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钢筋混凝土框架结构随机非线性受力行为研究

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摘 要

混凝土结构基于近似概率的极限状态设计法存在两个主要矛盾：截面层次的极限状态设计承认非线性，而在结构层次采用线弹性力学分析，忽略非线性；截面层次基于可靠性设计，承认随机性，而在结构层次采用确定性力学分析，不承认随机性。这两个主要矛盾使得人们难以科学地反映、合理地控制钢筋混凝土结构的性态。因此，本文以广泛应用的钢筋混凝土框架结构作为研究对象，试图通过数值模拟与试验手段，研究混凝土结构的随机非线性受力力学行为，寻求工程应用的可能。

在钢筋混凝土框架结构非线性有限元分析的研究中，基于力型函数插值的一维梁柱模型存在积分敏感性问题。本文建立了梁柱损伤扩展模型。采用分段变刚度的方式，将梁柱构件划分为两端的损伤区和中间的弹性区，建立了数值积分权重与构件损伤区长度的关系，成功解决了梁柱构件响应与积分点相关的问题。通过在数值计算过程中动态调整损伤区的长度，模拟了梁柱构件在受力过程中由构件两端向构件中部开裂发展的过程，避免了需要人为预先指定损伤区长度的缺陷。在此基础上，基于“本构-构件-结构”的研究思想，将钢筋混凝土梁柱损伤扩展模型应用于框架结构分析，建立了两种不同的迭代算法：N-N-L 算法和 N-L-L 算法。将这一进展与有限元分析软件 ADARCS 相结合，搭建了钢筋混凝土框架结构确定性非线性有限元分析平台。

基于动态位移型插值的思想，考虑剪切变形的影响，建立了一类钢筋混凝土梁柱弯剪耦合模型。这一模型通过预设高斯积分点位置处截面的剪切变形场函数，结合二维混凝土弹塑性损伤本构关系，实现了弯曲变形与剪切变形的综合反映。为保持单元内部之间的力平衡关系，在单元状态的确定过程中，采用力型函数插值进行迭代，使得这一模型不仅具有较好的计算效率（整根梁柱构件仅需采用一个单元），而且具有较好的计算精度，能够反映梁柱构件剪切破坏特征。

为揭示随机性与非线性对钢筋混凝土框架结构受力力学行为的影响，对三榀具有相同标号混凝土、相同配筋、相同养护条件下制作的三层两跨钢筋混凝土框架结构进行了单调静力推覆试验。试验结果表明：由于混凝土材料力学行为的随机性，造成三榀框架结构具有完全不同的混凝土开裂和梁柱出铰顺序，不同层次的结构响应具有不同程度的随机非线性表现。这一结论从试验角度揭示：只有基于混凝土随机性与非线性耦合这一物理背景展开研究，才能给出符

合客观实际的结果。

将随机场的基本理论应用于试验框架，采用回弹试验获得了框架结构梁柱构件上关键区段上的混凝土抗压强度分布。采用相关函数拟合法，获得了混凝土抗压强度随机场的相关函数，由此建立了混凝土抗压强度的随机场模型。采用随机谐和函数对混凝土抗压强度随机场进行分解，获得了钢筋混凝土框架结构抗压强度的二维随机场随机函数表述。

基于概率守恒原理，推导了钢筋混凝土框架结构静力随机非线性分析的广义概率密度演化方程。以框架结构非线性全过程分析和混凝土抗压强度随机场的研究结果为基础，开展了钢筋混凝土框架结构的随机非线性反应分析。研究结果表明：本文建议的钢筋混凝土框架结构随机非线性反应分析方法，可以初步反映钢筋混凝土框架结构的随机非线性受力行为。

利用材料均值进行了框架结构确定性非线性反应分析，并与试验样本的均值结果进行了比较，初步表明：从工程实用性出发，可以采用材料均值参数预测混凝土结构的均值反应。

关键词： 钢筋混凝土结构，非线性梁柱单元，损伤扩展模型，弯剪耦合模型，内力重分布，随机场建模，概率密度演化

ABSTRACT

The current limit state design method based on approximation probability theory for concrete structure states that there are two main contradictions: one is the admission of the nonlinear feature at the section level, but neglection of the nonlinear feature at the structure level with the analysis of linear-elastic mechanics. The other is the admission of random feature at the section levele based on the probability design, while neglection of the random feature at the structure level with the analysis of deterministic mechanics. These contradictions makes engineer could not relect and control the performance of concrete structures scientifically and reasonably. Therfore, in this thesis reinforced concrete frame structure is adopted due to its extent application. Stochastic nonlinear mechanical behavior of reinforced concretes is discussed in its entirety by means of numerical simulation and experimental research.

Under the consideration of nonlinear finite element analysis for reinforced concrete frame structures, the forced-based beam-column model with force interpolation function posses an integration senstivity issue. Thus, a damage spread beam-column model is proposed. The model divides the beam-column member with the elastic zone in the middle and the damage zone at both ends. With the establishment of relationship between numerical integral weight and damage zone length, the issue about response of beam-column member related to number of integration points is solved suceesfully. Damage zone length is continually updated in the numerical calculation procedure. The process of concrete cracking spreading from the both ends to the medial zone is simulated in the beam-column component load characteristic. So the model could avoid the shortcoming that the damage length needed to be prescribed by engineer. Based on the research thoughts of ‘Constitutive-Component-Structure’, the damage spread beam-column model is implemented into the frame structure analysis. Two different interation algorithms are provided: the N-N-L algorithm and N-L-L algorithm. Furthermore, the model is incorporated into the finite element analysis software ADARCS, and the platform of deterministic nolinear finite element analysis for reinforced concret frame is build.

Based on the idea of dynamical displacement extrapolation, the shear-bending

coupling model for reinforced concrete beam-column member is proposed. The model adopts the prescribed shear deformation function at the location of Gauss integration point and incorporates the twe-dimensional elastplastic damage constitutive model of concrete to take into account the shear effect. Further, force-based interpolation function is adopted to obtain the balance of internal force in the procedure for determination of element status. That makes the shear-bending coupling model has a better effcienty calculation, which means the beam-column component could be simulated with one element. The degree of freedom of structure analysis is greatly reduced. Meanwhile, the model also could possess a better computational accuracy and describe the basic features of brittle shear failure for beam-column members.

For the sake of revealing the effects on mechanical behavior influenced by nonlinear and stochastic to the reinforced concrete frame structures, the thesis conduct a monotonic static pushover experiment with the same concrete grade, distributed reinforcement and curing condition. The test results of these reinforced concrete structures with three layers and two spans state that there are completely different performances due to the randomness of mechanical behavior on concrete material. Three frames have different features of concrete cracking and reinforcedment yield sequence. Structural responses at different level appear the stochastic nonlinear behavior at different degree. Therefore, from the test point of view it is concluded that research based on the background of coupling in randomness and nonlinear for reinforced concrete structures is necessary. Then the research could achieve a conforming to objective practice.

With the basic theory of randon field to apply to the experimental frame structures, the distribution of concrete compressive strength on the key domain of beam-column component is obtained with the rebound test. Then cutocorrelation function of concrete compressive strength is established with correlation function fitting method and random field model of concrete compressive strength is constructed. The derived random field of concrete compressive strength is further decomposed with stochastic harmonic function method. Therefore, the two-dimensional stochastic field model of compressive strength for reinforced concrete frame structures is naturally obtained.

Based on principle of probability preservation, the generalized probability

density evolution equation of nonlinear static analysis for reinforced concrete frame structures is derived. On the basis of research results of nonlinear full-range analysis for frame structures and randomness field of concrete compressive strength, the stochastic nonlinear analysis of reinforced concrete frame structures is conducted. The research results show that the decomposition method of stochastic nonlinear analysis could reflect the stochastic nonlinear mechanical behaviors preliminarily for reinforced concrete frame structures.

Derterministic nonlinear analysis of frame structure is conducted with mean value of materials. Then, compared with the mean results of experimental samples, it indicates that the mean response of reinforced concrete structures could be predicted with mean parameters of material from the aspect of engineering practice.

Key Words: Reinforced concrete struture; Nonlinear Beam-column element; Damage spread model; Shear-bending coupling model; Redistribution of internal force; Modelling of randon field; Evolution of probability density

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