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A constitutive model for a novel modular all-steel buckling restrained brace

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ABSTRACT

Buckling Restrained Braces (BRBs) are installed in buildings to control lateral displacements caused by seismic events. Modelling BRBs involves predicting their hysteretic load–deformation curve and failure. We can distinguish between global models, adjusted with experimental tests, and local models, based on the constitutive equations for materials. Local models are usually implemented in FEM codes and, while they also require experimental verification, they can be extended to a wider range of geometries and materials.

In this paper a new material constitutive model is proposed for predicting the hysteretic response and failure of a new all-steel BRB. This BRB offers an almost symmetric response for both compression and tensile loading because of the low interaction between the core and the restraining unit. The hysteretic behaviour is simulated using a combined isotropic and kinematic hardening as a function of the plastic flow. Damage is computed using an uncoupled analysis based on a continuum damage mechanism model. The results from the tensile and BRB tests are used to adjust and verify the model.

The model has been implemented in an FEM commercial code and has proved effective in simulating the hysteretic response and predicting the failure point of the new all-steel BRB. The model presented could be extended to BRBs in general, although interaction between the core and the restraining unit would have to be taken into account.

1. Introduction

Buckling Restrained Braces (BRBs) are installed in buildings to control lateral displacements caused by seismic events. They are composed of a slender interior steel bar – core – and an exterior restraining unit. The core resists tensile and compression forces and dissipates energy by yielding, while the restraining unit stabilizes the core when compressed. The restraining unit has been designed to be either a hollow steel bar filled with mortar or an all-steel member [1].

BRB's response can be predicted by global or local models. Global models require full scale tests and so should be restricted to similar brace types. Local models require constitutive equations for materials, FE modelling and testing for model validation, however, they can also be extended to a wider range of braces (i.e. other geometries and materials) and so should reduce costs as experimental tests can be substituted by virtual tests. Essentially two prediction models are required for building design: the BRB load–displacement (or hysteretic) response along with a low-fatigue model to predict failure. The first model depends on the core load–deformation response and its interaction with the restraining unit, whereas the second depends on the core.

Our work is based on actual state-of-the-art local modelling for conventional – mortar filled – BRBs and all-steel BRBs. López-Almansa et al. [2], propose a model for conventional BRBs that considers metal plasticity, using either isotropic or kinematic hardening, plus scalar indexes to govern the isotropic damage in the core and in the mortar. All-steel BRBs are easier to simulate than conventional BRBs as the interaction between the encasing member and the core do not involve mortar cracking and the traditional rubber or silicone layer is substituted by an air gap. Yoshida [3] initially proposes a viscoplastic constitutive model to simulate the behaviour of steel under large plastic displacements and then follows up with a two surface model [4,5]. Kim et al. [6] propose a two surface model for metallic plate dampers with a damage parameter governed by the dissipated energy. Martinez et al. [7] propose a plastic damage model based on the combination of isotropic and kinematic hardening and a damage variable to predict failure. Bonora [8] defines a model with isotropic hardening based on Continuum Damage Mechanisms to reproduce ductile failure. This model is modified to include kinematic hardening

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and the authors [9] suggest that damage only increases under tension. Bonora et al. [10] adapt the model for structures under a multi-axial state of stress by considering isotropic hardening. Pirondi et al. [11] run several tests and simulations and compare the results to the models of Bonora et al. [10] and Leblond et al.[12]. Models from commercial software [13] allow isotropic and kinematic hardening to be combined at a constant ratio but they do not satisfy both the initial low amplitude, nor the fully developed amplitude cycles (at advanced stages of plastic deformation).

In this paper we propose a model for the material that is based on the continuum damage mechanism model defined by Bonora and Newaz [9] and combines kinematic and isotropic hardening as a function of the plastic flow. The model has been successfully applied to predict the hysteretic response and failure of a new all-steel BRB [14].

2. Constitutive model

We define a steel constitutive model to reproduce the hysteretic response and the low cycle fatigue of BRBs. We formulate it in an implicit integration algorithm, to ensure reliable results, and use a multi-axial constitutive law as the yielding direction is not unique.

2.1. Plasticity

Taking into consideration small deformations, the additive decomposition of the strain tensor ε_{ij} is:

$$\varepsilon_{ij} = \varepsilon^E_{ij} + \varepsilon^P_{ij} \tag{1}$$

where ε^P_{ij} and ε^E_{ij} are the plastic and elastic strain tensors, respectively.

Within the Von Mises concept, a yield criterion of mixed hardening is considered [15]:

$$f(s_{ij}, \alpha_{ij}, K) = \sqrt{\frac{3}{2}}\|s_{ij} - \alpha_{ij}\| - \sigma_y - K(r) \leqslant 0 \tag{2}$$

where σ_y is the yielding stress, r is an internal hardening variable, s_{ij} is the stress deviator, α_{ij} is the kinematic hardening tensor and $K(r)$ is the function that defines the evolution of the isotropic hardening. $\|x_{ij}\| = x_{ij}x_{ij}$. Fig. 1 shows the evolution of the yielding surface in the stress space.

The evolution of the internal variables are described using the scalar r from the flow rule:

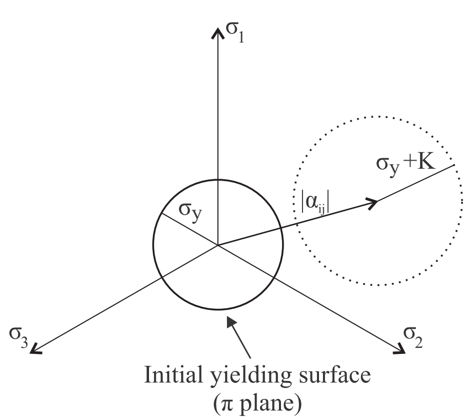

Fig. 1. Evolution of the yielding surface.

$$\dot{\varepsilon}^P_{ij} = \dot{r}\frac{s_{ij} - \alpha_{ij}}{\|s_{ij} - \alpha_{ij}\|} \tag{3}$$

where $\dot{\alpha}_{ij} = \beta\dot{\varepsilon}^P_{ij}$ and $\beta(r)$ is a function that defines the kinematic hardening.

2.2. Damage

The model considers an uncoupled damage analysis [9], which is based on the continuum damage mechanism model, where the damage variable (D) considers both the effects of the irreversible processes in the micro-structure (evolution and creation of the voids) and in the macro scale (macro cracks) of the material:

$$\dot{D} = \alpha' \frac{(D'_{cr} - D_0)^{(1/\alpha')}}{\ln(\varepsilon_{cr}/\varepsilon_{th})}\left(\frac{2}{3}(1+v) + 3(1-2v)\left(\frac{\sigma_H}{\sigma_{eq}}\right)^2\right) \times (D_{cr} - D)^{\frac{(\alpha'-1)}{\alpha'}}\frac{\dot{r}}{r} \tag{4}$$

where D'_{cr} is defined as 1 [9] and D_0 is the initial damage, ε_{th} is the strain at which damage starts, ε_{cr} is the failure strain from the tensile test, v is the Poisson's ratio, α' is a material parameter which defines the shape of the damage curve and σ_H and σ_{eq} are the hydrostatic stress and the Von Mises stress, respectively. The critical damage (D_{cr}) corresponds to the material failure produced by a macro crack, and can be formulated as [16]:

$$D_{cr} = 1 - \frac{\sigma_R}{\sigma_u} \tag{5}$$

where σ_R and σ_u are the rupture and the maximum stress, respectively, obtained from a tensile test.

3. Implementation

3.1. Algorithm

The algorithm entries are the current step deformation ε_{n+1} and the set of the internal variables ($\bullet$) from the previous step: $\varepsilon^P_n, \varepsilon^E_n, \alpha_n$ and r_n. The outputs of the algorithm will be the updated values of the internal variables, the stress tensor and the constitutive tangent tensor. The algorithm works by applying the following steps:

1. Compute elastic trial state
2. IF $f_{n+1} \leqslant 0$ THEN
   Elastic step: $(\bullet)_{n+1} = (\bullet)_n$ & EXIT
3. IF $f_{n+1} > 0$ THEN
   Plastic step: GO TO Step 4
4. Return mapping algorithm
   WHILE ABS(f_{n+1}) < TOLER DO
   Increment of plastic parameter:
   $\Delta r = \frac{f_{n+1}}{\frac{3}{2}(2G+\beta)}$
   Update the internal variables
   $r_{n+1} = r_n + \Delta r$
   $\Delta\varepsilon^p_{ij} = \frac{s_{ij}-\alpha_{ij}}{\|s_{ij}-\alpha_{ij}\|}\Delta r$
   $(\varepsilon^P_{ij})_{n+1} = (\varepsilon^P_{ij})_{n+1} + \Delta\varepsilon^p_{ij}$
   $(\varepsilon^E_{ij})_{n+1} = (\varepsilon^E_{ij})_{n+1} - \Delta\varepsilon^p_{ij}$
   ...
   $(\alpha_{ij})_{n+1} = (\alpha_{ij})_{n+1} + \beta\Delta\varepsilon^p_{ij}$
   f_{n+1}
   where G is the shear modulus.