Derivation of Optimized Design Properties for Steel Yielding Segments in BRBs and Evaluation of Seismic Performance of Steel BRBFs with such Members

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LISBOA 2012

SUMMARY:
Buckling-restrained-braced frames (BRBFs) are known for their high energy dissipation capacity, while limiting structural displacements within acceptable range. A number of yielding segments can be combined in one BRB member, in serial or parallel patterns. It is shown in this study that energy dissipation capacity of BRBs highly depends on that pattern. In addition to that, it depends on mechanical and geometric properties, and the number of yielding segments in that combination. For a given BRB with either serial or parallel yielding segments, its hysteretic damping under cyclic loading is analytically correlated to the aforementioned parameters in order to obtain design parameters that maximize hysteretic damping in that BRB. Two buildings of 3 and 8 stories with diagonal BRBs are designed and subjected to inelastic seismic analyses to evaluate their seismic performance. Compared to the BRBs in series, BRBs in parallel are concluded to be more efficient in dissipating seismic energy.

Keywords: BRBs in parallel, BRBs in series, hysteretic energy dissipation, yielding segments, ductility capacity.

1. INTRODUCTION

The excessive lateral deformability of a steel moment-resisting frame can lead to excessive non-structural damage under moderate earthquakes. The lateral stiffness of an unbraced moment frame can be increased by diagonal braces; however the inelastic behaviour of such a system may not be satisfactory because the cyclic behaviour of braces results in significant degradation of stiffness and strength, and thus of energy dissipation capability, due to the global instability of the brace. The energy dissipation capacity of a steel moment frame can be greatly enhanced by employing buckling-restrained braces. BRB usually consists of a steel core undergoing significant inelastic deformation when subjected to strong earthquake loads and a casing for restraining global and local buckling of the core element. According to previous experimental research (Saeki et al. 1995, Tremblay et al. 1999, Huang et al. 2000), BRB exhibits stable hysteretic behaviour and high energy dissipation capacity. Iwata et al. (2000) showed that BRB with yield stress of 262 MPa behaved stably when they were stressed more than 3% of strain, which corresponds to ductility ratio of 24. Similar results were obtained by Black et al. (2002) who showed that a structure with buckling restrained braces with yield stress around 280 MPa behaved stably at 3% of inter-story drift. The ductility ratio at this point reached 20. Yamaguchi, et al. (2000) carried out experiments of half frames with buckling-restrained braces made of low-strength steel (F_y =96 MPa), with a maximum ductility ratio of 30. Based on the experimental findings, it can be concluded that BRB has enough ductility to dissipate large amount of hysteretic energy.

A number of yielding segments can be combined in one BRB member, in serial or parallel patterns. It is shown in this study that energy dissipation capacity of BRBs highly depends on that pattern. In addition to that, it depends on mechanical and geometric properties, and the number of yielding segments in that combination. For a given BRB with either serial or parallel yielding segments, its hysteretic damping under cyclic loading is analytically correlated to the aforementioned parameters in order to obtain design parameters that maximize hysteretic damping in that BRB. Two buildings of 3 and 8 stories with diagonal BRBs are designed and subjected to inelastic seismic analyses to evaluate their seismic performance. Compared to the BRBs in series, BRBs in parallel are concluded to be more efficient in dissipating seismic energy.

2. EQUIVALENT STIFFNESS AND HYSTERETIC DAMPING OF BRBs IN SERIES

Figure 2.1 shows different components of two BRBs is series. For a total brace length of *L*, one can have *n* number of equal BRBs in series. l = the length of the yielding segment, l' = the length of non-yielding segment, l'' = the length of one transitional segment, A = cross-sectional area of the yielding segment, and $\alpha' A$ = cross-sectional area of the non-yielding segment, therefore,

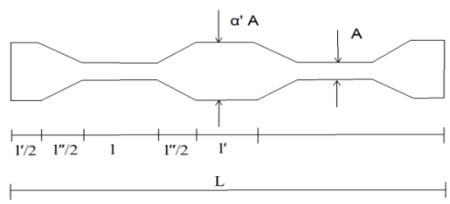


Figure 2.1 different components of two BRBs is series

$$L = n \times (l + l' + l'') \tag{2.1}$$

If m' is defined as $m' = \frac{l''}{l'}$, then the length of the yielding segment, *l* would be:

$$l = \frac{L}{n} - l' - l'' = \frac{L}{n} - l'(1 + m') \tag{2.2}$$

The stiffnesses of the non-yielding segment, k_1, the yielding segment, k_2, and the transitional part, k_3, are:

$$k_1 = \frac{\alpha' EA}{l'} \tag{2.3}$$

$$k_2 = \frac{EA}{\frac{L}{n} - l'(1+m')} \tag{2.4}$$

$$k_3 = \frac{EA(\alpha'-1)}{m'\, l'\, \ln\alpha'} \tag{2.5}$$

The equivalent elastic stiffness of a brace containing *n* equal BRBs in series, and each BRB having the aforementioned three parts in series as well, can then be calculated as below:

$$\frac{1}{k_e} = n\left(\frac{1}{k_1} + \frac{1}{k_2} + \frac{1}{k_3}\right) \tag{2.6}$$

And in turn,

$$k_e = \frac{EA\, \alpha'\, (\alpha'-1)}{L\, \alpha'(\alpha'-1) - n\, l'((\alpha'-1)^2 + \alpha' m'(\alpha'-1-Ln(\alpha')))} \tag{2.7}$$

where *E* is modulus of elasticity of steel and α' is the ratio of the cross-sectional area the non-yielding segment to that of the yielding segment. Logically, $\alpha' > 1.0$. For a given total brace length of L = 914 cm, a constant $\alpha' = 10$ and $l' = 30$cm and for different values of $m' = l''/l'$, Fig. 2.2 shows the variation of equivalent stiffness of one BRB containing n equal BRBs attached in series. It is clear that by increasing the number of BRBs, n and m', the equivalent stiffness increases.

For a given total brace length of L = 914 cm, a constant $m' = 1.5$ and $l' = 30$cm and for different values of α', Fig. 2.3 shows the variation of equivalent stiffness of one BRB containing n equal BRBs combined in series. It is clear that by increasing the number of BRBs, n and α', the equivalent stiffness increases.

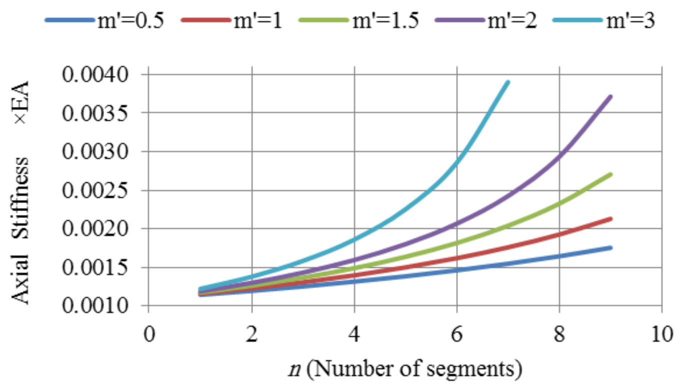


Figure 2.2 Variation of equivalent stiffness of n equal BRBs in series, for different m' ratios.

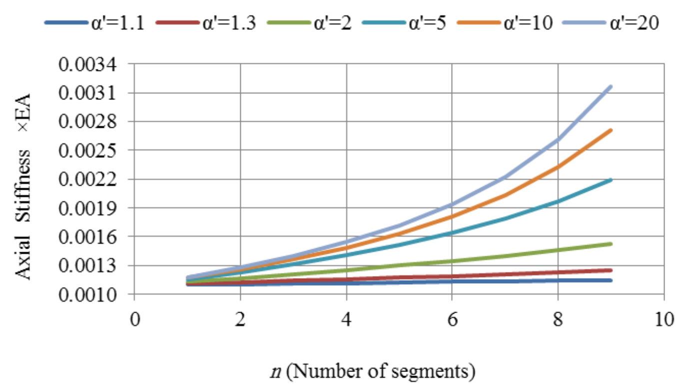


Figure 2.3 Variation of equivalent stiffness of n equal BRBs in series, for different area ratios, α'.

For n equal BRBs in series, and assuming they yield simultaneously under one axial force, the force-displacement relationship of the combined BRBs in series would be similar to Fig. 2.4.

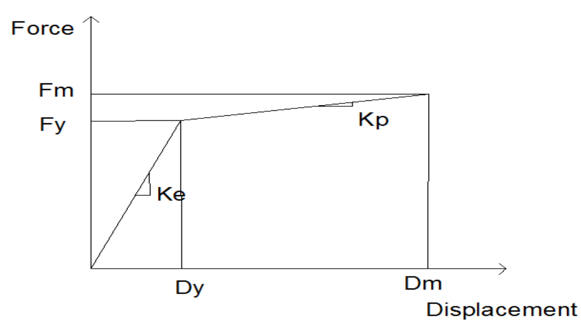


Figure 2.4. Bilinear force-displacement relationship n equal BRBs in series.

The equivalent post-yield stiffness, *kp* can then be obtained for these *n* serial BRBs as follows:

$$\frac{1}{k_p} = n(\frac{1}{k_1} + \frac{1}{k_{p2}} + \frac{1}{k_3}) \tag{2.8}$$

And in turn,

$$k_p = \frac{E_t A\alpha'(\alpha'-1)}{\alpha'(\alpha'-1)L - nl'(\alpha'(\alpha'-1)(1+m') - \frac{E_t}{E}(\alpha'-1+\alpha' m' Ln(\alpha')))} \tag{2.9}$$

Where E_t is the post yield modulus of steel ($E_t \approx E/1000$), k_1 and k_3 are similar to the elastic values since the non-yielding segment and the transitional parts are not supposed to yield, therefore,

$$k_{p2} = \frac{E_t A}{\frac{L}{n} - l'(1+m')} \tag{2.10}$$

For a given total BRB length of L=914 cm, a constant $m' = 1.5$ and $l' = 30$cm and for different values of α', Figure 2.5 shows the variation of equivalent post-yield stiffness of *n* equal BRBs combined in series. It is clear that by increasing the number of BRBs, *n*, the equivalent post-yield stiffness, k_p increases and since the ratio of E_t /E is very small (≈ 1/1000) it is independent of α'.

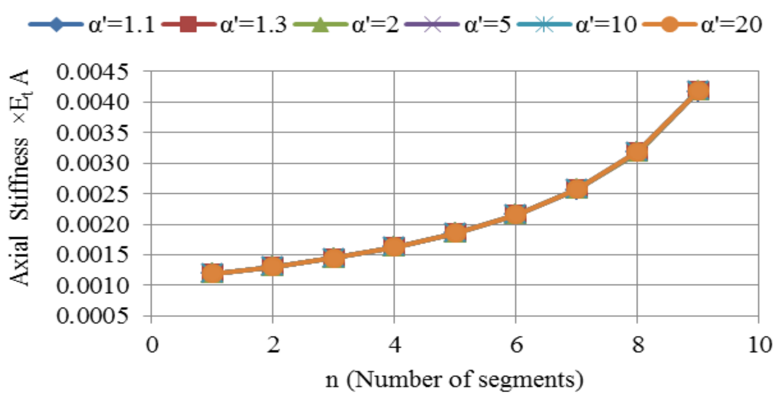


Figure 2.5. Variation of equivalent post-yield stiffness *n* equal BRBs in series, for different area ratios, α'.

Hysteretic/cyclic damping of n equal BRBs in series, ξ_o, depends on maximum displacement (ATC 40, 1997), where

$$\xi_0 = \frac{1}{4\pi}\frac{E_D}{E_S} \tag{2.11}$$

E_D is the energy dissipated per cycle, and E_S is the stored strain energy. According to FEMA-440, ξ_o is defined as:

$$\xi_0 = \frac{2(-1+\mu)(k_e - k_p)}{\pi\mu(k_e + (-1+\mu)k_p)} \tag{2.12}$$

where, ductility ratio, μ is defined as the ratio of maximum to yield displacement. If β is defined as k_p/k_e, therefore,

$$\xi_0 = \frac{2(1-\beta)(\mu-1)}{\pi(1+\beta(\mu-1))\mu} \tag{2.13}$$

Figure 2.6 depicts variation of hysteretic damping, ξ_o of serial-equal BRBs with ductility ratio, μ for different β ratios. According to this figure in general by an increase of ductility ratio, hysteretic damping increases, however, for $\beta \geq 0.05$ and $\mu \geq 5$, hysteretic damping, ξ_o tends to decrease.

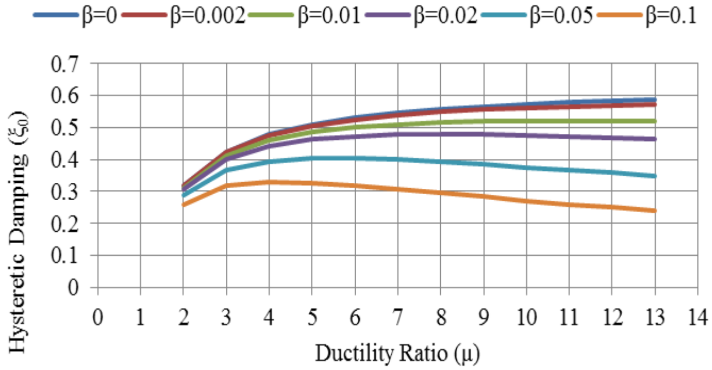


Figure 2.6. Variation of hysteretic damping, ξ_o serialequal BRBs with ductility ratio, μ for different β ratios.

Figure 2.7 shows variation of hysteretic damping, ξ_o versus the number of BRBs in series for different values of ductility ratio, μ, a given total brace length of L=914 cm, a constant $m' = 1.5, \alpha' = 10$, $l' = 30$cm, $E = 2.1\times 10^6 \frac{\text{kg}}{\text{cm}^2}$ and $E_t = 2.1\times 10^3 \frac{\text{kg}}{\text{cm}^2}$. It is clear that hysteretic damping is independent of the number of BRBs in series, while it increases with ductility ratio.

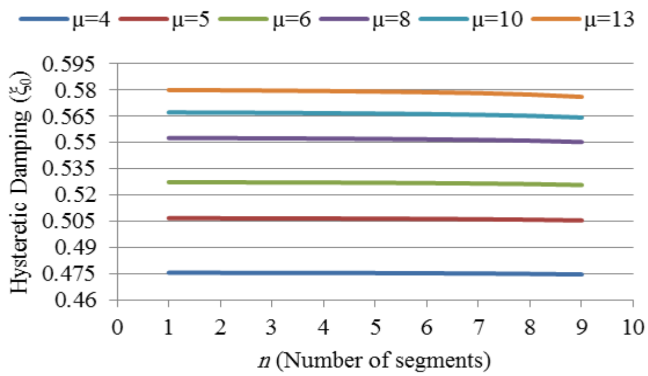


Figure 2.7. Variation of hysteretic damping, ξ_o, of n equal BRBs in series for different values of ductility ratio, μ.

3. EQUIVALENT STIFFNESS AND DAMPING OF BRBs IN PARALLEL

Figure 3.1 shows a typical three segmented parallel BRB.

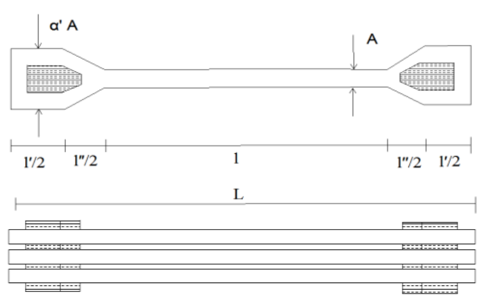
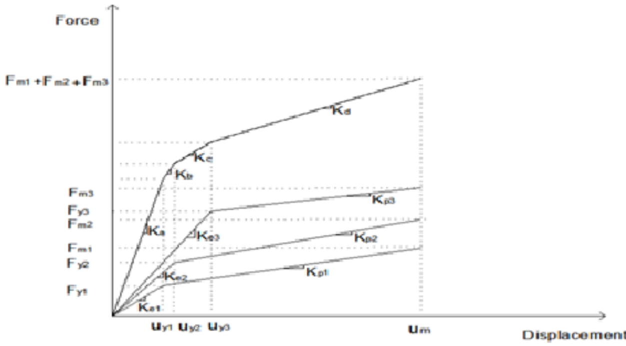


Figure 3.1. Geometric properties of a typical three segmented parallel BRB.

Figure 3.2 shows force-diplacement relationship of *n* different BRBs combined in parallel. Equivalent stiffness and/or slope of the force-displacement relationship of the combined BRB would then be as follows,



$$k_{eq} = k_1 + k_2 + k_3 + \ldots \quad (3.1)$$

$$k_a = k_{e1} + k_{e2} + k_{e3} \quad (3.2)$$

$$k_b = k_{p1} + k_{e2} + k_{e3} \quad (3.3)$$

$$k_c = k_{p1} + k_{p2} + k_{e3} \quad (3.4)$$

$$k_d = k_{p1} + k_{p2} + k_{p3} \quad (3.5)$$

Figure 3.2. Assumed load-displacement relationship of BRBs in parallel.

Three components of one BRB; non-yielding segment, yielding segment, and transition parts are acting in series and therefore, the equivalent stiffness of the i^{th} BRB, k_{ei} would be computed from:

$$k_{ei} = \frac{E_i A_i \alpha'_i\,(\alpha'_i - 1)}{L\,\alpha'_i(\alpha'_i - 1) - l'_i((\alpha'_i - 1)^2 + \alpha'_i m'_i(\alpha'_i - 1 - Ln(\alpha'_i)))} \quad (3.6)$$

and the equivalent post-yield stiffness of the i^{th} BRB, k_{pi} would be computed from:

$$k_{pi} = \frac{E_{ti}\,A\,\alpha'_i\,(\alpha'_i - 1)}{\alpha'_i\,(\alpha'_i - 1)L - l'_i(\alpha'_i(\alpha'_i - 1)(1 + m'_i) - \frac{E_{ti}}{E_i}(\alpha'_i - 1 + \alpha'_i\,m'_i\,Ln(\alpha'_i)))} \quad (3.7)$$

Following the concept in *Equ.2.11*and the definition of E_D, the energy dissipated per cycle, and E_S, the stored strain energy, the hysteretic damping, ξ_o for *n* different parallel BRBs, all having the same total length of *L*, would then be as follows:

$$\xi_o = \frac{2}{\pi}\left\{\frac{\sum_{j=1}^{n} \frac{(K_{ej} - K_{pj})(\mu_j - 1)}{\mu_j^{2}}}{\sum_{j=1}^{n}\left(\frac{K_{ej} - K_{pj}}{\mu_j}\prod_{i=1}^{n}\mu_i\right) + \prod_{i=1}^{n}\mu_i \times \sum_{j=1}^{n} K_{pj}}\right\} \times \prod_{i=1}^{n}\mu_i \quad (3.8)$$

where $\mu_i = u_m / u_{yi}$, u_m = maximum target displacement, and u_{yi}= the yield displacement of the i^{th} BRB.

Table 3.1 shows the design properties of the yielding segments in parallel, and Fig. 3.3 shows variation of hysteretic damping, ξ_o for the six combinations of parallel BRBs considered. The six different combinations of parallel BRBs or cases considered in this study are described below:

1) The yielding segment is one piece with yield strength of 100MPa,
2) The yielding segment is one piece with yield strength of 200MPa,
3) The yielding segment is one piece with yield strength of 300MPa,
4) The yielding segment consists of three pieces with yield strength of 100, 200 and 300MPa and cross sectional areas of each segment is so proportioned that each carries1/3rd of the design base shear (Parallel I).
5) The yielding segment consists of three pieces with yield strength of 100, 200 and 300MPa and cross sectional areas of each segment is so proportioned that they carry 1/4th, 1/4th and 1/2nd of the design base shear (Parallel II), respectively.
6) The yielding segment consists of three pieces with yield strength of 100, 200 and 300MPa and cross sectional areas of each is so proportioned that each carry 0, 1/3rd and 2/3rd of the design base shear (Parallel III), respectively.

It is clear that the softer the yielding segments the higher the ductility ratio and the higher hysteretic damping. Also, in parallel combinations where the percentage of softer steel is higher the hysteretic damping is higher as well.

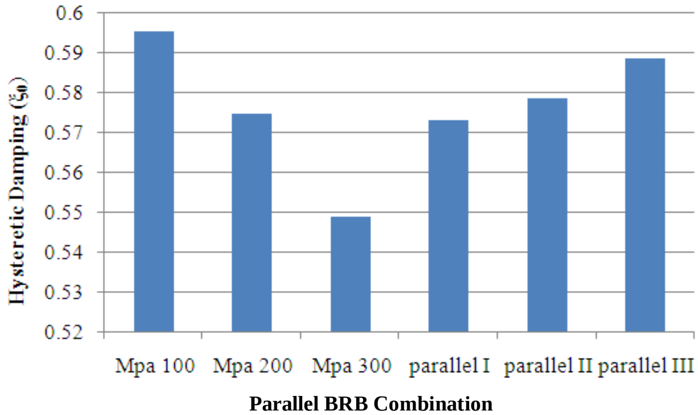


Figure 3.3. Variation of hysteretic damping, ξ_o for different combination of BRBs in parallel

Table 3.1. Strength and ductility capacities of the yielding segments of BRB in different parallel combinations

BRB Combination	Ductility Ratio	σ_y (Mpa)
Single segment	μ =23	100
Single segment	μ =11.5	200
Single segment	μ =7.6	300
Three segment (parallel I)	μ =23, 11.5, 7.6	100, 200, 300
Three segment (parallel II)	μ =23, 11.5, 7.6	100, 200, 300
Two segment (parallel III)	μ=23, 11.5	100, 200

4. STRUCTURAL MODELS

The structures considered are 3 and 8 story steel frames with pined beam-column connections. The frames are to carry the gravity loads and the BRBs to transfer the seismic loads. All the designs are according to AISC 360-05/ASCE7-05. The first story height is 5.5 m and the rest of story heights are 3.7 m. The bay sizes are equal to 7.30 m and the dead and live loads are 3 ton/m and 1.5 ton/m, respectively, and the total brace / BRB length is 9.14m. Fig. 4.1 and Tables 4.1 and 4.2 show the structural properties used in this study.

The seismic design parameters considered are: $S_S = 1.5\ g$, $S_1 = 0.6\ g$, $T_L = 8\ s$, Site Class = *D*, $F_a = 1.0$, $F_v = 1.5$, $S_{DS} = 1.0$, $S_{D1} = 0.6$, $c_u = 1.4$, $R = 7.0$, $C_d = 5.5$, and Ω_o=2.0. First mode design periods are 0.4995 s and 0.9696 s for 3 and 8 story buildings, respectively.

Table 4.1. Member sizes of the 3 story building and their BRB yielding segment cross section areas for 6 different BRB parallel combinations

3 Story	Beam	Colum	BRB (100 Mpa) cm^2	BRB (200 Mpa) cm^2	BRB (300 Mpa) cm^2	Parallel (I) cm^2	Parallel (II) cm^2	Parallel(III) cm^2
1	W18x71	W18x71	43.08	21.54	14.36	26.32	30.51	35.9
2	W18x71	W18x71	30.89	15.44	10.29	18.87	21.87	25.74
3	W18x71	W18x71	18.03	9.01	6.01	11.01	12.77	15.02

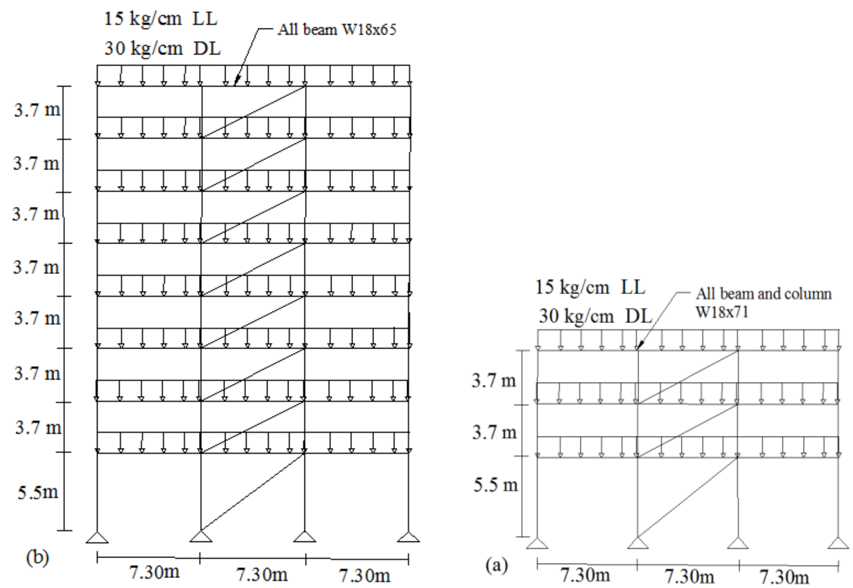


Fig. 4.1. 3 and 8 story model structures with 6 different parallel BRB combinations.

Table 4.2. Member sizes of the 8 story building and their BRB yielding segment cross section areas for 6 different BRB parallel combinations

8 Story	Beam	Column	BRB (100Mpa) Cm²	BRB (200Mpa) Cm²	BRB (300Mpa) Cm²	Parallel (I) Cm²	Parallel (II) Cm²	Parallel (III) Cm²
1	W18x65	W18x119	71.1	35.55	23.7	43.45	50.36	59.25
2	W18x65	W18x119	61.29	30.64	20.43	37.45	43.41	51.07
3	W18x65	W18x119	57.32	28.66	19.1	35.02	40.6	47.76
4	W18x65	W18x119	51.76	25.88	17.25	31.63	36.66	43.13
5	W18x65	W18x71	44.6	22.3	14.86	27.25	31.59	37.16
6	W18x65	W18x71	35.84	17.92	11.94	21.9	25.38	29.86
7	W18x65	W18x71	25.49	12.74	8.496	15.57	18.05	21.24
8	W18x65	W18x71	13.54	6.77	4.51	8.27	9.59	11.28

In the structures/BRBFs studied, the story displacements or drifts were significantly affected by the type of the parallel combination of the yielding segments (Figs. 4.3 and 4.4), however for base shears, the kind of combination of yielding segments did not play a major role, in affecting the maximum base shears (Fig. 4.5).

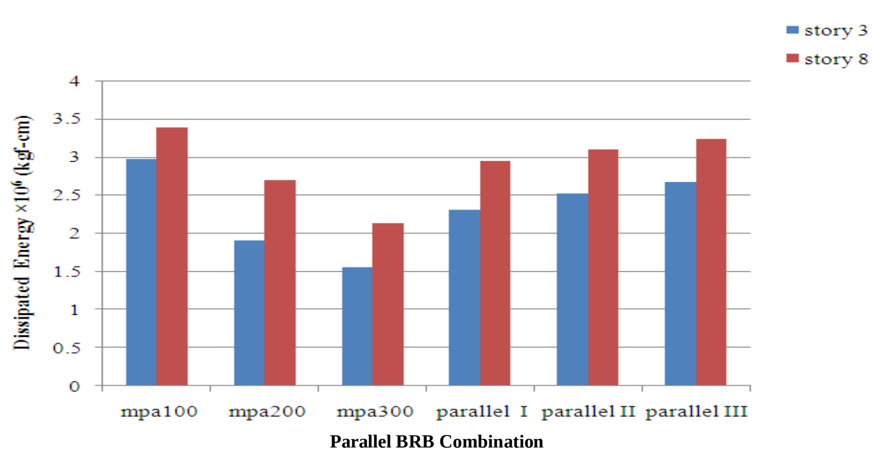


Fig. 4.2. Variation of dissipated energy for 3 and 8 story structures with 6 different parallel BRB combinations

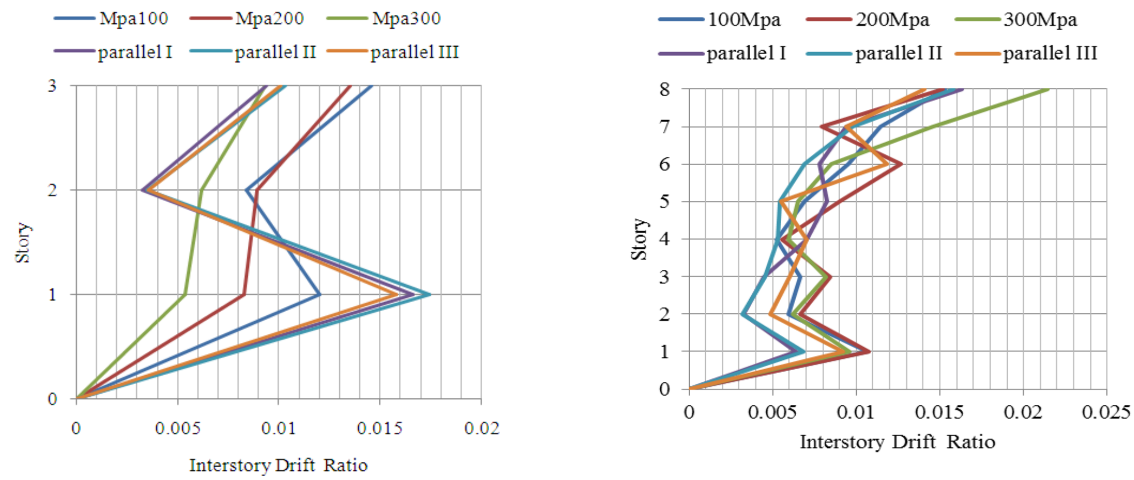


Fig. 4.3. Variation of interstory drift ratio along the height for 3 and 8 story structures for 6 different parallel BRB combinations

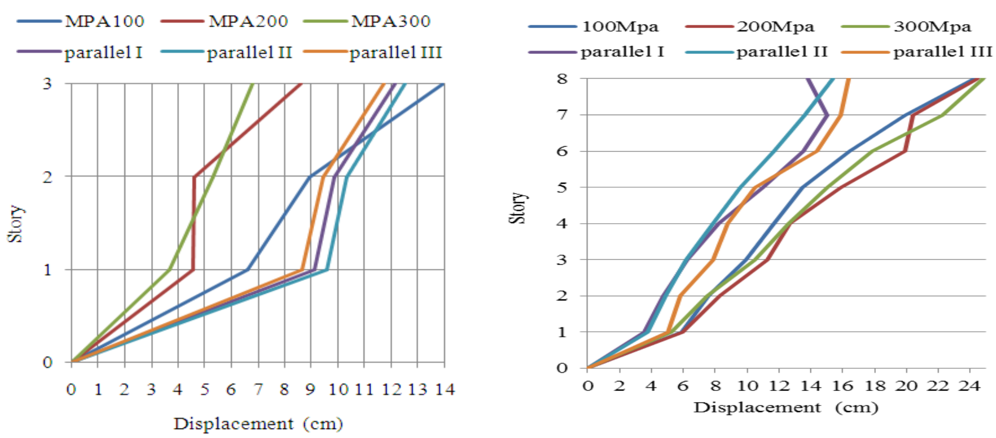


Fig. 4.4. Variation of story displacement along the height for 3 and 8 story structures for 6 different parallel BRB combinations

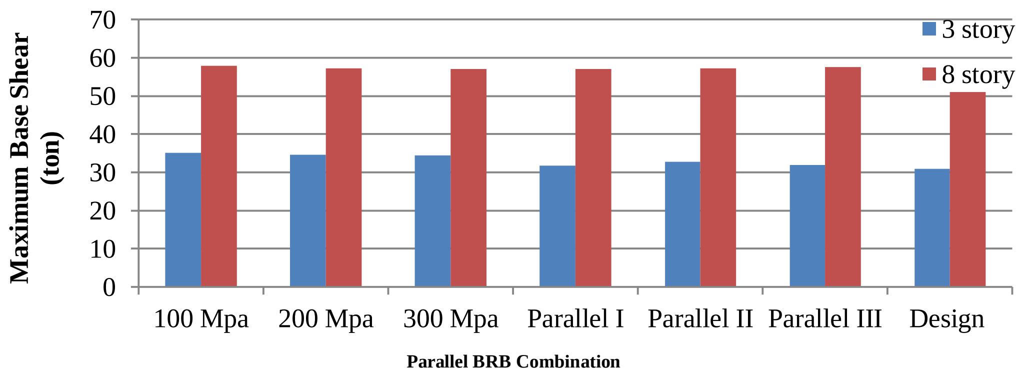


Fig. 4.5. Variation of maximum base shear for 3 and 8 story structures for 6 different parallel BRB combinations.

5. SUMMARY AND CONCLUSIONS

A comprehensive study was performed on hysteretic behaviour of BRBs made of different combinations of parallel or serial yielding segments. The following brief conclusions can be drawn. For BRBs in series, by increasing the number of BRBs, *n, α', and m'*, the equivalent stiffness increases. By increasing the number of BRBs, *n*, the equivalent post-yield stiffness, k_p increases and since the ratio of E_t /E is very small (≈ 1/1000), it is independent of α'. Figure 2.6 depicts variation of hysteretic damping, ξ_o of serial-equal BRBs with ductility ratio, μ for different β ratios. According to this figure in general by an increase of ductility ratio, hysteretic damping increases, however, for $\beta \geq 0.05$ and $\mu \geq 6$, hysteretic damping, ξ_o tends to decrease. It is clear that hysteretic damping is independent of the number of BRBs in series. For BRBs in parallel, It is clear that the softer the yielding segments the higher the ductility ratio and the higher hysteretic damping, and in turn the higher dissipated seismic energy. Also, in parallel combinations where the percentage of softer steel is higher the hysteretic damping is higher as well. This conclusion is made for one BRB with multi yielding segments in parallel, as well as an entire structure wuth many number of stories/BRBs. In the structures/BRBFs studied, the story displacements or drifts were significantly affected by the type of the parallel combination of the yielding segments, however for base shears, the kind of combination of yielding segments did not play a major role, in affecting the maximum base shears.

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