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Numerical simulation of steel I-shaped beams using a fiber-based damage accumulation model

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ABSTRACT

This study proposes a fiber-based hinge damage accumulation model that is able to replicate the nonlinear response of I-shaped beams of steel moment resisting frames. The model is developed in OpenSees and consists of a *beam with hinges* element with fiber cross-section discretization within the plastic hinge zone. Among various plastic hinge integration methods, the modified Gauss-Radau integration scheme was selected. The proposed model incorporates strength and stiffness deterioration caused by flange local buckling of I-shaped beams which is simulated by assigning a calibrated low-cycle fatigue material model to flange fibers. In this formulation, fatigue material uses a modified rainflow cycle counting algorithm to accumulate damage based on Miner's rule. The values of fatigue material coefficients were calibrated against 16 experimental test results selected from the literature. An equation able to predict the fatigue ductility coefficient that follows a linear variation along the flange width is proposed based on regression analysis. In addition, a global damage index, DI_s, defined as the ratio between the number of fibers that reach fatigue and the number of fibers within the top and bottom flanges of I-shaped cross-section, is developed and a global damage index value associated with the onset of beam failure, labelled $DI_{s(80\%)prop}$ is proposed. An application comprising a single-storey, one-bay steel MRF is carried out in OpenSees, which validates the proposed beam model as computationally effective under cyclic quasi-static and dynamic loading.

1. Introduction

Performance-based seismic design requires evaluating the performance of structures at different hazard levels. To assess the system behaviour from yielding to collapse, hysteretic models are needed to replicate the response upon collapse. Cyclic loading triggers damage accumulation in members of structures designed to behave in the nonlinear range, which may lead to member failure. To simulate this behaviour, several damage accumulation models have been proposed [1].

In the case of a steel moment resisting frame (MRF), the model for beams and columns should be reliable, robust and computationally economic during analysis [2]. To obtain accurate results, the selected hysteretic models need to incorporate all significant deterioration modes observed during experimental tests. In the past, the plastic hinge model for a steel MRF beam was based on an analytical method that involved observing cross-sections of deformed beams within the plastic hinge zone. More specifically, this method considered a plastic collapse approach and a yield-line model [3]. To compute the stress distribution in the buckled zone, the principle of virtual work was employed. However, this method did not provide practical solutions that could be applied in a global analytical model for MRFs.

In general, plastic hinge models used in nonlinear dynamic analysis were developed based on their physical and phenomenological characteristics. According to [4], parameters employed to simulate models developed based on physical characteristics are defined in terms of material properties, whereas parameters for phenomenological models are defined based on the component response (e.g. an MRF beam). Continuum nonlinear models consider physics of assigned materials and do not require definition of member stiffness, strength and deformation capacity because these are embedded in the definition of material properties. Concentrated hinge models and distributed plasticity models with fiber-based cross-section discretization are defined by phenomenological characteristics. Thus, the concentrated hinge model uses the overall force-deformation response of the beam member while considering the inelastic deformation rules associated with data obtained from experimental test results. The distributed plasticity model with fiber-based cross-section discretization embeds some behavioural assumptions (e.g. Euler-Bernoulli bending theory) in association with explicit modelling of uniaxial material. However, these models are limited in their ability to capture strength degradation. Therefore, there is a need to develop analytical models that incorporate cyclic deterioration. For example, local buckling of flanges and/or web, as well as lateral torsional

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buckling, lead to strength and stiffness deterioration of MRF beams. In the past, deterioration models considering deterioration of geometric and material properties by including different rate of cyclic deterioration in the two loading directions, as well as residual strength and ultimate rotation, were specifically developed for nonlinear rotational springs inserted in the model to replicate the behaviour of plastic hinges. As such, it is the modified Ibarra-Krawinkler model [5–7], which was based on the plastic hinge model reported in [8].

To account for cyclic deterioration, in the ATC 72-10 provisions [4] there are four *Options* for analytical modelling of component (e.g. beam) behaviour: (1) incorporate explicitly the cyclic deterioration, (2) use skeleton curve as a modified backbone curve and ignore additional cyclic deteriorations, (3) use factors for modification of an initial backbone curve, and (4) neglect strength deterioration. Among these *Options*, it is believed that *Option* (1) is the most realistic, *Options* (2) and (3) account for cyclic deterioration implicitly, and *Option* (4) does not implicitly consider a deterioration model but instead recommends a strict deformation limit associated with 80% of the capping strength of a descending branch (this means a 20% strength loss).

To overcome these drawbacks, this study proposes a refined cyclic deterioration beam model, able to simulate the strength and stiffness degradation of I-shaped flanges caused by local buckling, as well as the fracture mechanism caused by low-cycle fatigue. Although there are several finite element platforms, in this study it was selected the OpenSees framework (Open System for Earthquake Engineering Simulation) [9] because it facilitates the simulation of a multi-storey building response in the nonlinear range accurately and is computationally more efficient than other computer programs (e.g. ABAQUS), when the structure is subjected to dynamic loads.

2. Nonlinear numerical models

In general, the existing nonlinear numerical models for MRF beams are divided into three categories: i) an elastic beam model with attached nonlinear rotational springs at its ends, ii) a nonlinear beam model with distributed plasticity across the beam's length, and iii) a nonlinear beam model with concentrated plasticity within a finite plastic hinge length.

In the first case, behaviour of the beam's plastic hinges is replicated by nonlinear rotational springs that are generally made of modified Ibarra-Krawinkler material [6], known as *billin material* in OpenSees. The beam's hysteretic response, calibrated against experimental test results, embeds several modes of cyclic deterioration (basic strength, post-capping strength, and unloading/reloading stiffness deterioration), while the rate of cyclic deterioration is measured by the energy dissipated under cyclic loading. In addition, the strength bounds on the monotonic backbone curve are established. This deterioration model, reported in [6], complies with *Option* (1) of ATC 72-10 [4]. However, the MRF beam model made of an elastic beam element with attached nonlinear rotational springs at its ends has often showed numerical convergence problems under dynamic loading. In general, these are related to the high value of stiffness assigned to rotational springs in order to preserve the elastic stiffness of the beam. Meanwhile, the elastic deformability of the MRF beam is already taken into account within the linear elastic response of the beam member. Further, as reported in [10], the dynamic response is unreasonably sensitive to the assumed value of the initial stiffness when nonlinear rotational springs are employed and Rayleigh damping is considered.

In the second case, the MRF beam response is simulated using the nonlinear force-based beam-column elements with distributed plasticity and fiber-based cross-section discretization. Herein, plastic hinges form at the location of maximum bending moment when fibers start responding in the nonlinear range. However, the occurrence of strain softening behaviour causes localization in the beam element because the beam's deformation concentrates in a single integration point. According to [11], this phenomenon leads to a loss of objectivity because the response depends on the number of integration points per element rather than its length.

To overpass this drawback, the beam model made of a nonlinear force-based beam-column element with finite-length plastic hinges located at its ends, known as the *beam with hinges* element in OpenSees, is considered. In this case, the beam is divided into three segments: the central beam segment characterised by elastic behaviour, and the two outermost finite length segments characterised by nonlinear behaviour. Different integration methods were adopted for *the beam with hinges* element, which vary with the number and location of the integration points. Further, the nonlinear behaviour of plastic hinges can be defined by assigning either moment curvature relationships or fiber-based cross-sections. To avoid the numerical convergence problems under dynamic loading that were encountered by analysing the MRF beam with concentrated nonlinear rotational springs in OpenSees, Ribeiro et al. [2] proposed to use the *beam with hinges* element with an assigned moment-curvature relationship. In addition, they developed a procedure to define the above moment-curvature relationship starting from the moment-rotation constitutive law derived against experimental test results [6]. This procedure was required because the moment-curvature assigned to the plastic hinge could not be obtained by direct scaling of the associated moment-rotation relationship [12].

When plastic hinges of the *beam with hinges* element are made of fiber cross-sections, the strength and stiffness degradation is embedded by assigning various uniaxial materials to fibers. For example, researchers have assigned the Giuffrè-Menegotto-Pinto steel material to plastic hinge fibers and assigned a negative value to the parameter controlling the isotropic hardening in order to simulate degradation in the moment-curvature cyclic response [13]. However, after the occurrence of first yielding, the strength degradation was suddenly initiated, while the capping bending moment and the associated rotation were not reached. Recently, Bai et al. [14] proposed a beam with a fiber-based plastic hinge cross-section model that is able to replicate the strength and stiffness degradation caused by local buckling. In their model developed for steel square hollow structural section beam members, deterioration was explicitly incorporated in the stress-strain curve and the cyclic response was validated against experimental test results. However, this model was not verified for I-shaped beams. A similar approach was used by Kasai et al. [15] who simulated the strength and stiffness deterioration localized at a column's base by assigning a stress-strain response to fiber cross-sections inserted in the zero-length element attached to the column end. The finite length of bucking zone and the rotation characteristic of these fiber-based cross-sections were defined to simulate the experimental buckling behaviour of steel struts. A degradation rule for the compressive buckling zone was also embedded [15].

Other studies have emphasized the complexity phenomena of structural collapse under seismic loading. To overpass this drawback, an accurate numerical model should incorporate strength and stiffness degradation due to local buckling, as well as the fracture mechanism due to low-cycle fatigue [1]. The analytical model proposed in [16] comprises both aforementioned principles but the method developed is difficult to apply when analysing the entire MRF system.

Meanwhile, the strength and stiffness degradation of cross-sections can be simulated in OpenSees by considering a fatigue material wrapped around the uniaxial steel material assigned to the beam element. This approach has been mainly used to simulate the brace fracture of concentrically braced frame caused by low-cycle fatigue [17]. Herein, braces were made of elements with distributed plasticity and fiber cross-section discretization. In addition, the same approach was used to simulate the cyclic behaviour of long links of eccentrically braced frames designed to respond in flexure [18]. However, the cyclic behaviour of I-shaped links, modelled as explained above, has shown a sudden reduction in strength and stiffness because both top and bottom flanges have simultaneously reached the fatigue life due to the assumption of plane sections and the omission of composite steel deck in the model.