Best Combination of Design Parameters for Buildings with Buckling-Restrained Braces

Ángel de J. López-Pérez, Sonia E. Ruiz, Vanessa A. Segovia

***Abstract*—**Buildings vulnerability due to seismic activity has been highly studied since the middle of last century. As a solution to the structural and non-structural damage caused by intense ground motions, several seismic energy dissipating devices, such as buckling-restrained braces (BRB), have been proposed. BRB have shown to be effective in concentrating a large portion of the energy transmitted to the structure by the seismic ground motion. A design approach for buildings with BRB elements, which is based on a seismic Displacement-Based formulation, has recently been proposed by the coauthors in this paper. It is a practical and easy design method which simplifies the work of structural engineers. The method is used here for the design of the structure-BRB damper system. The objective of the present study is to extend and apply a methodology to find the best combination of design parameters on multiple-degree-of-freedom (MDOF) structural frame – BRB systems, taking into account simultaneously: 1) initial costs and 2) an adequate engineering demand parameter. The design parameters considered here are: the stiffness ratio ($\alpha = K_{frame}/K_{total}$), and the strength ratio ($\gamma = V_{damper}/V_{total}$); where K represents structural stiffness and V structural strength; and the subscripts "frame", "damper" and "total" represent: the structure without dampers, the BRB dampers and the total frame-damper system, respectively. The selection of the best combination of design parameters α and γ is based on an initial costs analysis and on the structural dynamic response of the structural frame-damper system. The methodology is applied to a 12-story 5-bay steel building with BRB, which is located on the intermediate soil of Mexico City. It is found the best combination of design parameters α and γ for the building with BRB under study.

***Keywords*—**Best combination of design parameters, BRB, buildings with energy dissipating devices, buckling-restrained braces, initial costs.

I. Introduction

THE use of seismic energy dissipating devices such as BRB is increasing in several parts of the world. These have proved to be effective in controlling displacement and absorbing a large portion of seismic energy, thus avoiding damage to the main structure [1]. For this reason, Segovia and Ruiz [2], which are the second and third coauthors of the present paper, have proposed a direct displacement-based design (DDBD) method for buildings with hysteretic energy dissipating devices (including BRBs), which takes into account both service and collapse limit states. The design parameters are defined by the stiffness- and strength-ratio of the main frame structure and the BRBs. In the present study, an extension of reference [2] is presented. Here the design parameters are selected based on the analysis of a set of three MDOF structural systems.

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II. Methodology

The methodology used in this study outlines a scheme for finding the best combination of the design parameters $\alpha = K_{frame}/K_{total}$, and $\gamma = V_{damper}/V_{total}$; where K represents structural stiffness and V structural strength; and the subscripts "frame", "damper" and "total" represent: the structure without dampers, the BRB dampers, and the total frame-damper system, respectively. The methodology considers the initial cost of the combined frame–BRB system and the average of a suitable performance value to establish the BRB efficiency, obtained from several non-linear time-history analyses of the MDOF structure. The steps of the methodology are as follows:

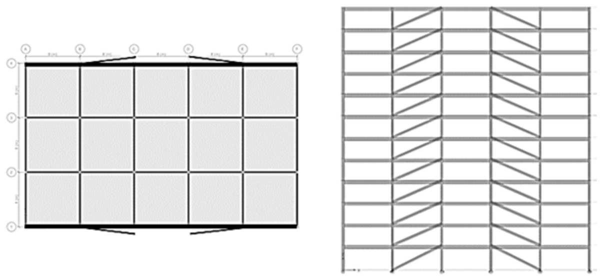
1) Set different combinations of design parameters $\alpha = K_{frame}/K_{total}$ and $\gamma = V_{damper}/V_{total}$.
2) Apply the DDBD method [2], specifying the service and collapse tolerable drifts.
3) Select the commercial steel shapes corresponding to beams and columns [3]. The BRBs are chosen from a commercial catalog [4] with the areas that best approximate the design result.
4) The design obtained for the main frame and BRBs is modeled in a structural analysis program [5].
5) Several ground motion records corresponding to the same family of stochastic processes are selected and scaled.
6) For each one of the selected and scaled records, a non-linear time-history analysis (NLTHA) is done.
7) From the results obtained from each NLTHA, a structural performance parameter (SPP) is calculated. In this study the SPP is the average value for maximum global ductility of the frame-BRB system.
8) The initial costs of the main frame and BRB system are estimated.
9) Then, with the data obtained from step 7 and step 8, a cost-efficiency criterion is applied, and the design parameters are obtained based on the minimum initial cost and the maximum efficiency of the building-damper system.

III. Application Example

A. Case Study

Here it is analyzed a regular 12-levels office steel building (considered as a medium-rise building) located in the intermediate soil of Mexico City, with a soil dominant period of 1.25 s.

The building consists in 5x3 bays equal spaced at 8 m in both directions, as shown in Fig. 1 (a). The first story height is 4.0 m, and the upper stories are 3.5 m high. BRBs are configured as simple diagonals placed in the external frames, as shown in Fig. 1 (b). For accidental loads combinations, the intermediate levels have an un-factored gravitational load of 5.93 kPa and a load of 3.87 kPa on the roof. It is considered that the frame elements are ASTM A572-Gr50 structural steel, and the BRB cores are ASTM A36 structural steel, as in [4].



(a) (b)

Fig. 1 Building geometric configuration (a) Floor plan (b) Exterior frame

B. Application of the Methodology

1. Combination of Design Parameters

Based on conclusions of previous studies ([1], [2] and [6]); for medium-rise buildings, the stiffness ratio parameter appropriate for design should be between 25% and 30%, so in this example, the parameter α was assumed as equal to 0.25. As previously mentioned, for each α value there is a possible range of values of resistances ratio, γ [2]. Table I contains the parameters combinations chosen here for the structural design, as well as some characteristics of the designs.

TABLE I
DESIGN PARAMETERS COMBINATION FOR CASE STUDY

Design parameter	Comb. I	Comb. II	Comb. III
Stiffness ratio, α	0.25	0.25	0.25
Strength ratio, γ	0.30	0.35	0.40
Core and total length ratio, η	0.50	0.65	0.80
Maximum ductility in SDOF system, μ	7.08	5.60	4.70
Main structural period, T_o (s)	2.20	2.30	2.38
Initial period frame-BRB system, T_i (s)	1.10	1.15	1.19

2. Application of the DDBD Procedure

Segovia and Ruiz's [2] DDBD approach was used for the design of the frame-BRB systems under study. For this purpose, a computational code was written.

3. Design of the Structures

Table II shows characteristics of the section properties corresponding to the combination I and combination II. Associated with these results, commercial shapes for columns, beams, and BRBs are selected. Table III shows the selected shapes of beams and columns, as well as the commercial BRB core areas for the structure corresponding to the combination I.

TABLE II
CALCULATED INERTIA IN MAIN FRAME AND BRB CORE AREAS VALUES

Level	Comb. I			Comb. II		
	Column inertia I_c (m^4)	Beam inertia I_v (m^4)	BRB core area (m^2)	Column inertia I_c (m^4)	Beam inertia I_v (m^4)	BRB core area (m^2)
1	5.3E-04	2.7E-04	2.6E-03	4.9E-04	2.4E-04	3.1E-03
2	1.1E-03	6.4E-04	2.5E-03	1.0E-03	5.9E-04	2.9E-03
3	8.2E-04	4.7E-04	2.5E-03	7.5E-04	4.3E-04	2.8E-03
4	1.0E-03	5.8E-04	2.3E-03	9.2E-04	5.3E-04	2.7E-03
5	8.4E-04	4.8E-04	2.2E-03	7.7E-04	4.4E-04	2.5E-03
6	8.9E-04	5.1E-04	2.1E-03	8.1E-04	4.6E-04	2.4E-03
7	7.7E-04	4.4E-04	1.9E-03	7.0E-04	4.0E-04	2.3E-03
8	7.2E-04	4.1E-04	1.8E-03	6.6E-04	3.8E-04	2.1E-03
9	6.0E-04	3.4E-04	1.5E-03	5.5E-04	3.1E-04	1.8E-03
10	4.7E-04	2.7E-04	1.2E-03	4.3E-04	2.5E-04	1.4E-03
11	3.1E-04	1.8E-04	8.6E-04	2.8E-04	1.6E-04	9.9E-04
12	1.4E-04	7.7E-05	3.8E-04	1.2E-04	7.1E-05	4.4E-04

TABLE III
COMMERCIAL SHAPES FOR MAIN FRAME ELEMENTS AND BRB CORE AREAS

Level	Comb. I		
	Column Shape	Beam Shape	BRB standard core area (m^2)
1	W14x211	W21x73	2.7E-03
2	W14x211	W21x73	2.6E-03
3	W14x193	W21x62	2.5E-03
4	W14x193	W21x62	2.4E-03
5	W14x176	W21x55	2.3E-03
6	W14x176	W21x55	2.1E-03
7	W14x159	W21x50	1.9E-03
8	W14x159	W21x50	1.8E-03
9	W14x120	W21x44	1.6E-03
10	W14x120	W21x44	1.3E-03
11	W14x68	W18x35	8.0E-04
12	W14x68	W18x35	6.5E-04

4. Structural Vibration Periods

Once the main frame and BRBs are modeled with their mechanical characteristics in the structural analysis program ETABS 2015 v.1.0 [5], a modal analysis is performed to determine their structural vibration periods; these are compared with those corresponding to the design results of the DDBD methodology. Table IV shows that the vibration periods calculated with both approaches present differences smaller than 10%.

5. Selecting and Scaling the Ground Motions

Five accelerograms recorded in the intermediate soil of Mexico City are used; the peak spectral acceleration of the five records used for the analysis lie between 1.13 s and 1.33

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s, as shown in Fig. 2, where the response spectra for 5% of critical damping are presented. The dominant period (T_s) of the accelerograms selected is similar to the fundamental period of the structures under study (see Table IV).

TABLE IV
COMPARISON OF STRUCTURE FUNDAMENTAL PERIOD CORRESPONDING TO DDBD METHOD AND ETABS ANALYSIS

Parameter	Comb. I		Comb. II		Comb. III	
	DDBD	ETABS	DDBD	ETABS	DDBD	ETABS
Main frame period, T_o (s)	2.20	2.14	2.30	2.24	2.38	2.31
Initial period frame-BRB system, T_i (s)	1.10	1.18	1.15	1.23	1.19	1.27

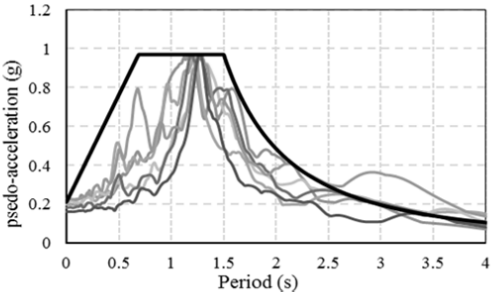


Fig. 2 Response spectra scaled to design spectrum

The records were scaled such that the maximum peak of the response spectra matched the ordinates of the design spectrum [7] (see Fig. 2).

6. Non-Linear Time-History Analysis

For the non-linear dynamic analysis, the Hilber-Hughes-Taylor integration method with $\alpha_o = 0$ was used. This method is considered equivalent to the Newmark integration method with average acceleration, [5] and [8]. The time increment used for the analysis was $\Delta t = 0.02$ s.

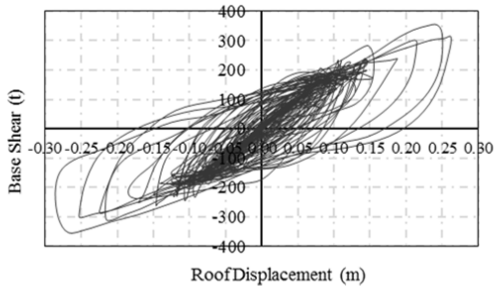
7. NLTHA Results

For each NLTHA corresponding to different design parameters combinations, it is obtained the shear history at the building base, as well as the roof displacement history. This data are necessary to create the global hysteresis cycle of the multi-degrees-of-freedom (MDOF) system and to identify the maximum displacement demanded of the structure. Fig. 3 shows one global hysteresis cycles corresponding to NLTHA 04 for each combination. Maximum roof displacement is obtained by using the record corresponding to NLTHA 04.

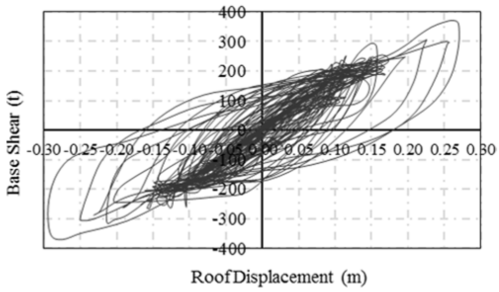
To verify that only BRBs enter to the non-linear interval and the main frame remains in an elastic state (plastic hinges are not present in beams and columns), the maximum displacement profile was obtained in each NLTHA. These are compared to the design profile, both in the yield and collapse limit state. Fig. 4 shows all displacement profiles corresponding to each combination. Next, the performance parameter (chosen as the maximum global ductility, μ_{Gmax} of the frame-BRB system) is calculated, as:

$$\mu_{G\max} = \frac{D_{\max}}{D_y} \quad (1)$$

where D_{max} is the maximum roof displacement, and D_y is the roof displacement associated with the yielding of the BRB system. D_y is determined on the hysteresis cycle at the point where the structure ceases to have an elastic behavior.



(a)



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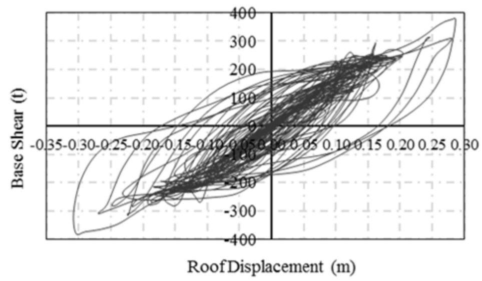
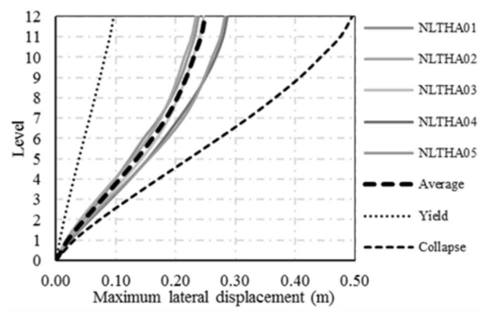
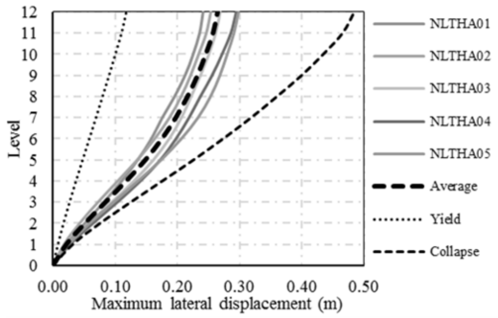


(c)

Fig. 3 Global hysteresis cycle of the MDOF frame-BRB system, corresponding to (a) Comb. I (b) Comb. II (c) Comb. III



(a)



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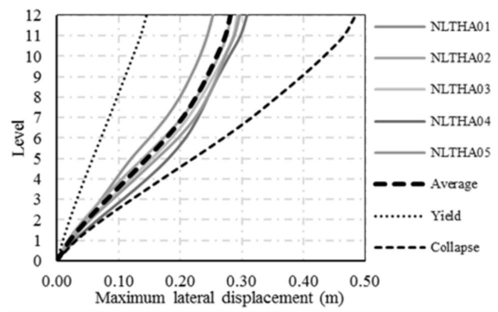

(c)

Fig. 4 Lateral displacement profile of the MDOF frame-BRB system, corresponding to (a) Comb. I (b) Comb. II (c) Comb. III

Table V shows a summary of the maximum global ductility corresponding to the five NLTHA, and the mean value of $\mu_{G\max}$ for each design parameters combination.

TABLE V
SUMMARY OF MAXIMUM GLOBAL DUCTILITY CORRESPONDING TO EACH NLTHA

Non-linear time-history analysis	Comb. I	Comb. II	Comb. III
NLTHA 01	2.462	2.053	1.736
NLTHA 02	2.419	2.158	1.935
NLTHA 03	2.552	2.287	2.009
NLTHA 04	2.960	2.507	2.116
NLTHA 05	2.920	2.537	2.035
Mean maximum global ductility	2.663	2.309	1.966

8. Analysis of Initial Costs

Fig. 5 shows the values of initial costs of the steel main frame and of the BRB system, expressed in $USD, assuming **α** = 0.25 and different values of **γ.**

From Fig. 5, it can be seen that the main frame cost and the total cost decreases as the strength ratio increases. When the strength ratio becomes larger, frame shapes with less inertia are required (Table II) and the main frame cost decreases. The main frame cost represents between 80% and 85% of the total cost; so, the frame structure cost is the most important. Fig. 5 also shows that the BRB cost has a relatively low variation, influencing very little the total cost.

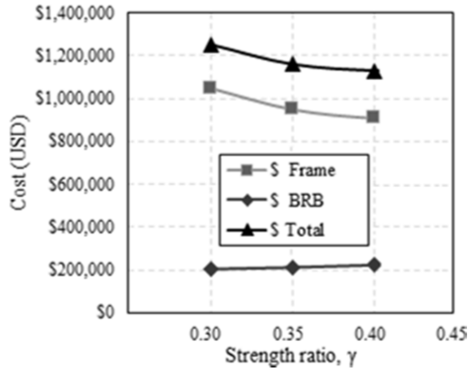

Fig. 5 Initial Cost versus strength ratio, and α =0.25

9. Cost - Efficiency Selection Criterion

Here the best combination of design parameters will be the one that presents the lowest cost and the highest performance index. Therefore, the best combination of design parameters will be given by the smallest value of the ratios calculated with (2):

$$\lambda = \frac{C_I}{\mu_{G\max}} \quad (2)$$

where: λ is cost-efficiency ratio and C_I is the initial cost of the frame-BRB structural system.

Table VI shows the cost-efficiency ratios for the cases corresponding to the three design parameters combinations. The bottom line indicates the values normalized with respect to the minimum value found. From Table VI it is concluded that the best combination corresponds to Comb I which is associated with α = 0.25 and γ = 0.30.

TABLE VI
COST – EFFICIENCY RATIOS

Cost - efficiency ratio	Comb. I α=0.25 γ=0.30	Comb. II α=0.25 γ=0.35	Comb. III α=0.25 γ=0.40
λ ($USD/ductility unit)	435858.94	489845.21	571597.91
Normalized λ	1.00	1.12	1.31

IV. CONCLUSIONS

A deterministic methodology to find the best combination of design parameters in MDOF buildings with BRB has been presented. The selection criterion takes into account initial costs of the frame-BRB structure system as well as a structural performance value.

A 12-story building was analyzed assuming three possible design parameter combinations. It was found that the best combination of design parameters for this building was α = 0.25 and γ = 0.30.

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