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Criteria for balanced design of diagonally braced moment resisting frames based on hierarchical yielding and failure sequences and their application

M. Lotfollahi [a,1], M.M. Alinia [a,2], E. Taciroglu [b,*,2]

[a] Department of Civil Engineering, Amirkabir University of Technology, Tehran, Iran
[b] Department of Civil and Environmental Engineering, University of California, Los Angeles, CA 90095, USA

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ABSTRACT

Inelastic behavior of diagonally braced moment resisting frame (DBMRF) dual systems are investigated to determine their yield mechanisms and failure modes, and to quantify the load sharing between the moment frame and the gusset–brace subsystems. An improved performance is sought through new balanced design criteria that will increase a DBMRF system's ductility, and permit yielding in multiple secondary stages at selected performance levels. The presented balanced design approach is based on a non-dimensional formulation, which addresses both tensile yielding and compressive buckling phases of DBMRF systems and considers the participation of all system constituents. The satisfaction of the proposed balanced design criteria is achieved through parametric studies carried out with high-fidelity three-dimensional finite element (FE) models that are globally and locally validated/verified against experimental data/numerical simulations available in open literature. Using the validated FE models, the collapse behavior of a representative set of DBMRF systems are examined, and the influences of the brace elements' demand-to-capacity ratios, as well as the gusset plate connection types/sizes on the yield mechanisms and the failure modes are scrutinized. Both pushover and cyclic analyses are carried out; and the overall system ductility and energy dissipation values are investigated for different width-to-height ratios. The responses of system constituents are evaluated using the specified, as well as the expected material properties. The worked examples clearly demonstrate the utility of the proposed balanced design criteria in improving the DBMRF systems' ductility, and in avoiding premature failure modes.

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1. Introduction

The key aspect of a braced moment resisting frame (BMRF) system is its dual character, which is manifested through the behavior and interaction of its two subsystems—*viz.*, the moment frame and the gusset–brace systems. The collapse mechanisms, energy dissipation, and ductility of a BMRF system can be controlled through design; and thus, BMRF systems can be gainfully utilized to meet the most severe seismic performance objectives. BMRFs come in a variety of different configurations and geometries, but typically comprise diagonal bracing members connected to a primary moment frame system with gusset plate connections. During earthquake loading, the braces must be capable of sustaining multiple cycles of inelastic tensile yielding as well as compressive buckling without any significant deterioration in their stiffness or strength. These primary mechanisms should be balanced with the other (complementary) ductile mechanisms of the system, so that the frame can tolerate inelastic deformations and dissipate energy, while various undesirable failure modes (e.g., failure of the gusset-to-brace connections) are avoided.

Small inter-story drifts that occur during the initial stages of a cyclic lateral loading scenario (e.g., minor earthquakes) can be accommodated by the brace elements. Brace buckling and initial yielding occur as the lateral loads increase (e.g., moderate earthquakes), and this behavior provides some energy dissipation. Additional lateral loading can initiate plastic hinge formation in the middle, and subsequently, at both ends of the brace element on the gusset plates in the compression phase, and propagation of yielding within the brace element during the tension phase of deformations. At this stage, the frame members become more active; but ideally they will remain in the state of immediate-occupancy (IO) performance level. Further increases in lateral loads (e.g., severe

* Corresponding author. Tel: +1 310 267 4655; fax: +1 310 206 2222.
E-mail address: etacir@ucla.edu (E. Taciroglu).
[1] Ph.D. Candidate. Also visiting Ph.D. Student at the University of California, Los Angeles (UCLA).
[2] Professor.

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earthquakes) lead to the formation of plastic hinges in the panel zones and within the frame members. The aforementioned sequence of events represents the intended functions of the gusset–brace and the moment frame systems for meeting life-safety (LS) and collapse-prevention (CP) performance objectives, and assures ductile response in the BMRF systems. Presently, the ANSI Seismic Design Provisions [1] for Special Concentrically Braced Frames (SCBFs) and Special Moment Resisting Frames (SMRFs) stipulate the aforementioned performance objectives for such systems.

In a BMRF system, the overall performance can be significantly influenced by the nonlinear behavior of its gusset–brace subsystem. In a general sense, the brace members are expected to exhibit ductile behavior under earthquake-induced lateral motions. Numerous research efforts [2–14] have experimentally and analytically explored the cyclic behavior of steel brace members and the findings are recognized in modern seismic design provisions. On the other hand, gusset-to-brace connections are required to exhibit higher capacity than the demands exceeding the capacity of the brace members. Current provisions for gusset-to-brace connections are based on several experimental and numerical studies [15–24] wherein complete frame-action is excluded through inelastic post-buckling deformations of the brace elements. Recent studies [25,26] showed that the existing provisions on gusset plate connections may lead to unintended responses, and offered a modification in the form of a "balanced design approach". This approach enables the connections to be properly designed such that undesirable failure modes are suppressed, yielding through a secondary yield mechanism in the gusset plate connections are assured, and only the desired failure modes in the gusset–brace system are observed. The behavior of gusset plate for buckling-restrained braces [27] and the uses of low yield point and stainless steel gusset plate connections [28,29] have also been the subject of other studies in this area.

The seismic design requirements of a BMRF system are mainly affected by the cyclic behavior of the complete frame system. Preliminary studies had revealed the complex panorama of asymmetric cyclic behavior of braced frame systems, which is primarily due to the alternating tensile yielding and compressive buckling responses of their brace members [30–34]. In those studies, the braces' width-to-thickness and the effective slenderness ratios were identified as the main system parameters that control, respectively, the energy dissipation capacity and resistance to local buckling. The post-buckling regime was reasonably bracketed, and then handled by applying a buckling reduction factor to the brace element's compressive strength. In recent years, a number of studies have focused on the evaluation of the effects of different corner and mid-span gusset plate connection sizes and types on the overall performance of the braced frame systems. These investigations have finally led to the proposition of a new *elliptical clearance* requirement in the design of gusset plate connections [35–37]. More recently, improved analytical models for brace members have been presented in [38]. While these aforementioned studies have improved the performance of braced frame systems, there is yet no work—to the best of the authors' knowledge—that comprehensively evaluates the overall nonlinear inelastic responses of BMRFs. The studies that exist have concentrated either on moment frames with tension-brace action [39], or those with buckling-restrained braces [40].

In the present study, we sought to evaluate multiple secondary yield mechanisms and probable failure modes in diagonally braced moment resisting frame (DBMRF) systems under cyclic loads, as well as within the tensile yielding and the compressive buckling regimes. Since both the local and the global responses of a DBMRF system highly depend on the nonlinear behavior of its gusset–brace subsystem, accurate modeling of that behavior is critical. To that end, we developed highly detailed three-dimensional finite element models, and validated and verified them—both in terms of global and local responses—using published data from both a comprehensive experimental program involving 13 large-scale specimens, which was carried out by Lehman et al. [25], and a companion numerical study, which was executed by Yoo et al. [35]. We then utilized the validated models (and the analysis procedures) in subsequent parametric sensitivity studies to identify DBMRF systems' collapse behavior by assessing their yield mechanisms and failure modes.

We are also proposing herein, a set of new and improved balanced design criteria for DBMRF systems, which prolong yielding in the main frame system through multiple secondary yield mechanisms, so that the system's ductility is enhanced and its drift capacity is increased. The proposed criteria are based on a non-dimensional formulation; address both tensile yielding and compressive buckling phases of DBMRF systems; and consider the participation of all system constituents. Derivation of the said criteria involved both cyclic and monotonic (pushover) parametric studies on DBMRF models with varying gusset-to-brace connection sizes and types as well as different frame geometries and specifications. In these analyses, the DBMRFs' ductilities and energy dissipation values are calculated, and the effects of expected yielding behavior in each model are evaluated. Utilizing those results, we offer in this study:

(1) New hierarchical yielding/failure sequence criteria that suppress the undesirable failure modes entirely and balance the primary yield mechanism against a number of multiple secondary yield mechanisms and desirable failure modes.

(2) A quantified understanding of the interplay between the degree of brace-to-frame rigidity and the brace element's demand-to-capacity ratio (this issue is examined through the DBMRFs' in-plane stiffness, and the brace-to-frame contribution shares in story shears at different stages of lateral loading).

2. Proposed balanced design criteria

To avoid premature (i.e., joint) failures in SCBF systems, Lehman et al. [25] proposed the following expressions (cf., Eqs. (1) and (2) in [25]):

$$R_{yield,mean} = R_y R_{yield} \leqslant \beta_{y1} R_{y1} R_{yield,1} \leqslant \beta_{y2} R_{y2} R_{yield,2} \leqslant \cdots \leqslant \beta_{yi} R_{yi} R_{yield,i} \quad (1)$$

$$R_{yield,mean} = R_y R_{yield} \leqslant \beta_{y1} R_{y1} R_{yield,1} \leqslant \beta_{fail,1} R_{fail,1} \leqslant \beta_{fail,2} R_{fail,2} \leqslant \cdots \leqslant \beta_{fail,i} R_{fail,i} \quad (2)$$

which separate and order the possible yield mechanisms and probable failure modes in the gusset-brace system. Here, R_y denotes ratio of the expected yield stress to the minimum specified yield stress, and $R_{yield,mean}$ denotes the primary yield resistance. The nominal resistances for various secondary yield mechanisms ($R_{yield,i}$) and different failure modes ($R_{fail,i}$) are separated by balancing factors (β_{yi} and $\beta_{fail,i}$) in order to control the resistance of possible secondary yield mechanisms and to maintain a balanced state through the probable failure modes. It is useful to note here that the β factors in Eqs. (1) and (2) are essentially all equal to zero within the existing Load and Resisting Factor Design (LRFD) approach [41].

The β factors considered in the present study are intended for ductility evaluation and nonlinear displacement estimation for an entire DBMRF system. Hence, the above states are substituted with the following expressions:

$$\Delta_y \leqslant \Delta_{y1} \leqslant \Delta_{y2} \leqslant \cdots \leqslant \Delta_{y(i-1)} \leqslant \Delta_{yi} \equiv 1 \leqslant \mu_{y1} \leqslant \mu_{y2} \leqslant \cdots \leqslant \mu_{y(i-1)} \leqslant \mu_{yi} \quad (3)$$

$$\Delta_y \leqslant \Delta_{y1} \leqslant \Delta_{y2} \leqslant \cdots \leqslant \Delta_{y(i-1)} \leqslant \Delta_{yi} \leqslant \Delta_{f1} \leqslant \Delta_{f2} \leqslant \cdots \leqslant \Delta_{fi} \equiv 1 \leqslant \mu_{y1} \leqslant \mu_{y2} \leqslant \cdots \leqslant \mu_{y(i-1)} \leqslant \mu_{yi} \leqslant \mu_{f1} \leqslant \mu_{f2} \leqslant \cdots \leqslant \mu_{fi} \quad (4)$$

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