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E.J. Kaufmann
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Final Report
to
American Institute of Steel Construction

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ACKNOWLEDGEMENT

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I. INTRODUCTION

In a series of cracking incidents that have occurred during fabrication with rolled column shapes [1] subsequent failure investigations found that the cracking frequently originated within the k-area of the column. The k-area of rolled shapes is regarded as the region of the web extending about 1.5 inches from the web-flange intersection. Further investigations into the cause of the cracking found that the mechanical properties in this area were substantially changed as a result of the rotary straightening process widely used in manufacturing rolled shapes to achieve the required final dimensional tolerances. The cyclic cold deformation introduced in this area during the rotary straightening process has been found to markedly elevate the yield strength and tensile strength to a lesser extent with concomitant decreases in ductility and fracture toughness [2]. This local elevation in strength and reduction in ductility and toughness in the k-area was believed to have been a key factor in the cause for the observed cracking.

Beyond the fabrication precautions which have now been implemented to mitigate future cracking in this region [3], the subsequent service performance of rolled sections containing these low ductility and toughness regions was also of concern, particularly under severe service conditions as can occur in earthquakes. The study reported herein is one of four studies initiated by the American Institute of Steel Construction to address these concerns. One of the studies examined the basic mechanical properties of inelastically strained steel sections to assess the effects of cyclic cold deformation on the strength, ductility, and fracture toughness of A572 Gr. 50 and A913 Gr. 50 steel sections [4,5]. The focus of the current study was to perform a comparative assessment of the effect of rotary straightening on the static strength and deformation behavior of full-size column sections in order to determine whether service performance is affected by rotary straightening and if so to what extent. A parallel investigation utilizing the same column section material in cyclically loaded moment frame connection tests was also performed at the University of California, San Diego [6]. Two additional studies related to the k-area examined existing continuity and doubler plate design requirements and the statistical variation of properties of A992 shapes [7].

I.1 RESEARCH OBJECTIVE AND APPROACH

The objective of the current study was to examine the strength and deformation behavior of as-rolled, rotary straightened, and gag straightened column sections to comparatively assess their ability to transmit tensile loads across the k-area. A series of static load tests of full-size sections were conducted using as-rolled, rotary straightened, and gag straightened A992/A572 Gr. 50 column sections. Gag straightened sections were included to assess the relative effect of this traditional straightening method used now on only the heavier Group 4 and 5 rolled sections in comparison to the rotary straightening method.

Tensile forces were applied to the k-area through pull-plates welded to the column flanges. Various web fabrication details were also included in the test matrix to simulate typical fabrication conditions which localize strains within the k-area and introduce discontinuities, both factors which tend to exacerbate fracture tendencies. The experimental test matrix consisted of four types of specimen configurations for each of the three differently processed sections. Tests using rotary

II.2 TENSION LOAD TEST SPECIMEN DESIGN

The design of the tension load test specimen is shown in Figure 4. Tensile forces were applied to the k-area of an 8 in. length of rolled section through high strength steel plates groove welded to the flange surfaces of the section. The 1.5 in. pull-plates were A709 Gr. HPS-70W with a yield strength of 87.2 ksi and tensile strength of 97.6 ksi. Four types of specimen configurations were fabricated by a commercial steel fabricator. Type I configuration specimens were intended to evaluate the strength and deformation behavior of plain rotary straightened, gag straightened, and as-rolled sections. Figure 5a shows a fabricated Type I test specimen. Type II configuration specimens included a 1 in. hole located in the k-region adjacent to each flange (Figure 5b). The original intent was to use a punched hole to introduce potential microdiscontinuities associated with the punching operation which could affect the k-area fracture behavior. Unfortunately, a drilled hole had to be substituted since a punched hole could not be fabricated in the k-area close to the flange.

Types III and IV specimen configurations included 1.5 in. stiffeners welded to the web and only one flange. The k-area weld termination in these configurations simulated a continuity plate detail which has been observed to exacerbate k-area cracking but also provided a more severe strain concentration at the termination of the stiffener. In one case the web groove weld terminated on the k-region (Type III) as shown in Figure 5d. In Type IV specimen configurations the weld terminated outside of the k-region as is currently recommended [3] and shown in Figure 5e.

A single specimen was fabricated for each of the four configurations for as-rolled and gag straightened sections. Rotary straightened sections were tested in triplicate to account for statistical variability in the rotarizing process resulting in a total of 20 tests. A summary of the test conditions is provided in Table 3. Upon delivery of the test specimens it was noted that the web in one rotary straightened Type IV specimen had been weld repaired in the web gap region, apparently due to cracking in this area during fabrication, and was not load tested. Additional information was not available from the fabricator regarding this occurrence. It was also noted that a second as-rolled Type III specimens was mistakenly fabricated instead of a third rotary straightened Type III specimen.

II.3 TEST PROCEDURE AND INSTRUMENTATION

Specimens were statically loaded at a constant displacement rate of 0.1 in/min in a 600 kip capacity universal test machine. Figure 6 shows a typical test arrangement. Web elongation was measured by a pair of linear variable displacement transducers (LVDT) attached to the flange edges (see Figure 7). Type III and IV configuration specimens also utilized an additional LVDT attached to a web stiffener in order to measure web gap displacement and is also seen in Figure 7. Strain gauges were attached to selected test specimens to characterize strain distributions in and outside the k-area and local strains at web gap locations.

II.4 TEST RESULTS

II.4.1 Type I Specimens

A composite plot of load vs. web elongation for the three Type I configuration tests of rotary straightened, gag straightened, and as-rolled sections is shown in Figure 8. A tabulated summary of the test results is also given in Table 4. All three specimens failed by ductile fracture of the web at the mid-depth after significant elongation and development of necking at this location (see Figure 9). The as-rolled and gag straightened specimens behaved nearly identically with yield and tensile loads of 332 kips and 453 kips (52 ksi and 71 ksi), respectively and final web elongations of 2.6in. (18% strain). This is consistent with the similar tensile properties obtained in the coupon tension tests. The rotary straightened section exhibited a small elevation in yield and tensile strength (54 ksi and 72 ksi) and a reduction in tensile elongation (13% strain) apparently due to the prior strain hardening of the k-area during rotary straightening and the constraining effect of this higher strength material on the web. The narrower necked region seen in Figure 9 shows this effect of constraint. Although the overall ductility of the web appears to be reduced by rotary straightening a general yielding condition is still developed and the fracture mode remains ductile for a plain section.

II.4.2 Type II Specimens

Introducing holes in the k-area of Type II specimens did not alter the loading behavior of the k-area for the three differently processed sections from the plain section behavior. As indicated in Section II.2 punched holes could not practically be made in the k-area and drilled holes were substituted. The lessened severity of drilled holes as a stress concentration due to the absence of crack-like microdiscontinuities resulted in only plastic deformation of the hole area prior to ductile fracture of the web at the mid-depth as occurred in the Type I test specimens with the exception of the gag straightened section which failed ductilely through a hole.

Load vs. web elongation plots for the three differently processed sections are shown in Figure 10. The as-rolled and rotary straightened specimens (NR-II and R1-II) mid-depth fractures and elongated appearance of the holes in both types of specimens are shown in Figure 11. Visual inspection of the hole areas did not reveal any crack-like tears within the holes which may have developed under load. The gag straightened specimen (G-II) also exhibited significant deformation in the hole area prior to ductile fracture of the web through a hole (see Figure 12). It is believed that the cause for the different failure location was associated with weld distortion of one of the pull-plates in this specimen outside of the specified fabrication tolerance which introduced bending in the web. Early evidence of yielding on the tension side of the web and ductile fracture of this side of the web at the hole was observed as seen in Figure 12.

In the absence of an initial crack-like defect both the as-rolled and rotary straightened specimen behaved the same despite the large difference in fracture toughness of the k-area in which the holes resided. More generally, the results of both the Type I and Type II configuration test specimens indicate that in the absence of a crack-like discontinuity the low fracture resistance of the k-area in rotary straightened sections does not appear to impair the sections strength or ductility under the most severe inelastic loading conditions.

II.4.3 Type III Specimens

Type III configuration specimens introduced a significantly more severe strain concentration and defect condition in the k-area at the stiffener weld termination than the drilled hole in the Type II specimens. The constraining effect of the adjacent flange and heavy web stiffeners in the small web gap area would also be expected to develop a high level of constraint (see Figure 14).

Figure 13 shows the load vs. web elongation behavior for the three differently processed sections. Web elongation was significantly reduced ranging from 0.004-0.009 in. in the rotary straightened sections to 0.012-0.02 in. in the as-rolled and gag straightened sections. In all three differently processed sections failure occurred by brittle fracture initiating in the web gap (see Figures 15 and 16) at loads approaching the tensile strength of the k-area (462-529 kips) with the exception of one rotary straightened test specimen (R2-III) which failed below the web yield strength (311 kips).

Examination of the fractures revealed a fundamental difference in the fracture behavior of the rotary straightened sections compared to the as-rolled and gag straightened sections. Both rotary straightened test specimens (R1-III and R2-III) developed a brittle fracture at one or two of the stiffener weld toes (see Figure 15). No indication of an initial defect was observed in either case. In contrast, the as-rolled and gag straightened sections developed stable ductile tearing at the stiffener weld toes prior to cleavage fracture of the web (see Figure 16). The gag straightened test specimen (G-III) developed a 3/8 in. deep semi-elliptical tear at one stiffener weld termination. In the as-rolled test specimens (NR-III) two semi-elliptical tears at both stiffener weld terminations propagated to a through web crack condition before cleavage developed.

The cause for the widely different fracture load observed in the two rotary straightened test specimens is not entirely clear. The severity of the detail in combination with very low toughness material may enhance its sensitivity to the actual weld toe geometry at the stiffener termination which varies from specimen to specimen.

The strength and deformation behavior of all three differently processed sections were not significantly different largely due to the severe conditions imposed in the web gap. However, the progressively smaller initial crack tolerated by the as-rolled, gag straightened, and rotary straightened sections, respectively, is a result of the reduced fracture toughness in the k-area of the sections and demonstrates that under high stresses and constrained conditions, the risk of brittle fracture from small weld toe defects in the k-area of rotary straightened sections is substantially increased.

II.4.4 Type IV Specimens

Type IV configuration specimens were essentially the same design as Type III with the exception that the stiffener welds terminated just outside the k-area (approx. 1-3/4 " from the flange inside face) as current AISC guidelines recommend. A typical Type IV test specimen and stiffener weld termination is shown in Figure 17. (see Figure 14 for Type III comparison).

Figure 18 shows the load vs. web elongation behavior for the three differently processed sections. Both the as-rolled (NR-IV) and gag straightened (G-IV) specimens exhibited fully ductile behavior. The specimens developed ductile through-web tears in the web gap region prior to ductile fracture of the remaining web ligaments (see Figure 19). Both rotary straightened Type IV specimens also developed ductile tears in the web gap region before brittle fracture of the remaining web ligament (see Figure 20). In all cases the effect of terminating the stiffener weld beyond the k-area resulted in increased ductility, particularly for the rotary straightened sections.

For the as-rolled and gag straightened sections the reduced constraint in the web gap region resulted in a fully ductile fracture compared to similarly processed Type III specimens. For the rotary straightened sections, the combination of reduced constraint in the web gap and stiffener weld terminating beyond the low toughness k-area permitted development of ductile weld toe tears prior to instability resulting in increased ductility compared to similarly processed Type III specimens with the stiffener terminating within the k-area.

To further investigate the effect of moving the stiffener weld termination away from the k-area an additional Type IV test specimen was fabricated by modifying a rotary straightened Type I specimen where the stiffener was terminated 1 in. further from the k-area than the previous Type IV specimens (approx. 2-3/4 " from the flange inside face) as seen in Figure 21. The load vs. web elongation behavior of this test specimen (R3-IVM) is shown in Figure 22 along with the standard Type IV specimen results. The effect of increasing the web gap an additional 1 in. resulted in additional web ductility and fully ductile fracture behavior.

The results of these tests indicate that terminating stiffener welds beyond the k-area of rotary straightened sections markedly reduces the risks of brittle fracture by removing small fracture initiating discontinuities from the low toughness k-area and allowing development of sufficient plasticity for stress redistribution before reaching a fracture instability condition. By terminating welds at least 1-3/4 in. from the flange inside face the fracture behavior of rotary straightened sections was observed to be nearly the same as the as-rolled sections.

The effect of web gap on ductility is further illustrated in Figures 23 and 24 where results of Type III and IV tests have been plotted for as-rolled and rotary straightened sections. The increase in ductility and reduction in yield load with increasing web gap is apparent for both types of rolled sections.

III. SUMMARY AND CONCLUSIONS

1. Rolled sections manufactured from the same heat of steel and straightened by the rotary straightening process exhibited a marked change in the mechanical properties in the k-area compared to the as-rolled condition. Gag straightening the same sections resulted in negligible change in k-area properties.

2. The k-area strength and deformation behavior of plain rotary straightened sections (Type I) were found to be nearly the same as as-rolled or gag straightened sections. The overall ductility of the web of rotary straightened sections was reduced, however, a general yielding condition was still developed and the fracture mode remained ductile. No effect on behavior was observed by introducing drilled holes in the k-area of the three differently processed sections (Type II).

3. The strength and deformation behavior of all three differently processed sections with welded stiffeners terminating in the k-area (Type III) was similar due to the severe stress concentration and constraint condition imposed in the web gap. All three types of sections failed by brittle fracture, however, a progressively smaller initial crack was tolerated by the as-rolled, gag straightened, and rotary straightened sections, respectively, as a result of the reduced fracture toughness in the k-area of the sections. The results indicated that under high stresses and constrained conditions, the risk of brittle fracture from small weld toe defects in the k-area of rotary straightened sections is substantially increased.

4. Increasing the web gap and terminating stiffener welds outside of the k-area as is currently recommended by AISC resulted in increased ductility in all three differently processed sections and reduced sensitivity to brittle fracture. The strength and deformation behavior of rotary straightened sections were found to approach that of as as-rolled sections when the web gap was increased to 2-3/4 in. The test results suggest that the difference in strength and deformation behavior of rotary straightened sections and gag straightened or as-rolled sections is substantially reduced if these recommendations are followed and welds are not introduced in the k-area of these sections.

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TABLE 1
CHEMICAL COMPOSITION (WT%)
(ASTM A992/A572 Gr.50 , W14 X 176)

C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Cb	Sn	B	CE
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

TABLE 2
COLUMN SECTION MECHANICAL PROPERTIES

W14 X 176	Test Location	Y.S. (ksi)	T.S. (ksi)	Elong. (8") (%)
Rotary Straightened	Web	54.14	70.34	29.7
	K-area	77.13, 82.41	85.64, 84.86	9.4, 9.4
	Flange	54.01	70.89	31.3
Gag Straightened	Web	55.06	70.39	28.9
	K-area	52.15, 53.00	69.92, 71.04	29.7
	Flange	53.92	70.99	28.9
As-Rolled	Web	56.03	71.22	28.8
	K-area	54.18, 54.09	71.44, 70.78	29.4, 30.1
	Flange	54.92	71.87	31.3

TABLE 3
SUMMARY OF TENSION LOAD TEST CONDITIONS

Straightening Method	No. Tests			
	Specimen Configuration			
	Type I	Type II	Type III	Type IV
Rotary	3	3	2**	3*
Gag	1	1	1	1
As-Rolled	1	1	2**	1

* One Specimen Cracked in Fabrication and Repaired. Not Tested.

**Additional As-Rolled Specimen Substituted for Rotary Straightened Specimen

TABLE 4
K-AREA LOAD TEST SUMMARY

Specimen Configuration	Straightening Method	Specimen ID	P_{max} (kips)	$\Delta_{web, max}$ (in.)	Fracture Location	Fracture Type	Notes
Type I	As-Rolled	NR-I	453.4	2.595	Web Mid-depth	Ductile	
	Gag	G-I	453.8	2.680	Web Mid-depth	Ductile	
	Rotary	R1-I	459.7	1.786	Web Mid-depth	Ductile	
Type II*	As-Rolled	NR-II	462.3	1.793	Web Mid-depth	Ductile	
	Gag	G-II	429.8	0.091	Hole Area	Ductile	Bending Due to Pull-Plate Distortion
	Rotary	R1-II	457.7	1.915	Web Mid-depth	Ductile	
	Rotary	R2-II	457.5	1.933	Web Mid-depth	Ductile	
	Rotary	R3-II	461.1	1.769	Web Mid-depth	Ductile	
Type III (3/4" Web Gap)	As-Rolled	NR-III	497.8	0.012	Web Gap	Ductile/Brittle	Through-Web Tear
	As-Rolled	NR-III	469.8	0.021	Web Gap	Ductile/Brittle	Through-Web Tear
	Gag	G-III	462.4	0.015	Web Gap	Ductile/Brittle	3/8" Weld Toe Tear
	Rotary	R1-III	529.3	0.009	Web Gap	Brittle	No Initial Tearing
	Rotary	R2-III	311.6	0.004	Web Gap	Ductile/Brittle	No Initial Tearing
Type IV (1-3/4" Web Gap)	As-Rolled	NR-IV	469.9	0.121	Web Gap	Ductile	
	Gag	G-IV	470.4	0.088	Web Gap	Ductile	
	Rotary	R1-IV	512.5	0.031	Web Gap	Ductile/Brittle	½" Depth Weld Toe Tear
	Rotary	R3-IV	523.0	0.026	Web Gap	Ductile/Brittle	Through-Web Tear
	Rotary	R3-IVM**	483.2	0.074	Web Gap	Ductile/Brittle	Through-Web Tear

* Drilled Holes
** Web Gap Increased to 2-3/4 in.

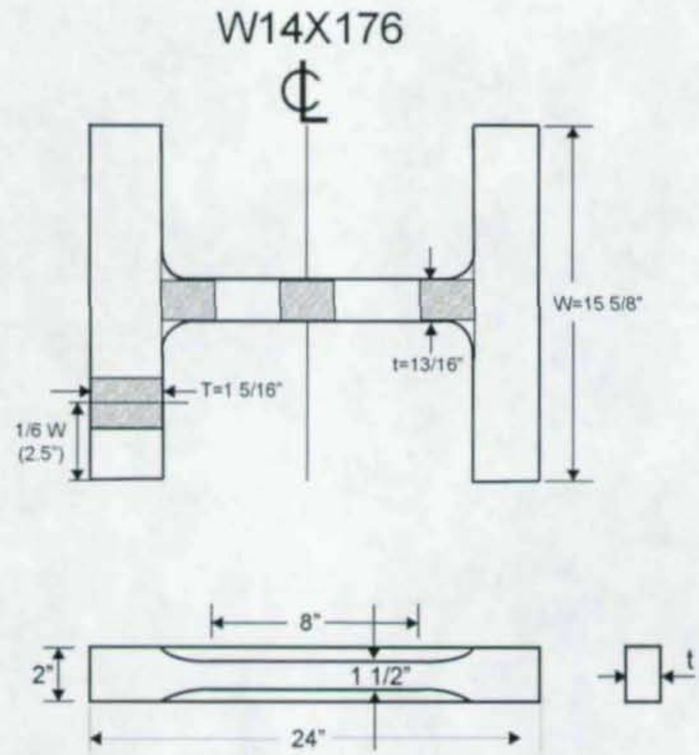

Figure 1 Column Section Tensile Coupon Locations.

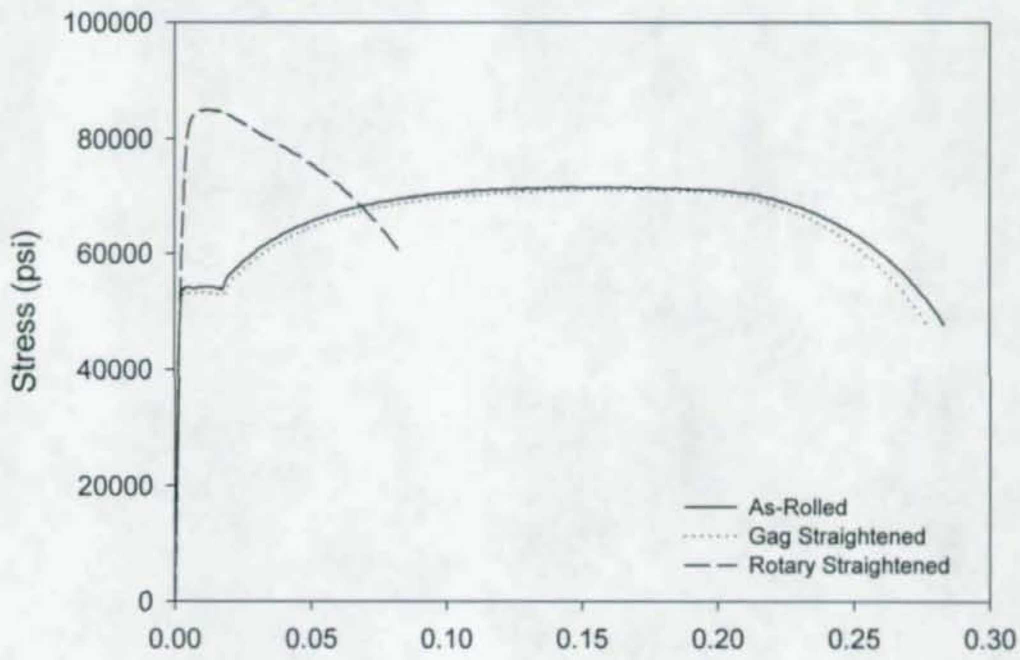

Figure 2 K-area Stress-Strain Behavior for the Three Differently Processed Sections.

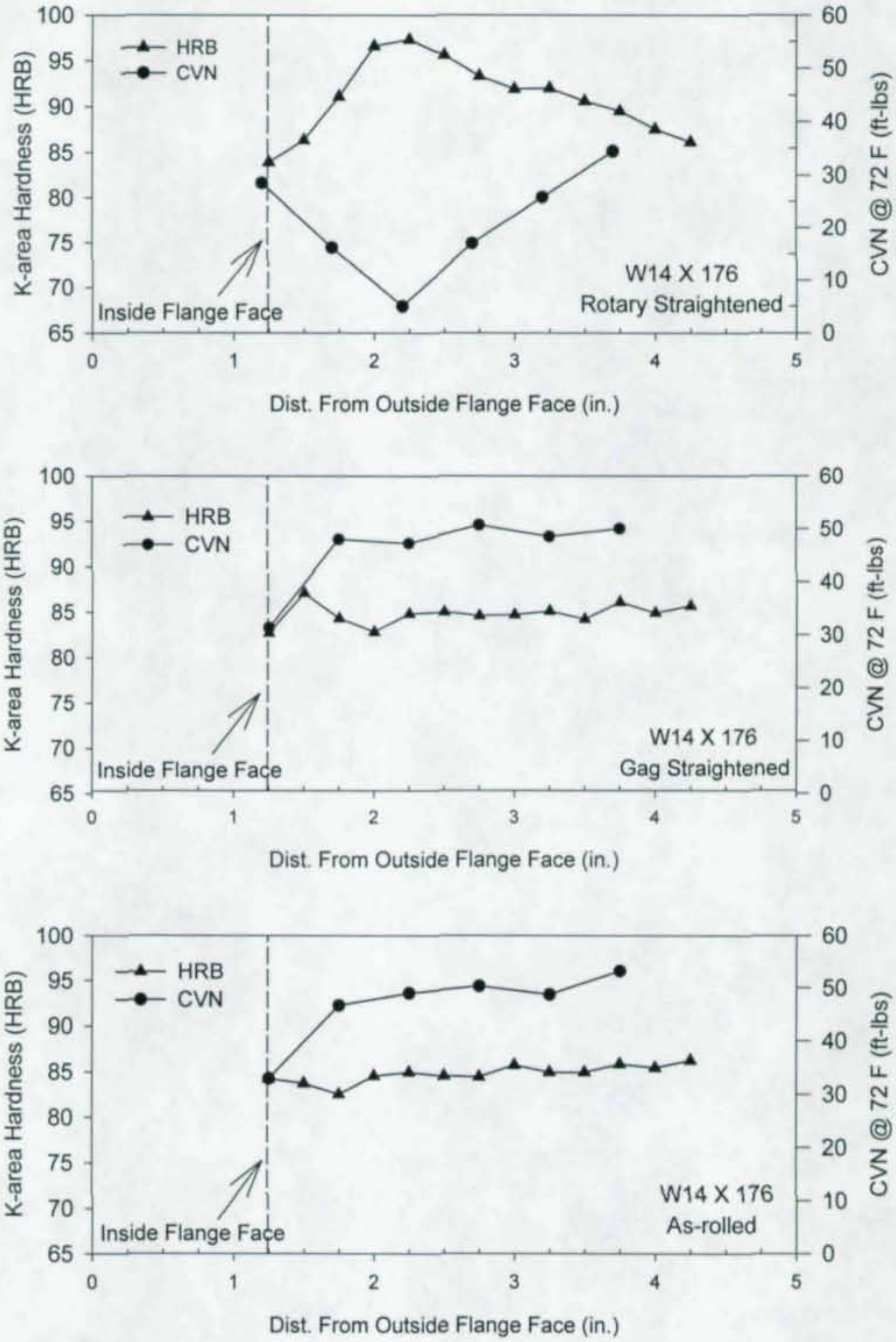

Figure 3 K-area Hardness and CVN for the Three Differently Processed Sections.

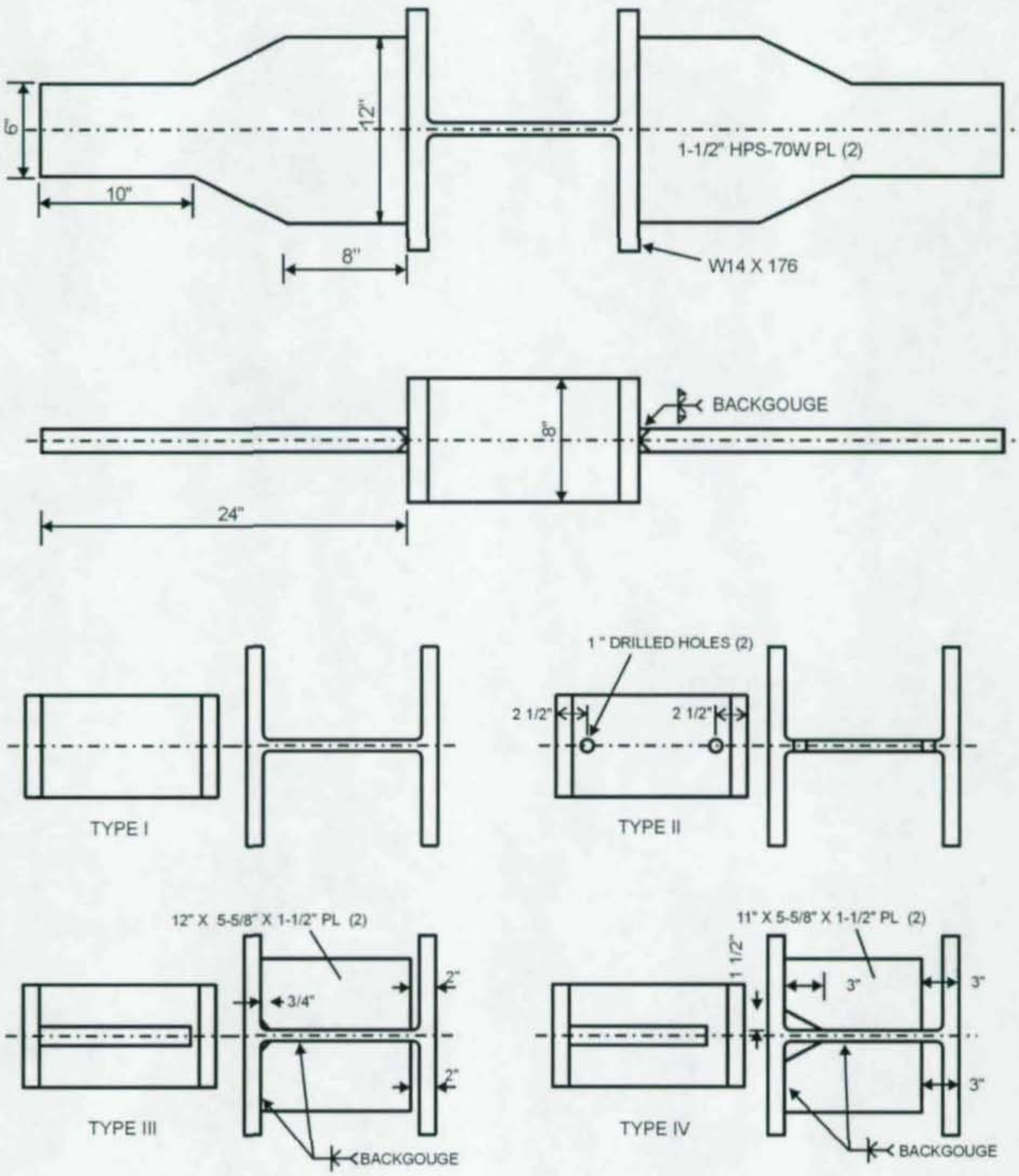

Figure 4 K-area Tension Test Specimen Design and Test Configurations.

Figure 5a Type I Specimen Configuration.

Figure 5b Type II Specimen Configuration.

Figure 5c Type III and IV Specimen Configuration.

Figure 5d Type III Web Gap Detail.

Figure 5e Type IV Web Gap Detail.

Figure 6 Tension Load Test Specimen Installed in the 600 kip Capacity Test Machine.

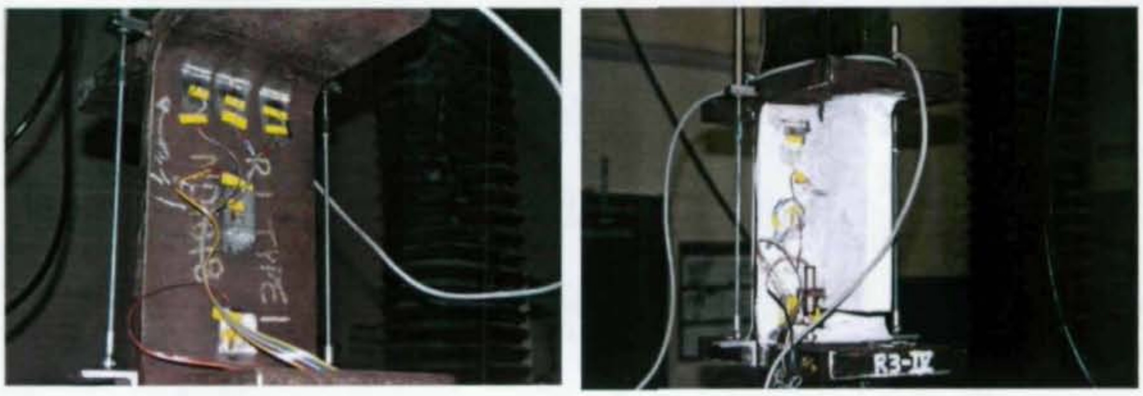

Figure 7 LVDT Sensor Positions for Measurement of Web and Web Gap Displacements.

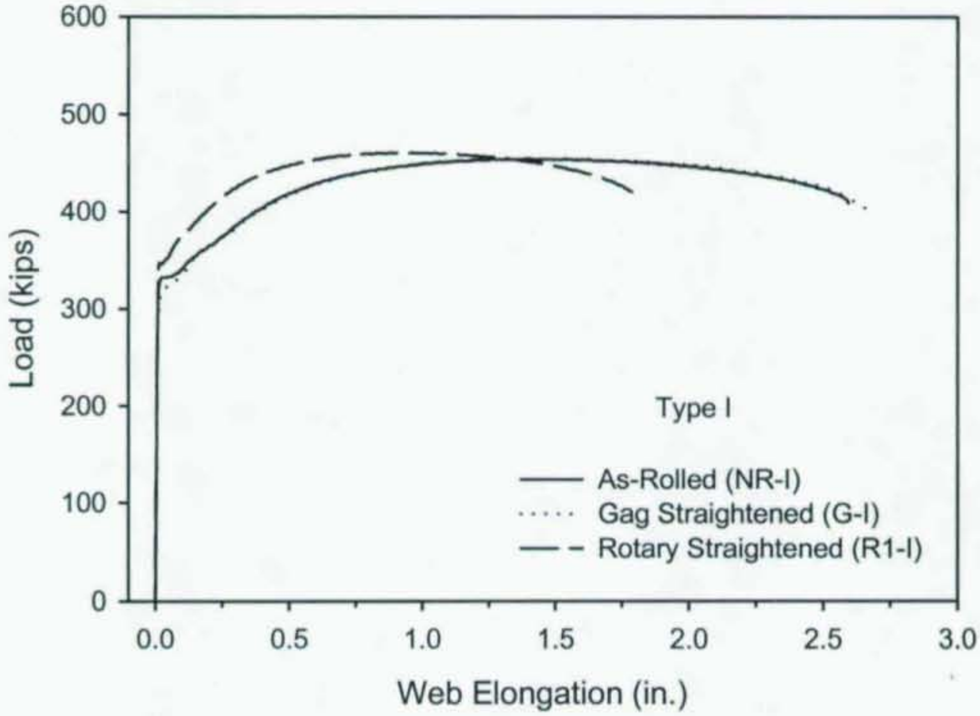

Figure 8 Load vs. Web Elongation Behavior For Type I Specimens.

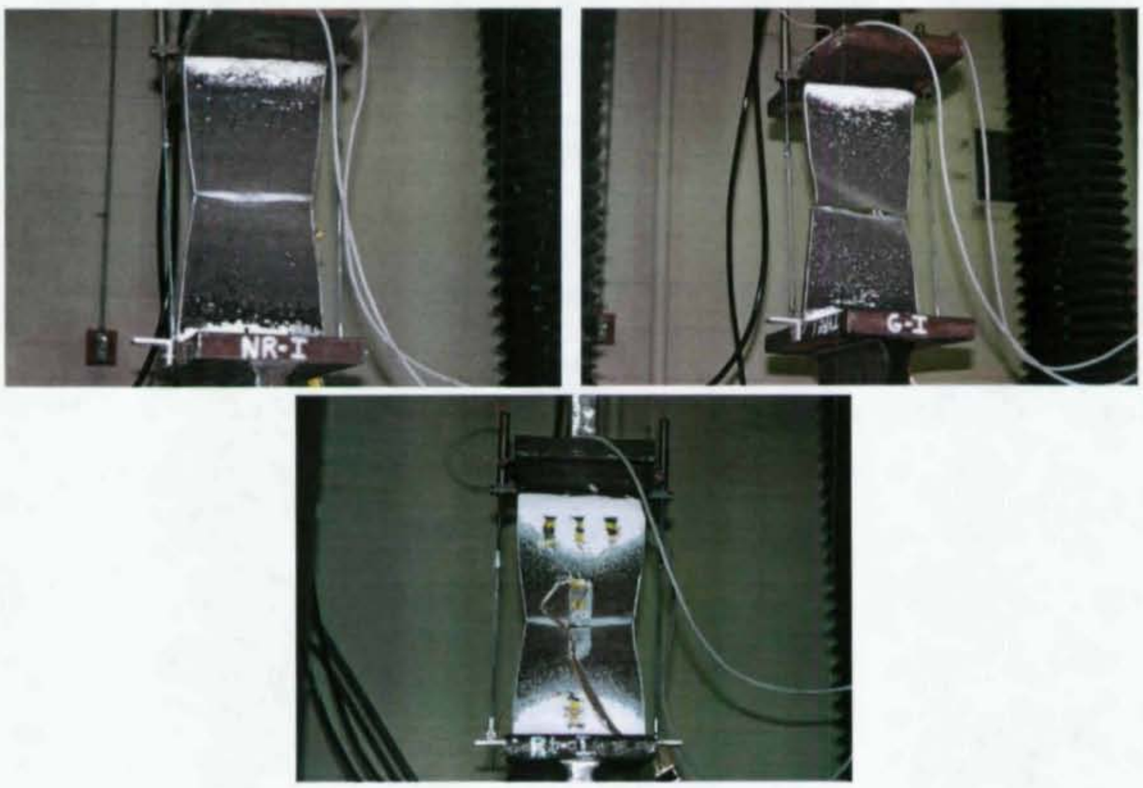

Figure 9 Ductile Web Fracture of As-Rolled (NR-I), Gag Straightened (G-I) and Rotary Straightened (R1-1) Type I Test Specimens.

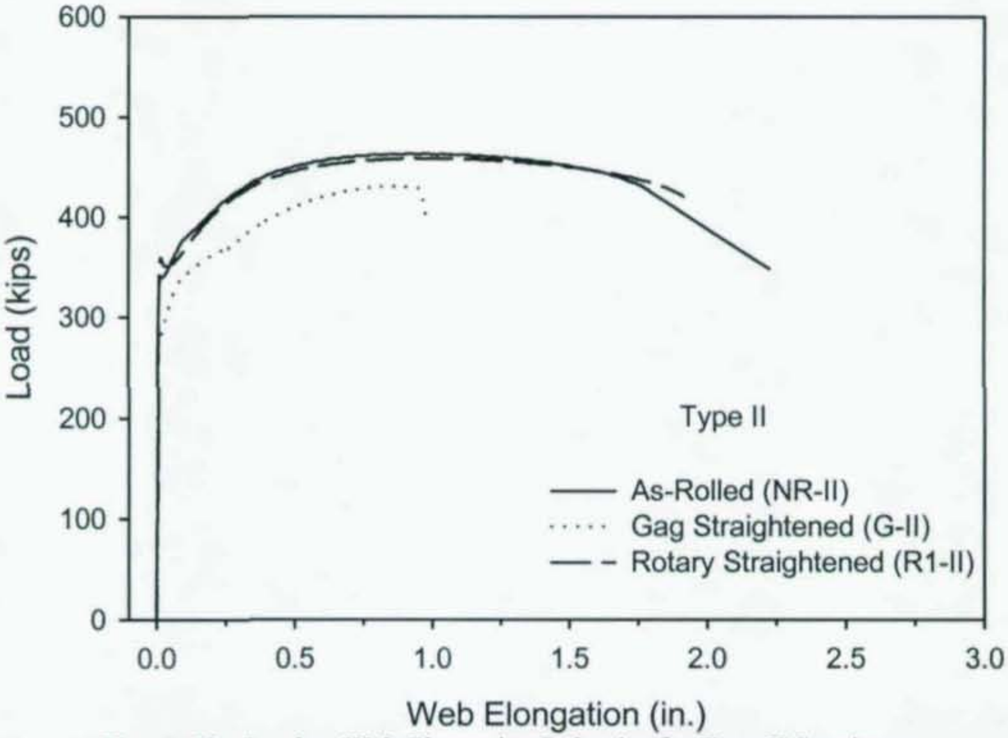

Figure 10 Load vs.Web Elongation Behavior for Type II Specimens.

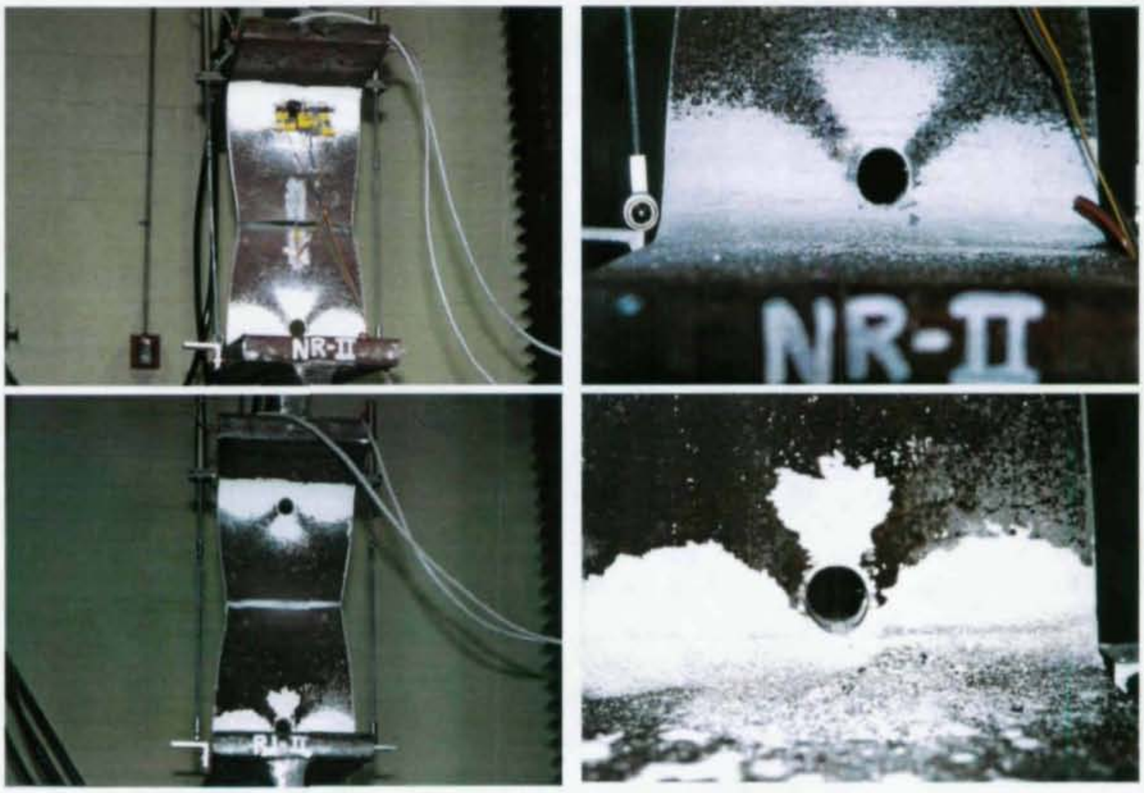

Figure 11 Ductile Web Fracture of As-Rolled (NR-II) and Rotary Straightened (R1-II) Type II Specimens. Note Large Elongation of Drilled Hole in NR-II and Lesser Deformation in R1-II.

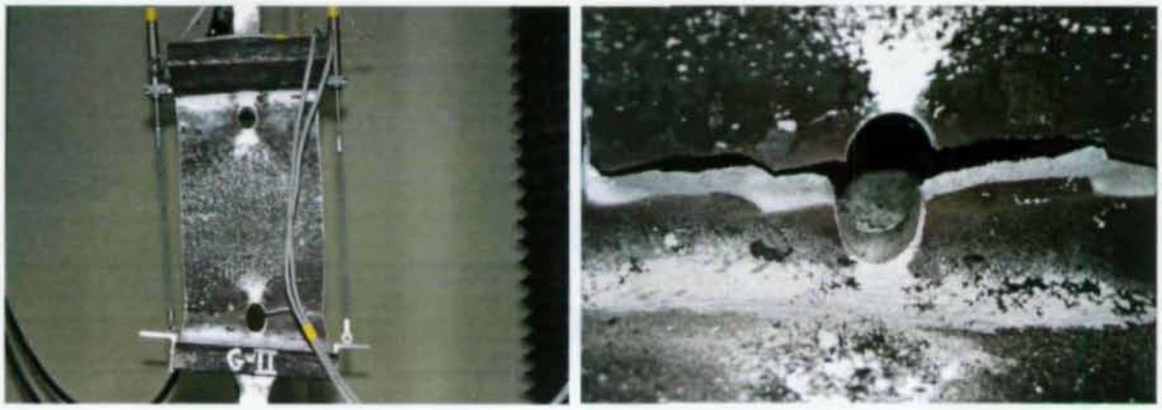

Figure 12 Ductile Fracture of Type II Gag Straightened Specimen at Drilled Hole Due to Bending From Pull-Plate Weld Distortion.

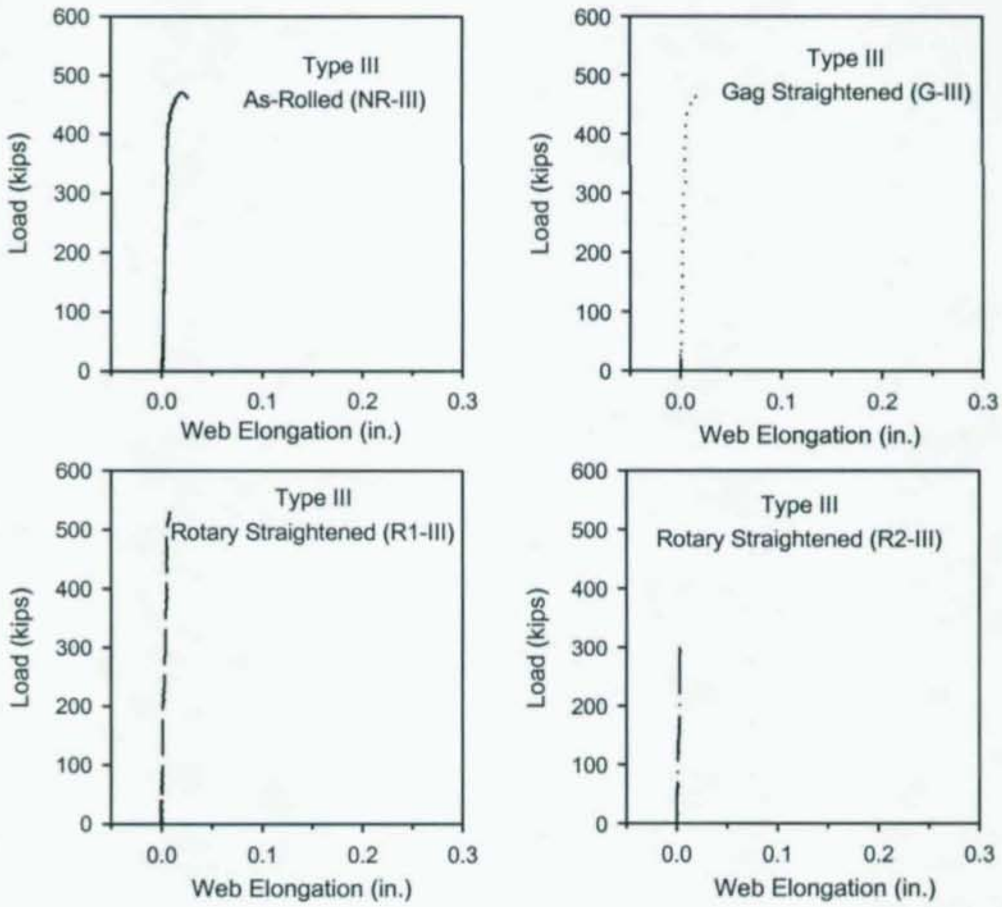

Figure 13 Load vs. Web Elongation Behavior For Type III Specimens.

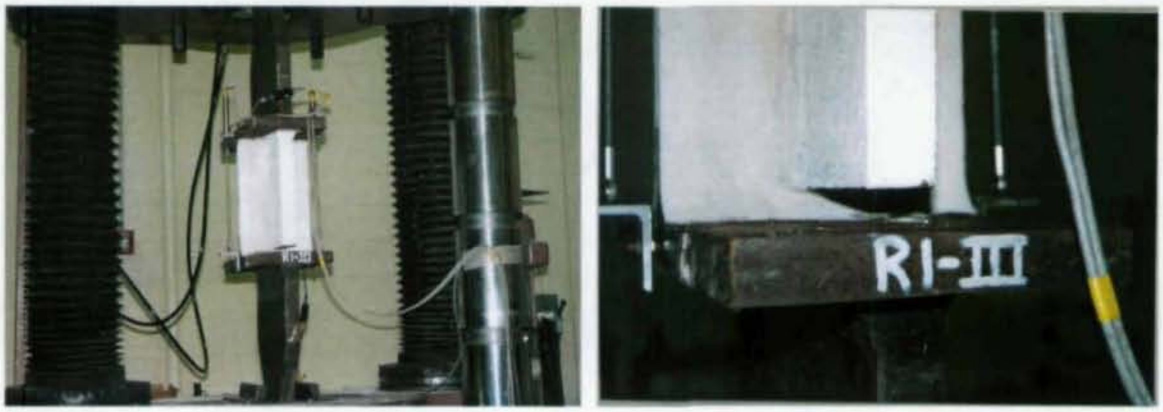

Figure 14 Type III Specimen Configuration Showing Stiffener Weld Terminating in the K-area (Approx. 3/4 in. From Flange Inside Face).

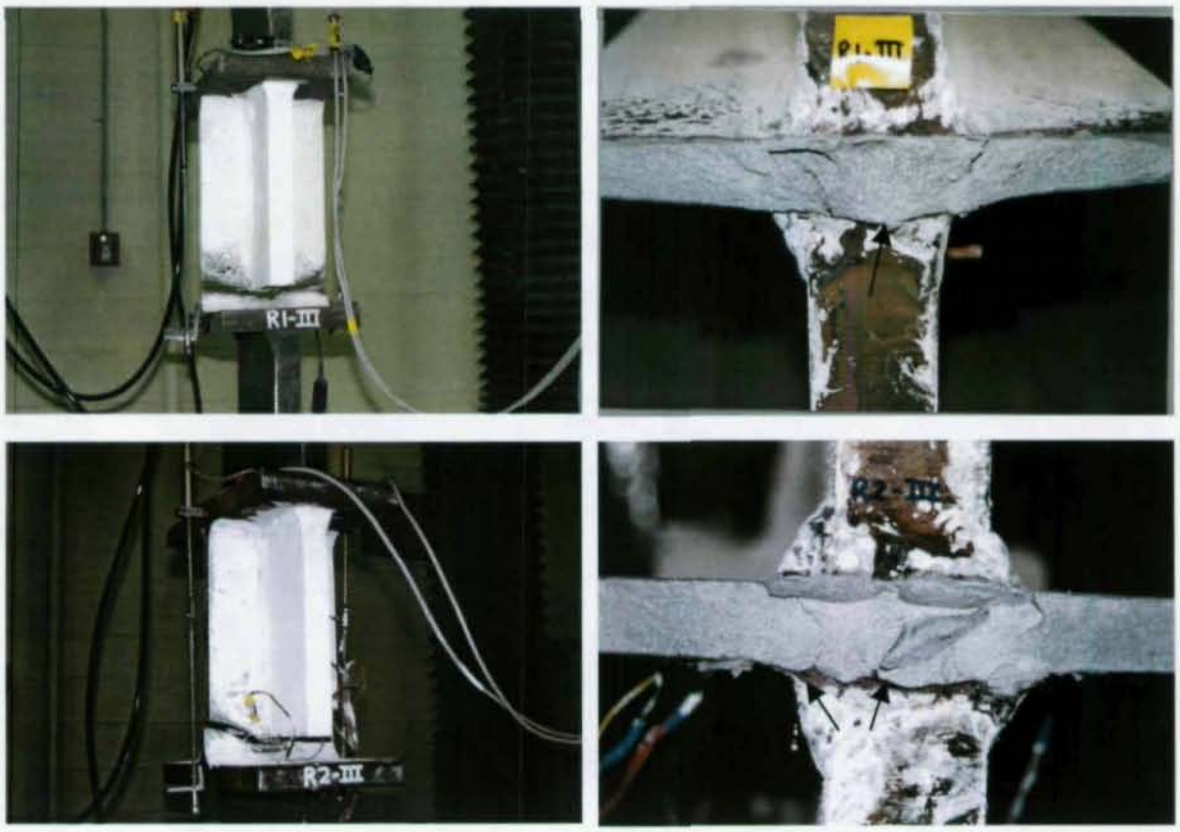

Figure 15 Brittle Fracture of Rotary Straightened Type III Specimens. Arrow Denotes Weld Toe Cleavage Fracture Origin(s).

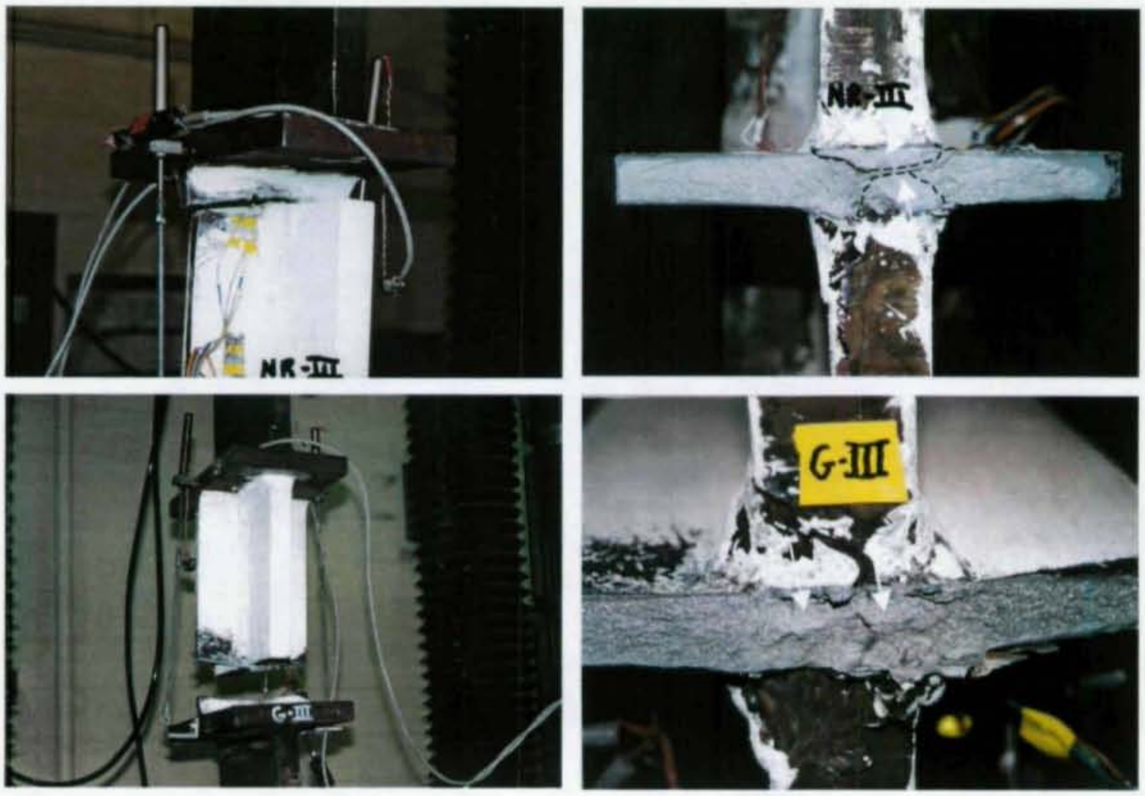

Figure 16 Ductile/Brittle Fracture of As-Rolled (NR-III) and Gag Straightened (G-III) Type III Specimens. Arrows Show Initial Ductile Tearing.

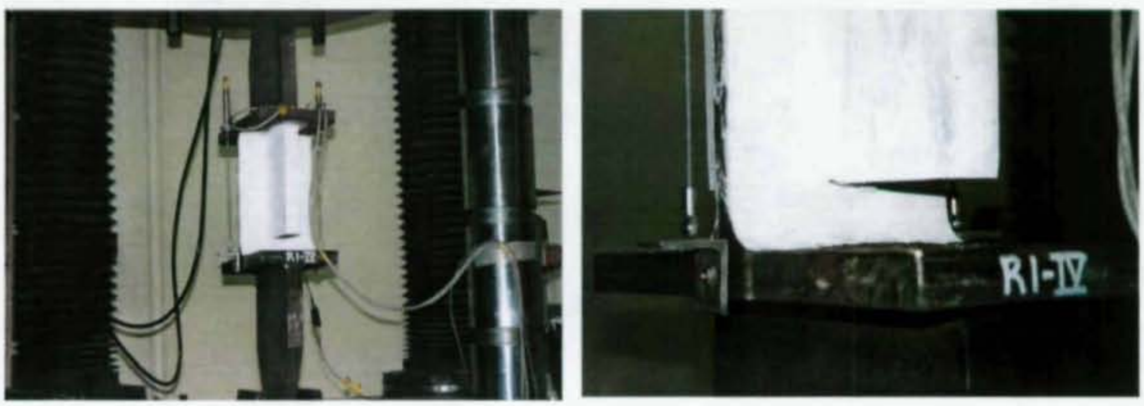

Figure 17 Type IV Specimen Configuration Showing Stiffener Weld Terminating Beyond the K-area (Approx. 1-3/4 in. From Flange Inside Face).

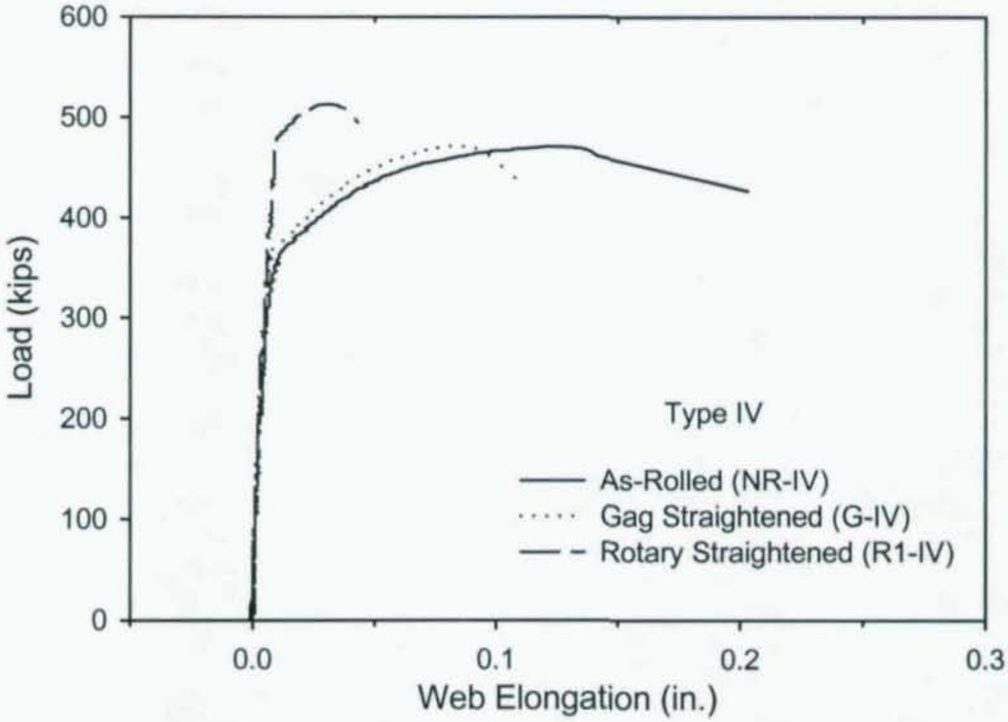

Figure 18 Load vs. Web Elongation Behavior For Type IV Specimens.

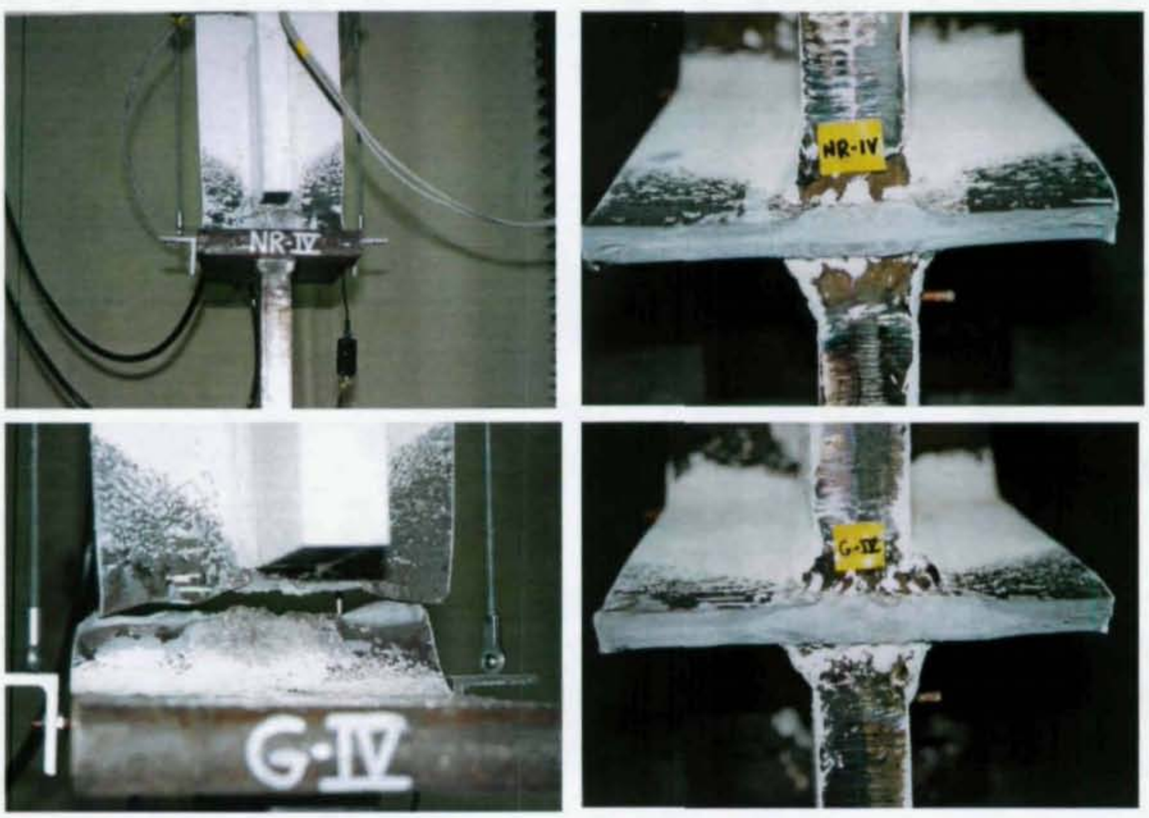

Figure 19 Fully Ductile Fracture of As-rolled (NR-IV) and Gag Straightened Type IV Specimens.

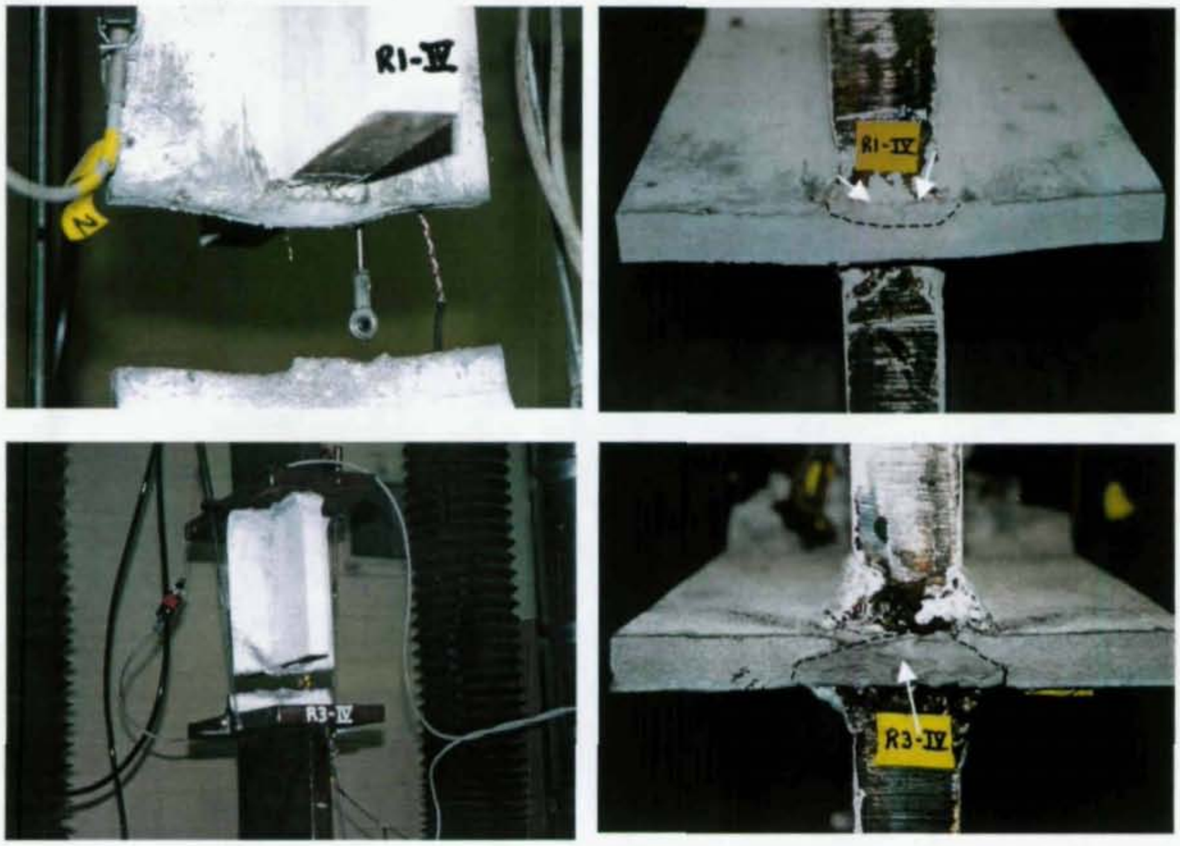

Figure 20 Ductile/Brittle Fracture of Rotary Straightened Type IV Specimens. Arrows Show Ductile Tearing Region.

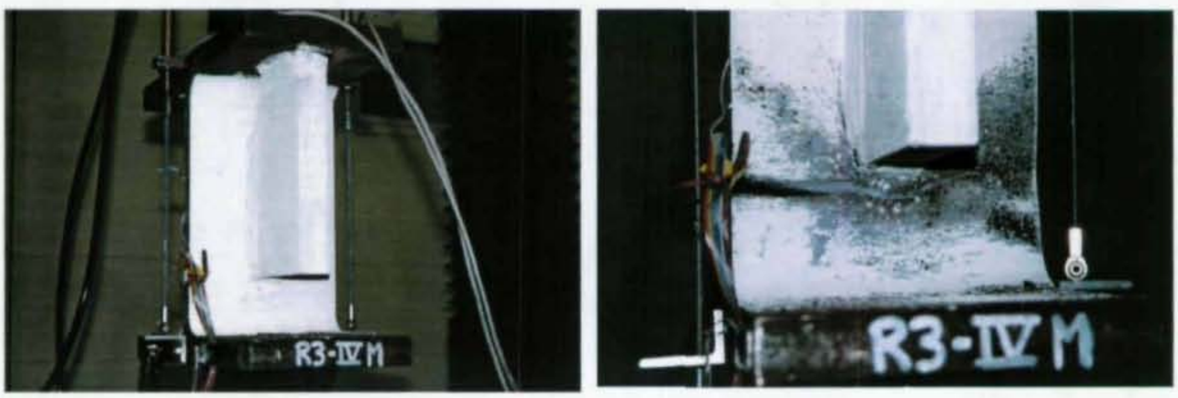

Figure 21 Modified Rotary Straightened Type IV Specimen Showing Fully Ductile Fracture Behavior (Stiffener Weld Terminates Approx. 2-3/4 in. From Flange Inside Face).

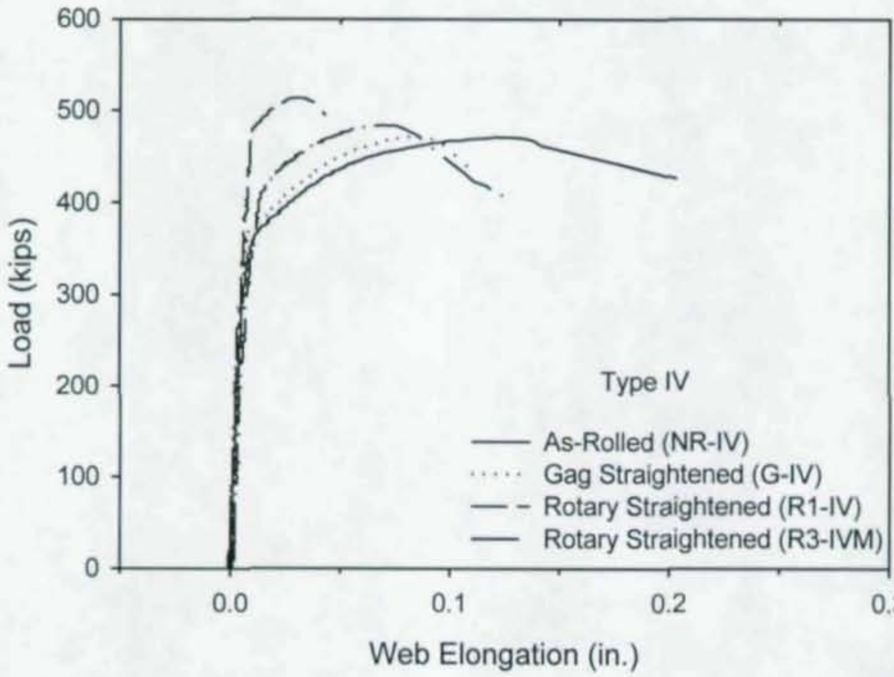

Figure 22 Load vs. Web Elongation Behavior of Modified Type IV Rotary Straightened Specimen (R3-IVM) With Larger Web Gap in Comparison to Standard Type IV Specimens.

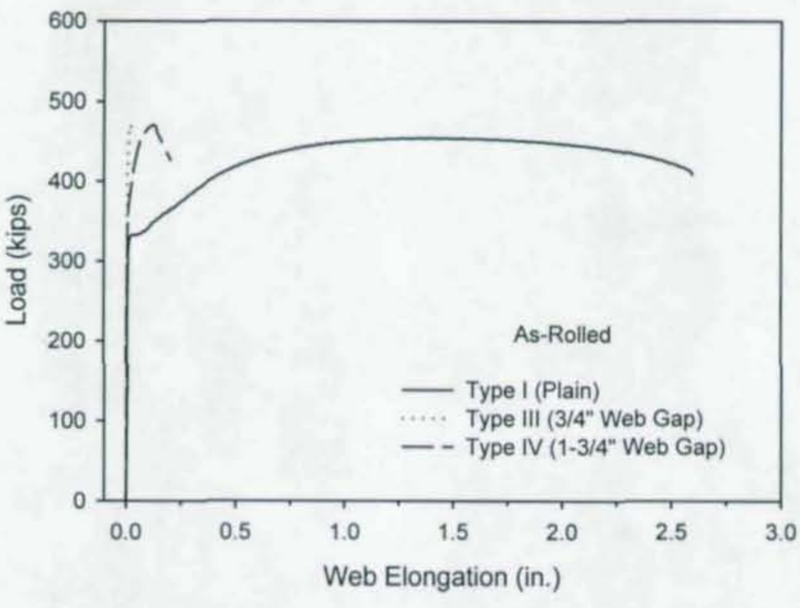

Figure 23 Effect of Stiffener Web Gap on As-Rolled Section Behavior.

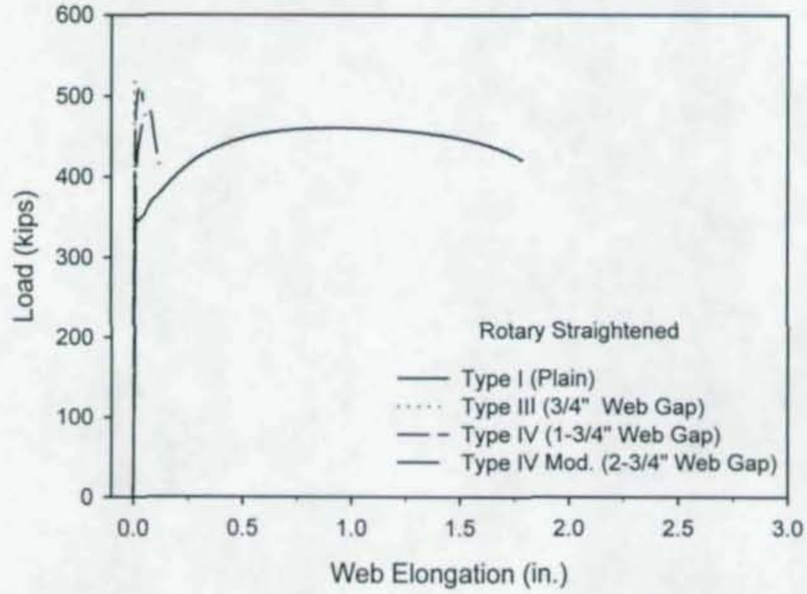

Figure 24 Effect of Stiffener Web Gap on Rotary Straightened Section Behavior.