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Equivalent constitutive model of steel with cumulative degradation and damage

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ABSTRACT

To accurately predict the response of steel frames subjected to strong earthquakes, a uniaxial equivalent constitutive model of structural steel under cyclic loading is proposed for fiber beam element model, considering cumulative degradation and damage of strength and stiffness. The model consists of three types of skeleton curves, hysteresis criteria and degraded criteria, and each criterion is described by mathematical expressions with related dimensional parameters. By using the user subroutine interfaces UMAT provided by finite element software ABAQUS, the equivalent model was implemented as fiber beam element model. The proposed model was proved correct and available with comparison of typical experimental results including static cyclic loading tests of members and non-linear time history tests of structures. In the last, the model was applied in a four-storey frame for dynamic time history analysis with comparison of traditional bilinear model. The research shows that: the proposed model is independent of tests and three-dimensional models well simulate the degraded characteristics of strength and stiffness and accurately predict the failure modes. The model balances both computational accuracy and efficiency, which provides a powerful tool for nonlinear analysis of steel frames subjected to strong seismic excitation.

1. Introduction

In order to investigate the accurate response of steel structure subjected to severe earthquakes, tests and numerical simulation are commonly adopted. Due to high cost and limited conditions of the tests, nonlinear time history analysis is widely used for predicting ultimate limit state of structures. It may be one of the relatively reliable methods for seismic study. The simulation work adopted for nonlinear time history analysis consist of full scale three-dimensional solid element model, multi-scale model, beam element model and beam model with spring element [1–9] (as illustrated in Fig. 1). However, analysis carried out with full scale three-dimensional solid element model is time-consuming and quite inconvenient to extract internal forces. Multi-scale model is more efficient than solid element model, but the problems of substantial computations and high storage costs are still not solved. Therefore, beam element models or beam models with spring element are more commonly used in seismic analysis (see the path of analysis and research process for beam element model in Fig. 2), which can satisfy the computational requirements and are convenient to obtain concerned internal forces.

Although many studies have shown that the beam element model without considering damage and degradation could be used for analysis of structure suffering from "frequent earthquakes" (earthquake with high probability of occurrence), it cannot satisfy the computational accuracy of the analysis subjected to severe and rare earthquakes. Under strong seismic excitations, accumulative damages are caused by plastic local buckling and accompanied with fracture of members and connections, which lead to stiffness and strength degradation, even collapse of the high-rise steel structures. It is difficult for traditional beam element models (bi-linear or tri-linear models) to simulate this damage process as the irreversible and unrecoverable characteristics of degradation cannot be described [10]. Hence, many researchers have carried out a lot of work on this field. Shen et al. [11] developed a hysteresis model for plane steel members with cumulative damage by reducing active area. Sivaselvan and Reinhorn [10] presented a versatile smooth hysteretic model based on internal variables, with stiffness and strength deterioration and with pinching characteristics. Della Corte et al. [12] proposed a semi-empirical model taking account of strength degradation and pinching phenomena. Sucuoglu and Erberik [13] suggested an energy-based low-cycle fatigue model for developing hysteretic and damage models. A simplified approach of cyclic buckling had been undertaken by defining negative rotational stiffness and softening peak orientation. Ibarra et al. [14] proposed the relatively simple hysteretic models of plastic hinge that included degraded properties of strength and stiffness based on typical bilinear, peak-oriented, and pinching model. Castiglioni and Zambrano [15] defined a factor q for multi-storey steel frames, accounting for cumulative damage in structural components, which was defined as the ratio of the peak ground acceleration producing collapse of the structure (a_{max}) to that of design (a_d). All of them have conducted outstanding works on damage and degradation behaviors of steel members and frames, but the model were mainly based on the lumped plastic hinge model with macro

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