculation accuracy can be obtained in calculating the responses of RC beam-column members by using fiber beam-column model, based on the uniaxial material constitutive model, which is within the functions of the two above software. However, for 3D structural models, the concrete model in Abaqus can not be used for the beam-column elements. In addition, the explicit analysis function is more easily to use in the Abaqus than OpenSees in some analyses having convergence problems.

In order to simulate the nonlinear behavior of reinforced concrete (RC) frame structure, we presented an explicit algorithm-based and an implicit algorithm-based fiber beam-column element model, respectively (Li and Liu, 2016). For each model, the corresponding concrete and steel material subroutines are developed and implemented into the explicit and implicit modules of ABAQUS software by means of user-defined subroutine interface VUMAT and UMAT, respectively. The steel stress-strain
behavior is described by the nonlinear model of Menegotto and Pinto (1973), as modified by Fillippou et al. (1983) to include isotropic strain hardening. The concrete uniaxial constitutive model adopted by the paper is the Scott-Kent-Park model, which adopts the Kent-Park model (1971) and modified by the Scott et al. (1982) with the cyclic unloading and reloading behavior in compression follow the rules proposed by Yassin (1994). The hysteretic performance of RC columns under cyclic loading is numerically simulated and compared with experiment results (see Figure 2). The results show that the two kinds of fiber beam-column element models can accurately simulate the hysteretic performance of RC columns under axial and horizontal loads. The numerical convergence of explicit algorithm-based model is better. The established model can meet the demand of analyzing the elastic-plastic response of RC frame structures. A shaking table experiment was also conducted and verified by dynamic analysis results (Li et al., 2016, 2017).

Figure 2. The results of the experimental (RC columns under cyclic loading, carried out by Ohno and Nishioka, 1984) and numerical with VUMAT and UMAT (Li and Liu, 2016)

Another problem is the masonry structures, which is not easy to be well simulated by the commonly used software, both due to the lack of proper material model and the convergence problem. We presented a solution method that with development of a masonry material constitutive model in Abaqus by VUMAT. For the normal stress and strain, the skeleton curve of the masonry material is based on Liu’s experiment (Liu, 2005) and hysteretic rule is followed by Crisafulli (1997). For the shear stress and strain, material constitutive model follows the study by Karapitta et al. (2011). Figure 3 shows the comparison results of the numerical results with the two reinforced masonry experiments (W1 and W3 specimens) conducted in the study by Li (2011). Explicit analysis method gives better convergence in analysis of the masonry structures.
Horizontal force (kN) Displacement (mm)

(c) Experimental result of W1 (Li, 2011)  (d) Numerical result of W1

Horizontal force (kN) Displacement (mm)

(e) Experimental result of W3 (Li, 2011)  (f) Numerical result of W3

Figure 3. The results of the experimental and numerical with VUMAT

2.3 Design method: A Robust design

Most of the current code-specific seismic design methods are strength-based method. The distribution of the equivalent static seismic lateral forces used in current structural design codes are derived by the structural elastic vibration modes. Such force pattern may be not consistent to the real condition when the structure behaves into inelastic range or even into the collapse stage. In order to solve this problem, a new design method using optimum lateral force pattern for multi-story buildings is proposed based on the concept of uniform damage distribution at the collapse state of these buildings (Yu, 2016). To reduce the computation cost in statistical analyses for deriving the optimum lateral force pattern, the non-linear story behaviors are represented by the story shear-deformation model. The collapse resistant capacities of the structures designed by the proposed methods can significantly improve the seismic performance of the structure under the same construction cost. Figure 4 shows an example that the design method applied on a 4-story frame structure, which shows that the improved design enhances the structural capacity.
2.4 Evaluation method: Casualty

The economic loss can be due to the damage of structures, the downtime, and the occupant casualty. Here, the evaluation on loss induced by the downtime is not considered. The evaluation on loss induced by the damage of structures was studied by many researchers, hence it can refer to many other studies. However, up to now, there are not enough studies on the evaluation on loss induced by occupant casualty. The occupant casualty loss is one of the main parts of the economic loss caused by earthquake loadings, and it is commonly a demand in implementation of performance-based earthquake engineering methodology. It is obvious that the occupant evacuation behaviors will affect the occupant casualty number in earthquakes. Generally speaking, the building-specific casualty prediction method needs to be developed and the consideration of occupant evacuation process in a building is a foreseeable way to achieve a more accurate and quantitative prediction on occupant casualties in the building under earthquakes.

We predict the occupant casualty by considering the occupant movements. The cellular automata model is adopted to simulate the occupant movements in the building. The behaviors of directional moving to exits, directional moving with crowds, and the competitive phenomenon to a position are included in the model. Evacuation processes at different regions of the building containing room, corridor and staircase are considered and effects of model parameters, competition, exit width, and occupant density are studied. The building collapse under earthquake hazards is simulated by explicit finite element method. The occupant casualties in an earthquake are evaluated by coupling the building collapse simulation and evacuation process simulation with time and space synchronization. The casualty occurrence criterion is presented using relative displacement between two adjacent floor slabs. Abruptly appeared obstacles are considered in the evacuation process simulation to reflect the blocked effect of above failed floor slabs. Comparing with exiting methods, the presented method can provide estimations on occupant evacuation process and occupant casualties in a more quantitative way. Details of the present method was given in study by Li et al. (2015).

Figure 5 shows an example that the casualty is predicted in a collapsed 3-story frame building (school building) under a ground motion excitation. This school building is collapse under the ground motion. After the casualty number has been predicted, the economic loss induced by the casualty can be calculated with the value determination studies of the occupant in assurance industry. Such studies present the data for equivalent money of casualty. Therefore, the economic loss induced by the casualty can be calculated as the casualty number multiplies the equivalent money of the casualty.
3. CONCLUSIONS

This paper presents a framework on seismic resistant design of structures. Generally, the numerical analysis tools are the basic problem that to be developed. OpenSees and Abaqus are software that are easily used, full functionality, and easy further development. A robust design method is proposed. The design method aims to enlarge the structural collapse resistant capacity by using a new lateral load pattern, while keeps the initial construction cost unchanged as compared to the current seismic design codes. The casualty is predicted in a quantitative way by coupling the numerical simulation on the structural collapse and cellular automata based occupant evacuation simulation.

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5. REFERENCES


