Effect of Straightening Method on the Cyclic Behavior of k-Area in Steel Rolled Shapes

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Incidents of brittle fracture that initiated from the k-area of wide flange sections have been reported (Tide, 2000). One example in seismic applications is the cracking in the column web when the continuity plates (in other words, column transverse stiffeners) are shop-welded in the connection region.

The majority of rolled steel shapes have been produced from scrap steel in an electric furnace and cast continuously into near-shape configuration in the past two decades. Except for heavy sections these structural shapes are typically straightened by the rotary straightening process in order to bring them into the dimensional tolerance specified in the ASTM standard. The process involves passing a structural shape through a series of rollers placed near the k-areas. Cold bending in these areas generally produces cyclic plastic deformations. Strain hardening together with strain aging results in a higher tensile strength, lower ductility and toughness (Tide, 2000; Jaquess and Frank, 1999). If welding is performed in or near the k-area, thermal strains may cause brittle fracture.

In response to the concerns raised by the designers and fabricators, AISC initiated a series of research projects to study the issue. As part of these studies, tests on the k-area of column sections were conducted at the University of California, San Diego to determine the straightening effects on the performance of seismic moment connections. A parallel study including material tests and pull-plate tests was conducted at Lehigh University (Kaufmann and Fisher, 2001).

TEST SPECIMENS AND TEST METHOD

Table 1 shows the test matrix, where the column and beam sizes for all five specimens were W14×176 and W21×166, respectively; A992 steel was specified. The first three specimens (Specimens K1 to K3) did not use continuity or doubler plates; the only variable was the method of straightening. To increase the potential for fracture in the k-area, a 1-in. diameter drilled hole in the k-area, at the bottom flange level of the beam, was specified. A572 Gr. 50 continuity plates and a ½-in. thick A36 doubler plate were used for Specimens K4 and K5. Doubler plates were groove-welded to the column web near the k-area.

Figures 1 and 2 show the moment connection details for Specimens K1 to K3 and Specimens K4 and K5, respectively. The beam was sized to introduce high concentrated forces through flanges to the column without experiencing significant yielding and buckling. Since this research aimed to study the k-area in the column, not the beam flange groove-welded joints, these welds were made in the shop. Electrodes having a minimum Charpy V-Notch impact value of 20 ft-lbs at −20 °F were specified. It should be noted that these connections were not designed to meet the seismic design provisions.

Material Characteristics

Table 2 shows the chemical analysis of the steels as obtained from the certified mill test reports. Tensile coupon, hardness, and Charpy V-notch tests were conducted by Kaufmann and Fisher (2001) and the average values of the yield and tensile strengths are presented in Table 3.

Test Setup

The test setup is shown in Figure 3. Cyclic loading, which was applied at the beam tip, followed the SAC* standard loading protocol (Clark, Frank, Krawinkler, and Shaw, 1997). Loading was controlled by story drift angle and positive drift was defined as the upward displacement causing positive bending to the beam.

Specimen Design

Specimen K1 to K3

Based on the yield strengths in Table 3, strengths for the limit states of local flange bending and web yielding of the column are 536 kips and 490 kips, respectively (AISC, 1994). Therefore, local web yielding governs the strength.

Assuming that the beam remains elastic and that the beam theory can be applied to compute the bending stress in the beam flange, it can be shown that the beam flange

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Table 1. Test Matrix

Specimen No.	Column Straightening Method	Continuity Plates, Doubler Plate
K1	Rotary	No
K2	Gag	No
K3	None	No
K4	Rotary	Yes
K5	None	Yes

Table 2. Chemical Compositions

Member[a]	C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Cb	Sn	B	CE
Columns W14×176	0.06	1.34	0.015	0.021	0.24	0.34	0.10	0.11	0.03	0.05	0.00	0.01	0.0005	0.35
Beams W21×166	0.06	1.10	0.015	0.033	0.24	0.37	0.12	0.07	0.03	0.00	0.00	0.01	0.0005	0.29

[a] Nucor-Yamato steel, Heat Nos. 150314 and 154423 for column and beam, respectively.

Table 3. Beam and Column Mechanical Characteristics

Member	Coupon	Yield Strength (ksi)	Tensile Strength (ksi)	Elongation[a] (%)
Column W14×176	Flange	54.3	71.3	31
	Web	55.1	70.7	29
	(Mill Cert.)	(58)	(76)	(21)
Beam W21×166	(Mill Cert.)	(50.0)	(74.0)	(22)

[a] Based on 8-in. gage length.

force, P_f, at the column face and the applied load, P, at the beam tip are related to each other as follows:

$$P_f = \frac{PL_b(d - t_f)b_f t_f}{2I_x} = 6.4P \qquad (1)$$

where
L_b = distance from the loading point to the column face
d = beam depth
b_f = beam flange width
t_f = beam flange thickness
I_x = major-axis moment of inertia of beam

Equating the governing strength (490 kips) and Equation 1 gives a P value of 76.6 kips when the web local yield strength is reached.

The panel zone strength based on Equation 9-1 of the AISC *Seismic Provisions for Structural Steel Buildings* (AISC, 1997) is:

$$V = 0.6F_{yc}d_c t_{cw}\left[1 + \frac{3b_{cf}t_{cf}^{\;2}}{d_b d_c t_{cw}}\right] = 506 \text{ kips} \qquad (2)$$

The relationship between the panel zone shear force and the applied load is:

$$V_{pz} = P_f - V_c = P_f - \frac{PL_c}{H_c} = 6.4\,P - 1.1\,P = 5.3\,P \qquad (3)$$

where

V_c = column shear force

L_c = distance from the loading point to the centerline of the column

H_c = column height.

Equating Equations 2 and 3 gives an applied load of 95.5 kips when the panel zone shear strength is reached.

A comparison of local web yielding and panel zone shear strengths indicates that local web yielding would govern the strength of Specimens K1 to K3.

Specimens K4 and K5

Continuity plates were used such that local flange bending and local web yielding are not the governing limit states. With a ½-in. thick doubler plate, the panel zone strength is increased to 822 kips. This strength corresponds to an

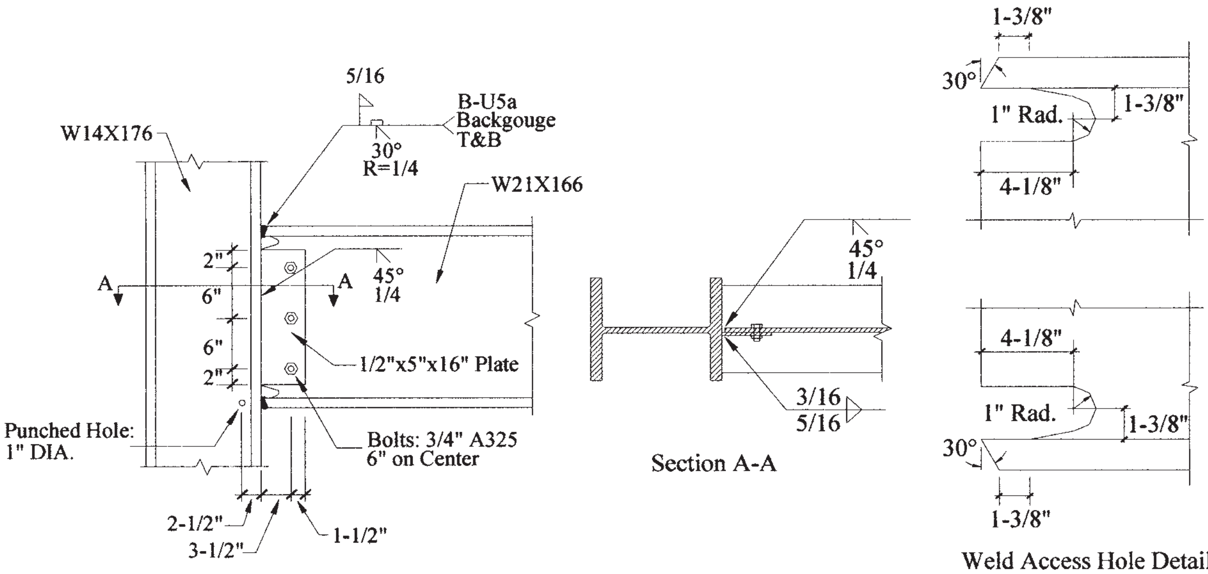


Fig. 1. Specimens K1 to K3: moment connection details.

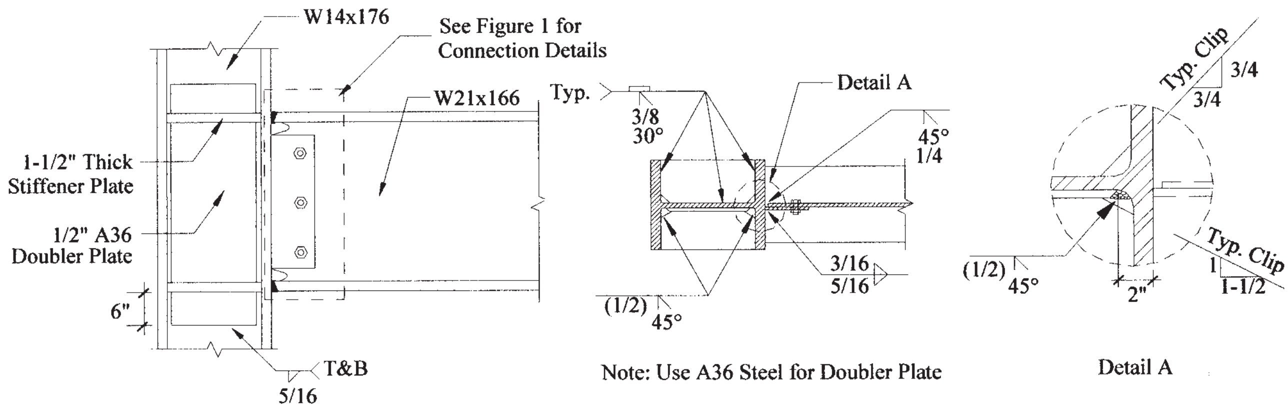


Fig. 2. Specimens K4 and K5: moment connection details.

applied load of 155.1 kips per Equation 2. Therefore, the strength of Specimens K4 and K5 is expected to be 53 percent stronger than the first three specimens. The strong column-weak beam condition is satisfied for all test specimens.

TEST RESULTS

Specimens K1 to K3

All three specimens performed and failed in a similar way. Significant yielding in the panel zone occurred first. Figure 4 shows the typical yielding pattern at 3 percent drift; also note the yielding pattern around the 1-in. hole. Hairline cracks developed at the toe of the beam flange groove welds at this drift level; significant kinking of the column flange was also observed. Figure 5a depicts the typical crack initiation at the toe of the beam flange groove welds. Local flange bending of the column produced stress concentration and crack initiation at the center of the column flange. The crack then propagated toward the edges of the flange that eventually fractured the column flange across its width. Complete fracture of the column flange occurred at 4 percent drift for Specimen K1 and 5 percent drift for Specimens K2 and K3 (see Figure 5b).

Figure 6 shows the readings from strain gages that were placed along the k-line of the column at the top flange level

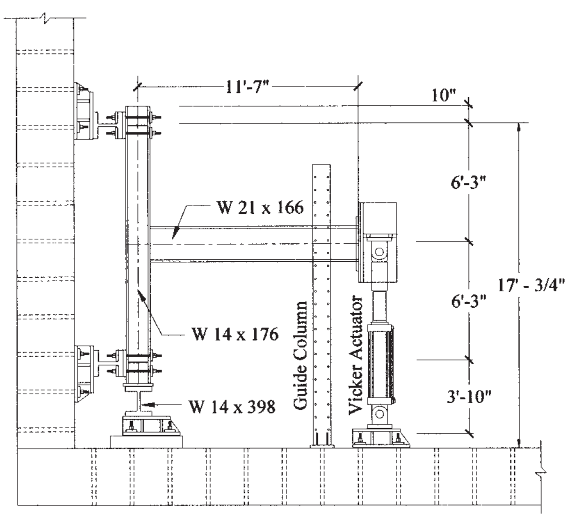
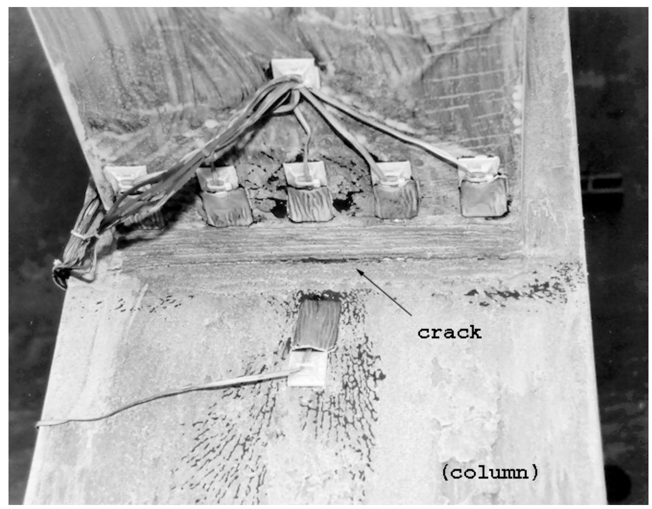


Fig. 3. Test setup.

Fig. 4. Panel zone yielding pattern of specimen K3 (3% drift).



(a) Crack Development

(b) Column Flange Fracture

Fig. 5. Crack development and failure mode of specimen K3 (5% drift).

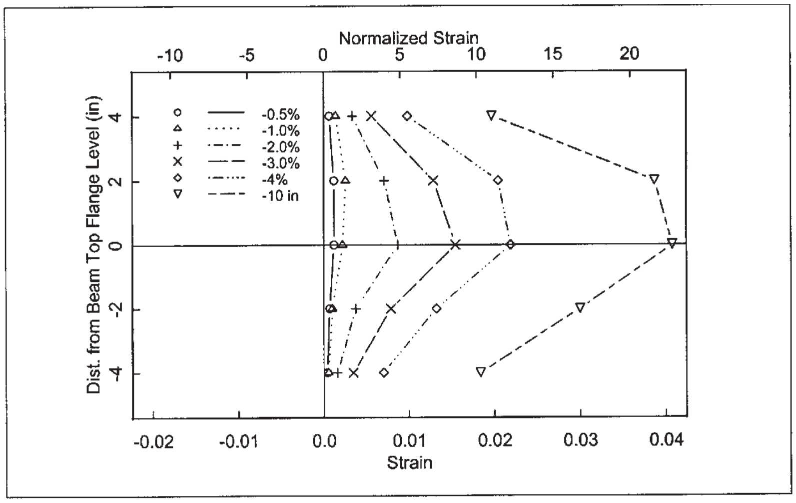


Fig. 6. Strain profiles along column k-line (Specimen K1).

(a) Drift = 7 in.

(b) Drift = 8 in.

(c) Drift = 9 in.

(d) Drift = 10 in.

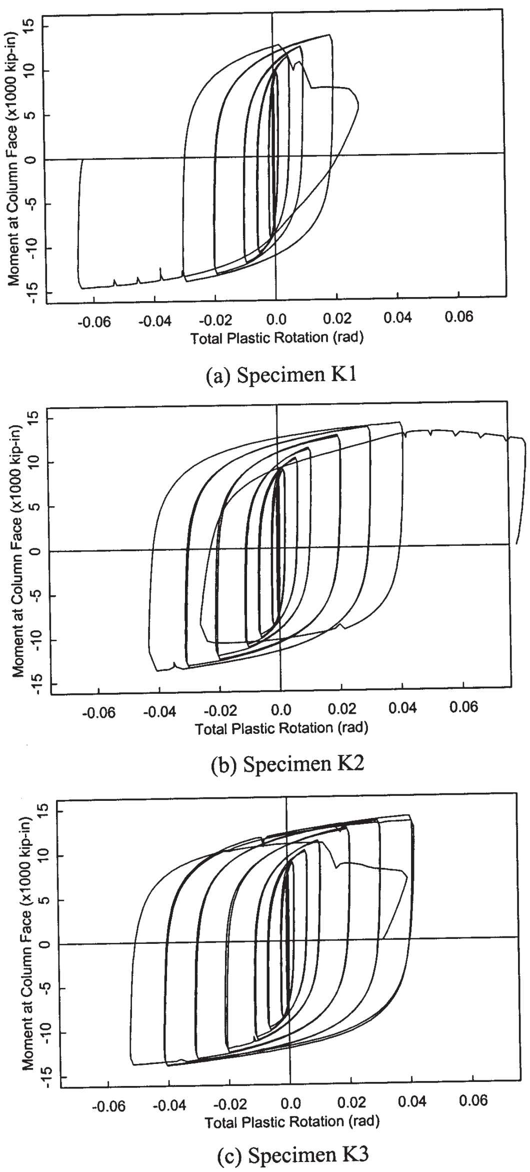
Fig. 7. Fracture propagation in hole region (Specimen K2).

for Specimen K1. The maximum strain that developed in the k-area was $24\varepsilon_y$, where ε_y = yield strain. No fracture was observed at such high strain levels.

At the bottom flange level, where a 1-in. hole was drilled, a crack did not initiate from the hole in Specimen K1, even though crack developed in Specimens K2 and K3 at 5 percent drift. Figure 7 shows the fracture propagation in the hole region for Specimen K2. Although the crack propagation along the k-line was relatively fast, the behavior was not brittle and the amount of strength degradation was limited.

The moment versus total plastic rotation relationships for three specimens are shown in Figure 8. Because the details and welding of the beam flange groove-welded joints were not intended to simulate field conditions, large plastic rotations do not imply that continuity plates are unnecessary. On the contrary, for the column size tested the test results clearly show that local flange bending tends to promote crack development at the toe of the beam flange groove welds.

The maximum force applied by the top flange of the beam to the column can be estimated from Equation 1. A comparison of these forces with the LRFD strength for local web yielding (LWY) is shown in Figure 9. The LRFD strength is exceeded by 34 percent on average.



(a) Specimen K1

(b) Specimen K2

(c) Specimen K3

Fig. 8. Moment vs. total plastic rotation relationships.

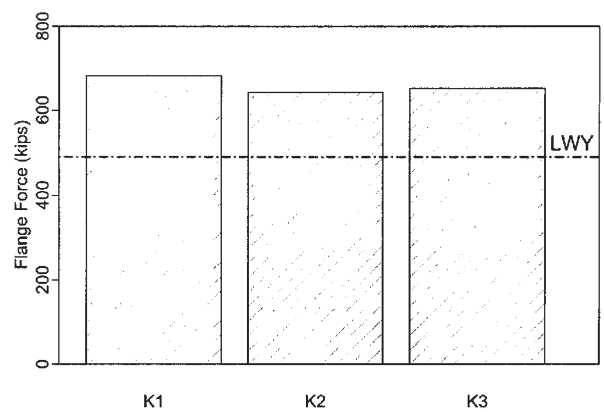


Fig. 9. Comparison of local web yielding strength.

Fig. 10. Specimen K4 column kinking at 5 percent drift.

Specimens K4 and K5

The performance of Specimens K4 and K5 was similar. Minor flaking of the whitewash in the panel zone (both the column web and doubler plate) was first observed at 1 percent drift. Flaking in the beam flanges was observed at 3 percent drift. At 5 percent drift, sign of stress concentration at the weld access hole started to show; kinking of the column due to significant panel zone yielding was also evident in these two specimens (Figure 10). Brittle fracture of the beam flanges occurred during the first cycle at 6 percent drift for both specimens. Figure 11 shows a close-up view of the fracture for specimen K4. The fracture occurred in the k-area of the beam web due to stress concentration in the weld access hole.

Moment versus total plastic rotation relationships for the two specimens are shown in Figure 12. The maximum load applied to Specimens K4 and K5 was about 58 percent higher than those of the first three specimens. Although the beam flanges applied a much higher force to the column, no fractures in the k area were observed.

CONCLUSIONS

1. Maximum strains reached in the k-area of the column at the top flange level of the beam were 24 times the yield strain in the rotary-straightened column (Specimen K1). No fracture in this area was observed.

2. The crack did not initiate from the drilled 1-in. hole in Specimen K1. But cracks did initiate from the hole of Specimens K2 (gag-straightened) and K3 (non-straightened), although this occurred at a high (5 percent) drift level. For the type of details and member size tested, no consistent trend indicating that a drilled hole would trigger early fracture in the k-area of a rotary-straightened column was observed.

3. The test results indicated that, under a cyclic loading condition, the strength as predicted by the LRFD Specification for the limit state of local flange bending and local web yielding is conservative. An average overstrength factor of 1.34 for local web yielding was observed. To reduce the thickness and the associated welding of continuity plates for the seismic design of steel moment connections, it appears desirable to take advantage of this overstrength.

4. The plastic rotation capacity varied from 0.02 to 0.04 radian for the first three specimens. Although this modest amount of plastic rotation could be achieved without using the continuity plates, it should be noted that the details and welding of the beam flange groove welds were not intended to simulate a field condition.

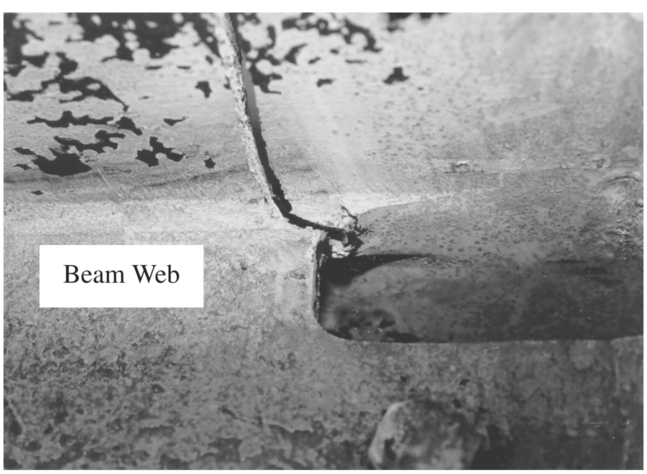


Fig. 11. Brittle fracture of specimen K4 beam top flange.

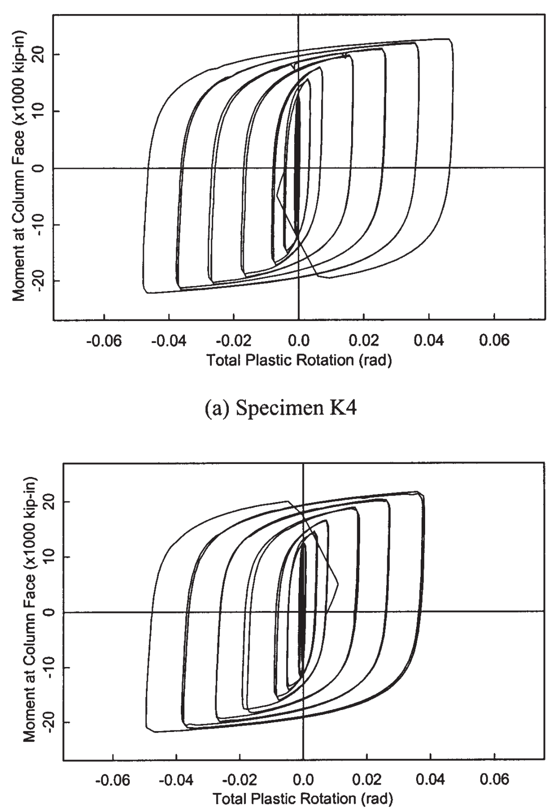


Fig. 12. Moment vs. total plastic rotation relationships.

5. When continuity plates and doubler plate were used for the last two specimens, the behavior and failure mode were similar, no matter whether the column was rotary-straightened (K4) or non-straightened (K5). Both specimens experienced brittle fracture of the beam flange at high drift levels (≥ 5 percent). The fracture initiated from the weld access hole in the k-area of the beam, where the transition (in other words, the profile) was not made smooth. To prevent this type of fracture, it is essential to provide a smooth transition in the weld access hole.

6. This study did not reveal adverse effects caused by rotary-straightening. However, since in a beam-column geometry under cyclic loading Kaufmann and Fisher (2001) and others have reported much inferior material properties locally in the k-area of rotary-straightened members, it is prudent that welding in these areas be avoided, as indicated in the earlier AISC Advisory (Iwankiw, 1997).

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