TONGJI UNIVERSITY

博士学位论文

混凝土结构随机倒塌分析理论与抗震整体可靠性研究

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Theoretical Study on Stochastic Collapse Analysis and Anti-Seismic Global Reliability of Concrete Structures

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摘 要

实际工程结构在其服役期内可能遭受各种灾害性动力荷载作用，而工程结构特别是混凝土结构自身的性态也因为材料的随机性而具有不可精确预测的性质。本文从混凝土材料的非线性和随机性两个基本点出发，系统地发展了混凝土结构随机倒塌分析理论和整体抗灾可靠性分析方法。探讨了具有随机动力激励和随机结构参数条件下的结构非线性动力响应特征和整体抗灾可靠性。

搭建了混凝土结构由本构到结构的非线性动力反应分析和倒塌数值模拟平台。以连续介质-损伤力学为基础，结合精细化结构单元模型和高效数值算法，实现对复杂混凝土结构在灾害性动力荷载作用下的倒塌全过程模拟。对比了混凝土弹-脆性、弹塑性和损伤本构关系三类不同本构模型对结构倒塌分析结果的影响，证实了混凝土材料的本构关系在结构非线性分析中的基础性地位。利用混凝土损伤本构关系模型进行结构非线性动力反应分析，能够较好地模拟结构从材料损伤到构件失效，再到结构部分或整体倒塌等不同阶段的破坏形态。

发展了一种基于有效能量的结构整体倒塌判别准则。在 Xu-Li 动力稳定性判别的能量准则基础上，提出了结构有效特征能量和有效输入能量的概念。指出结构发生动力失稳致倒塌的本质在于：某一时刻结构的有效特征能量超过了有效输入能量。采用不同类型的结构动力稳定性分析算例对本文建议的倒塌准则进行了系统深入地验证，并与 Xu-Li 动力稳定性判别准则进行了对比分析。研究表明，所建议的倒塌准则能够定量描述各类结构系统的全过程动力稳定状态，可以准确判断结构发生倒塌与否，并给出倒塌发生的具体时刻。

建立了混凝土结构随机地震倒塌分析与整体抗灾可靠性分析框架。引入具有物理机制的随机地震动模型定量刻画地震激励的随机性，采用概率密度演化方法描述输入随机性在结构系统中的传播，从非线性与随机性耦合的角度考察了某真实混凝土结构的随机地震响应特征和整体抗灾可靠性。研究发现，源于地震激励的随机性会对混凝土结构的动力响应规律产生显著影响，使结构产生截然不同的倒塌破坏模式。概率密度演化方法与基于有效能量的结构倒塌判别准则相结合，可以准确给出结构整体发生动力灾变的概率。

提出了一种考虑材料力学性质空间变异性的混凝土结构多尺度随机损伤分析方法。以混凝土随机损伤本构关系模型为基础，通过引入协方差约束和多尺度分析的思想，构建满足预期相关尺度的细观断裂应变随机场和宏观强度随机场，实现了混凝土结构的两尺度随机损伤分析。通过将混凝土细观尺度和宏观尺度的随机特性置于统一框架内考察，可以描述随机性在不同尺度之间的传播。协方差

约束可有效保证随机结构模型满足细观和宏观尺度的相关长度及其关联特性。本文建议方法不仅可以避免随机有限元分析中网格尺寸改变对相关长度的影响，而且相比于传统的随机模拟方法具有更高的计算效率。

发展了考虑材料性质随机性的复杂高层混凝土结构整体抗灾可靠性分析方法。综合概率密度演化理论、结构多尺度随机损伤分析方法和结构整体倒塌判定准则，实现了某真实混凝土结构在相同地震激励条件下的随机结构倒塌分析和倒塌评估。研究发现，源于混凝土材料的随机性亦会对混凝土结构的动力响应规律产生影响，且这一影响会随着结构系统非线性程度的发展与深入表现得愈发显著。即使在同一地震动激励条件下，不同的样本随机结构依然可能产生截然不同的倒塌破坏模式。随机性的存在，使得结构在灾害性动力荷载作用下的非线性动力性能明显有别于传统设计预期。从概率密度演化的角度考察工程结构的非线性性状，并定量评价结构的整体抗灾可靠性，是准确把握结构抗灾性能、实现工程结构优化设计的必由之路。

最后，阐明了本文研究中存在的问题，对进一步的研究工作做出了展望。

关键词：混凝土结构，损伤本构关系，倒塌准则，协方差约束，多尺度随机场，概率密度演化方法，整体可靠性

ABSTRACT

Actual engineering structures may suffer from various static or dynamic loadings in service life periods. Moreover, the randomness widely exists in the construction materials. It is difficult to accurately predict the performances and potential behaviors of structures, in particular, regarding the concrete structures subjected to disastrous dynamic loadings. The present dissertation therefore is focused on the description of nonlinearity and randomness of concrete materials and structures. New theory and methods for stochastic collapse analysis and anti-seismic global reliability analysis of concrete structures are systematically developed. The nonlinear dynamic response characteristics combined with the global anti-disaster reliability of complex concrete structures under stochastic dynamic excitations and random structural properties are respectively investigated.

A constitutive model-based numerical platform for nonlinear dynamic response analysis and collapse simulation of concrete structures is established. Combining the refined structural element models with the efficient and robust numerical algorithms, the simulation regarding the entire process of collapse of complex conctrete structures is achieved based on the continuum damage mechanics. Different seismic collapse simulations with elasto-brittle, elasto-plastic, and damage constitutive relationships of concrete are compared and investigated in terms of a prototype reinforced concrete frame-shear wall structure. It is indicated that the concrete constitutive model plays a fundamental role in the collapse analysis of structures. The damage constitutive model can represent almost all the typical nonlinear behaviors of concrete and thus is capable of simulating the multi-stage destructive patterns and processes from material damage and component failure to structural partial or overall collapse.

An effective energy criterion for identification of structural overall collapse is proposed. On the basis of Xu-Li energy criterion for structural dynamic stability, the concepts of effective intrinsic energy and valid input energy are put forward. The first passage of the structural effective intrinsic energy over the valid input energy is shown to be an important indicator of the dynamic instability that leads to the collapse of the structure. The suggested criterion is thoroughly verified on various benchmark models. A comparison study is carried out regarding the validity and applicability between the Xu-Li energy criterion and the effective energy criterion as applied to the dynamic stability analysis of different structures. It is demonstrated that the effective energy criterion can quantitatively identify the structural whole-process stabilities and predict the specific time of collapse occurrence of various structures.

A comprehensive framework for stochastic seismic collapse analysis and global anti-disaster reliability assessment of complex concrete structures is recommended. A physical random ground motion model is introduced to quantitatively characterize the randomness of earthquake excitations. The probability density evolution method is employed to capture the randomness propagation from input excitations to structural systems. The stochastic seismic response features and global anti-disaster reliability of a certain prototype reinforced concrete frame-shear wall structure are investigated considering the coupling of nonlinearity and randomness. Numerical results indicate that the randomness from ground motions dramatically affects the collapse behaviors of the structure and even leads to entirely different collapse modes. The probability density evolution method combined with the effective energy-based collapse criterion provides a feasible approach towards the collapse prediction of actual structures.

A multi-scale stochastic damage analysis method that incorporates the spatial variability of material mechanical properties for concrete structures is developed. Within the framework of stochastic damage mechanics, the spatial variability of concrete is modeled as a two-scale stationary random fields. At the micro-level, the damage evolution law of concrete is mapped to a random field corresponding to the microscopic fracture strain. At the macro-level, the strength distribution of any concrete component forms a lognormally distributed random field. The connection between the two-scale random fields is established by a covariance constraint such that the scale-of-fluctuation of the random material properties is satisfied in both scales. Thereout, both the microscopic random damage evolution of concrete and the fluctuation of macroscopic structural responses can be numerically represented in a unified framework. The present method can effectively eliminate the mesh sensitivity with respect to the correlation length in stochastic finite element analysis. Moreover, the method is of higher computational efficiency compared with the conventional stochastic simulation approaches.

A global anti-disaster reliability analysis method regarding the complex high-rise concrete structures with random mechanical properties in concrete is developed. By integrating the multi-scale stochastic damage analysis method, the probability density evolution method, and the effective energy collapse criterion, the stochastic structural damage analysis and collapse assessment of an actual concrete structure induced by the same seismic excitations are accomplished and investigated. It is shown that the randomness in concrete also makes a difference to the dynamic response regularity of structures. This influential effect can become more remarkable with the development of nonlinearity of the structural system. Due to the random damage evolution of concrete, distinct structural collapse modes can be observed even under the same earthquake excitation. With the presence of randomness, the performance of structures under disastrous dynamic loadings may deviate from the hypothetical expectation in conventional design. In this regard, it is recommended to predict the anti-disaster performance and implement the optimum design of engineering structures from the probability density evolution analysis as well as the global reliability analysis point of view in future to ensure safety.

In the end, some open questions and problems regarding the present research are summarized. Some future research perspectives are clarified as well.

Key Words: Concrete structure, Damage constitutive relation, Collapse criterion, Covariance constraint, Multi-scale random fields, Probability density evolution method, Global reliability

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