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Simulation models of concrete structures for multi-disaster mitigation

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ABSTRACT: Engineering structures could be destroyed by various disaster loads, such as earthquake, fire, blast et al. In concrete structures, frames, shear walls and slabs are major structural elements, and therefore accurate simulation for the nonlinear behavior of them in various disasters is the key problem for the researches on disaster resistance of concrete structures. The Department of Civil Engineering in Tsinghua University developed a micro-plane material model, a fiber beam model and a multi-layer-shell model for the ultimate analysis of concrete structures. These models could accurately simulate the nonlinear failure process of concrete structures in earthquake, fire, blast, progressive collapse and so on. And with the high efficiency of these models, they can be used in the whole process simulation of real large-scale complicated RC structures under various disasters. This paper presents the principles of the models and their typical applications in researches and practices.

1 INTRODUCTION

Building structure may experience different kinds of disasters during its whole life period. Accurate prediction of the response of structures subjected to various disasters, especially the collapse process and the collapse mechanism, is receiving more and more attentions for the safety of the people and properties in the buildings.

Due to the difficulties of full-scale experimental research on collapse, numerical simulation becomes a major research tool to study the collapse problem, in which the numerical model will be critical for the simulated results. Therefore, the Department of Civil Engineering in Tsinghua University developed a series of material and structural models to provide a more efficient and accurate simulation for reinforced concrete (RC) structures subjected to dynamic or high-temperature loads, including a micro-plane material model, a multi-layer-shell and a fiber-beam model. This paper briefly introduces these models and their applications in disaster simulation through several research or application examples, such as the progressive collapse of frame structures, blast damage of frame structure and shear-wall structure, fire resistance of frame structures and seismic design of real building.

2 MATERIAL AND STRUCTURAL MODELS

Micro damage of material (movement of yield surfaces or opening of cracks) continuously accumulates due to the action of disaster loads, which results in macro damage of structural elements and even the collapse of the whole building. In order to simulate such process, the macroscopic mechanical behavior of structural elements should be directly connected with the material constitutive law. Following this principle, a concrete constitutive model (micro-plane model) and two structural models (multi-layer-shell and fiber beam) are developed to simulate the ultimate behavior of concrete structures under complicated loading conditions.

2.1 *Concrete micro-plane model*

In the micro-plane model (Bazant & Prat 1988), a set of interfacial planes between the aggregate and cement-mortar in concrete are referred as the “micro-planes”. Nonlinear stress-strain relationships are developed based on these micro-planes. And the macroscopic stress and strain tensors are formulated via the integration of all micro-planes. Although the micro-plane model has more computational workload than common elasto-plastic constitutive model, it can model the complicated nonlinear triaxial behavior as well as the behavior subjected to cyclic load. Figure 1 shows the comparison between the test and the predictions for uniaxial cyclic behavior of concrete with micro-plane model and the material models in the commercial finite element (FE) software (von Mises Plasticity, Drucker-Prager plasticity and Buyukozturk Concrete in MSC. MARC (MSC 2005) and Concrete smeared cracking and Concrete damaged plasticity in ABAQUS (HKS 2005)). More comparison and discussion can be found in Miao *et al.* (2008).

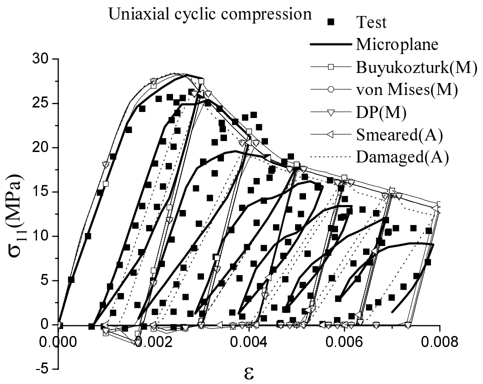
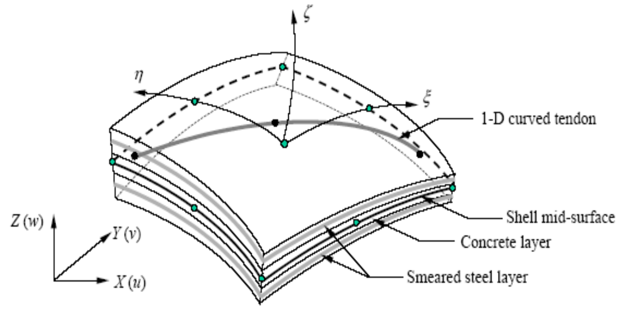


Figure 1. Simulations for uniaxial cyclic behavior of concrete.

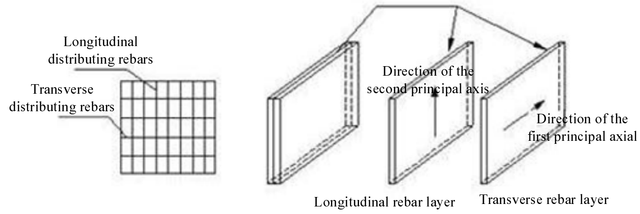
2.2 *Multi-layer-shell model for reinforced concrete (RC) shear wall*

RC shear wall is the major lateral-resistant structural member in high-rise buildings. As the cross section of shear wall is bigger than that of the slender beam or column, its nonlinear behavior under the lateral load is more complicated. The proposed multi-layer-shell model is based on the principles of composite material mechanics and it can simulate the coupled in-plane/out-plane flexural behavior and the coupled in-plane axial-flexural-shear behaviors of RC shear walls. The shell element is made up of many layers with different thickness. And different material properties (concrete or steel) are assigned to various layers (Fig. 2). During the finite element computation, with “plane section remains plane assumption”, the strains of concrete or steel in different layers can be obtained from the strains and curvatures of the shell mid-surface. Then the stresses of different layers can be obtained from the material constitutive law (for example, the micro-plane model of concrete mentioned above). By integrating the stresses in different layers, the internal force of the shell element can be obtained. Therefore, this element can directly connect the constitutive law of concrete or steel with the nonlinear behavior (forces or bending moments) of shear wall, so it has obvious advantages on the simulation of shear wall subjected to complicated load conditions. A typical computational result of the multi-layer-shell model is shown in Figure 3, which agrees well with the test results (Miao *et al.* 2008).

In the fire disaster, the mechanism of RC slabs in high temperature tends to be the membrane tension mechanism rather than the flexural mechanism in normal temperature, which greatly influences the fire resistance of structural system. Therefore, base on the normal multi-layer-shell model, a coupled thermal-mechanical multi-layer-shell model is also developed to accurately simulate the behavior of RC structural system in fire (Chen *et al.* 2008). In order to consider the non-uniform temperature distribution across the shell section, an additional temperature degree of freedom is assigned to element nodes and



(a) Multi-layer-shell element



(b) Rebar layers

Figure 2. Multi-layer-shell model.

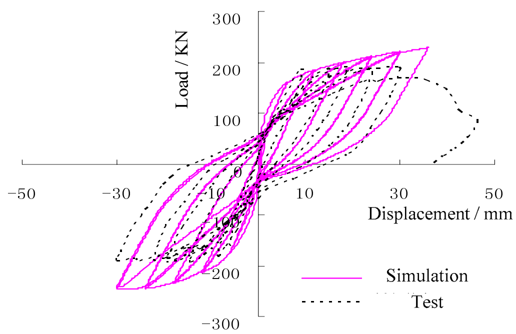
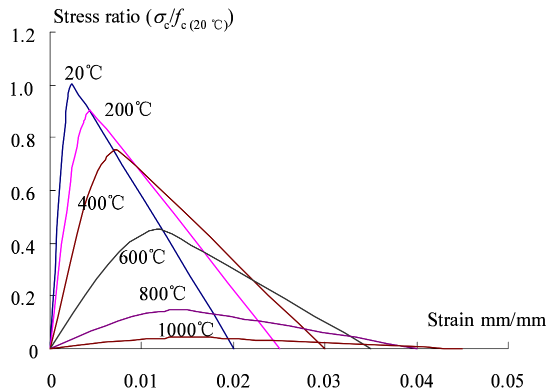
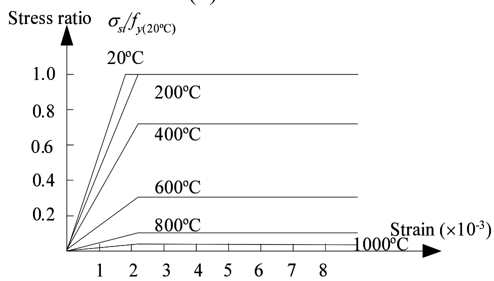


Figure 3. A shear wall under reversed cyclic loading: multi-layer-shell model vs. test.



(a) Concrete



(b) Steel

Figure 4. Material constitutive laws under high-temperature.

the heat conduction equilibrium equation is set up. The heat transfer boundary conditions such as thermal convection and radiation are simplified to improve the efficiency of the model according to the characters of temperature field in the RC slabs. The constitutive laws of materials under different temperature are introduced (Fig. 4). And the explicit tangential stiffness matrix is deduced with Total Lagrangian Formulation, so the model can be used for large deformation analysis of concrete slabs in fire disaster simulation. The model proposed in this paper is validated by comparing with the experimental results (Linus 2004) as shown in Figure 5 and Figure 6.

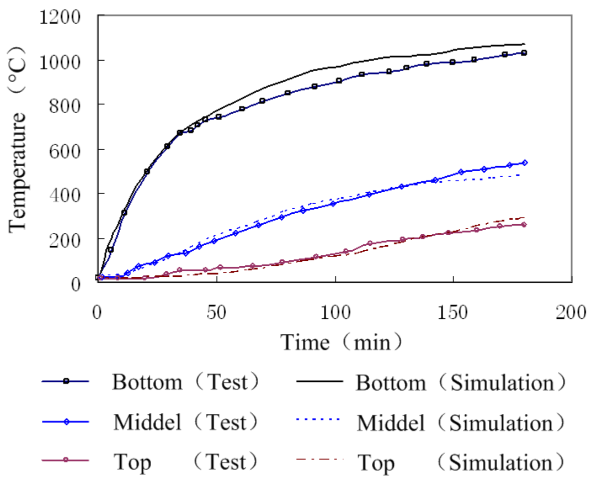


Figure 5. Temperature distribution along the cross-section of a RC slab in fire: multi-layer-shell model vs. test.

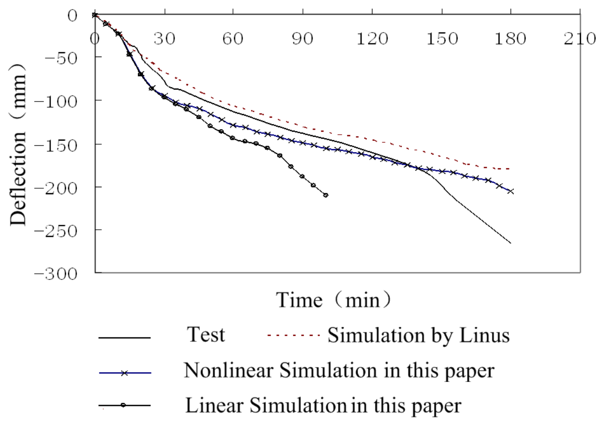


Figure 6. Deflection of a RC slab in fire: multi-layer-shell model vs. test.

2.3 *Fiber-beam model for RC frames*

Columns and beams are also major elements in structures. A fiber-beam model referred as THUFIBER is developed to simulate the RC columns and beams under disaster loadings (Ye *et al.* 2006). In the THUFIBER program, the cross section of each RC member is divided into a number of concrete and steel fibers. Users can define the position, area and constitutive model of each fiber. The program calculates the strain of each fiber by plane-section-assumption. The concrete constitutive law in THUFIBER can consider the confinement of stirrups and the cyclic behavior including degradation of stiffness and strength (Fig. 7). The steel constitutive law can consider the Bauschinger, the hardening and the softening effect (Fig. 8). For the elements with large slenderness ratio, the fiber model can accurately consider the interaction between the bending moment and the axial force. Figure 9 shows the simulated results by THUFIBER for the collapse test of a planar RC frame (Yi *et al.* 2008). Figure 10 shows the simulated results by THUFIBER for a RC column under cyclic loading. Both of them are in good agreement with the test results.

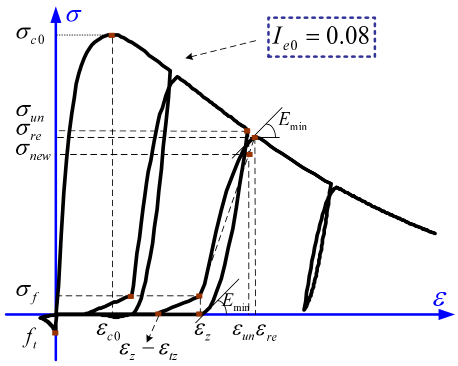


Figure 7. Stress-strain constitutive law of concrete in fiber-beam model.

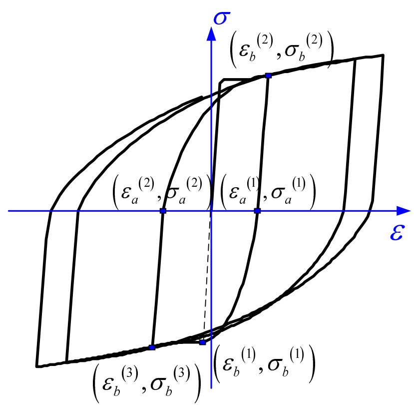


Figure 8. Stress-strain constitutive law of steel in fiber-beam model.

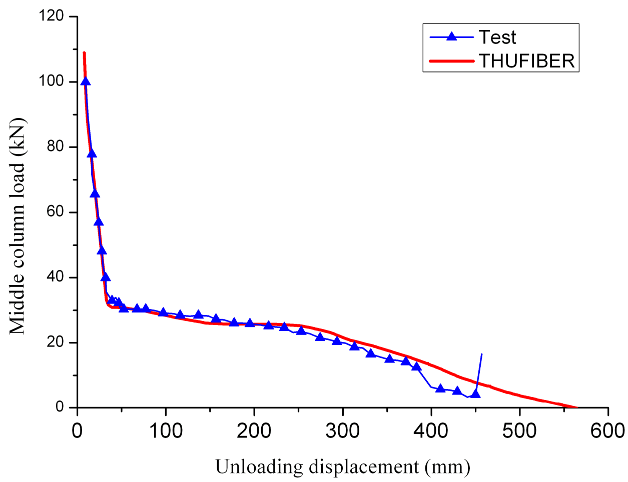


Figure 9. Collapse process of a RC frame: THUFIBER vs. test.

The fiber model can also be applied for coupled thermal-mechanical analysis with the same method used in multi-layer-shell model mentioned above. So it can also be applied in fire disaster simulation. Figure 11 and Figure 12 (Chen *et al.* 2009) show the heat transfer and coupled thermal-mechanical simulation of the fiber-beam model [6]. The predicted results agree well with the test results (Lie & Irwin 1993).

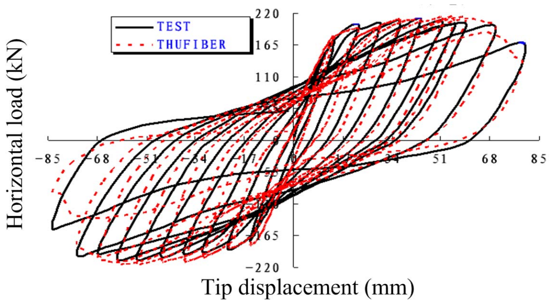


Figure 10. RC column under reversed cyclic loading: THUFIBER vs. test.

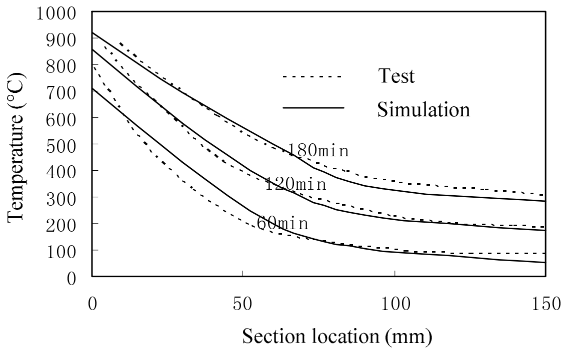


Figure 11. Temperature distribution along the cross-section of a RC column in fire: fiber-beam model vs. test.

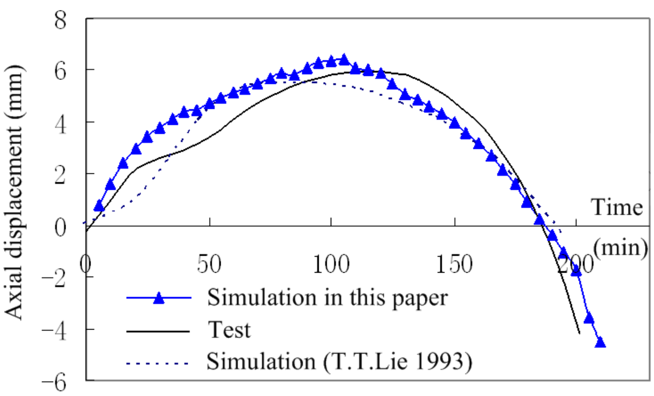


Figure 12. Axial displacement of a RC column in fire: fiber-beam model vs. test.

3 APPLICATIONS

3.1 *Progressive collapse of RC frames*

Progressive collapse is a kind of situation that a local damage to the building caused by an incident leads to a disproportional collapse of the whole building. However, there is no detailed design specification in China to resist progressive collapse. Typical Chinese RC frames are built up with THUFIBER to study their progressive collapse resistances, and corresponding collapse prevention design methods are proposed (Lu *et al.* 2008a). Figure 13 and Figure 14 show the nonlinear dynamic responses of a typical RC frame with and without proposed collapse prevention design method, respectively.

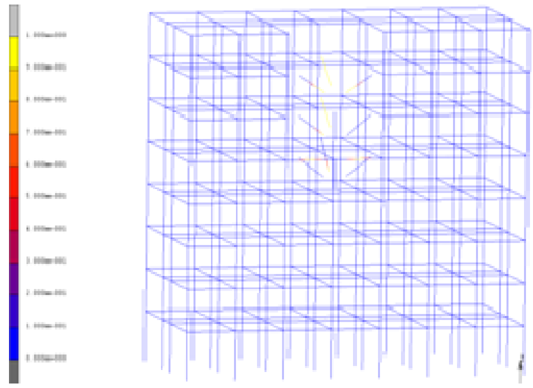


Figure 13. Progressive collapse of original frame.

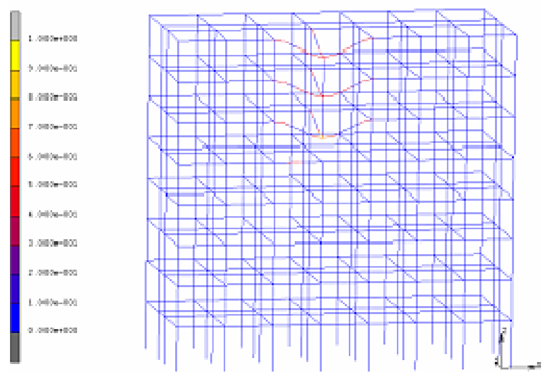


Figure 14. Frame avoids progressive collapse after designed with proposed progressive collapse prevention method.

3.2 *Building structure subjected to strong blast shock waves*

The basement of high-rise building in China should follow the civil air defense requirement. The horizontal load and the overturning moment that are transferred from the superstructure subjected to blast shock wave may damage the basement. When the blast loading exceed the limitation of the design code, the computer simulation should be introduced to predict the damage of structures. The fiber-beam model and the multi-layer-shell model mentioned above are used to study the collapse of the superstructure and the overturning of the basement. The collapse modes of frame building and shear wall building are obtained, as shown in Figure 15 and Figure 16. And the failure of basement due to the overturning moment from superstructure is show in Figure 17.

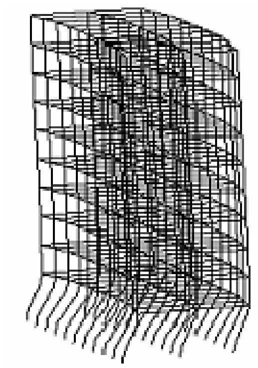


Figure 15. Collapse mode of frame subjected to blast shock wave.

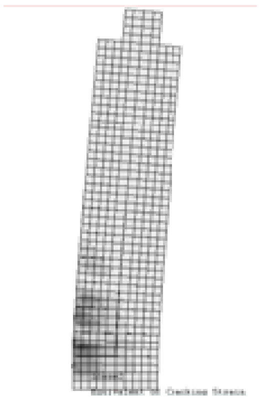


Figure 16. Collapse mode of shear wall structure subjected to blast shock wave.

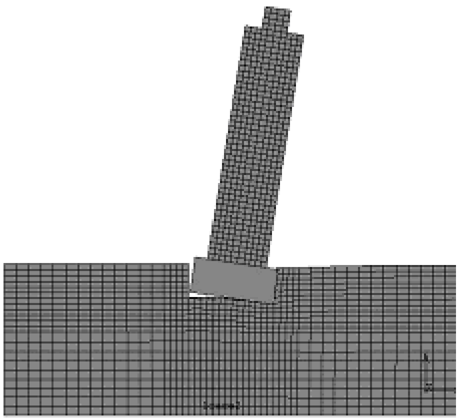


Figure 17. Failure of basement due to the overturning moment from superstructure.

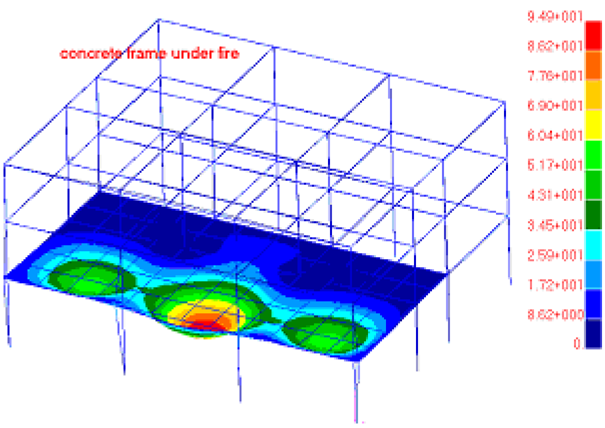


Figure 18. Fire response of RC frame with floor slabs.

3.3 *Fire resistance of whole building*

Numerical simulation is the most convenient way on the fire researches of whole building. Based on the fiber-beam model and multi-layer-shell model mentioned above that can consider the coupled thermal-mechanical interaction, a RC frame model with floor slabs is built up (Fig. 18). And the effect of slabs on fire resistance is studied as shown in Figure 19 and Figure 20.

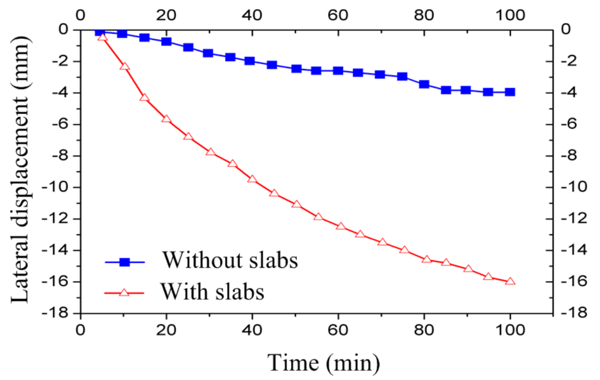


Figure 19. Comparison for lateral displacement of column in models with and without slabs.

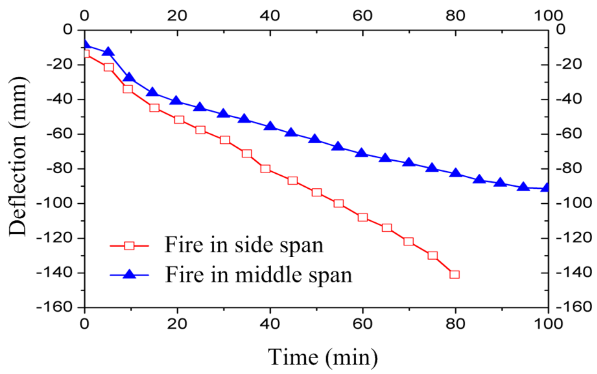


Figure 20. Comparison for deflection of slab exposed to fire in different locations.

3.4 *Seismic design of real structures*

The models proposed in this paper can also be applied for engineering design. For example, a museum (as shown in Fig. 21) with a frame-shear wall structure has an unsymmetrical plane layout, and contains various structural elements including steel trusses, normal rebar reinforced concrete beams/columns/shear wall and shaped steel reinforced concrete beam/columns. The pushover analysis and dynamic elastic-plastic time history analysis for the structure is implemented to check its seismic resistance, as shown in Figure 22. The complicated joint of the building is specially evaluated by using a microscope model (Fig. 23), and the safety of the joint is check by comparing the strength of the joint from the microscope model and the load from the global model, as shown and Figure 24.

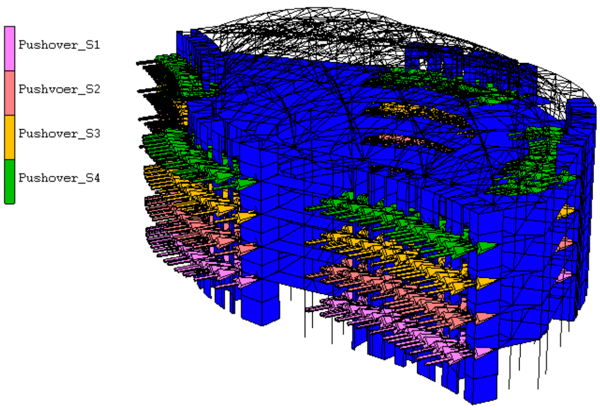


Figure 21. Computing model of the whole structure of the museum.

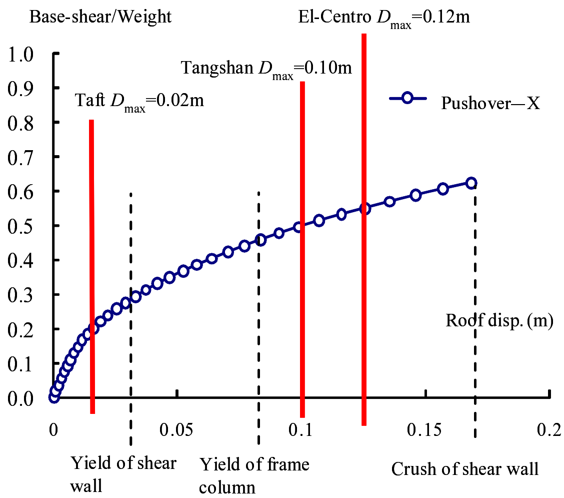


Figure 22. Comparison of roof displacement: pushover analysis and the time-history analyses (El-Centro, Taft and Tangshan ground motion records).

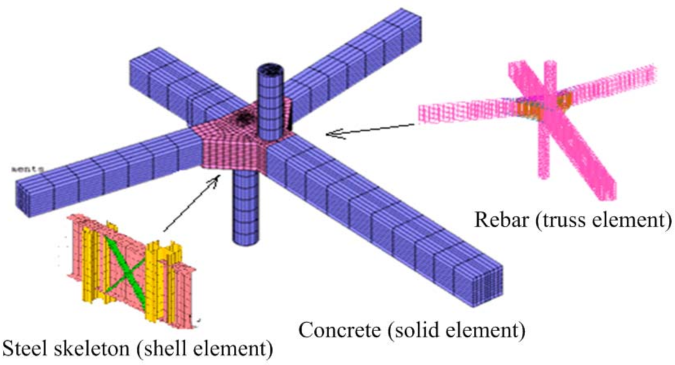


Figure 23. Finite element model of the complicated joint.

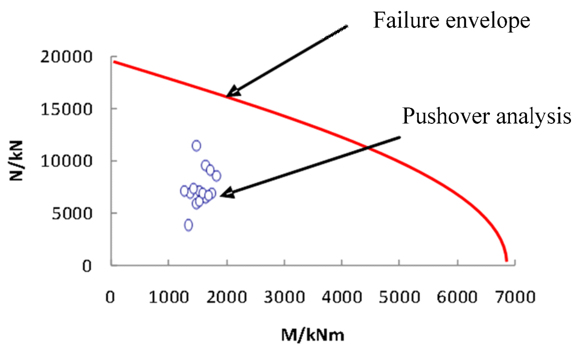


Figure 24. Safety check for the complicated joint.

Another example is the collapse simulation of a high-rise frame-core tube building due to extremely strong earthquake with proposed model (Lu *et al.* 2008b). The deformation and plastic hinges in different stages of the collapse process are shown in Figure 25. At the first stage, the building vibrates slightly around its original place and no damage occurs, shown as Figure 25a. At the second stage (Fig. 25b), shear walls in the weak story fail due to large compressive-shear internal force. And frame begins to yield and many plastic hinges appear around the weak story (Fig. 25b). At the third stage (Fig. 25c) and forth stage (Fig. 25d), the weak story is destroyed and the whole structure comes into a complete collapse. The structure above the failed weak story falls down and impact on the lower stories, which results in a progressive collapse. Hence, the

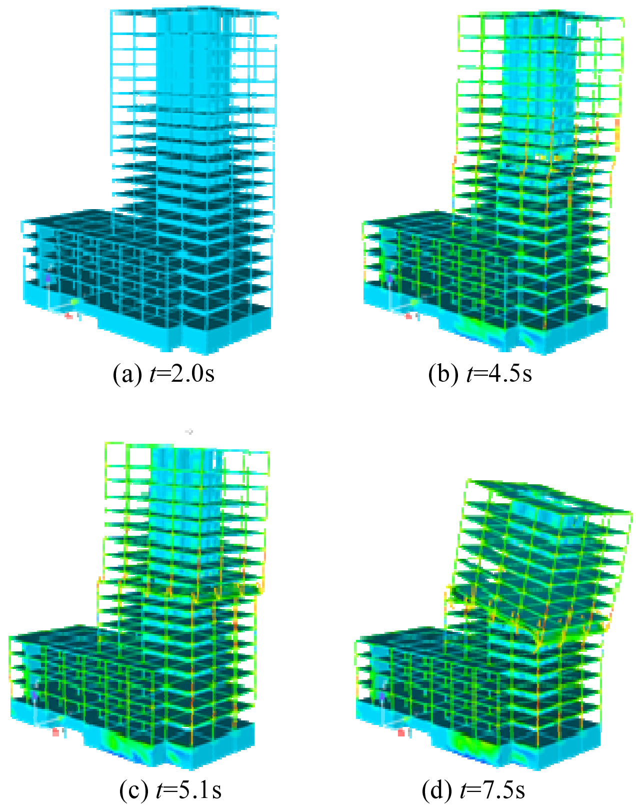


Figure 25. Collapse process simulation of high-rise structure (PGA=4000gal).

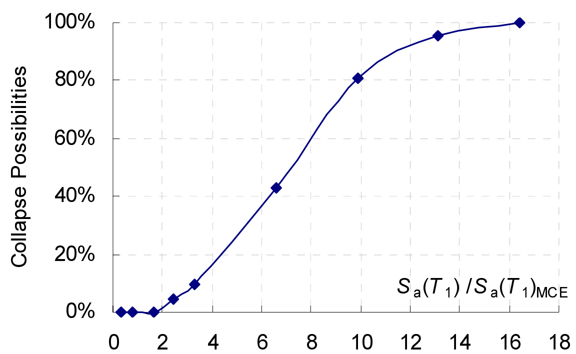


Figure 26. Collapse fragility curve of the high-rise building.

model gives a good simulation on the failure mode and the whole collapse process of frame-core tube structure. If the ground motion database proposed by ATC-63 reports (ATC 2008) is inputted into this high-rise building model with various ground motion intensities, the collapse fragility curve can be obtained as shown in Figure 26, which is very important to predict the seismic loss.

4 CONCLUSION

The proposed fiber-beam model and multi-layer-shell model with suitable material constitutive laws can accurately simulate the deformations and failure modes of the structures under various disaster loads including earthquake, fire, blast and progressive collapse. Their precision and efficiency satisfy the demand of researches and applications.

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