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Flexural behavior of web elements with openings

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Third Progress Report

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Introduction

The purpose of this research project has been to investigate the flexural behavior of C-shaped members with web openings. Three common industry standard C-sections have been studied as summarized in the First and Second Progress Reports. To date two testing sequences have been completed. Test sequence No.1 investigated sections with web openings fabricated from nominally low yield strength material. Test sequence No. 2 examined sections both with and without web openings. Specimens in test sequence No. 2 have nominally higher yield strengths. This report summarizes the test procedure and results of the research to date.

Test Specimens

Three sizes of C-sections were tested: 2.5-in., 3.625-in. and 12-in. web depths. Various thicknesses of each C-section were also tested. The cross-sectional dimensions and thickness of each test specimen are recorded in Tables 1-1 and 1-2. The material properties of the steel, for each test specimen, were established by standard tensile coupon tests. Tables 2-1 and 2-2 list the tensile test data for thickness, yield point, ultimate tensile strength and percent elongation in 2-in. gage length.

For both test sequences, the web openings were located at 24 inches on center as illustrated in Fig. 1. Each test specimen was subjected to two point loads until the ultimate flexural strength of the member was obtained.

Test Setup

Each test specimen consisted of two C-shaped beams connected together using 3/4 x 3/4 x 1/8 inch angles and self drilling screws. See Fig. 2.

Each specimen was tested as a simply supported beam. Two concentrated loads were applied six feet apart positioning a hole at mid-span as shown in Fig. 1. This loading configuration provided a pure moment region between applied loads. The load was applied using a hydraulic jack. An electronic load cell placed between the jack and the cross beam measured the applied load. Figure 3 shows the test setup. The span length and the "a" dimension are given in Tables 3-1 and 3-2.

The ends of the beam were supported with vertical rollers to prevent lateral movement of the ends. See Fig. 4. In order to prevent premature failure of the beam due to lateral-torsional buckling, lateral bracing was also provided along the length of the span. A typical bracing scheme is shown in Figs. 4 and 5.

Test Procedure

Each test specimen was loaded to failure. The load was applied to the test specimen in predetermined increments using a hydraulic jack. At each load increment the load and strain gauge readings were recorded to a data file. In addition, for each load increment the vertical displacement at midspan of the beam was measured by using a dial gauge. The load was increased in increments until the beam reached failure and could no longer sustain additional load.

Test Results

The applied failure load, P, for each test specimen is recorded in Tables 3-1 and 3-2. The value of P is the load applied by the hydraulic jack at mid-span. Tables 4-1 and 4-2 list the tested moment capacity M_{ut} for each specimen as well as the predicted moment capacity M_{uc} calculated according to the 1986 AISI Specification. The dead load due to the cross beam and the test specimen have been accounted for in the moment calculations.

Discussion of Test Results

The moment ratio M_{ut}/M_{uc} is a measure of how well the AISI Specification estimates the bending strength of C-sections. Tables 4-1 and 4-2 list the values of M_{ut}/M_{uc}. A discussion of the test results for each test sequence follows.

Test Sequence 1:

A total of 15 tests were conducted in this test sequence. The cross-sectional dimensions, material properties and test results are summerized in Tables 1-1, 2-1 and 3-1, respectively. Table 4-1 compares the tested and calculated moment capacities.

For the 12-in. deep sections, the mean moment ratio, M_{ut}/M_{uc}, is 0.74 (Table 4-1). Based on the test results from test sequence No. 2 (Table 4-2), this low mean value is not being attributed to the presence of punchouts, but is believed to be caused by the flange-web interaction. The narrow flange, nominally 1.625-in., does not appear to provide adequate edge restraint for the rather deep 12-in. web.

For the 3.625-in deep sections the value of M_{ut}/M_{uc} ranged from 0.86 to 0.92 with a mean of 0.89. The lower ratios for the 3.625-in. sections are attributed to the presence of a punchout. For each test specimen, the failure occurred at the location of a punchout (Fig. 6). The punchout depth to web depth ratio, y/h, for these sections is 0.46.

The ratio of M_{ut}/M_{uc} for the 2.5-in. deep sections varied from 0.95 to 1.05 and had a mean of 0.98. This moment ratio indicates good correlation between the tested and computed moments capacity. The 2.5-in. sections have a y/h ratio of 0.36.

Test Sequence 2:

A total of 26 tests were conducted in test sequence No.2. The cross-sectional dimensions, material properties and test results for this sequence are summerized in Tables 1-2, 2-2 and 3-2, respectively. Table 4-2 compares the tested and calculated moment capacities.

As indicated by Table 4-2, for the 12-in. deep sections, there was no significant difference in the tested moment capacity between C-sections with and without web openings. The ratio of M_{ut}/M_{uc} ranged from 0.76 to 0.79 with a mean of 0.77 for unpunched webs and ranged from 0.78 to 0.82 with a mean of 0.79 for punched webs. As in test sequence No. 1, the narrow flange of the 12-in. deep sections, may be the cause of the poor correlation between tested and calculated moment capacities.

For the 3.625-in deep sections the value of M_{ut}/M_{uc} ranged from 0.83 to 0.98 with a mean of 0.93 for test specimen with web openings. For test specimen without web openings the mean moment ratio was 1.10. The web punchout depth to web depth ratio, y/h, for these sections is 0.47.

The ratio of M_{ut}/M_{uc} for the 2.5-in. deep sections having web openings varied from 0.85 to 0.98 and had a mean of 0.92. For those without web openings the mean value of M_{ut}/M_{uc} was 1.09. The 2.5-in. deep sections have a y/h ratio of 0.74.

Possible Modification

The test data indicates that for certain geometries, the moment capacity predicted by the AISI Specification can not be achieved. One possible solution is to make a simple modification to the effective width equation. Tables 5-1 and 5-2 show the results of an analysis of the moment capacity in which the value of b_2 as given in section B2.3 of the AISI Specification was set equal to zero. Combining the data from both test sequences leads to a better understanding of the modification's results.

For test specimens having y/h ratios of approximately 0.35, it appears no modification is necessary. The mean moment ratio for both test sequences is 0.995.

For test specimens having a y/h ratio of about 0.45, the mean moment ratio without the $b_2=0$ modification is 0.898 and with the modification is 0.960.

For test specimens with a y/h ratio of approximately 0.73, the mean moment ratio is 0.923 without the $b_2=0$ modification, and 0.975 when b_2 equals zero.

The $b_2=0$ modification was not applied to the 12" deep sections because the premature failure of these sections does not appear to be caused by the presence of a web punchout.

Future Work

The research to date indicates that some type of modification is necessary when computing the moment capacity of C-sections with web openings. The modification of setting b_2 equal to zero is only one possible solution. Analytical work will continue on the existing test results in order to determine other alternatives. Also, additional analysis for the 12-in. deep sections will be conducted.

TABLE 1-1
DIMENSIONS OF TEST SPECIMENS
TEST SEQUENCE No. 1

Beam Specimen No.	Cross-Section Dimenisions (inches)											Hole Geom. (in.)	
	Thick.	D1	D2	B1	B2	B3	B4	d1	d2	d3	d4	x	y
12,14,1&2(H)	0.098	12.08	12.07	1.64	1.63	1.69	1.63	0.69	0.60	0.60	0.62	4	1.5
12,14,3&4(H)	0.098	12.05	12.00	1.64	1.60	1.67	1.71	0.65	0.64	0.65	0.64	4	1.5
12,16,1&2(H)	0.055	11.96	11.97	1.57	1.57	1.57	1.56	0.50	0.61	0.52	0.43	4	1.5
12,16,3&4(H)	0.055	12.07	11.96	1.56	1.57	1.57	1.58	0.42	0.53	0.58	0.53	4	1.5
3,14,1&2(H)	0.077	3.68	3.68	1.65	1.64	1.63	1.63	0.57	0.55	0.56	0.52	4	1.5
3,14,3&4(H)	0.077	3.69	3.69	1.63	1.62	1.64	1.63	0.53	0.53	0.62	0.55	4	1.5
3,18,1&2(H)	0.044	3.75	3.65	1.56	1.56	1.57	1.58	0.58	0.56	0.58	0.54	4	1.5
3,18,3&4(H)	0.044	3.65	3.64	1.56	1.58	1.56	1.57	0.56	0.57	0.54	0.54	4	1.5
3,20,1&2(H)	0.044	3.65	3.71	1.56	1.64	1.55	1.59	0.52	0.56	0.55	0.56	4	1.5
3,20,3&4(H)	0.044	3.67	3.69	1.56	1.59	1.55	1.61	0.60	0.56	0.52	0.59	4	1.5
2,16,1&2(H)	0.062	2.51	2.51	1.61	1.61	1.63	1.61	0.40	0.45	0.42	0.43	2	0.75
2,20,1&2(H)	0.039	2.50	2.48	1.60	1.60	1.60	1.60	0.42	0.41	0.42	0.41	2	0.75
2,20,3&4(H)	0.039	2.51	2.52	1.59	1.62	1.58	1.60	0.36	0.42	0.47	0.41	2	0.75

Note: See Fig. 2 for the symbols used for dimensions.
See Fig. 1 for the symbols used for the hole geometry.
Specimen Designation: 12,14,1&2(H)
12-Nominal Depth
14-Gage Thickness
1&2-Individual Cross Section
(H)-Web Opening

TABLE 1-2
DIMENSION OF TEST SPECIMENS
TEST SEQUENCE No. 2

	Cross-Section Dimensions (inches)											Hole (in.)	
Beam Specimen No.	Thick.	D1	D2	B1	B2	B3	B4	d1	d2	d3	d4	x	y
12,16,1&2(H)	0.060	11.95	11.95	1.63	1.63	1.63	1.63	0.53	0.54	0.52	0.53	4.0	1.5
12,16,3&4(H)	0.060	11.98	12.02	1.63	1.63	1.62	1.63	0.47	0.50	0.55	0.53	4.0	1.5
12,16,5&6(H)	0.060	11.96	11.97	1.63	1.63	1.63	1.63	0.51	0.50	0.51	0.52	4.0	1.5
12,16,7&8(H)	0.060	11.97	11.96	1.63	1.63	1.62	1.63	0.48	0.55	0.56	0.49	4.0	1.5
12,16,1&2(N)	0.062	11.95	11.94	1.63	1.63	1.63	1.63	0.51	0.55	0.54	0.48		
12,16,3&4(N)	0.062	11.96	11.98	1.64	1.63	1.63	1.63	0.46	0.55	0.56	0.49		
3,14,1&2(H)	0.071	3.65	3.62	1.62	1.66	1.63	1.63	0.54	0.55	0.49	0.50	4.0	1.5
3,14,3&4(H)	0.071	3.64	3.63	1.63	1.62	1.62	1.63	0.54	0.47	0.49	0.54	4.0	1.5
3,18,1&2(H)	0.044	3.61	3.63	1.61	1.65	1.65	1.62	0.51	0.52	0.50	0.50	4.0	1.5
3,18,3&4(H)	0.044	3.62	3.63	1.62	1.66	1.65	1.64	0.50	0.50	0.52	0.52	4.0	1.5
3,18,1&2(N)	0.044	3.66	3.68	1.66	1.61	1.62	1.66	0.52	0.47	0.47	0.52		
3,18,3&4(N)	0.044	3.64	3.64	1.66	1.64	1.65	1.63	0.49	0.49	0.50	0.48		
3,20,1&2(H)	0.036	3.61	3.60	1.63	1.62	1.63	1.62	0.46	0.47	0.46	0.47	4.0	1.5
3,20,3&4(H)	0.036	3.61	3.61	1.64	1.63	1.64	1.63	0.46	0.47	0.47	0.47	4.0	1.5
3,20,5&6(H)	0.036	3.60	3.60	1.63	1.63	1.62	1.63	0.46	0.46	0.46	0.47	4.0	1.5
3,20,1&2(N)	0.035	3.60	3.60	1.63	1.62	1.63	1.63	0.47	0.47	0.46	0.46		
3,20,3&4(N)	0.035	3.60	3.60	1.63	1.63	1.63	1.63	0.48	0.46	0.46	0.47		
3,20,5&6(N)	0.035	3.59	3.60	1.63	1.62	1.62	1.62	0.47	0.47	0.47	0.46		
2,16,1&2(H)	0.059	2.46	2.46	1.62	1.63	1.62	1.61	0.47	0.46	0.51	0.51	4.0	1.5
2,16,3&4(H)	0.059	2.47	2.46	1.63	1.62	1.62	1.63	0.47	0.52	0.52	0.46	4.0	1.5
2,16,1&2(N)	0.057	2.48	2.48	1.62	1.63	1.61	1.61	0.45	0.45	0.51	0.51		
2,16,3&4(N)	0.057	2.48	2.48	1.61	1.63	1.63	1.61	0.51	0.46	0.47	0.51		
2,20,1&2(H)	0.033	2.42	2.42	1.63	1.64	1.63	1.62	0.42	0.42	0.50	0.50	4.0	1.5
2,20,3&4(H)	0.033	2.42	2.43	1.63	1.64	1.63	1.62	0.42	0.41	0.50	0.50	4.0	1.5
2,20,1&2(N)	0.033	2.44	2.44	1.63	1.64	1.63	1.62	0.41	0.40	0.49	0.50		
2,20,3&4(N)	0.033	2.46	2.45	1.63	1.63	1.61	1.61	0.39	0.40	0.52	0.51		

see Table 1-1 for Notes

TABLE 2-1
MATERIAL PROPERTIES
TEST SEQUENCE No. 1

Specimen No.	Thickness (in.)	F_y (ksi)	F_u (ksi)	Elongation (%)
12,14(H)	0.098	36	47	35
12,16(H)	0.055	49	57	32
3,14(H)	0.077	64	78	23
3,18(H)	0.044	47	60	31
3,20(H)	0.044	47	60	31
2,16(H)	0.062	37	49	38
2,20(H)	0.039	34	48	44

TABLE 2-2
MATERIAL PROPERTIES
TEST SQUENCE NO. 2

Specimen No.	Thickness (in.)	F_y (ksi)	F_u (ksi)	Elongation (%)
12,16(H)	0.06	61	75	38
12,16(N)	0.06	62	74	38
2,16(H)	0.06	54	75	39
2,16(N)	0.06	58	78	36
2,20(H)	0.03	67	72	35
2,20(N)	0.03	65	75	33
3,14(H)	0.07	81	104	22
3,14(N)	0.08	52	110	20
3,18(H)	0.04	53	70	24
3,18(N)	0.04	63	81	14
3,20(H)	0.04	64	79	29
3,20(N)	0.04	61	82	33

TABLE 3-1
TEST RESULTS
TEST SEQUENCE No. 1

Beam Specimen No.	Span Length (ft)	a (in.)	P (kips)
12,14,1&2(H)	16	60	7.16
12,14,3&4(H)	16	60	7.50
12,14,5&6(H)	16	60	7.95
12,14,7&8(H)	16	60	7.98
12,16,1&2(H)	16	60	4.38
12,16,3&4(H)	16	60	4.79
3,14,1&2(H)	12.5	39	3.70
3,14,3&4(H)	12.5	39	3.54
3,18,1&2(H)	12.5	39	1.35
3,18,3&4(H)	12.5	39	1.37
3,20,1&2(H)	12.5	39	1.35
3,20,3&4(H)	12.5	39	1.43
2,16,1&2(H)	12.5	39	1.04
2,20,1&2(H)	12.5	39	0.46
2,20,3&4(H)	12.5	39	0.46

TABLE 3-2
TEST RESULTS
TEST SEQUENCE No.2

Beam Specimen No.	Span Length (ft)	a (in.)	P (kips)
12,16,1&2(H)	16	60	6.49
12,16,3&4(H)	16	60	6.44
12,16,5&6(H)	16	60	6.39
12,16,7&8(H)	16	60	6.67
12,16,1&2(N)	16	60	6.50
12,16,3&4(N)	16	60	6.76
3,14,1&2(H)	12.5	39	4.31
3,14,3&4(H)	12.5	39	4.26
3,18,1&2(H)	12.5	39	1.60
3,18,3&4(H)	12.5	39	1.51
3,18,1&2(N)	12.5	39	2.44
3,18,3&4(N)	12.5	39	2.15
3,20,1&2(H)	12.5	39	1.20
3,20,3&4(H)	12.5	39	1.10
3,20,5&6(H)	12.5	39	1.34
3,20,1&2(N)	12.5	39	1.17
3,20,3&4(N)	12.5	39	1.26
3,20,5&6(N)	12.5	39	1.41
2,16,1&2(H)	12.5	39	1.35
2,16,3&4(H)	12.5	39	1.36
2,16,1&2(N)	12.5	39	1.59
2,16,3&4(N)	12.5	39	1.62
2,20,1&2(H)	12.5	39	0.60
2,20,3&4(H)	12.5	39	0.64
2,20,1&2(N)	12.5	39	0.77
2,20,3&4(N)	12.5	39	0.76

TABLE 4-1
COMPARSION OF TEST RESULTS
(Based on 1986 AISI Specification)
TEST SEQUENCE No. 1

Beam Specimen No.	h/t	y/h	M_{ut} (k-in.)	M_{uc} (k-in.)	$(M_{ut})/(M_{uc})$
12,14,1&2(H)	118	0.13	219.52	323.42	0.68
12,14,3&4(H)	118	0.13	229.87	326.30	0.70
12,14,5&6(H)	118	0.13	243.37	323.64	0.75
12,14,7&8(H)	118	0.13	244.27	320.54	0.76
12,16,1&2(H)	210	0.13	135.97	181.89	0.75
12,16,3&4(H)	211	0.13	148.27	182.18	0.81
				MEAN	0.74
3,14,1&2(H)	42	0.47	75.17	82.30	0.91
3,14,3&4(H)	42	0.47	72.01	81.02	0.89
3,18,1&2(H)	75	0.45	29.32	33.93	0.86
3,18,3&4(H)	74	0.46	29.70	33.93	0.88
3,20,1&2(H)	74	0.46	29.31	33.84	0.87
3,20,3&4(H)	74	0.46	30.78	33.46	0.92
				MEAN	0.89
2,16,1&2(H)	33	0.36	23.37	22.35	1.05
2,20,1&2(H)	54	0.36	11.85	12.51	0.95
2,20,3&4(H)	54	0.35	11.95	12.04	0.99
				MEAN	0.98

TABLE 4-2
COMPARSION OF TEST RESULTS
(Based on 1986 AISI Specification)
TEST SEQUENCE No. 2

Beam Specimen No.	h/t	y/h	M_{ut} (k-in.)	M_{uc} (k-in.)	$(M_{ut})/(M_{uc})$ (H)	(N)
12,16,1&2(H)	192	0.13	198.93	255.17	0.78	
12,16,3&4(H)	192	0.13	197.52	248.50	0.80	
12,16,5&6(H)	192	0.13	195.93	251.17	0.78	
12,16,7&8(H)	192	0.13	204.33	249.23	0.82	
12,16,1&2(N)	186		199.38	264.18		0.76
12,16,3&4(N)	186		207.03	262.83		0.79
				MEAN	0.79	0.77
3,14,1&2(H)	45	0.47	86.99	89.50	0.97	
3,14,3&4(H)	45	0.47	85.68	88.68	0.97	
3,18,1&2(H)	73	0.47	34.15	34.85	0.98	
3,18,3&4(H)	73	0.47	32.39	35.07	0.92	
3,18,1&2(N)	74		50.53	39.28		1.29
3,18,3&4(N)	74		44.87	39.28		1.14
3,20,1&2(H)	90	0.47	26.35	31.86	0.83	
3,20,3&4(H)	90	0.47	24.40	31.73	(0.77)	
3,20,5&6(H)	89	0.47	28.88	31.60	0.91	
3,20,1&2(N)	92		25.76	29.50		(0.87)
3,20,3&4(N)	92		27.42	29.62		0.93
3,20,5&6(N)	92		30.34	29.50		1.03
				MEAN	0.93	1.10
				MEAN	(0.91)	(1.05)
2,16,1&2(H)	34	0.74	29.17	29.90	0.98	
2,16,3&4(H)	35	0.74	29.47	30.23	0.98	
2,16,1&2(N)	36		33.85	31.09		1.09
2,16,3&4(N)	36		34.54	31.32		1.10
2,20,1&2(H)	62	0.73	14.65	17.19	0.85	
2,20,3&4(H)	62	0.73	15.33	17.19	0.89	
2,20,1&2(N)	63		17.96	16.56		1.09
2,20,3&4(N)	63		17.77	16.69		1.07
				MEAN	0.92	1.09

TABLE 5-1
COMPARISON OF TEST RESULTS
(Based on 1986 AISI Specification, b_2=0)
TEST SEQUENCE No. 1

Beam Specimen No.	h/t	y/h	M_{ut} (k-in)	M_{uc} (k-in) b_2=0	$(M_{ut})/(M_{uc})$
3,14,1&2(H)	42	0.47	75.17	80.13	0.94
3,14,3&4(H)	42	0.47	72.01	75.90	0.95
3,18,1&2(H)	75	0.45	29.32	32.99	0.89
3,18,3&4(H)	74	0.46	29.7	32.90	0.90
3,20,1&2(H)	74	0.46	29.31	33.18	0.88
3,20,3&4(H)	74	0.46	30.78	31.58	0.97
				MEAN	0.92
2,16,1&2(H)	33	0.36	23.37	17.02	1.37
2,20,1&2(H)	54	0.36	11.85	11.90	1.00
2,20,3&4(H)	54	0.35	11.95	11.90	1.00
				MEAN	1.12

TABLE 5-2
COMPARSION OF TEST RESULTS
(Based on 1986 AISI Specification, b_2=0.0)
TEST SEQUENCE No. 2

Beam Specimen No.	h/t	y/h	M_{ut} (k-in)	M_{uc} (k-in)	$(M_{ut})/(M_{uc})$
3,14,1&2(H)	45	0.47	86.99	87.00	1.00
3,14,3&4(H)	45	0.47	85.68	83.27	1.03
3,18,1&2(H)	73	0.47	34.15	33.36	1.02
3,18,3&4(H)	73	0.47	32.39	33.07	0.98
3,20,1&2(H)	90	0.47	26.35	29.14	0.90
3,20,3&4(H)	90	0.47	24.40	29.04	(0.84)
3,20,5&6(H)	90	0.47	28.88	28.98	1.00
				MEAN	0.99
				MEAN	(0.97)
2,16,1&2(H)	34	0.74	29.17	28.35	1.03
2,16,3&4(H)	35	0.74	29.47	28.61	1.03
2,20,1&2(H)	62	0.73	14.65	16.34	0.90
2,20,3&4(H)	62	0.73	15.33	16.33	0.94
				MEAN	0.97

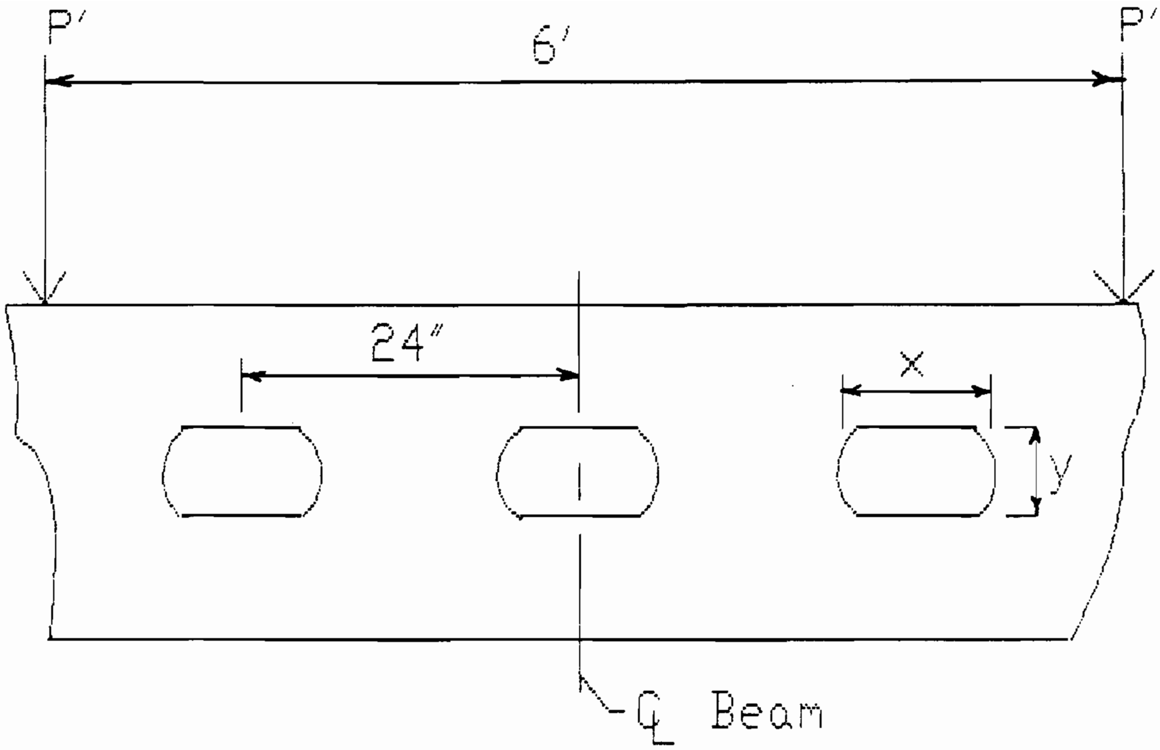

Figure 1. Opening Configuration

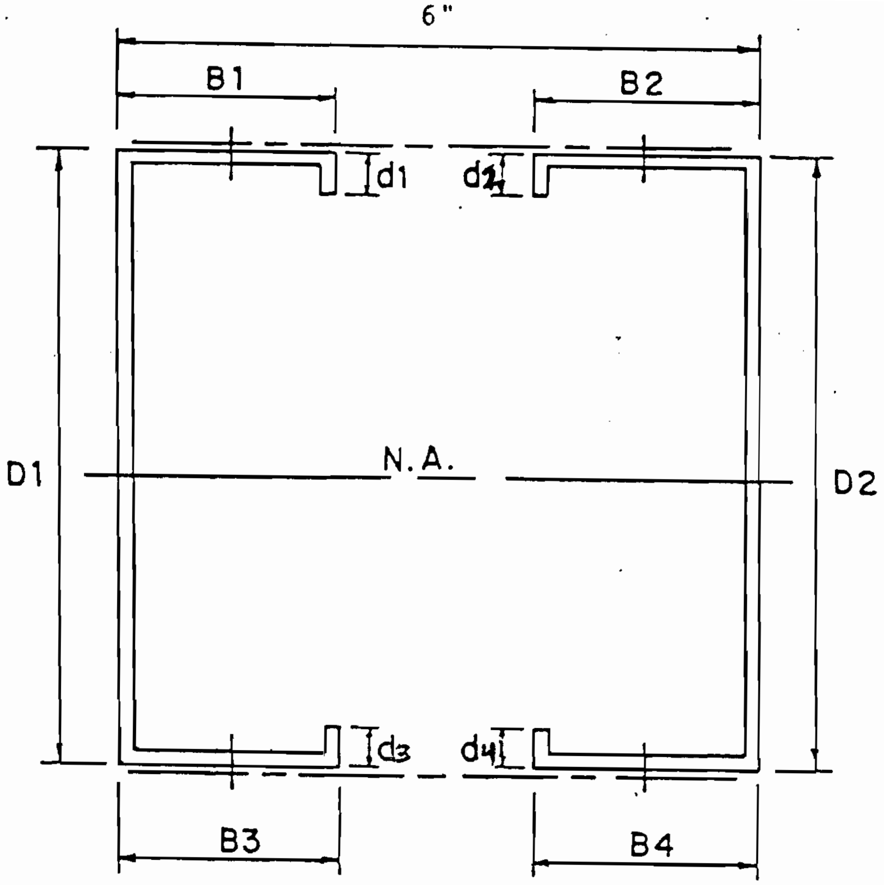

Figure 2. Beam Cross-Section

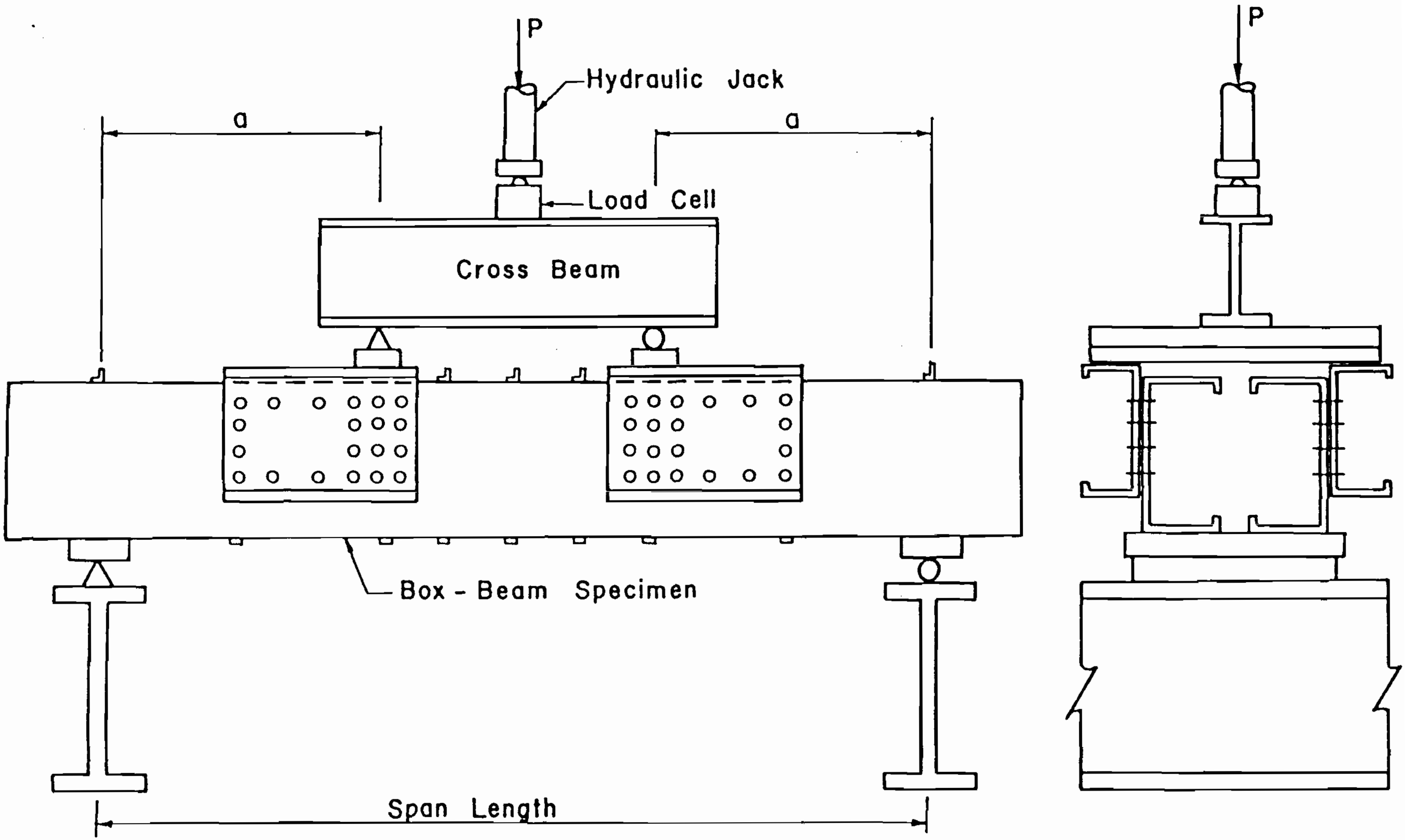

Figure 3. Test Setup

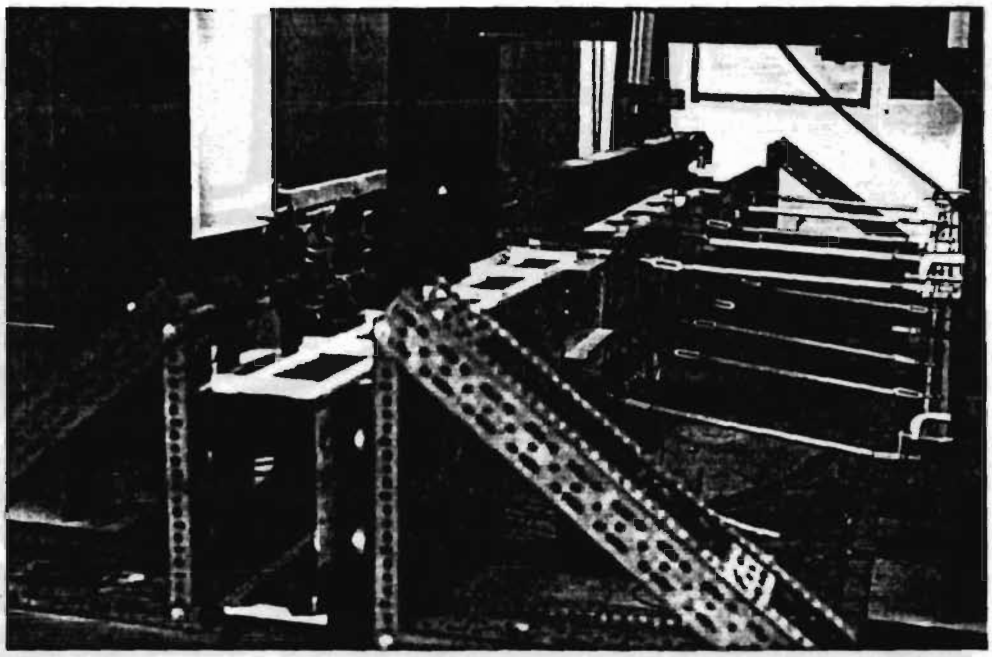

Figure 4. Support at End of Beam

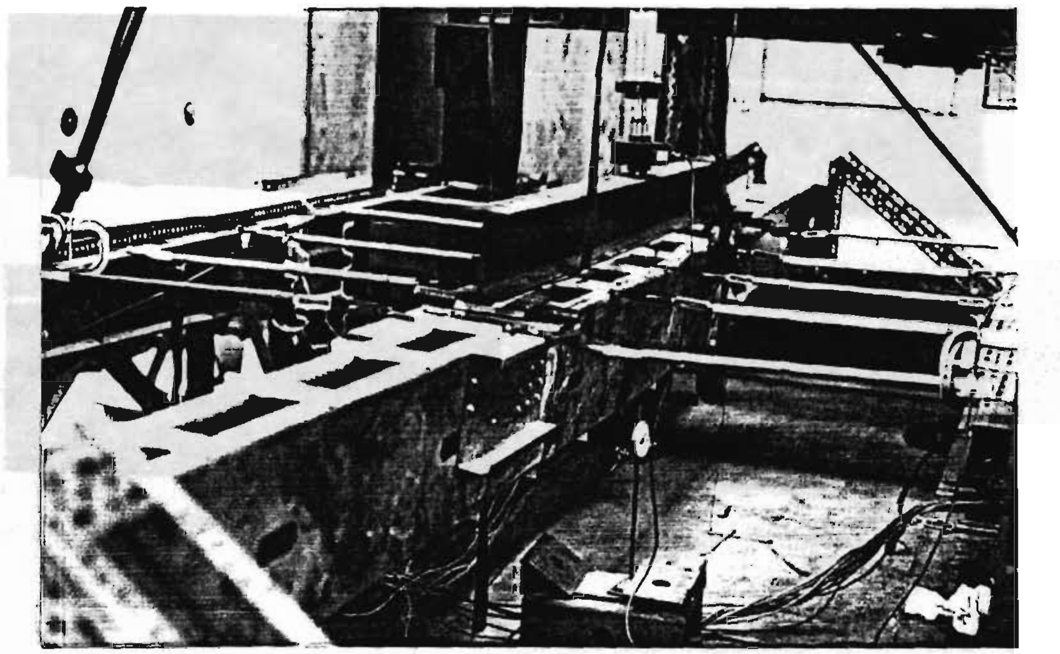

Figure 5. Typical Bracing System

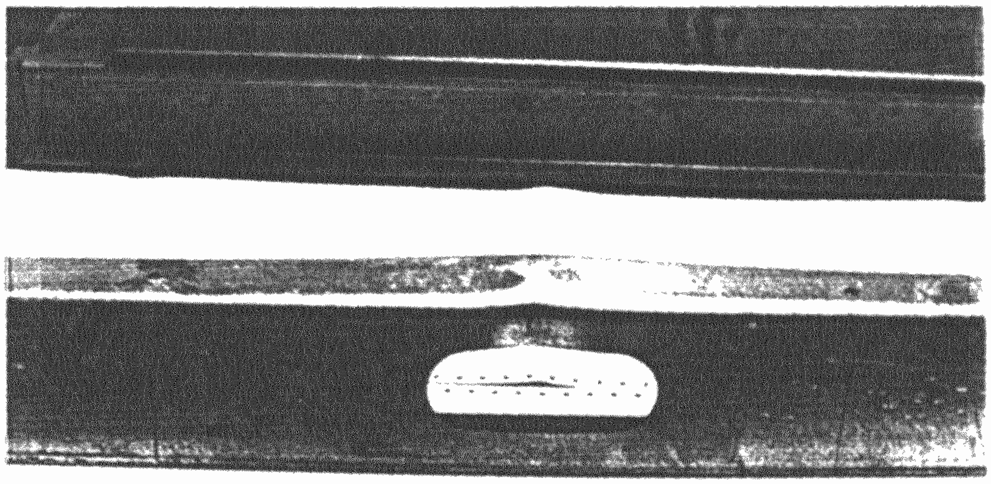

Figure 6. Typical Failure Mode