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Modelling of steel link beams of short, intermediate or long length

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In this paper a model is developed for steel links. The theoretical development of the model is based on the approach proposed by Ramadan and Ghobarah although some modifications are introduced. The model consists of five elements connected in series. The central element has the same length and moment of inertia as the link and simulates the elastic flexural behaviour of links (the shear stiffness of this element is fixed at infinity). The two elements on each end are zero-length. They connect the beam segments outside the link to the flexural element of the link and reproduce the behaviour of the links in shear (in both the elastic and inelastic ranges) and the inelastic behaviour of the links in flexure. The force–displacement relationship of the shear spring and the bending moment–rotation relationship of the flexural spring are schematized by means of the uniaxial material model recently proposed by Zona and Dall'Asta for steel buckling restrained braces. The parameters that characterise the response of the shear and flexural springs are adjusted on the basis of laboratory tests on short and long links. The effectiveness of the model with the average values of the calibrated parameters is proved for short, intermediate and long links and compared with that of other models often used in non-linear dynamic analysis of eccentrically braced frames.

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1. Introduction

The seismic performance of eccentrically braced structures is strongly affected by the response of the steel link beams. The inelastic behaviour of these members may be governed by shear, flexure or shear combined with flexure, depending upon their geometric and mechanical properties. The axial force may also affect their response significantly if these members are part of frames with D-type geometric configuration [1]. As proved by many experimental tests, e.g. [1–14], the seismic performance of the links is strongly influenced by the flange and web stiffeners and by the connections to the adjacent members. The ultimate internal forces of the links are much higher than the plastic resistances because of the kinematic and isotropic hardening of steel and gradual yielding of the section at large deformations.

Owing to their higher deformation capacity, short links are generally preferred in practice. Intermediate length and long links are used, instead, occasionally and especially in cases where, for architectural purposes, large openings are required in braced bays. Because of the much wider use of short links, numerical models have been developed chiefly for this type of link [2,15–18]. Most of these models [15–18] are fairly simple and usually based on the combination of elements separately devoted to the flexural and shear responses. Roeder and Popov [15] modelled the link as a sandwich beam and considered the responses of the flexural and shear elements as bilinear with kinematic hardening. The web yielded in pure shear and the flanges in flexure under uniaxial stresses. Isotropic hardening was considered only for the shear element. A more complex model was proposed some years later by Ricles and Popov [16]. This model consisted of a linear elastic beam element with nonlinear zero length hinges at the ends. Each hinge consisted of a series of sub-hinges with rigid-plastic force–deformation and moment–rotation relationships and the sub-hinges were combined to reproduce a multilinear behaviour. Yielding of each sub-hinge was defined by means of a shear force–bending moment yield surface. While isotropic and kinematic hardening was considered in shear, only kinematic hardening was considered in flexure. The rate of expansion of the yield surface due to shear yielding was expressed as a function of the plastic shear deformation. As observed in [17], this model was accurate but required extensive knowledge of computer programming to be used. Owing to this, Ramadan and Ghobarah [17] proposed a similar model but with simpler ending hinges. In particular, two independent flexural and shear hinges were defined at each end. The flexural hinge consisted of three flexural sub-hinges with kinematic hardening only while the shear hinge consisted of three shear sub-hinges with

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both kinematic and isotropic hardening. Also in this case the rate of expansion of the yield surface due to shear yielding was expressed as a function of the plastic shear deformation. The model proposed by Ramadan and Ghobarah was modified later by Richards and Uang [18] to better describe the response of links made of A992 grade steel. In particular, the latter researchers proposed different relationships for the response of the three shear sub-hinges and considered only kinematic hardening. They also removed the rotational springs from the model because their study concerned only with short links.

Other models were proposed later to anticipate also the seismic response of intermediate and long links [19–26]. In particular, the simple model proposed in the past by some of the writers consisted of three elements connected in series. The central beam element with concentrated flexural plastic hinges simulated the flexural behaviour of the link. The remaining ending elements were translational springs and simulated the shear behaviour. The behaviour of the flexural hinge and shear spring was elastic–plastic with kinematic strain hardening. The model was suitable for reproducing the main characteristics of the response of links (elastic stiffness, yield and ultimate internal forces), but not proper to provide a thorough description of the cyclic response of links. In particular, it is of concern that the stiffness provided by this model of the link at large deformations is quite different from zero and thus different from the value reported in laboratory tests. This difference may produce errors in the prediction of the response of structures with eccentrically braced frames, particularly when P–Δ effects are expected to be important (e.g. see [27]). The recent model proposed by Malakoutian [22], formally similar to the one used by the authors in the past, is appealing in that it considers a more sophisticated modelling of both the shear and flexural responses of the link. In particular, the central element is a distributed plasticity beam–column element with a fibre cross-section and is aggregated with an independent nonlinear shear force versus shear deformation section. The responses of the shear spring and material of the central element are dictated by a trilinear model that allows the reduction of the lateral stiffness to zero values at large deformations. Two different models are also included to simulate the degradation of the response of short and long links. Specifically, in short links the shear stress is assumed to decrease very quickly to a near zero value after a specified maximum shear strain has been reached. In long links, instead, the slower strength degradation model uses a Coffin–Manson low cycle fatigue curve and a Miner damage accumulation index. The accuracy of the model considered to simulate degradation appears, however, to be questionable because local buckling depends on a number of factors (e.g. spacing of stiffeners, geometric properties of flanges, web and stiffeners) which are not considered explicitly in the calibration of the model. Finally, a description of the procedure followed for the calibration of the parameters of the model is not reported.

In recent years, finite element models [8,28–35] were also developed to predict the response of links in more detail and generalize the results of the laboratory tests to ranges of geometric and mechanical properties not fully investigated yet. However, because of the computation burden and complexity of these models, they are not suitable for inelastic dynamic analyses of structures with eccentric bracings.

In this paper, the authors develop a simple but fairly refined model of the link. The model consists of an elastic beam with plastic shear and flexural hinges concentrated at its ends. The response of the hinges is dictated by the uniaxial material model recently proposed by Zona and Dall'Asta [36] for buckling restrained braces and now present in the program OpenSees [37]. This model allows a gradual variation of the flexural and shear stiffness of the link and considers both kinematic and isotropic hardening.

The model neglects the effect of the axial force and thus it is intended for links of buildings with split-K eccentric braces only. Further, the model does not consider any degradation of stiffness and strength of links and thus it is suitable for simulating only the stable part of the cyclic response of links.

The model parameters that mostly characterise the post-yield response of the shear and flexural hinges are first calibrated to simulate separately the response of short and long links tested in the past by several researchers. The calibration procedure is thoroughly described so as to allow other researchers and engineers to retrace it in the case of specific link sections. The average values of the parameters returned by the calibration procedure are validated on the short and long links above and on a set of intermediate length links. Finally, the response predicted by the model developed is compared with that obtained by means of other models present in the literature.

2. The proposed model

The adopted link model consists of five elements connected in series (Fig. 1). The central element (EL0) has the same length and moment of inertia of the link and simulates the flexural elastic behaviour of the link (the shear stiffness of this element is infinity). The two elements on each end of the link (EL1 and EL2) are zero length and connect the beam segments outside the link to the central element EL0. While the first of these two elements (EL1) simulates the elastic and inelastic shear behaviour of half a link, the second (EL2) simulates the inelastic flexural behaviour of the ending part of the link (the elastic stiffness of this element is assumed equal to infinity). The nodes of EL1 are allowed to have only relative vertical displacements; those of EL2 may have only relative rotations.

3. Inelastic response of elements EL1 and EL2

The response of the two elements EL1 and EL2 is defined by means of the model proposed by Zona and Dall'Asta [36] for buckling restrained braces. This model considers the isotropic hardening explicitly and represents an improvement of the elasto-plastic models with kinematic hardening used in some studies on buckling restrained braces [38,39]. The model of Zona and Dall'Asta considers a simple rheological scheme where a spring "0" is connected in series with a friction slider in parallel with a spring "1" (see Fig. 2). The stiffness of the spring "0", named k_0, is equal to the initial elastic stiffness of the element while the stiffness of the spring "1", named k_1, influences the post-yield behaviour of the element. The hysteretic response is described by the nonlinear relationship between force and deformation in the friction element. The model considers one internal variable $\delta_1(t)$ which represents the deformation of the elastic-friction component, i.e. the plastic deformation. Being $\delta(t)$ the total deformation and $\delta_0(t)$ the deformation of the spring "0", the increment in the deformation of the latter spring is

$$\dot{\delta}_0(t) = \dot{\delta}(t) - \dot{\delta}_1(t) \tag{1}$$

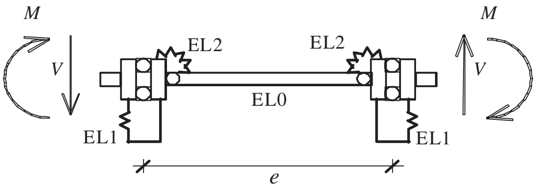

Fig. 1. Proposed model of the link.

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