Energy Dissipation of Compression Members in Concentrically Braced Frames: Review of Experimental Data

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Abstract: Design and detailing requirements of seismic provisions for concentrically braced frames (CBF) were specified based on the premise that bracing members with low KL/r and b/t will have superior seismic performance. However, relatively few tests investigate the cyclic behavior of CBF. It is legitimate to question whether the compression member of CBF plays as significant a role as what has been typically assumed explicitly by the design provisions. In this paper, the existing experimental data are reviewed to quantify the extent of hysteretic energy achieved by bracing members in compression in past tests, and the extent of degradation of the compression force upon repeated cycling loading. Although it is recognized that many parameters have an influence on the behavior of braced frames, the focus of this paper is mostly on quantifying energy dissipation in compression and its effectiveness on seismic performance. Based on the experimental data review from previous tests, it is found that the normalized energy dissipation of braces having moderate KL/r (80–120) do not have significantly more normalized energy dissipation in compression than those having a slenderness in excess of 120. The normalized degradation of the compression force envelope depends on KL/r and is particularly severe for W-shaped braces.

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CE Database subject headings: Building frames; Slenderness ratio; Energy dissipation; Compression; Bracing; Seismic response.

Introduction

Braced frames are expected to yield and dissipate energy through postbuckling hysteresis behavior of bracing members upon cyclic loading. Seismic provisions for the analysis, design, and detailing of concentrically braced frames (CBF) were gradually introduced into seismic regulations and guidelines in California in the late 1970s (SEAOC 1978) and on a nationwide basis in the early 1990s (AISC 1992). In these documents, design and detailing requirements were specified based on the premise that bracing members with low effective slenderness ratio, KL/r, and low width-thickness ratio (low local buckling slenderness ratio), b/t, will have superior seismic performance. The philosophy was that low KL/r ensures that braces in compression can significantly contribute to energy dissipation. Upon buckling, flexure develops in the compression member and a plastic hinge eventually develops at the middle length of the brace, i.e., at the point of maximum moment. It is through the development of this plastic hinging that a member in compression can dissipate energy during earthquakes. Further, in these code provisions, low b/t limits were prescribed to prevent brittle failure due to local buckling. Indeed, the reversed cyclic loading induced by earthquakes leads to repeated buckling and straightening of the material at the local buckling location, which combined with very high strains present at the tip of the local buckle, precipitate low cycle fatigue.

Although much attention has been paid to moment resisting frames (MRF) after the 1994 Northridge earthquake, with a large number of tests conducted since, relatively fewer tests exist that investigate the cyclic behavior of CBF. This is surprising given the reliance imposed on compression brace energy dissipation (complementary to the primary energy dissipation in tension) by the existing codes and guidelines. Further, given the fact that for a relatively constant plastic hinge moment capacity at midspan of the brace, the axial force applied to the brace will decrease as a function of the amplitude of buckling, resulting in strength degradation of the structural member in compression. It is legitimate to question whether the compression member plays as significant a role as what has been typically assumed explicitly by the design provisions. Codified equations have been introduced in some documents to capture the reduction in compression strength upon cyclic loading. The recommended lateral force requirements and commentary (SEAOC 1990) recommended the following equation to quantify the reduced strength:

$$C_r' = \frac{C_r}{1+0.50\left(\frac{KL}{\pi r}\sqrt{\frac{0.5F_y}{E}}\right)} = \frac{C_r}{1+0.5\left(\frac{KL/r}{C_c}\right)} \qquad (1)$$

where C_r'=design (reduced) buckling capacity; C_r=first buckling load of bracing member; KL/r=slenderness ratio; F_y=yield stress of brace; and E=Young's modulus. For example, for an A36 steel brace with a slenderness ratio equal to 0, $C_r'=C_r$. If the slenderness ratio is increased to $720/\sqrt{36}=120$, $C_r'=0.68\ C_r$. The American Institute of Steel Construction Seismic Provisions (AISC 1992) specified a value of 0.8 for ordinary concentrically

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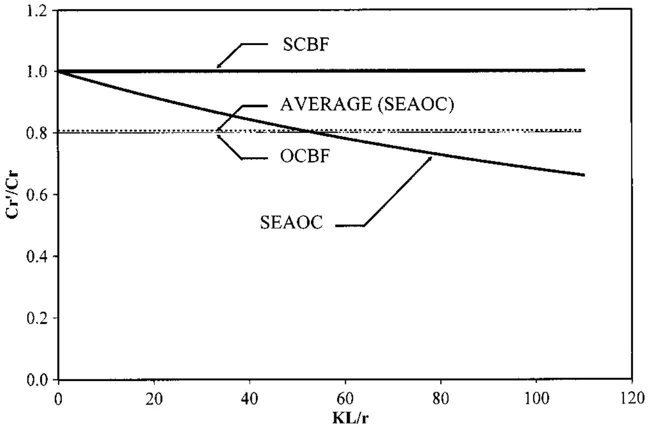

Fig. 1. Normalized codified equations of reduced buckling strength due to inelastic cyclic loading

braced frames which incidentally is approximately equal to the average reduction factor over the permissible range of KL/r for this type of system (although it is not known whether this was the rationale supporting the choice of this 0.8 factor). This is illustrated in Fig. 1.

However, there exists a compelling argument that slender braces in some instances could have desirable behavior in the perspective that elastic global buckling means no damage to braces in compression (Tremblay and Lacerte 2002). Hence, for a brace with large slenderness ratio, there would be no need to consider the reduced compression strength, C_r', since it would provide no energy dissipation in compression and no loss of compression capacity upon repeated cyclic loading. Interestingly, Eq. (1) would not predict this correctly.

Further, in absence of plastic hinging in the middle of the brace, there is no need to be concerned about low cycle fatigue life of the brace due to local buckling at that location.

However, even for braces that are stockier and do yield in compression, the relevance of the factor C_r' is debatable. In that case, the capacity of the brace in compression when the entire frame reaches its maximum sway deformation, which will be defined as C_r'' here, is more significant than C_r'. At the plastic hinge that develops in the middle of the brace, C_r'' drops as deformation increases. This means that at maximum sway, when the tension brace has yielded, only a small fraction of the original compression buckling strength of the other brace is effective.

In light of these facts, one could argue that the design provisions should accurately account for the above effects. However, no quantified data obtained from parametric experimental studies on C_r'' and on the cyclic energy dissipation of braces in compression, as related to KL/r, could be found in the literature.

In this paper, the existing experimental data are reviewed to quantify the extent of hysteretic energy achieved by bracing members in compression in past tests, and the extent of degradation of the compression force upon repeated cycling loading at various magnitudes of the axial deformation in compression, δ, as a function of KL/r, and for various types of structural shapes.

Damage concentration at single stories in braced frames, as well as residual deformations/drifts and required drifts to dissipate specified amount of hysteretic energy at each cycles, which are also significant issues related to the slenderness of braces in frames subjected to seismic excitation, are beyond the scope of this paper.

Experimental Data on the Hysteretic Energy and Strength Degradation of Braces

The experimental data on cyclic testing of braces have been reviewed to quantify the energy dissipation of braces in compression and loss of compression strength at various magnitudes of compressive axial displacements. For this purpose, experimental reports by Jain et al. (1978), Black et al. (1980), Zayas et al. (1980), Astaneh-Asl et al. (1982), Archambault et al. (1995), Leowardi and Walpole (1996), and Walpole (1996) were collected. However, some data were excluded from review. First, bracing members tested as parts of X-braced frames were not considered, because of the difficulty in accurately defining the KL/r values of these braces. Second, test specimens of hollow structural shapes built-up using double angles or double channels welded toe-to-toe were excluded, because these were typically reported to fail at their connections, resulting in nonconventional hysteretic behavior. Third, concrete filled tubular sections were also excluded, as they were considered to be a special case beyond the scope of this study. The resulting data set considered in this study is summarized in Table 1, described in terms of test I.D., section dimension, and some test results for each type of structural members. Detailed information on this data set is presented in the technical report by Lee and Bruneau (2002), making it possible for other investigators to expand the data set in the future.

Note that more data were collected than reported here was collected; however in addition to the reasons described previously, due the lack of detailed information on the reported tests in the available conference proceedings or journal papers, the review of data was limited to those specimens presented in Table 1.

Here, all quantitative information on energy dissipation and strength degradation has been generated from the hysteretic force-axial deformation curves of bracing members. Note that in all cases, only the graphical data were available, and that quantification was achieved directly from those figures (although some were photocopied at a magnified scale to enhance precision of the readings).

Energy Dissipation of Brace in Compression

The energy dissipation of a brace for one compression cycle, E_C, is equal to the work produced by the compression force times the axial deformation, δ. As the compression decreases under increasing axial deformations, the energy can be obtained graphically by calculating the area under the force-axial deformation curve, as shown in Fig. 2. Here, because the energy corresponding to each hysteretic loop is considered, note that the axial deformation in compression, δ, is measured from the point of zero member force (which may not correspond to the original zero displacement position) up to the point of maximum compressive deformation, as illustrated in Fig. 3.

Further, to facilitate comparison between results from various experiments, all results are expressed in a normalized manner. The normalized compressive energy, E_C/E_T, is obtained by dividing the compressive energy by the corresponding tensile energy, E_T, defined as the energy that would have been dissipated by the member in tension if the same maximum axial displacement was reached during unloading of the member after its elongation. This corresponding E_T is illustrated in Fig. 2. Likewise, the axial displacements are normalized by the axial displacement value attained at the corresponding theoretical elastic buckling of the brace, δ_B. This value is defined as

Table 1. Data Set Considered

Reference	Test I.D.	Section (metric)	KL/r	δ_B (mm)	δ_T (mm)	T_y (kN)	C_r (kN)	Max. (δ/δ_B)
Black et al. (1980)	1	W—200×300	120.0	2.1	5.3	1107.0	429.7	38.02
	2	W—150×37	40.0	1.8	2.3	1377.8	1116.8	29.75
	3	W—150×30	80.0	3.6	4.3	1049.7	893.4	9.53
	4	W—150×30	80.0	3.7	4.5	1101.9	905.0	24.28
	5	W—150×30	80.0	2.7	4.5	1101.9	676.6	33.79
	6	W—150×24	120.0	2.5	4.5	942.5	513.1	32.66
	7	W—150×23	40.0	2.3	2.6	1020.9	905.0	19.87
	8	2L—152×89×9.5	80.0	2.8	4.0	1241.4	889.6	23.40
	9	2L—127×89×9.5	40.0	2.5	2.2	1183.0	1307.9	5.31
	10	2L—102×89×9.5	120.0	2.4	5.5	988.1	432.3	28.88
	11	2C—200×17	120.0	2.1	3.7	1067.5	621.7	41.03
	12	WT—125×33.5	80.0	2.5	3.5	1164.9	836.0	30.89
	13	WT—205×33.5	80.0	3.3	4.6	1232.8	889.6	29.26
	14	○—102×6.02	80.0	3.9	5.0	669.8	521.5	13.25
	15	○—102×6.02	80.0	3.6	5.0	669.8	484.8	25.41
	16	○—102×8.56	80.0	2.0	2.5	470.8	382.2	48.41
	17	□—102×102×6.4	80.0	3.6	6.2	942.2	545.9	20.11
	18	□—102×102×12.7	80.0	4.2	7.8	2319.8	1242.4	17.77
	19	W—150×30	40.0	3.1	3.0	1049.7	1067.6	9.68
	20	2L—152×89×9.5	80.0	3.7	5.7	1241.4	800.7	11.19
	21	○—102×8.56	40.0	1.7	1.8	470.8	434.9	19.67
	22	□—102×102×12.7	80.0	4.6	11.2	2319.8	949.0	10.68
	23	W—130×24	120.0	4.5	4.5	743.2	740.0	13.42
	24	○—89×5.74	80.0	4.4	6.2	552.0	388.2	11.58
Zayas et al. (1980)	1	○—102×2.11	54.0	1.1	1.5	140.7	102.3	15.99
	2	○—102×3.05	54.0	1.3	1.5	201.3	177.9	12.71
	3	○—102×2.11	54.0	2.9	4.5	417.4	268.7	2.75
	4	○—102×3.05	54.0	1.9	3.6	480.6	255.8	4.89
	5	○—102×2.11	25.0	2.0	1.9	140.7	144.6	12.34
	6	○—102×3.05	25.0	1.9	1.9	201.3	197.9	15.83
Jain et al. (1978)	1	□—25×25×2.7	57.0	0.5	0.9	89.6	46.5	22.42
	2L	L 25×25×6.4	120.0	0.3	2.2	103.3	14.1	86.65
	3L	L 38×38×3.2	85.0	0.5	2.3	81.4	17.2	56.81
	4	□—25×25×2.7	30.0	0.6	1.0	89.6	53.3	18.53
	4L	L—32×32×3.2	120.0	0.4	2.8	71.3	9.1	94.39
	6	□—25×25×2.7	94.0	0.5	1.5	89.6	29.5	37.67
	9	□—25×25×2.7	50.0	0.9	1.7	89.6	49.4	21.64
	12A	□—25×25×2.7	115.0	0.7	2.4	89.6	24.5	43.02
	15	□—25×25×2.7	80.0	2.4	2.7	89.6	79.6	14.21
Astaneh-Asl et al. (1982)	1	2L—127×76×6.4	174.0	2.1	5.2	724.9	291.1	42.55
	2	2L—127×76×6.4	114.0	1.8	5.2	724.9	245.4	18.84
	3	2L—102×76×9.5	81.0	2.9	5.2	928.5	511.8	27.71
	4	2L—76×51×12.7	143.0	1.7	5.2	840.7	271.4	66.34
	5	2L—102×76×9.5	81.0	3.6	5.2	928.5	643.4	17.61
	6	2L—76×51×12.7	143.0	2.0	5.2	840.7	324.4	77.96
	8	2L—89×64×12.7	110.0	3.8	5.8	1149.9	742.4	28.66
	9	2L—64×38×7.9	174.0	1.1	5.8	480.9	90.9	106.25
	10	2L—76×51×6.4	151.0	2.4	5.2	444.6	206.6	23.90
	11	2L—76×51×6.4	124.0	1.8	5.2	444.6	150.5	36.05
	13	2L—76×51×6.4	124.0	1.8	5.2	444.6	155.8	78.20
	15	2L—64×38×6.4	171.0	1.2	5.8	393.0	83.6	65.19
	16	2L—89×64×12.7	110.0	3.5	5.8	1149.9	688.1	13.42
	18	2L—64×38×6.4	189.0	1.6	5.8	393.0	105.2	67.35

Table 1. (*Continued.*)

Reference	Test I.D.	Section (metric)	KL/r	δ_B (mm)	δ_T (mm)	T_y (kN)	C_r (kN)	Max. (δ/δ_B)
Archambault et al. (1995)	1B	□—76×127×4.8	80.5	3.6	9.2	707.8	279.9	28.18
	1QB	□—76×127×4.8	80.5	4.7	8.2	632.0	361.6	19.31
	2B	□—76×102×4.8	98.5	4.2	9.5	591.2	260.1	32.75
	3B	□—76×76×4.8	128.3	2.5	9.6	509.5	132.3	77.38
	4B	□—64×127×4.8	82.8	3.7	8.2	577.8	258.8	25.78
	4QB	□—64×127×4.8	82.8	4.0	9.1	620.4	273.8	23.52
	5B	□—76×102×6.4	100.6	3.8	9.8	772.7	298.0	42.62
Leowardi and Walpole (1996)	1	W—150×30	80.0	3.9	3.8	1241.7	1266.9	45.86
	2	W—150×30	60.0	2.3	2.6	1241.7	1090.5	30.73
	3	W—150×30	40.0	4.7	4.8	1241.7	1204.2	30.86
Walpole (1996)	1	□—150×100×6	80.0	3.0	4.6	1282.3	835.0	23.46
	2	□—150×100×6	60.0	2.6	3.1	1282.3	1051.0	16.34
	3	□—150×100×6	40.0	5.0	6.1	1282.3	1060.5	8.29

$$\delta_B = \frac{C_r L}{AE} \tag{2}$$

where L=length of the specimen; A=cross sectional area of the specimen; E=Young's modulus (=29,000 ksi); and C_r=experimental buckling load as presented in Fig. 4.

Note that the value of δ_B is limited to δ_T to account for stocky members that yield in compression prior to buckling, where δ_T is the axial displacement attained when the brace yields in tension, and defined as

$$\delta_T = \frac{T_y L}{AE} \tag{3}$$

where T_y=tensile yield load defined as

$$T_y = AF_y \tag{4}$$

and F_y=yield stress from the results of coupon test.

The normalized energy dissipated in compression during each hysteretic cycle is calculated for all the tests considered in this study. Detailed numerical results are provided in the technical report by Lee and Bruneau (2002). A typical resulting plot of normalized energy as a function of normalized axial deformation is shown in Fig. 5.

Strength Degradation of Brace in Compression

A number of manipulations were necessary to quantify the strength degradation of a brace upon repeated cycling. First, the compression excursions were extracted from the complete hysteretic force-displacement curve obtained from a test, and overlaid to start from the same zero displacement, as shown in Fig. 4. As schematically shown in this figure, for the tests considered in the database, the magnitude of axial deformations typically increases upon subsequent cycles. In the first cycle, beyond first buckling (defined experimentally as C_r), compressive strength of the brace progressively decreases; At the point of maximum displacement for that compressive excursion, δ_1, the value of C''_{r1} is reached, the numeral subscript indicating the cycle number. Hence, for any given cycle "n," the compressive strength C''_{rn} is reached at the maximum displacement δ_n (note that only cycles that produce displacements exceeding the previously obtained values are considered by this procedure). These values of C''_r are then divided by C_r for normalization. This normalized strength is labeled C''_r/C_r(first), the qualifier "first" implying "the strength obtained the first time this displacement is reached." Fig. 6 shows a typical curve obtained following this procedure. That curve can be considered a normalized force-displacement envelope of the brace in compression. Note that notation C''_r is used to avoid confusion

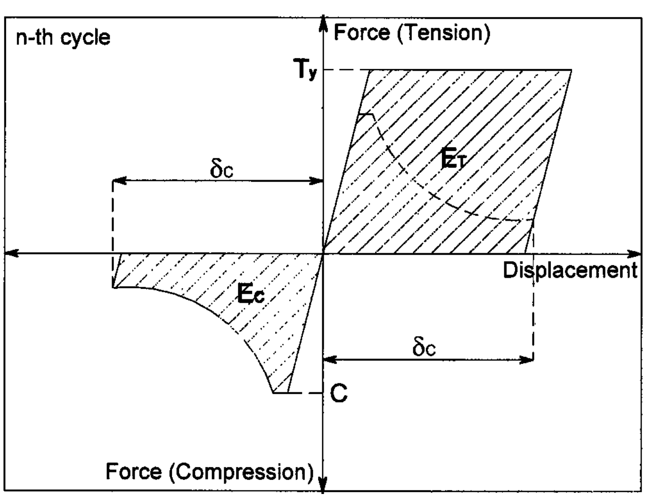

Fig. 2. Definition of dissipated energy ratio, E_c/E_T

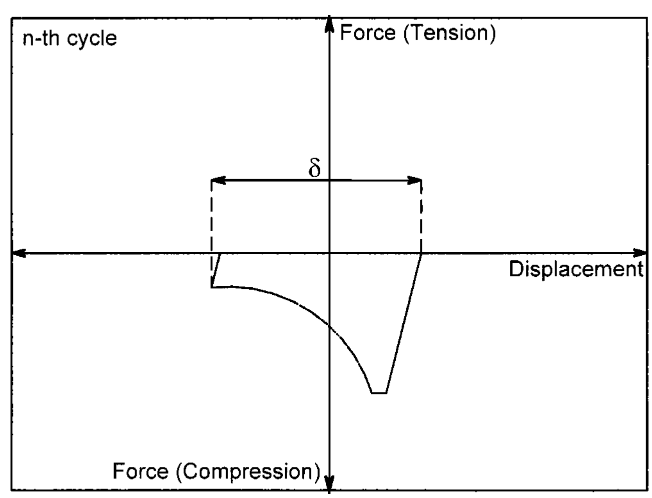

Fig. 3. Definition of axial displacement, δ

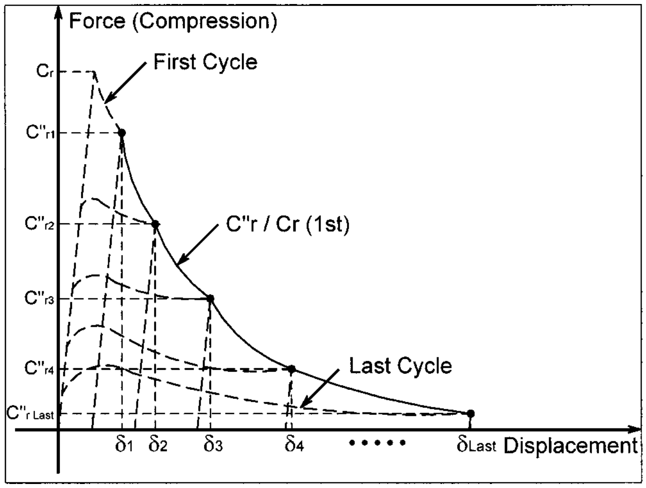

Fig. 4. Definition of normalized buckling capacity, C_r''/C_r (first)

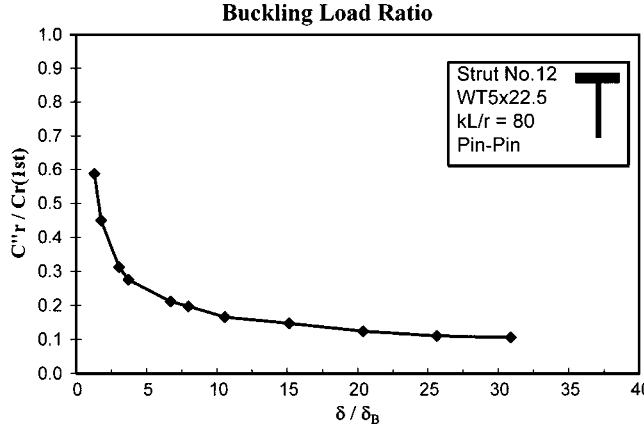

Fig. 6. Example of normalized maximum compression strength reached upon repeated cycling data, C_r''/C_r(first)

with the term C_r' which has been used in other codes and publications (CSA 1994; Bruneau et al. 1998) and has a different meaning.

Strength degradation upon repeated cycling also occurs over the entire range of brace deformations, as exhibited by the force-deformation curves shown in Fig. 4. As such, the brace compressive strength recorded during the last cycle of testing is also of interest. It can be calculated at each of the previously considered displacement points, δ_n, as shown in Fig. 7, giving results as typically shown in Fig. 8. This normalized strength is labeled C_r''/C_r(last), the qualifier "last" implying "the strength obtained during the last cycle of testing."

Using the same displacement points to calculate both C_r''/C_r(first) and C_r''/C_r(last) makes it possible to calculate the ratio of these values. A large ratio indicates a considerable drop in strength at a specific displacement δ/δ_B, whereas a lower ratio expresses a rather stable strength degradation from the first to last cycle. A typical result is shown in Fig. 9. Note that in this paper, Figs. 5, 6, 8, and 9, are typically presented together for each case or group considered, as shown in Fig. 10 for illustration purposes.

Observations on Behavior

All results are grouped over ranges of KL/r values, then results are grouped again per type of cross sections, namely for braces made of square hollow structural shapes (HSS) (a.k.a. tubes), W-shape, double angles back-to-back, structural pipes, angles, and structural tees. Complete detailed results are available in the technical report by Lee and Bruneau (2002).

Obtained average curves, as a function of KL/r, are grouped and summarized in Fig. 11 for all types of cross sections, and in Figs. 12–14, respectively, for W-shapes, square HSS, and double-angles back-to-back. Note that the average curves were computed over the entire range of δ/δ_B for which at least one specimen was tested; a resulting peculiarity of this decision is that the line of average results is sometimes seen to increase in a jagged manner as weaker specimens were not pushed to the same large δ/δ_B as the stronger specimens.

A number of observations can be made from these figures. First, as the normalized energy dissipation E_C/E_T typically decreases with increasing normalized displacements δ/δ_B, the ratios are consistently smaller for larger KL/r values. This is not surprising as members with smaller KL/r typically have a larger inertia, and thus larger plastic modulus, which translates in a

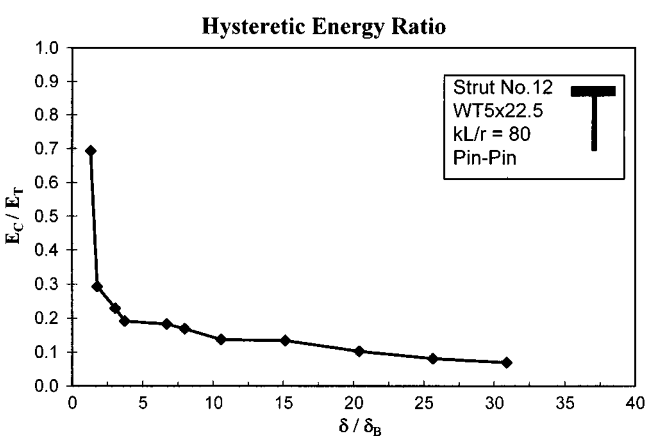

Fig. 5. Example of normalized hysteretic energy data

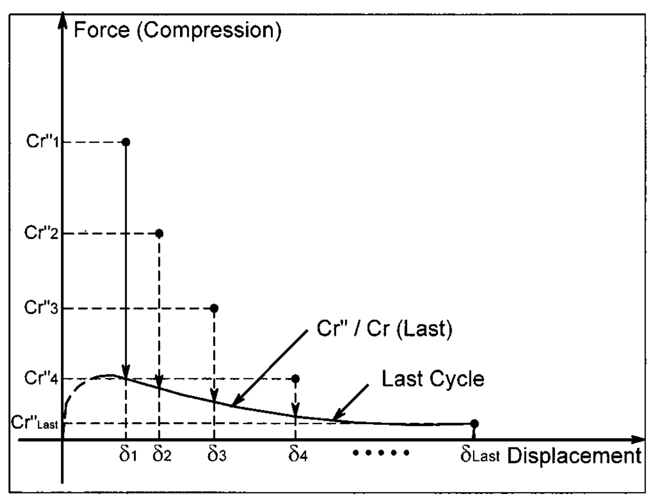

Fig. 7. Definition of normalized buckling capacity, C_r''/C_r(last)

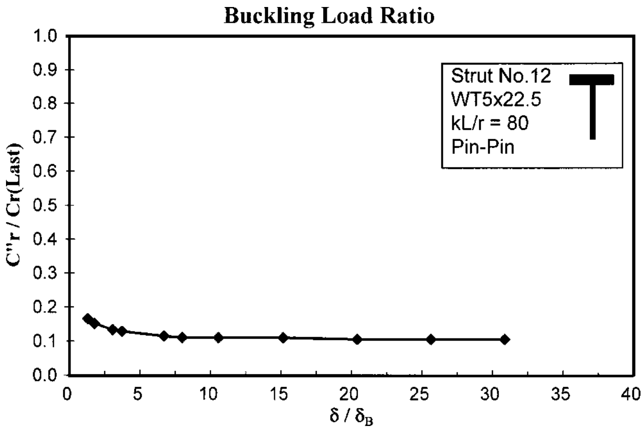

Fig. 8. Example of normalized maximum compression strength reached upon repeated cycling data, C_r''/C_r(last)

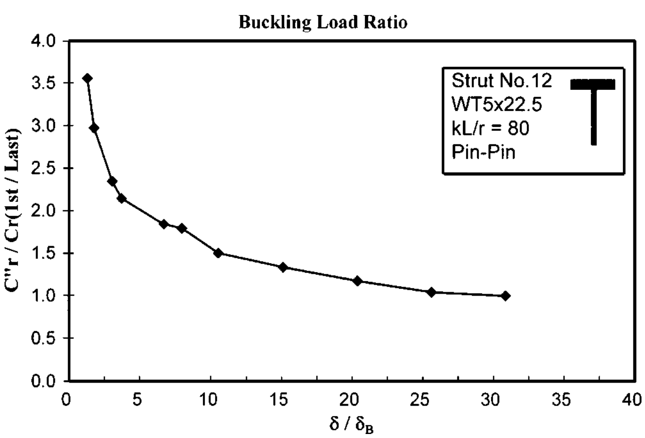

Fig. 9. Example of normalized maximum compression strength reached upon repeated cycling data, C_r''/C_r(first/last)

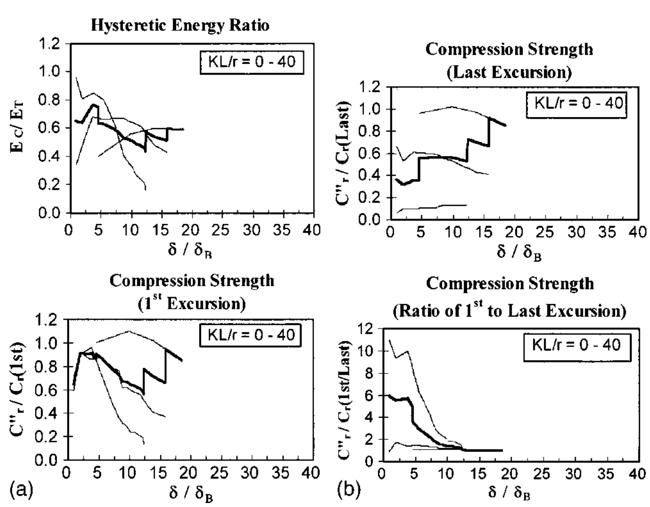

Fig. 10. All structural shapes with $KL/r = 0-40$ (average shown by thicker line)

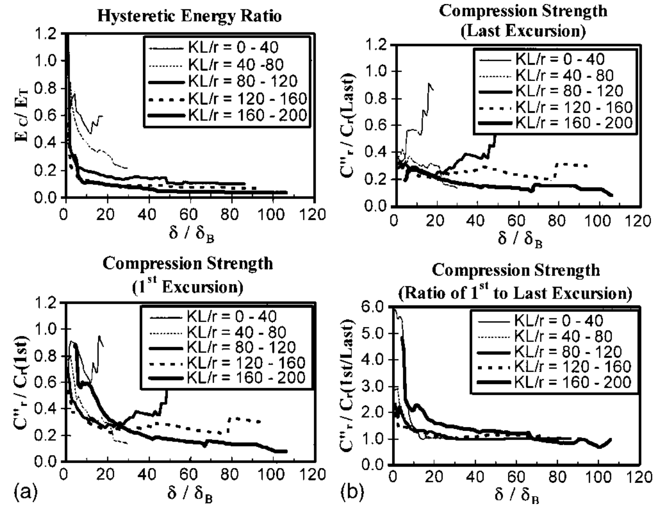

Fig. 11. Averages of data by KL/r value ranges

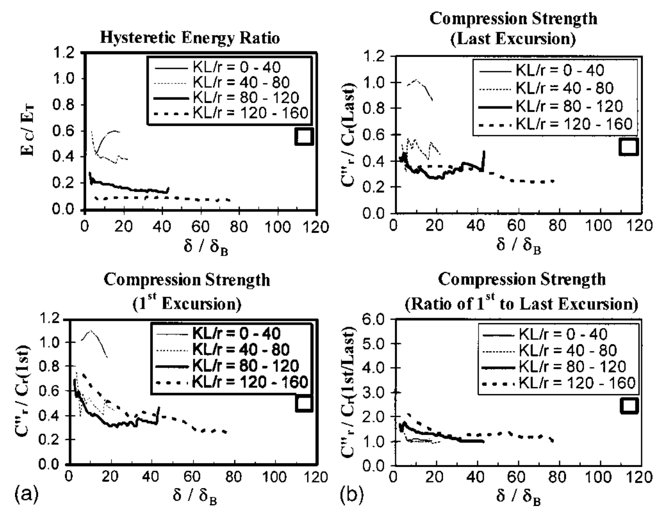

Fig. 12. Averages of data by KL/r value ranges for tubular sections

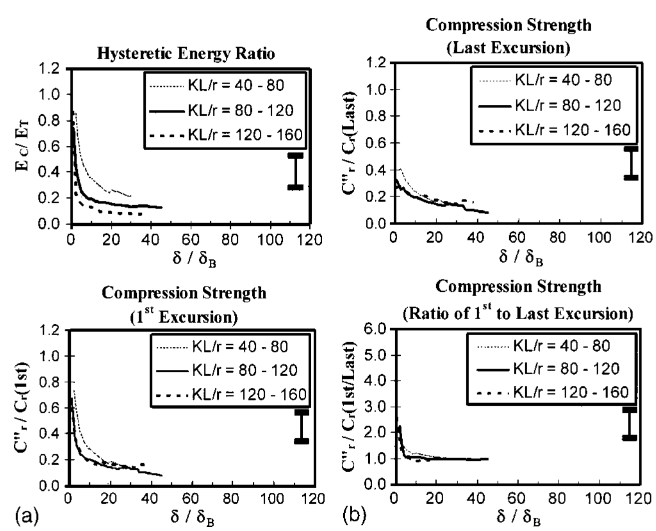

Fig. 13. Averages of data by KL/r value ranges for wide flange section

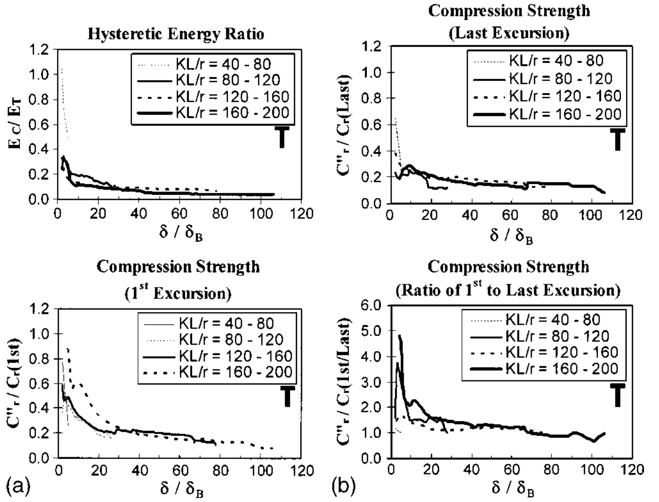

Fig. 14. Averages of data by KL/r value ranges for double angles, back-to-back

larger plastic moment and energy dissipation at the mid-length plastic hinge. However, it is noteworthy that braces having KL/r in the 80–120 range do not have significantly more normalized energy dissipation in compression than those having a slenderness in excess of 120. This is significant considering the large number of braced frames designed and built with braces having a KL/r of approximately 100. The rapid drop in energy dissipation effectiveness (down to 0.3 or less for braces having KL/r above 80) as the normalized displacement approximately exceed 3 is also significant; this suggests that reliance on the compression brace to dissipate seismic energy, while effective at very low KL/r, may be overly optimistic for the slenderness more commonly encountered in practice.

As a minor point, it is observed that a few values of E_C/E_T counter-intuitively exceed 1.0 at low magnitudes of displacement. Closer scrutiny of the seven specimens for which this was noted revealed this to be a consequence of errors introduced due to: (1) an initial near vertical returning down-slope segment of the hysteretic loops, and; (2) the difficulty in accurately graphically reading the data or calculating Young's modulus. In addition, as shown in Fig. 15, for Specimen 9 by Black et al. (1980), the experimentally obtained buckling strength exceeded the tensile yield strength (A_gF_y calculated with the experimentally obtained F_y value) for reasons unexplained by the authors.

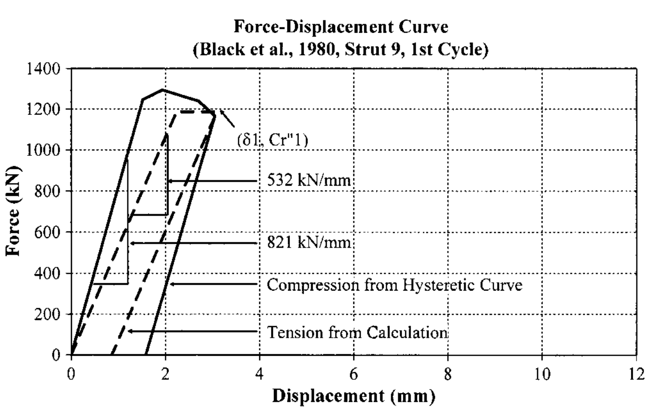

Fig. 15. Hysteretic energy ratio from the first cycle of strut 9 [based on data from Black et al. (1980)]

Reduction in the normalized C_r''/C_r(first) envelope is particularly severe for the W-shaped braces, again having KL/r above 80 dropping to approximately 0.2 when the normalized displacements exceed 5. However, behavior is not significantly worse for KL/r in the 120–160 range. In that perspective, tubes perform significantly better, over all slenderness range. The performance of double-angle braces is in between these two extremes. Observation of the results for C_r''/C_r(last) and C_r''/C_r(first/last) show that the compression capacity at low δ/δ_B values drops rapidly upon repeated cycling, and that C_r''/C_r(first) is effectively equal to C_r''/C_r(last) at normalized displacements above 3 in most instances.

Hence, considering that a brace with KL/r of 80 has a buckling load equal to 60% of yielding tensile force, when the braced bent will have reached its expected displacement ductility of 3–4 [$4\delta_T=4(\delta_B/0.6)=6.7\delta_B$], the brace compression strength will have already dropped considerably to approximately 20% of its original buckling strength (40% for square HSS).

Conclusion

The objective of this paper was to review existing experimental data to quantify the extent of hysteretic energy dissipation achieved by bracing members in compression and the extent of the degradation of braces compression strength upon repeated cycling loads, at various magnitudes of the axial deformation in compression, δ, as a function of the effective slenderness ratio, KL/r, and for various types of structural shapes.

For the section shapes considered in this study, bracing members having tubular cross-section were found to suffer less degradation of compressive strength and normalized energy dissipation in compression at a given level of normalized inelastic displacements (although it is recognized that tubes with large width-to-thickness ratio are sensitive to fracture due to cyclic local buckling, this important consideration is beyond the scope of this paper). Degradation of behavior in compression was particularly severe for the W-shaped braces having KL/r above 80 dropping to approximately 0.2 when the normalized displacements exceed 5. However, behavior is not significantly worse for KL/r in the 120–160 range.

Although results vary somewhat as a function of brace cross-section type, collected data shows that upon cyclic loading, the normalized energy dissipation capacity in compression and the compressive strength of bracing members with KL/r above 80 significantly drops to a small percentage of values obtained at first occurrence of the buckling load. This confirms that limits on KL/r specified in seismic design requirements are not correlated to brace effectiveness in compression, but rather relate to other factors.

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