申请同济大学工学博士学位论文

基于非线性发展过程的结构体系可靠度分析

（国家自然科学基金委创新研究群体资助项目　编号：50621062）

培养单位：土木工程学院

一级学科：土木工程

二级学科：结构工程

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二〇〇八年十月

A dissertation submitted to
Tongji University in conformity with the requirements for
the degree of Doctor of Philosophy

The System Reliability Analysis of Structures based on Nonlinear-Development Process

(Supported by the Natural Science Foundation of China for
Innovative Research Groups, Grant No.50621062)

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Discipline: Civil Engineering
Major: Structural Engineering
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October, 2008

摘要

结构体系可靠度问题是结构工程领域的经典难题，自上世纪 70 年代初至今虽然研究热情不减，但重大突破并不多见。本文试图基于物理随机系统的基本观点和概率密度演化理论的框架，以结构非线性发展过程为主线，研究结构体系可靠度分析问题。

基于概率守恒原理的随机事件描述导出的广义密度演化方程，其维数可以与结构系统无关，从而为大规模随机动力系统的分析提供了可能的途径。本文在广义密度演化方程形式解的基础上，引入δ函数的逼近序列，提出了一种求解广义密度演化方程的新算法——δ序列解法，为后续的研究提供了高效的数值算法。

对于静力系统，将加载参数视为广义时间参数，导出了结构非线性发展过程的概率密度演化方程，为在非线性发展过程中考察结构体系可靠度提供了理论基础。

根据物理随机系统的基本观点，结构性能可靠度可以在考察非线性发展过程中得以解决。针对非线性发展过程的特定阶段，本文由体系可靠度分析问题的不同表述方式导出了随机静力系统的密度变换解。同时，对于整体失效和局部倒塌共存等类型的失效事件，引入吸收边界，导出了广义目标量的概率密度演化方程和密度变换解。

根据上述理论与方法，本文对结构体系可靠度进行了具体研究。首先，将经典的结构体系可靠度转化为对极限承载力的概率结构的考察，基于极限承载力的密度变换解，分析了理想弹塑性框架结构和钢筋混凝土框架结构的体系可靠度问题，并对非完全相关荷载的处理进行了详细的讨论。其次，分析了同时考虑构件层次抗剪强度失效的结构体系可靠度问题：对于静定结构，引入等价极值事件原理，分析了同时考虑构件层次抗剪强度失效的静定结构可靠度问题；对于超静定结构，建立了考虑吸收边界条件的广义目标量的密度变换解，分析了同时考虑构件层次抗剪强度失效的超静定结构可靠度问题。同时，本文还考察了在不同荷载水平下的结构“不坏”和结构“可修”的可靠度分析问题，初步建立了材料应变层次上的性能水准量化模型。

在各部分研究中，均通过实例分析，验证了本文建议算法的有效性。

最后，本文在简要总结全文的基础上，对进一步的研究方向进行了讨论。

关键词：结构体系可靠度，非线性发展过程，广义密度演化方程，密度变换方程，δ序列解法，等价极值事件，吸收边界

ABSTRACT

System reliability evaluation of structures has long been a challenging problem in the field of structural engineering although great endeavors have been devoted to it in the past over 30 years. The development of the basic thoughts of physical stochastic systems and the theoretical framework of the probability density evolution method (PDEM) throw new light on this topic. This dissertation is devoted to the development of such an approach for the system reliability evaluation of structures from the perspective of nonlinear development process of structural behaviors under loading.

The generalized density evolution equation (GDEE), which is generated by incorporating the uncoupled physical equations into the random event description of the principle of preservation of probability, and of which the dimension is independent to the original dynamical system, provides a family of new method for analysis of large-scale nonlinear stochastic systems. On the basis of the formal solution of the GDEE, through introducing the asymptotic delta sequences of the Dirac's function, a new numerical algorithm different from the finite difference method, i.e. the solution via a family of detla sequences, is proposed to numerically solve the GDEE. This algorithm provides an effective numerical method for the following researches.

Taking the loading parameter as a generalized time parameter, the probability density evolution equation for the nonlinear development process is derived for static systems, which provides the theoretical basis for structural system reliability evaluation during the development process of structural nonlinearity.

Based on the thoughts of physical stochastic systems, the reliability of structural performance can be captured in the nonlinear development process. For the given states in the nonlinear development process, the transformation solution of probability density for static systems is derived from the two equivalent descriptions of the reliability problem. What's more, adopting the absorbing boundary, the probability density evolution equation for the generalized quantities, together with the transformation solution of probability density of the generalized quantities, are derived for the failure events where the integral failure mode and local collapse mode co-exist.

Following the theories and methods elaborated above, the structural system reliability is studied in detail. Firstly, from the perspective of physic approach, the classical structural system reliability analysis can be transformed to analysis of the probabilistic structure of the ultimate limit capacity (ULC), and based on the transfomation solution of probability density for the ULC, the structural system reliability of the perfect elastoplastic frame structures and the reinforced concrete (RC) frames is investigated. The problem on how to deal with the correated loads in reliability analysis is also discussed. Secondly, the reliability considering structural failure in intergrity together with shear failure of members is analyzed. For the statically determinate structures, by introducing the equivalent extreme-event, the reliability with double failure mechanisms is investigated.For statically indeterminate structures, the reliability is obtained based on the transformation solution of probability density for the generalized quantity with absorbing boundary condition. What's more, the reliability of 'the structure is undamaged' and 'the structure is repairable' under different load levels are investigated. A new quantified model of structural performances based on strains of section fibers is proposed.

The rationality of the ideas and the effectiveness of the proposed method in this dissertation are verified through corresponding numerical examples.

Finally, after summarizing the researches of this dissertation, the problems for future study are discussed at the end of the dissertation.

Key Words: Structural system reliability, Nonlinear-development process, generalized density evolution equation (GDEE), Transformation solution of probability density, Numerical solution via detla sequences, Equivalent extreme-value event, Absorbing boundary

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