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FLEXURAL BUCKLING STRENGTH OF CENTRALLY LOADED COMPRESSIVE HIGH-STRENGTH STEEL MEMBERS

by

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1.INTRODUCTION

The flexural buckling strength of centrally loaded compressive members is essential to proportion member sizes in design procedure of steel structures. The so-called column curves, which express the strength of a column with a given slenderness ratio, are proposed in various ways in current design codes. These are usually based on experimental results, and for this purpose data bases are built up from available experimental reports by many researchers (1).

Recently, high-quality steels with high strength and low yield ratio are developed and available in use for structural frames. Experimental data to formulate a design column curve are, however, very few so far and demanded for a new data base. This paper presents test results obtained by the tests on relatively long columns with various section shapes which were made of the above mentioned high strength steels.

2. EXPERIMENTS

Steel materials : The steels used for the tests are tentatively called 60K steel and 80K steel (No official name is given yet).The test results for basic parameters are summarized in Table 1. The values of the 60K steel satisfy the tentative specification proposed by steel makers, while the specification for 80K steel as structural material is not proposed. Important properties are the yield ratio YR and the elongation until the maximum tensile stress EL. Both guarantee some amount of plastic deformation after yielding. This is essential for the limit state design including the seismic design. The 60K steel plate shows the yield plateau, but it does not appear in 60K steel pipe and 80K steel plate. Existence of the yield plateau is preferable for structures which are expected to undergo plastic deformation, even though rigorous verification is not carried out.

Test specimens : Test specimens are built-up column with end plates, which sections are H-shaped, square hollow and pipe. The length of columns is determined to cover the elastic and the elastic-plastic range in the expected column curve. The nominal section properties are summarized in Table 2, while measured values were used for calculation of compressive stresses and slenderness ratios to present the experimental

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results. All sections were made of steel plates by welding for H-shaped and square hollow and by seaming for pipes. No annealing process is provided to remove residual stress.

Test procedure : A test column is placed vertically in a 500 ton test machine as shown in Figure 1, and compressed through the knife-edges at the both ends of the column. Thus, flexural buckling deformation was appeared as in a simply supported column in a direction, but the column was fixed in another direction. The deformation can be drawn schematically as in the figure. The vertical deformation between the knife-edges δ_V and the lateral deformation at the middle height δ_H were measured throughout the test. The load applied was measured by the load cell installed in the machine.

3. EXPERIMENTAL RESULTS

The results obtained by the tests are summarized in Figures 2 and 3. Figure 2 shows the critical axial strength N_{cr} against the slenderness ratio λ_c. The critical axial strength N_{cr} was found as the axial load at the time when the lateral deformation starts to increase. To find this value easily, the lateral deformation was multiplied by 10^4 for exaggeration in the load vs. lateral deformation relationship as shown in Figure 4(a). The maximum axial strength N_m was simply determined as the crest value in the load vs. vertical deformation relationship as shown in Figure 4(b). N_{cr} and N_m are expressed in Figures 2 and 3 by a non-dimensional form like N_{cr}/N_y and N_m/N_y, where N_y is the yield strength. The slenderness ratio λ_c in the figures is also expressed by a generalized form defined as follows:

$\lambda_c = N_y/N_E$
$N_y = \sigma_y A$
$N_E = \pi^2 EI/L^2$
A = Cross-sectional area
E = Modulus of elasticity
I = Moment of inertia
L = Length between the knife-edges

In the test of H-shaped section columns, the test columns were always placed as the columns could buckle about the strong axis. All test results obtained are summarized in the Appendix.

4. DISCUSSIONS

Usually the buckling test results scatter widely. It is caused by uncontrolled imperfection in fabrication of test structures and arrangement of test-rig and alignment of loading machine. Moreover, in the data base which is built from experimental results by many researchers, scattering of the data is accelerated due to various steel materials, various section profiles, different test rig used, loading speed applied and types of test machines. From this viewpoint , the dispersion of test results in Figures 2 and 3 is relatively small. The results, though these were obtained by the tests on the different section profiles, scatter within a relative narrow band. Some exceptions , however, are found in the results of H-shaped sections, where the strength of the columns between 1.0 to 1.3 in slenderness ratio is scattering in the lower values. This was caused by the occurrence of flexural and torsional buckling. This is one of the important findings from the tests.

The solid curve in Figures 2 and 3 is the reference curve used for expressing the basic column strength in AIJ Design Standard (2). Namely,

$$N_c = N_y \qquad \text{for } \lambda_c \leq {}_p\lambda_c$$

$$N_c = \left(1.0 - 0.5\frac{\lambda c - p\lambda c}{{}_e\lambda_c - {}_p\lambda_c}\right) Ny \qquad \text{for } {}_p\lambda_c < \lambda_c \leq {}_e\lambda_c$$

$$N_c = \frac{1}{1.2\,\lambda_c^2} Ny \qquad \text{for } {}_e\lambda_c < \lambda_c$$

where N_c = Compressive axial strength
λ_c = Generalized slenderness ratio = $\sqrt{N_y / N_e}$
${}_p\lambda_c$ = Plastic limit slenderness = 0.15
${}_e\lambda_c$ = Elastic limit slenderness = $1/\sqrt{0.6}$
N_y = Yield strength = $\sigma_y A$
N_e = Elastic buckling strength = $\pi^2 EI/{}_kL_c^2$
${}_kL_c$ = Effective length for flexural buckling

Design values are actually reduced by use of the resistance factor Φ, which varies between 0.85 ~ 0.9. Thus, it can be concluded from Figure 3 that a safe side evaluation for the maximum axial strength is possible. In some cases, however, not negligible lateral deformation may be noticed, though the load bearing capacity of the column is not lost. No remarkable difference in the strength is noticeable among 60K steel and 80K steel materials. The difference in the stress vs. strain relationship is not reflected on the compressive strength. A slight difference can be seen due to the section profile; the pipe columns show a little higher strength.

5. CONCLUDING REMARKS

The buckling tests were carried out on the columns made of the newly developed high strength steels. The findings from the tests are:

1) The new steel materials can be used for structural members.

2) The design column curve, which was proposed recently in AIJ Standard for Limit State Design of Steel Structures, can be applied to the design of compressive

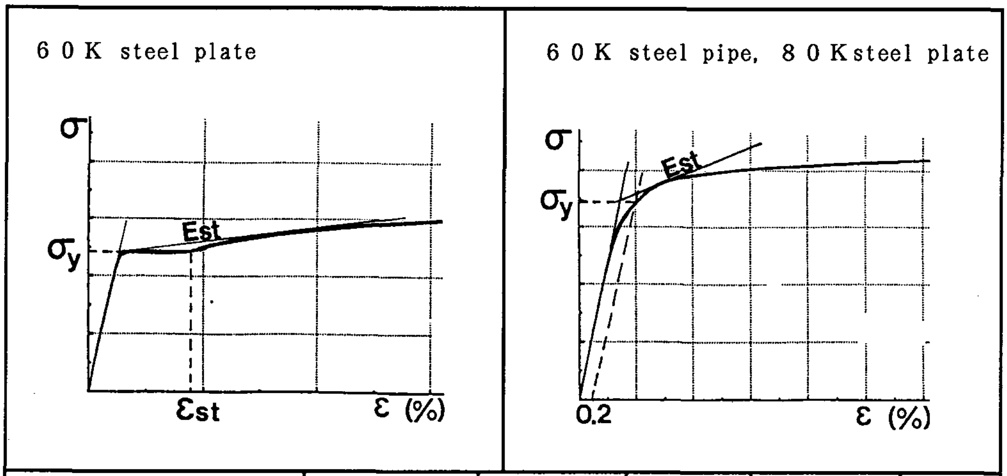
3) No remarkable difference is noticeable in the column test results of various steel materials.
4) No remarkable difference is found among the test results conducted on the columns with various cross section profiles.

REFERENCES

1. Fukumoto, Y. and Itoh, Y., "Evaluation of Beam Strength from the Experimental Data-base Approach," 3rd International Colloquium, Stability Metal Structures, Structural Stability Research Council 1983 pp. 133 ~ 149

2. AIJ, "Standard for Limit State Design of Steel Structures(draft)", Architectural Institute of Japan, 1990.

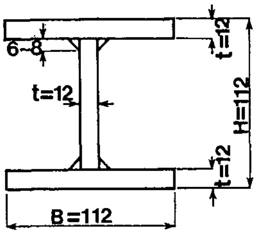
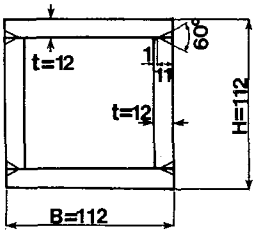
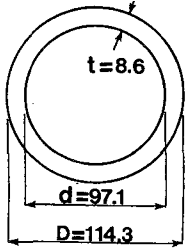
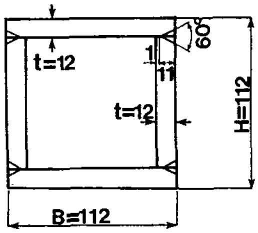
Table 1 Stress-strain Relationship



		σ_y(t/cm^2)	σ_u(t/cm^2)	YR(%)	E／E_{st}	EL(%)
60K	H	4.80～5.11	6.60～6.79	71～76	1/34～1/54	37～39
	SQUARE	4.69～5.11	6.52～6.60	71～75	1/30～1/37	18～20
60K	PIPE	5.02～5.25	7.30～7.45	68～71	1/27～1/29	23～27
80K	SQUARE	7.06～7.54	8.58～8.71	83～85	1/19～1/26	11～13

σ_y:Yield stress σ_u :Tensile stress YR:Yield ratio=σ_y/σ_u
E :Young's modulus E_{st}:Strain hardening modulus EL:Elongation at σ_u

Table 2 Section Properties

60K steel			80K steel
			
$A=37.4$ cm^2	$A=48.0$ cm^2	$A=28.6$ cm^2	$A=48.0$ cm^2
$I_x=743$ cm^4	$I=812$ cm^4	$I=402$ cm^4	$I=812$ cm^4
$r_x=4.46$ cm	$r=4.11$ cm	$r=3.75$ cm	$r=4.11$ cm
$B/t_f=4.7$	$B/t=9.3$	$D/t=13.3$	$B/t=9.3$

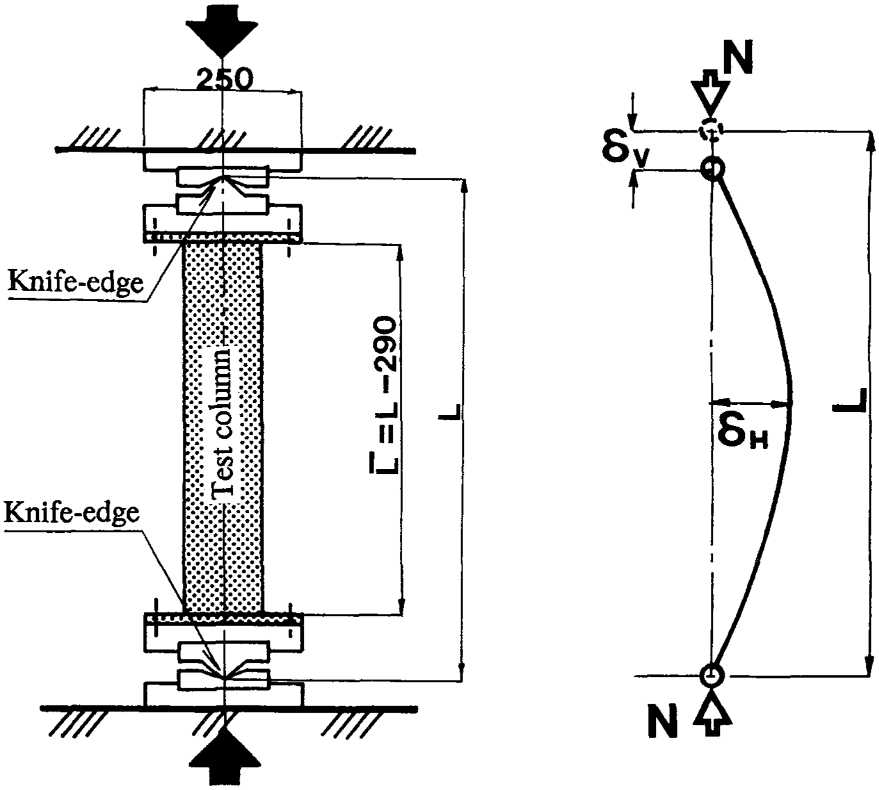


Fig. 1 Test Set-up and Measurement of Deformation

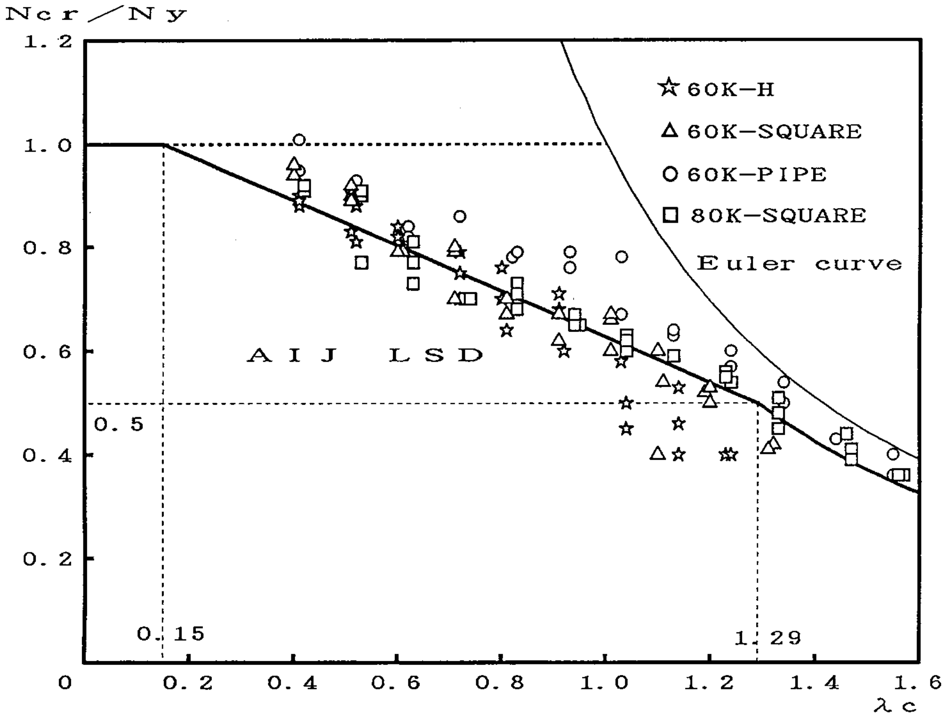


Fig. 2 Critical Axial Strength of Compressive Columns

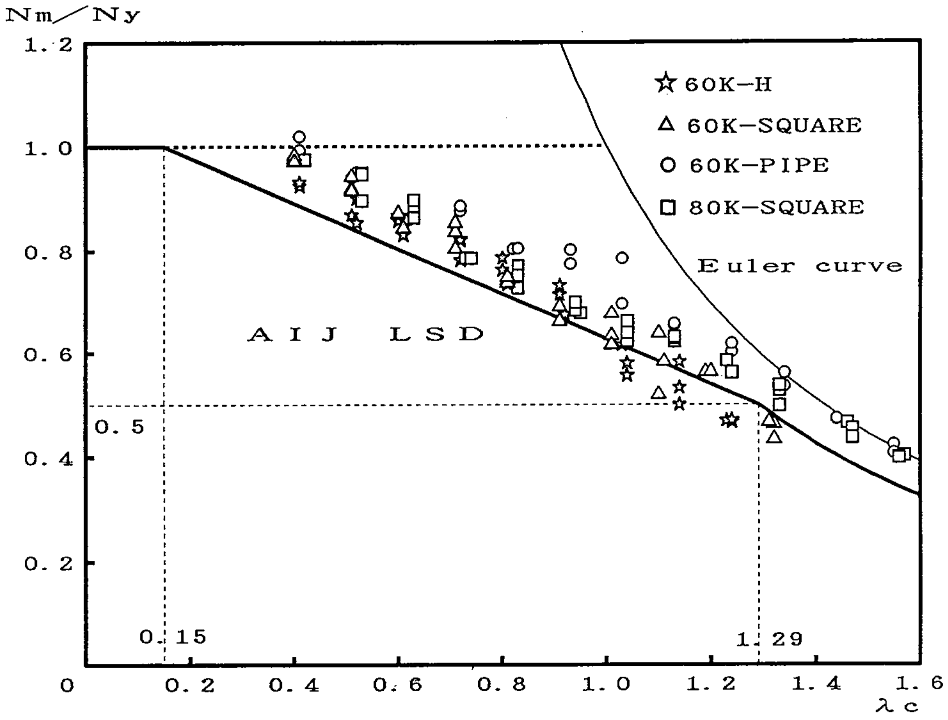
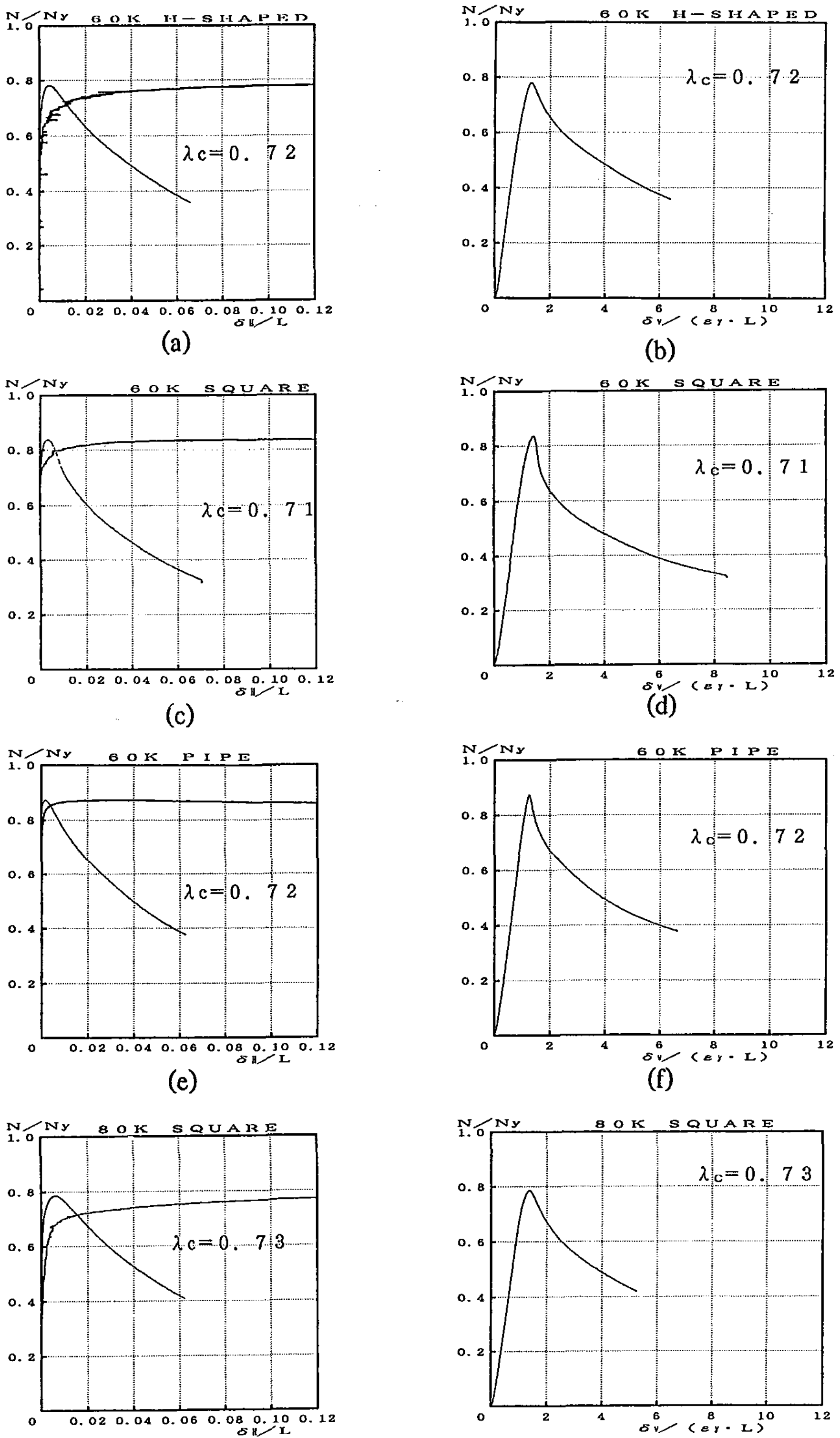


Fig. 3 Maximum Axial Strength of Compressive Columns



(a) (b)

(c) (d)

(e) (f)

(g) (h)

Fig. 4 Axial Stress vs. Lateral Displacement and Axial Stress vs. Axial Strain

APPENDIX :

60K H-SHAPED

λ	λ_c	(cm) L	(cm^2) A	t/cm^2 σ_y	t/cm^2 σ_m	(ton) N_y	(ton) N_{cr}	(ton) N_m	$\frac{N_{cr}}{N_y}$	$\frac{N_m}{N_y}$
26.4	0.41	117.00	37.380	5.02	4.64	187.6	168.8	173.4	0.90	0.92
26.5	0.41	117.00	37.302		4.64	187.3	164.8	173.0	0.88	0.92
26.5	0.41	117.02	37.134		4.68	186.4	165.9	173.6	0.89	0.93
33.2	0.52	147.00	37.671	5.02	4.52	189.1	166.4	170.2	0.88	0.90
33.1	0.51	147.00	37.695		4.36	189.2	157.0	164.2	0.83	0.87
33.2	0.52	146.99	37.607		4.28	188.8	152.9	161.0	0.81	0.85
40.2	0.61	176.00	37.419	4.90	4.06	183.4	146.7	152.2	0.80	0.83
39.7	0.60	176.00	37.528		4.20	183.9	150.8	157.6	0.82	0.86
40.0	0.60	176.00	37.360		4.25	183.1	153.8	158.8	0.84	0.87
47.1	0.72	206.05	37.162	4.84	3.78	179.9	125.9	140.5	0.70	0.78
46.9	0.72	206.05	37.138		3.98	179.8	142.0	148.0	0.79	0.82
47.3	0.72	206.07	37.134		3.97	179.7	134.8	147.4	0.75	0.82
52.8	0.80	235.10	37.852	4.82	3.67	182.4	127.7	139.0	0.70	0.76
53.0	0.81	235.08	37.712		3.53	181.8	116.4	133.2	0.64	0.73
52.8	0.80	235.08	37.747		3.79	181.9	138.2	143.0	0.76	0.79
59.5	0.91	264.10	37.409	4.84	3.54	181.1	128.6	132.6	0.71	0.73
59.7	0.92	264.09	37.301		3.26	180.5	108.3	121.6	0.60	0.67
59.5	0.91	264.06	37.496		3.46	181.5	123.4	129.6	0.68	0.71
66.4	1.04	293.15	37.450	5.06	2.81	189.5	85.3	105.4	0.45	0.56
66.2	1.03	293.13	37.555		3.11	190.0	110.2	116.8	0.58	0.62
66.5	1.04	293.13	37.473		2.94	189.6	94.8	110.0	0.50	0.58
73.3	1.14	322.17	37.450	5.00	2.50	187.2	74.9	93.6	0.40	0.45
73.1	1.14	322.17	37.450		2.91	187.2	99.2	109.0	0.53	0.58
73.0	1.14	322.15	37.403		2.66	187.0	86.0	99.6	0.46	0.53
79.8	1.24	352.18	37.355	4.76	2.22	177.8	71.1	82.8	0.40	0.47
79.8	1.23	352.14	37.235		2.23	177.2	70.9	83.2	0.40	0.47
79.9	1.24	352.11	37.165		2.24	176.9	70.8	83.2	0.40	0.47

60K SQUARE HOLLOW

λ	λ_c	(cm) L	(cm²) A	t/cm² σ_y	t/cm² σ_m	(ton) N_y	(ton) N_{cr}	(ton) N_m	$\frac{N_{cr}}{N_y}$	$\frac{N_m}{N_y}$
26.3	0.40	108.10	46.781	4.84	4.72	226.4	217.3	221.0	0.96	0.98
26.4	0.40	108.09	46.859		4.76	226.8	213.2	223.0	0.94	0.98
26.3	0.40	108.06	46.711		4.70	226.1	217.1	219.5	0.96	0.97
33.1	0.51	135.08	46.407	4.84	4.45	224.6	202.1	206.5	0.90	0.92
33.2	0.51	134.99	46.297		4.56	224.1	206.2	211.0	0.92	0.94
33.1	0.51	135.10	46.407		4.43	224.6	199.9	205.5	0.89	0.92
39.4	0.61	162.04	46.341	4.85	4.09	224.8	177.6	189.5	0.79	0.84
39.5	0.60	161.97	46.559		4.22	225.8	178.4	196.5	0.79	0.87
46.6	0.71	189.04	46.173	4.82	4.03	222.6	175.8	186.0	0.79	0.84
46.5	0.71	189.07	46.348		4.11	223.4	178.7	190.5	0.80	0.85
46.6	0.71	189.02	46.215		3.87	222.8	156.0	179.0	0.70	0.80
52.7	0.81	216.04	46.449	4.86	3.60	225.7	158.0	167.2	0.70	0.74
52.0	0.81	216.05	46.386		3.57	225.4	151.0	165.6	0.67	0.74
52.9	0.81	216.04	46.519		3.63	226.1	158.3	169.0	0.70	0.75
59.6	0.91	243.07	46.379	4.99	3.32	231.4	143.5	154.0	0.62	0.67
59.6	0.91	243.12	46.461		3.47	231.8	155.3	161.0	0.67	0.69
65.9	1.01	270.12	46.758	4.83	3.06	225.8	135.5	143.0	0.60	0.63
65.8	1.01	270.12	46.833		3.27	226.2	149.3	153.0	0.66	0.68
65.9	1.01	270.12	46.699		2.97	225.6	151.2	138.8	0.67	0.62
72.3	1.10	297.12	46.828	5.06	2.63	236.9	94.8	123.0	0.40	0.52
72.3	1.10	297.12	46.723		3.23	236.4	141.8	150.8	0.60	0.64
72.4	1.11	297.05	46.753		2.95	236.6	127.8	138.0	0.54	0.58
78.9	1.19	324.11	46.730	4.71	2.65	220.1	114.5	123.8	0.52	0.56
79.5	1.20	324.12	46.435		2.65	218.7	115.9	123.2	0.53	0.56
79.3	1.20	324.08	46.653		2.59	219.7	109.9	120.8	0.50	0.55
86.5	1.32	351.08	46.384	4.83	2.23	224.0	94.1	103.4	0.42	0.46
86.0	1.31	351.14	46.501		2.25	224.6	92.1	104.6	0.41	0.47
86.6	1.32	351.09	46.330		2.09	223.8	80.6	96.8	0.36	0.43

60K PIPE

λ	λ_c	(cm) L	(cm^2) A	t/cm^2 σ_y	t/cm^2 σ_m	(ton) N_y	(ton) N_{cr}	(ton) N_m	$\frac{N_{cr}}{N_y}$	$\frac{N_m}{N_y}$
26.4	0.41	99.01	28.099	5.12	4.91	143.9	136.7	142.9	0.95	0.99
26.4	0.41	99.00	28.125		5.10	144.0	145.4	146.8	1.01	1.02
32.8	0.51	123.02	28.107	5.12	4.81	143.9	130.9	135.2	0.91	0.94
32.8	0.52	123.06	28.085		4.87	143.8	133.7	136.8	0.93	0.95
39.5	0.62	148.08	28.125	5.12	4.42	144.0	121.0	124.2	0.84	0.86
39.4	0.62	147.99	28.125		4.40	144.0	118.1	123.8	0.82	0.86
45.7	0.72	172.04	28.205	5.12	4.49	144.4	124.2	126.5	0.86	0.88
45.7	0.72	172.01	28.186		4.53	144.3	124.1	127.8	0.86	0.89
52.6	0.82	197.11	28.099	5.12	4.11	143.9	112.2	115.5	0.78	0.80
52.6	0.83	197.03	28.080		4.12	143.8	113.6	115.6	0.79	0.80
59.2	0.93	222.05	28.099	5.12	4.10	143.9	113.7	115.3	0.79	0.80
59.1	0.93	221.98	28.160		3.96	144.2	109.6	111.6	0.76	0.77
65.6	1.03	246.10	28.133	5.12	3.56	144.0	96.5	100.2	0.67	0.70
65.7	1.03	246.13	28.099		4.01	143.9	112.2	112.8	0.78	0.78
72.2	1.13	271.07	28.125	5.12	3.35	144.0	90.7	94.1	0.63	0.65
72.2	1.13	271.04	28.146		3.36	144.1	92.2	94.5	0.64	0.66
78.9	1.24	296.15	28.138	5.12	3.08	144.1	82.1	86.8	0.57	0.61
78.9	1.24	296.19	28.138		3.17	144.1	86.5	89.1	0.60	0.62
85.4	1.34	320.20	28.120	5.12	2.75	144.0	72.0	77.2	0.50	0.54
85.4	1.34	320.17	28.085		2.87	143.8	77.7	80.7	0.54	0.56
92.0	1.44	345.11	28.112	5.12	2.42	143.9	61.9	68.0	0.43	0.47
92.1	1.44	345.12	28.093		2.42	143.8	61.8	68.0	0.43	0.47
98.6	1.55	370.06	28.120	5.12	2.17	144.0	57.6	60.9	0.40	0.42
98.6	1.55	370.08	28.125		2.09	144.0	51.8	58.7	0.36	0.41

80K SQUARE HOLLOW

λ	λ_c	(cm) L	(cm^2) A	t/cm^2 σ_y	t/cm^2 σ_m	(ton) N_y	(ton) N_{cr}	(ton) N_m	$\frac{N_{cr}}{N_y}$	$\frac{N_m}{N_y}$
22.2	0.42	89.99	46.417	7.33	7.14	340.2	309.6	331.5	0.91	0.97
22.2	0.42	90.04	46.359		7.13	339.8	312.6	330.5	0.92	0.97
27.9	0.53	113.01	46.586	7.44	6.66	346.6	266.9	310.5	0.77	0.90
27.8	0.53	113.04	46.756		7.06	347.9	313.1	330.0	0.90	0.95
27.8	0.53	113.01	46.615		7.05	346.8	315.6	328.5	0.91	0.95
33.3	0.63	135.07	46.745	7.44	6.56	347.8	267.8	306.5	0.77	0.88
33.4	0.63	135.07	46.527		6.67	346.2	280.4	310.5	0.81	0.90
33.1	0.63	135.03	46.874		6.42	348.7	254.6	301.0	0.73	0.86
38.7	0.73	158.02	46.752	7.44	5.85	347.8	243.5	273.5	0.70	0.79
39.0	0.74	158.09	46.662		5.84	347.2	243.0	272.5	0.70	0.79
44.2	0.83	179.96	46.551	7.33	5.33	341.2	232.0	248.0	0.68	0.73
44.2	0.83	179.97	46.624		5.64	341.8	249.5	263.0	0.73	0.77
44.2	0.83	180.03	46.676		5.51	342.1	242.9	257.0	0.71	0.75
50.0	0.95	203.02	46.662	7.44	5.04	347.2	225.7	235.0	0.65	0.68
49.9	0.94	203.05	46.615		5.07	346.8	225.4	236.5	0.65	0.68
49.9	0.94	203.01	46.820		5.19	348.3	233.4	243.0	0.67	0.70
55.1	1.04	225.06	46.430	7.33	4.57	340.3	204.2	212.0	0.60	0.62
55.1	1.04	225.06	46.442		4.84	340.4	214.5	225.0	0.63	0.66
55.4	1.04	225.00	46.407		4.69	340.2	210.9	217.5	0.62	0.64
60.6	1.13	248.07	47.267	7.18	4.44	339.4	200.2	211.0	0.59	0.62
60.6	1.13	248.06	47.322		4.51	339.8	200.5	213.5	0.59	0.63
60.5	1.13	248.13	47.376		4.53	340.2	200.7	214.5	0.59	0.63
66.4	1.24	270.11	46.571	7.18	4.04	334.4	180.6	188.0	0.54	0.56
66.0	1.23	270.07	46.746		4.20	335.6	187.9	196.5	0.56	0.59
65.9	1.23	270.12	46.809		4.20	336.1	184.9	196.5	0.55	0.59
71.6	1.33	293.12	47.258	7.12	3.55	336.5	151.4	167.7	0.45	0.50
71.9	1.33	293.11	47.139		3.76	335.6	161.1	177.2	0.48	0.53
71.5	1.33	293.12	47.310		3.82	336.8	171.8	180.8	0.51	0.54
77.3	1.46	315.14	46.922	7.44	3.46	349.1	153.6	162.2	0.44	0.47
77.5	1.47	315.18	46.855		3.37	348.6	142.9	158.1	0.41	0.45
77.4	1.47	315.14	46.827		3.25	348.4	135.9	152.3	0.39	0.44
83.3	1.57	338.12	46.262	7.33	2.96	339.1	122.1	136.7	0.36	0.40
83.1	1.56	338.07	46.407		2.93	340.2		136.0		0.40
83.0	1.56	338.15	46.543		2.92	341.2	122.8	135.8	0.36	0.40