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Effect of buckling-restrained brace model parameters on seismic structural response

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ABSTRACT

This paper illustrates the derivation of response sensitivities for a hysteretic model specifically developed for buckling-restrained braces (BRBs) in order to provide a tool that can be used to evaluate the effect of BRB constitutive parameters on structural response as well as a tool in gradient-based methods in structural optimization, structural reliability analysis, and model updating. The adopted BRB model, shown in an earlier study to give accurate predictions of the experimental behaviour of BRBs, is differentiated with respect to its material constitutive parameters using the direct differentiation method (DDM) and the obtained response sensitivities are validated by comparisons with the finite difference method (FDM). Results for a case study consisting of a steel frame with BRBs subjected to seismic input are reported to illustrate the influence on global and local structural response quantities of the BRB constitutive parameters. In addition, the derived response sensitivities are used in a simulated finite element model updating problem to show the efficiency of DDM over FDM. This work opens the way to many applications and potentialities such as sensitivity analysis of complex BRB design solutions, performance-based selection of optimal BRB properties, development and use of optimization-based design procedures.

1. Introduction

Buckling-restrained braces (BRBs) are used in seismic areas for both new construction and rehabilitation of existing structures due to their effective and stable energy dissipation capacity, as shown in many experimental and numerical studies, e.g., [1–23]. Although different typologies are available, basically a BRB is made of a ductile core and an external sleeve that precludes global buckling of the core in compression. An unbonding material and/or a small gap between the steel core and the external sleeve is provided to avoid the transfer of axial force between the two components. Because buckling is prevented during the compression phase, the BRB core can yield both in tension and compression; thus, it dissipates seismic energy through the hysteretic behaviour of the core material. However, the global behaviour of the BRB can't be relied upon to replicate the local behaviour of its core material. Tension–compression asymmetry is observed with force resisted in compression about 10 to 15% higher than forces resisted in tension due to friction between core and sleeve in compression fostered by a limited core buckling made possible by the clearance left between the core and the sleeve [1,3,14]. Other aspects requiring attention in model-based analysis of BRBs are the description of their isotropic hardening that can be significant due to the capacity of sustaining stable hysteresis loops at high strains [1–3], and the calculation of the cumulative plastic deformation needed for verifications based on BRB capacity models [24–26]. In order to incorporate within a mathematically simple and physically consistent formulation the tension–compression asymmetry, the hardening behaviour as observed in experimental tests, and the direct evaluation of plastic strain, a constitutive elastoplastic model specifically developed for BRBs was presented in [27]. Such a constitutive model requires only one internal variable (plastic strain), has a simple physical interpretation, allows straightforward control of the dissipative properties of the model and direct computation of the response quantities related to failure and dissipated energy as derived from the plastic strain. Various experimental test results available in the literature were compared to the response results obtained using the proposed model, showing good predictions of the experimental behaviour of different BRBs subjected to symmetric and non-symmetric cyclic loadings with variable amplitudes [27].

The availability of a proper cyclic model for BRBs in a finite element (FE) software for nonlinear dynamic analysis is important for an accurate seismic assessment of the structural behaviour of constructions equipped with BRBs, especially when BRBs are the only lateral resisting components, as is the case in braced non-moment resisting steel frames.

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In these situations, the post-elastic stiffness of BRBs is limited and hardening might not be sufficient to avoid soft-storey formations [28–30]. In addition, given that various BRB typologies are available, each with its cyclic behaviour defined by a specific set of constitutive parameters, it is important, together with accurate response models, to have qualitative and quantitative information on the influence of such parameters on the seismic response of the structure. This information can be efficiently obtained through response sensitivity analysis [31], a very efficient tool for gaining deeper insight into the effect and relative importance of a large number of modelling and design parameters that otherwise would require extensive parametric analyses. In addition, response sensitivities have useful applications in gradient-based methods used in structural optimization [32], structural reliability analysis [33], and model updating [34]. A first application of response sensitivity analysis for the study of the behaviour of steel frames with BRBs was presented in [35] where response sensitivities were computed with respect to the brace section area (geometric parameter at the element level) and used to gain insight into the tendency to soft storey formation, as influenced by brace over-strength distributions. Conversely, response sensitivities with respect to the BRB constitutive parameters (material level) remained unexplored despite their important applications. Thus, the objective of this paper is to provide a sensitivity-based tool for studying the influence of the BRB constitutive parameters on the seismic response of structures equipped with such bracing systems. To this end, the response sensitivities of the BRB cyclic model presented in [27] are derived with respect to its constitutive parameters (elastic modulus, initial yield stress, ultimate stresses in tension and compression, hardening moduli in tension and compression, hardening rates in tension and compression, elastic-to-plastic transition shape parameters in tension and compression) using the direct differentiation method (DDM), i.e., response gradients are obtained by analytically differentiating the governing equations, a method proven accurate and efficient especially for nonlinear static and dynamic FE response sensitivity analysis [31,36–38]. Both the BRB model [27] and the response sensitivities illustrated in this paper are implemented into the open source FE software OpenSees [39] to make them available to the structural engineering community, taking advantage of the fact that OpenSees provides capabilities for DDM-based response sensitivity analysis [40,41].

In this paper the analytical formulation of the elastoplastic constitutive model for BRBs [27] is briefly reviewed, its time-explicit and time-implicit integration algorithms are presented, and the derivation of response sensitivities to the material constitutive parameter is illustrated. Response sensitivity results obtained using DDM are validated by comparisons with those obtained using the finite difference method (FDM) [31]. Results for a braced non-moment resisting steel frame under seismic excitations are reported to illustrate the use of the presented approach to evaluate the influence of the constitutive parameters considered independent for each BRB on the predicted global and local structural response quantities. In addition, response sensitivity results are used in the considered case study in a simulated FE model updating problem to show the efficiency of DDM over FDM.

2. BRB model for response analysis

2.1. Time-continuous formulation

The BRB constitutive behaviour is modelled with a rheological scheme (Fig. 1) consisting of a spring "0" (with stiffness E_0) in series with a friction slider (with one internal variable, i.e., its plastic deformation ε_{pl}) in parallel with a spring "1" (with stiffness $\beta_t E_0$ in tension and $\beta_c E_0$ in compression) from which the following evolution laws are derived [27]:

$$\dot{\sigma}(t) = \dot{\sigma}_{el}(t) = E_0\dot{\varepsilon}_{el}(t) = E_0\left(\dot{\varepsilon}(t) - \dot{\varepsilon}_{pl}(t)\right) \tag{1}$$

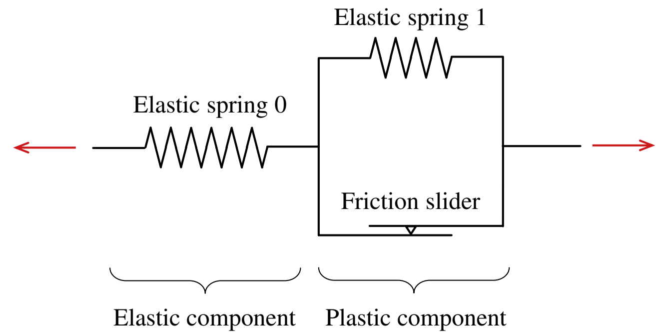

Fig. 1. Elastoplastic rheological model.

$$\dot{\sigma}_1(t) = \begin{cases} \beta_t E_0 \dot{\varepsilon}_{pl}(t) & \text{if } \dot{\varepsilon}(t) > 0 \text{ and } \sigma(t) > 0 \\ \beta_c E_0 \dot{\varepsilon}_{pl}(t) & \text{if } \dot{\varepsilon}(t) < 0 \text{ and } \sigma(t) < 0 \\ 0 & \text{otherwise} \end{cases} \tag{2}$$

$$\dot{\mu}(t) = \left|\dot{\varepsilon}_{pl}(t)\right| \tag{3}$$

where σ is the stress resisted by the model, σ_{el} is the stress and ε_{el} the strain in spring "0", σ_1 is the stress in the spring "1", μ the cumulative plastic deformation, and a superimposed dot represents the derivative with respect to time. The plastic flow rules furnishing the time evolution of the internal variable ε_{pl} are [27]:

$$\dot{\varepsilon}_{pl}(t) = \begin{cases} \left|\dfrac{\sigma(t) - \sigma_1(t)}{\sigma_{y,t}(t)}\right|^{\alpha_t} \dot{\varepsilon}(t) & \text{if } \dot{\varepsilon}(t) > 0 \text{ and } \sigma(t) > 0 \\ \left|\dfrac{\sigma(t) - \sigma_1(t)}{\sigma_{y,c}(t)}\right|^{\alpha_c} \dot{\varepsilon}(t) & \text{if } \dot{\varepsilon}(t) < 0 \text{ and } \sigma(t) < 0 \\ 0 & \text{otherwise} \end{cases} \tag{4}$$

where $\sigma_{y,t}$ and $\sigma_{y,c}$ are the yield stresses in tension and compression respectively, α is a positive nondimensional constant that controls the trend of the transition from the elastic to the plastic range, i.e., a higher value of α fosters the tendency to a sharper transition from the elastic to the plastic range, and a lower value of α gives a smoother and more progressive transition from the elastic to the plastic range (subscript "t" refers to tension and "c" to compression) [27]. The hardening rules that give the increments of the yield stresses in tension and in compression are nonlinear functions of the cumulative plastic deformation and are given by [27]:

$$\dot{\sigma}_{y,t}(t) = \left(\sigma_{y\max,t} - \sigma_{y0}\right) \exp\left(-\frac{\mu(t)}{\delta_{r,t}}\right) \frac{\dot{\mu}(t)}{\delta_{r,t}} \tag{5}$$

$$\dot{\sigma}_{y,c}(t) = \left(\sigma_{y\max,c} - \sigma_{y0}\right) \exp\left(-\frac{\mu(t)}{\delta_{r,c}}\right) \frac{\dot{\mu}(t)}{\delta_{r,c}} \tag{6}$$

where σ_{y0} is the initial yield force, $\sigma_{y\max}$ the maximum yield force for the fully saturated hardening condition, δ_r is a positive non dimensional constant that influences the rate of hardening, i.e., a higher value of δ_r results in a slower hardening [27]. Damage models, e.g. softening after necking, plastic fatigue and fractures, are not included in order to keep the analytical formulation as simple as possible for the sake of numerical efficiency and to allow its subsequent analytical differentiation with respect to the sensitivity parameters.

The above time-continuous analytical formulation must be discretized when used within time-discrete solution frameworks, as is the case in nonlinear dynamic finite element analysis of structural