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Validated finite element techniques for quasi-static cyclic response analyses of braced frames at sub-member scales

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ABSTRACT

In this study, a numerically robust finite element procedure is described, which is based on explicit time-stepping, for high-fidelity simulations of inelastic and post-buckling cyclic responses of braced frame systems. The use of an explicit time-stepping method with properly chosen increments permits accurate results while avoiding (implicit) equilibrium iterations throughout the entire loading history, during which multiple yielding and buckling events occur. A number of essential techniques for properly calibrating the discrete models and to constrain their responses in order to obtain quasi-static outcomes are provided. The procedure is globally and locally validated (verified) using experimental data (implicit numerical simulations) from three types of specimens—namely, individual braces, and single and multi-story braced frame systems with diagonal and X-brace arrangements—under both monotonic and cyclic loading protocols. Results from these validation and verification studies indicate that the proposed simulation methodology can accurately capture sub-member (i.e., plastic hinges), member, and system behavior very accurately; and thus, it can be confidently used—e.g., as a virtual laboratory—to predict the responses of braced frames with configurations and dimensions other than those tested, and to seek optimum designs beyond those offered by basic guidelines.

1. Introduction

Braced frame systems are presently being designed to satisfy performance-based seismic design (PBSD) criteria [1,2]. They are required to exhibit significant ductility while undergoing multiple yielding events. The "*life safety*" and "*collapse prevention*" PBSD limit states are governed by inelastic post-buckling and tensile yielding behaviors of the brace elements, which are coupled to the main frame through gusset-to-brace connections. As such, both local and global responses of braced frames are highly dependent on the behavior of their gusset–brace sub-systems. Consequently, gusset–brace systems must be accurately modeled and analyzed to avoid unexpected premature failure modes and to meet the overall system performance objectives.

There are essentially three main varieties of modeling approaches for brace elements—phenomenological, physics-based analytic/semi-analytic, and fully discrete. Phenomenological models (e.g., Zayas et al. [3]; Ikeda et al. [4]; Khatib et al. [5]) offer computational efficiency, and can be easily implemented into existing computer codes. In this approach, braces are typically represented by truss elements that display hysteretic behavior, calibrated to mimic experimentally observed responses. The obvious shortcoming of this approach is that the said hysteretic elements can only confidently represent the behavior of the specimens with which they were calibrated. More specifically, a phenomenological model cannot, in general, capture the effects of different boundary conditions or differentiate the hysteretic responses of two elements with identical cross-sectional areas and different moments of inertia.

In the second modeling approach, usually beam-column finite elements that possess a pre-computed buckling mode shape of the brace are employed, and the physical properties of the brace (i.e., cross-sectional geometry and material yield stress) are used in a variety of ways to capture the post-buckling responses. Models that can be cited under this category include those by Ikeda and Mahin [6], Hall and Challa [7], Jin and El-Tawil [8], Lee and Noh [9]. These models display reasonable agreements with experimental data in the tension-yielding regimes; but they are generally less accurate in representing the compressive/buckling responses of the braces. Other nominal difficulties for models under this category include the consideration of partial end-restraints, Bauschinger effects, and compressive strength reductions under

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cyclic loading. Studies by Uriz et al. [10] and later by Hsiao et al. [11] can be cited among state-of-the-art examples in this category, who employed force-based frame elements with fiber-based cross-sectional discretization for distributed plasticity, and co-rotational kinematics for finite deformations. Incidentally, the computational expense of such models approaches those in the third category [12].

The third, and the most general, approach is to model and analyze brace elements using three-dimensional finite element models (3D-FEMs). If carefully constructed with adequate plasticity models and endowed with finite-deformation kinematics, these models produce results that display excellent agreement with experimental observations/measurements (see, for example, Yoo et al. [13], and Lumpkin et al. [14]). 3D-FEMs are complex and bear a commensurately high computational expense. As such, they are not yet suitable for routine design tasks. However, due to their high accuracy, they can supplement experimental data and allow system/element behavior to be probed under different loading scenarios through parametric studies. Recent examples adopting this approach include studies by Chou and Chen [15], and Wigle and Fahnestock [16] who evaluated performance of buckling restrained braces as well as Yoo et al. [17,18], Nip et al. [19], Wrad et al. [20], and Nascimbene et al. [21] who investigated post-buckling responses of individual braces and braced frame systems.

Finite Element (FE) models can also be used to explore, in detail, the behavior of gusset plates and brace-to-gusset plate connection details, possible yield mechanisms, and probable failure modes in braced frame systems. In order to achieve practically useful results from simulations with FE models—with requisite accuracy in both the global and local responses—the adopted constitutive models and analysis techniques must be efficient and exhibit numerical stability and convergence. The use of commercial software packages in their default settings do not, in general, produce viable results for the analyst, because the aforementioned problems involve large deformations and inelastic strains under multiple load reversals. The pertinent literature in this area—i.e., three-dimensional FE analyses of braced frames in post-buckling regimes under reversed cyclic loads—is sparse (a notable recent example is the study by Lumpkin et al. [14]); and the offerings are essentially confined to results only, with little information given on the modeling and analysis details, how convergence is achieved, and what the sensitivity of computed responses to the analysis parameters (e.g., solution increment, mesh refinement, initial imperfections, etc.) are.

As such, the objective of the present study is to identify a validated set of *robust* procedures for modeling and simulating the response of steel frames at sub-member scales (i.e., centimeters) under general cyclic loading conditions including the *post-buckling regimes*. The procedures herein presented are *broadly applicable*—i.e., they can be carried out in a straightforward manner using most of the commonly available/used commercial finite element analysis packages. This work is a substantial extension of earlier efforts (as an overture) in this area presented in Lotfollahi et al. [22,23].

The adopted track of analysis method is based on explicit time-stepping, which inherently involves no equilibrium iterations, and thus, it is computationally robust; but, of course, adequately small (pseudo-) time increments are required for maintaining stability. However, even with the increased number of load/time increments, the explicit procedure will be computationally more efficient than an implicit approach for braced frames, which exhibit multiple interacting modes in their inelastic and nonlinear responses (i.e., global and local buckling, snap-through/back behavior, yielding, and fracture). The explicit procedure circumvents equilibrium iterations, and requires less memory allocation. It also typically scales better in parallel computations.

Similar approaches have been adopted in previous studies for a variety of structural engineering problems: For example, Yu et al. [24] performed FE simulations of bolted steel connections with contact mechanics at ambient and elevated temperatures using explicit dynamics. Dhanasekar and Haider [25] proposed explicit FE procedures for lightly reinforced masonry shear walls, wherein the effect of kinetic energy as well as proper selection of explicit integration parameters were discussed. Green et al. [26] performed nonlinear explicit finite difference analyses in order to outline the calibration and validation of the numerical models for determining the dynamic response of a cantilever retaining wall. Karapitta et al. [27] developed an explicit time-stepping method for in-plane cyclic loading of masonry walls for expanding experimental results. Nonlinear explicit FE analyses were also employed by Son and Lee [28] who simulated the blast resistance of cable-stayed bridge pylons; and by Jayasooriya et al. [29] who investigated the impact of near field explosions in the nonlinear plastic response of reinforced concrete frames. Sun et al. [30] evaluated the progressive collapse behavior of steel buildings under fire conditions; and Salih et al. [31] examined the net-section rupture of stainless steel single angles that are bolt-connected to gusset plates using explicit integration methods.

The present paper—to the best of the authors' knowledge—delineates, for the first time, a set of systematic procedures for finite element model calibration and parameter evaluation that enable robust simulation of individual bracings as well as braced frame systems under reversed cyclic loads with high fidelity down to the scale of the interconnects using explicit time-stepping. The solution does not require strenuous trial and error load increment adjustments; nor does it bear any specific limitations on the material properties and imperfection magnitude during the subsequent cycles of lateral loading as required in implicit analyses. The presented procedure—henceforth referred to as the *cyclic explicit dynamic* (CED) analysis procedure—is globally/locally validated (verified) using test data (numerical records) available in open literature. It is presented in an algorithmic and generalized format so that it can be applied to frames and sub-systems other than those employed in the present study, and can be used in a straightforward manner for a variety of purposes, including the identification of possible yield mechanisms and failure modes.

The remainder of the manuscript is organized as follows: In Section 2, the test specimens used for model verification and validation are described. In Section 3, a procedure is presented for calibrating the material parameters; finite element models are developed; and mesh refinement and sensitivity studies (with respect to modeling parameters) are carried out. In Section 4, the proposed CED method is presented in detail; verification and validation studies are carried out; and comparisons are made with results from implicit static solutions. Conclusions and recommendations are provided in Section 5.

2. Description of test specimens used in model verification and validation

2.1. Gusset–brace systems

The first dataset that will be used are from tests conducted at UC-Berkeley by Black et al. [32]. Their general testing arrangement for pinned–pinned ends and pinned–fixed ends are shown in Fig. 1(a and b). Model validation/verification studies are performed on three different gusset–brace systems with hollow square, circular, and double angle sections, which are henceforth referred to as struts "17", "20", and "24", respectively. Details of specimen geometries, boundary conditions, material properties, and buckling loads are given in Table 1, wherein the experimental buckling loads