Design of Diagonal Cross-bracings Part 2: Experimental Study

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The theoretical study reported in the first part of the paper (*AISC Engineering Journal*, 3rd Qtr., 1987, pp. 122–126) showed the transverse stiffness offered by the tension diagonal in cross-bracing systems is sufficient for assuming that, for out-of-plane buckling, the effective length of the compression diagonal is 0.5 times the diagonal length, when the diagonals are continuous and attached at the intersection point.

Two series of tests were performed to demonstrate the validity of the theoretical study. Seven transverse stiffness tests were carried out to demonstrate the validity of the equations used to determine the transverse stiffness provided by the tension diagonal. Fifteen buckling tests were carried out to demonstrate the validity of the equation used to determine the effective length factor. Both series of tests are reported in this second part of the paper.

TEST SPECIMENS

The tests were performed on flat bars. The bar cross section was 1-in. wide with ¼ in., ⅜ in. or ½ in. thicknesses (nominal dimensions). The actual dimensions of the flat bar cross section were measured at various locations along their length. The mean width and thickness were used to compute the cross-sectional properties in Table 1. These properties were used in the calculations. The mean yield stress obtained from standard tensile tests is also in Table 1.

For convenience, the test specimens are identified by two letters and a number. The first letter identifies the type of tests: series T – transverse stiffness tests; series B – buckling tests. The second letter identifies the specimen cross-section: X – 1 × ¼ in.; Y – 1 × ⅜ in.; Z – 1 × ½ in. For instance, test BX-1 is the first buckling test on cross bracings with 1 × ¼-in. diagonals.

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Table 1. Properties of Test Specimens

Nominal Dimensions, (in.)	A (in.^{2})	I ($\times 10^3$in.^{4})	r (in.)	F_y (ksi)
1 × ¼	0.2604	1.4319	0.0742	50.8
1 × ⅜	0.3829	4.5888	0.1095	46.0
1 × ½	0.4991	10.3332	0.1439	43.9

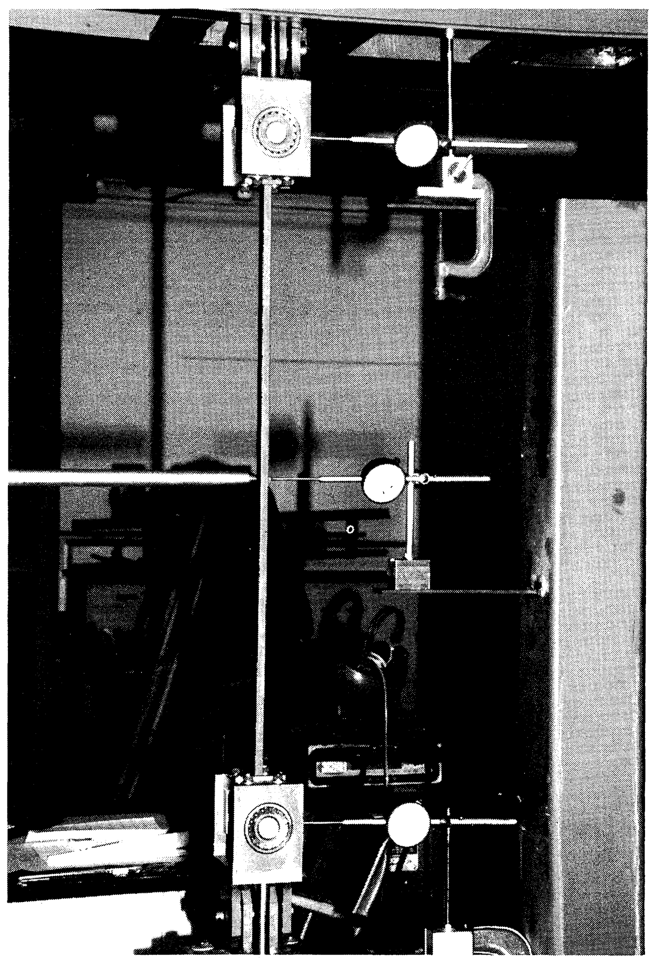

Fig. 1 Test set up: Series T

In the transverse stiffness tests (Series T), the flat bars were bent about their weak axis, which was the out-of-plane buckling axis in the buckling tests on cross bracings (Series B).

TEST APPARATUS AND MEASUREMENTS

The test set up is shown in Figs. 1 and 2. In both series of tests, the tension member was vertical and loaded with a 20-kip hydraulic servo-controlled jack. The concentrically applied tensile force was measured with a sensitivity of ± 1%. The compression member in test Series B was horizontal and loaded with a 20-kip hydraulic jack. The same jack was used to apply the transverse point load in test Series T. The compression or transverse load was measured with a sensitivity of 0.2% by means of a calibrated pressure captor.

The gripping device shown in Fig. 3 was used to connect the members to the test frame. It is constructed of pins and plates, including self-aligning spherical roller bearings, so that rotation was completely free in the plane of the test frame and in the orthogonal vertical or horizontal plane for the vertical and the horizontal bar, respectively. The center-to-center length of the inside pins (L) was 39.4 in. (1 m) for both members.

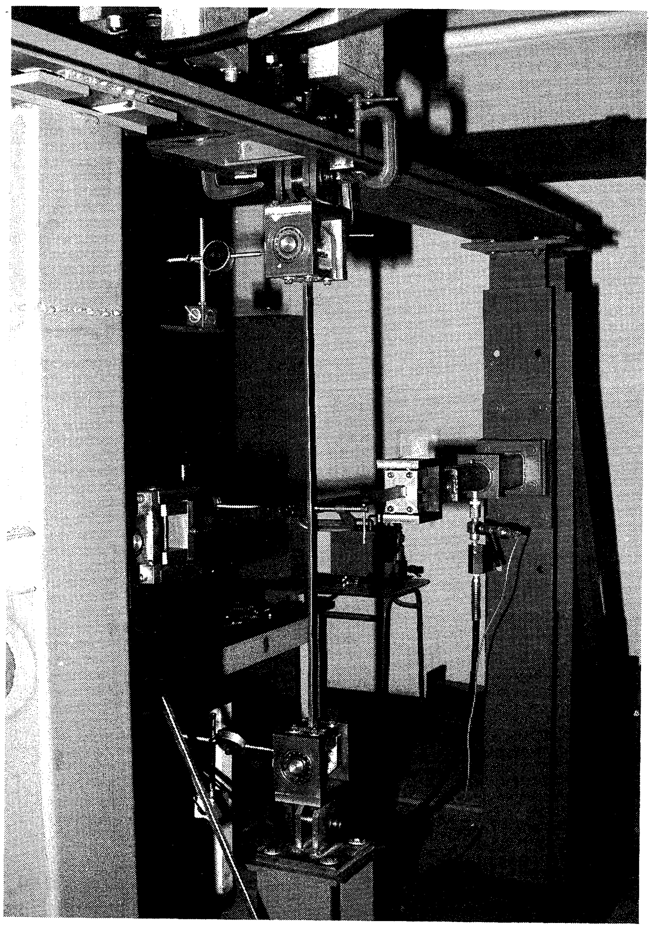

Fig. 2. Test set up: Series B

As shown in Fig. 4, the two members in test Series B were held together at the point of intersection by means of a C-clamp. Small steel balls were used to permit free rotation of the compression member about its midpoint. Obviously the rotational restraint of the connections in the tests was much lower than the one currently met in practice. Consequently, the test results are on the conservative side.

Dial gages were used to measure the lateral deflections at the ends and at the center of the members (sensitivity ± 0.0004 in.).

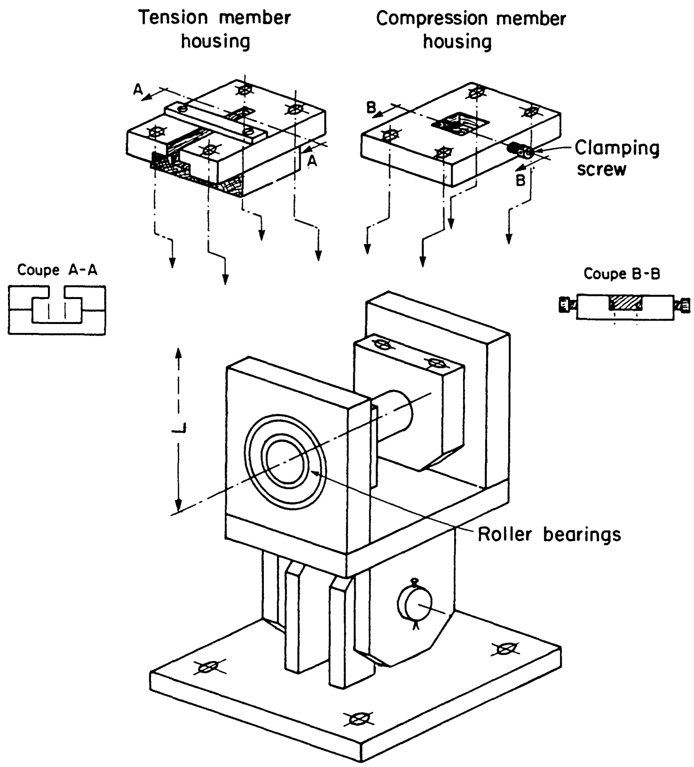

Fig. 3. Typical pinned connection at member ends

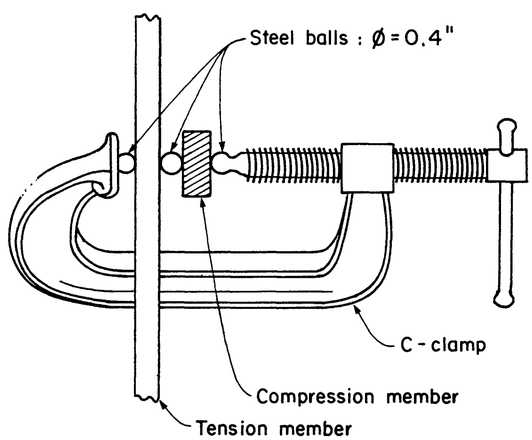

Fig. 4. Connection at intersection point

TEST RESULTS: SERIES T

It was shown in the first part of the paper that the dimensionless transverse stiffness provided by the tension diagonal is given by,

$$\gamma = \frac{16}{\pi^2}(3 + 1.09\,\nu^2) \tag{1}$$

where

$$\nu^2 = \left(\frac{L}{2}\right)^2 \frac{T}{EI} \tag{2}$$

In this equation, I is the moment of inertia of one diagonal considering out-of-plane bending of the X-bracing, L the length of the diagonals and T the tensile force in the tension diagonal. To obtain Eq. 1, it was assumed both diagonals of the X-bracing system are identical (common practice). It was also assumed the connections at the ends of the diagonals are perfect hinges.

The dimensionless transverse stiffness is related to the transverse stiffness or spring stiffness α (kips/in. or kN/mm) by the following equation:

$$\gamma = \frac{\alpha L^3}{\pi^2 EI} \tag{3}$$

Combining Eqs. 1, 2 and 3, we get:

$$\alpha = \frac{48EI}{L^3} + 4.36\frac{T}{L} \tag{4}$$

The purpose of test Series T was to verify the validity of Eqs. 1 and 4. In this series, the testing procedure was as follows. A given tensile force was first applied to the tension member. The transverse point load Q was then applied at the center of the tension member. The magnitude of the tensile force was checked and the lateral deflection at midpoint δ was measured. The transversal load was then decreased to zero. A load increment ΔT was applied to the tension member and the transverse load was again applied to the member. This procedure was repeated for several tensile force levels.

For a given value of the tensile force, the spring stiffness is given by: $\alpha = Q/\delta$. A typical experimental curve, α as a function of T, is shown in Fig. 5. In all tests, the experimental α values were larger than the values predicted by Eq. 4. However, the experimental and theoretical values are quite close and Eq. 4 is slightly conservative.

All the test results are summarized in Fig. 6, which shows the dimensionless transversal stiffness as a function of ν^2. The previous comments and conclusions also apply to Eq. 1.

TEST RESULTS: SERIES B

In the first part of the paper it was shown the effective length factor is given by:

$$K = \frac{4}{\sqrt{16 + 3\gamma}} \geq 0.50 \tag{5}$$

With the values of α measured during the buckling tests, the experimental values of γ are obtained from Eq. 3 and the experimental values of K from Eq. 5.

In the theoretical study, it was also shown the effective length factor of the compression diagonal in an X-braced frame is given by,

$$K = \sqrt{0.523 - \frac{0.428}{C/T}} \geq 0.50 \tag{6}$$

In this equation, C and T are the forces in the compression and the tension diagonals, respectively, obtained from an elastic analysis of the X-braced frame, the behavior of this frame being elastic up to buckling of the compression diag-

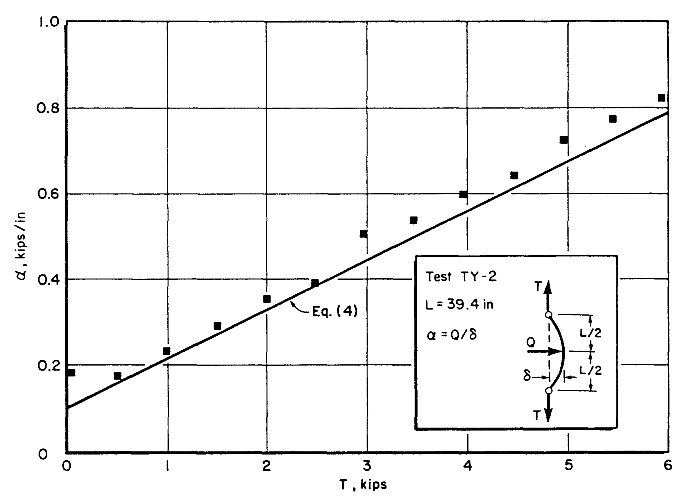

Fig. 5. Transverse stiffness vs. tensile force

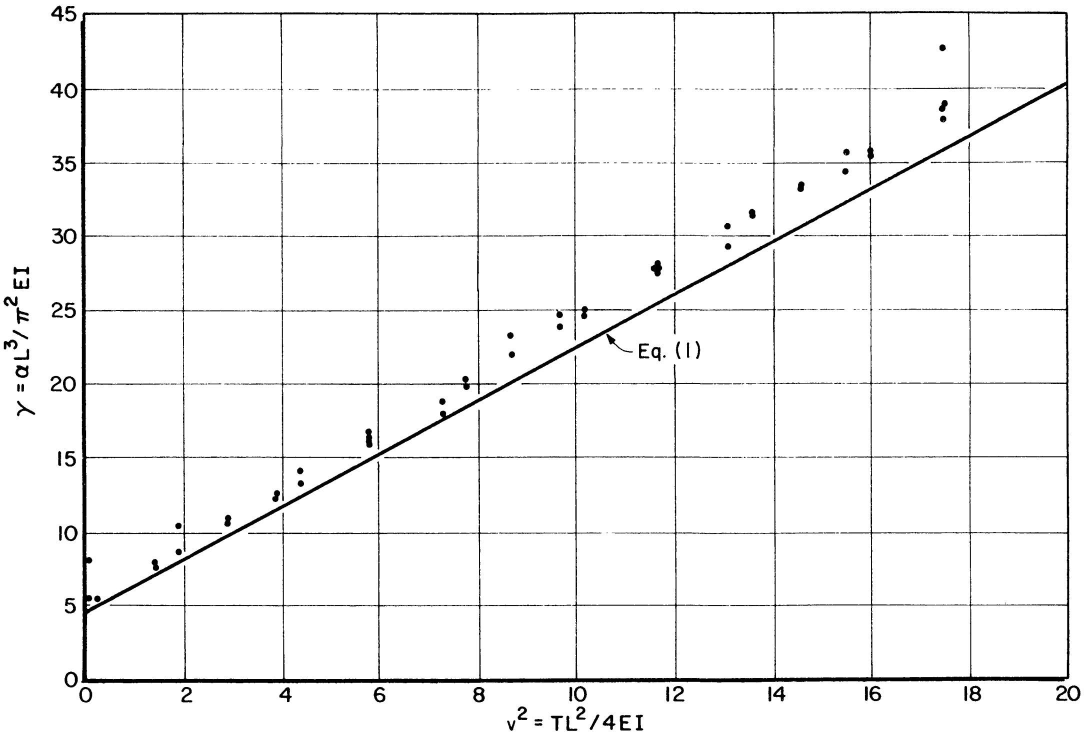

Fig. 6. Comparison of experimental results and theoretical relationship (Test Series T)

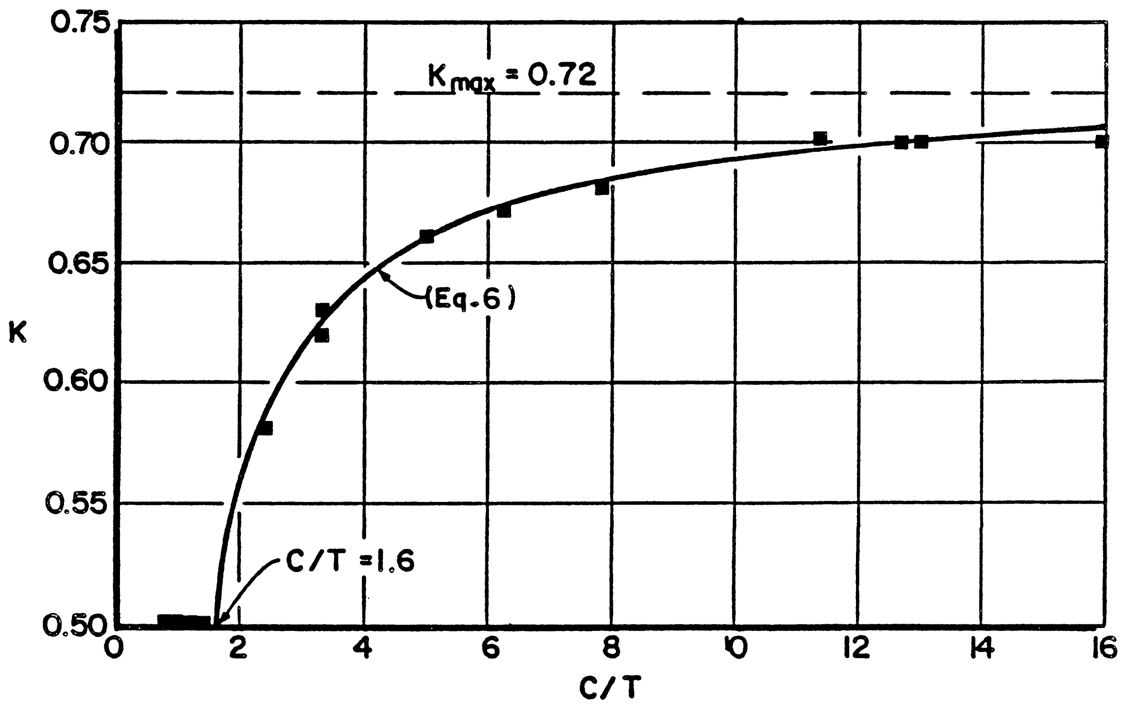

Fig. 7. Comparison of experimental results and theoretical relationship (Test Series B)

Table 2. Summary of Test Results (Series B)

Test No.	T^a (kips)	C_{cr} (kips)	δ^a (in.)	α (kips/in.) From Eq. 4	Q^b/C_{cr} (%)
BX−1	1.283	1.048	0.049	0.175	0.82
BX−2	0.740	1.012	0.278	0.115	3.16
BX−3	0.218	0.710	0.314	0.057	2.52
BX−4	0.075	0.587	0.234	0.041	1.64
BX−5	0.046	0.585	0.318	0.038	2.07
BY−1	3.201	3.322	0.036	0.459	0.50
BY−2	0.741	2.370	0.141	0.186	1.11
BY−3	0.305	1.880	0.386	0.138	2.84
BY−4	0.171	1.939	0.074	0.123	0.48
BY−5	0.110	1.771	0.461	0.117	3.05
BZ−1	7.293	6.691	0.378	1.042	5.89
BZ−2	5.835	6.390	0.296	0.881	4.08
BZ−3	2.192	5.155	0.486	0.478	4.51
BZ−4	0.876	4.440	0.148	0.332	1.11
BZ−5	0.300	3.903	0.641	0.268	4.40

[a] Last measured values before buckling.
[b] $Q = \alpha\delta$

Table 3.
Experimental Values of the Effective Length Factor

Test No.	C_{cr}/T	γ^a	K From Eq. 5	K From Eq. 6	K From Eq. 7
BX−1	0.82	26.12	0.50	0.50	0.47
BX−2	1.37	17.16	0.50	0.50	0.48
BX−3	3.26	8.51	0.62	0.63	0.57
BX−4	7.83	6.12	0.68	0.68	0.63
BX−5	12.72	5.67	0.70	0.70	0.63
BY−1	1.04	21.37	0.50	0.50	0.47
BY−2	3.20	8.66	0.62	0.62	0.56
BY−3	6.16	6.43	0.67	0.67	0.63
BY−4	11.34	5.73	0.69	0.70	0.62
BY−5	16.10	5.45	0.70	0.70	0.65
BZ−1	0.92	21.55	0.50	0.50	0.50
BZ−2	1.10	18.22	0.50	0.50	0.51
BZ−3	2.35	9.89	0.59	0.58	0.57
BZ−4	5.07	6.87	0.66	0.66	0.61
BZ−5	13.01	5.54	0.70	0.70	0.65

[a] Eq. 3 and the values of α given in Table 2 were used to compute γ. The same results are obtained with Eqs. 1 and 2.

onal. The C/T ratio in Eq. 6 thus can be replaced by C_{cr}/T where C_{cr} is the measured buckling load. Consequently, the experimental values of K can also be obtained from Eq. 6.

In the theoretical analysis, it was also shown that for X-braced frames currently met in practice the C/T ratio is smaller than 1.6. Therefore, the most important conclusion of the theoretical analysis can be stated as follows: in double diagonal bracing systems, the K value is equal to 0.5 (see Fig. 7).

However, in test Series B, various values of T were chosen so Eq. 6 can be checked over a wider range. The experimental procedure in this test series was as follows: a given tensile force was first applied to the tension diagonal. The compression diagonal was then loaded by small increments up to buckling. For each load increment ΔC, the magnitude of the tensile force was checked and the out-of-plane lateral deflection at the point of intersection of the diagonals was measured (δ).

The test results are summarized in Table 2. The measured values are T, C_{cr} and δ. With the measured values of T, the transverse stiffness offered by the tension diagonal α is obtained from Eq. 4. The transverse force transmitted to the tension diagonal by the compression diagonal at buckling Q can thus be evaluated. As shown in Table 2, this force varies between 0.5% and 6% of the buckling load. These percentages are not strictly correct because it was not possible to measure the lateral deflection δ at the exact moment of buckling.

For comparison purposes, the design strength equations of AISC's LRFD Specification were used to compute K. Using Eq. E2-3 of the Specification and the measured buckling stresses $F_{cr} = C_{cr}/A$, it can be shown the column slenderness parameter λ_c is always larger than 1.5. Therefore Eq. C-E2-3 of the Commentary can be used to evaluate K.

$$K = \sqrt{\frac{0.877\pi^2 E}{F_{cr}\left(\frac{L}{r}\right)^2}} \tag{7}$$

The experimental values of K obtained from Eq. 7 are given in Table 3 and plotted in Fig. 7. It can be seen that Eq. 6 predicts conservatively the value of the effective length factor.

The values of K obtained from Eq. 7 are lower than the values obtained from Eqs. 5 and 6. However, it should be remembered that these two equations were derived assuming perfect hinges at the ends of the diagonals and no rotational restraint at the intersection point. The lower limit of $K = 0.5$ imposed on Eqs. 5 and 6 is the result of these assumptions.

CONCLUSION

In the theoretical study reported in the first part of this paper, equations were derived to determine the transverse stiffness or spring stiffness provided by the tension diagonal in cross-bracing systems where the diagonals are connected at their intersection point. Equations were also derived to determine the effective length factor of the compression diagonal. The test results reported in this paper have demonstrated the validity of the theoretical analysis.