Small Scale Models for Steel Frameworks

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THE ANALYSIS AND DESIGN of steel structures has become increasingly sophisticated and efficient in the last decade. For conventional structures, present methods of analysis can be employed with confidence with the proportioning of members based upon some prescribed criteria, such as building and bridge construction codes. When these methods can be employed, there can be no economic justification for a model study of a structure. Some aspects of both member and whole structure behavior, however, are still not well understood for these conventional structures and as new design criteria are developed for these situations, testing programs will be required. For unconventional structures, mathematical analyses that appropriately account for the complex geometries and behavior may not be available. It is in these areas, the development of design criteria for conventional structures and the study of unconventional structures, that model analysis can be useful.

The use of experimental methods has already been demonstrated in tests carried out on full scale sections at Lehigh University and other schools. These tests have effectively contributed to the incorporation of plastic design into building codes. On the other hand, full scale tests have a number of limitations. To date tests have been restricted to simple members and simple one, two or three story plane frames. While more complex structures, in many cases, would have masked the phenomenon under study there are situations where tests on larger or more complete structures would have been appropriate. Even in those situations where full scale study is feasible, the same total investment in small scale study would often permit a more comprehensive investigation.

The purpose of this paper is to present the results of the first phase of a study aimed at establishing a reliable small scale ultimate strength modeling technique for wide-flange steel frameworks. This paper will cover the aspects of:

1. Selection of an appropriate model material
2. Fabrication techniques for individual members
3. Fabrication techniques for complete frameworks
4. Tests on beams and fabricated joints

Currently being conducted at M.I.T. but not reported here, are

5. Forty-eight beam-column tests on one-tenth scale 8WF31 sections
6. Two tests on one-eighth scale models of the two-bay three-story plane frames tested at the 1965 Plastic Design Summer Conference at Lehigh University

These latter studies, while more significant than the work reported here, do depend directly upon the results of this first phase.

MODEL MATERIAL

Brass, bronze and steel have all been used at M.I.T. for ultimate strength model studies of steel structures. On the basis of its mechanical properties and its weldability, SAE C1020 hot rolled steel is a satisfactory material for ultimate strength model studies of ASTM A36 steel structures. Its availability in thin plate sizes lends to its use in models of a variety of structural forms. Table 1 lists the results of forty simple tension tests of SAE C1020 and SAE C1010 specimens. Test specimen numbers 6 through 15 were taken from milled model beams and it is seen that the yield stress in one beam was about 36 ksi while it was about 46 ksi in the other. This fact only emphasizes that the mechanical properties of SAE C1020 steel are subject to statistical variations and the properties of each piece of stock must be determined separately. Test specimen numbers 4 and 5 indicate that the full strength of the base material can be developed at a TIG (tungsten inert gas) butt weld. The ultimate elongation for the butt welded specimens was only about one-half that for plain specimens, but it is still adequate as subsequent joint tests indicate.

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The lower yield and ultimate stress in the SAE C1010 specimens led to its rejection in favor of SAE C1020 steel although the SAE C1010 could be used if the lower strength values were ever desired. One fact that comes clearly from the SAE C1010 butt welded specimens is that the unannealed specimens have a tendency to fracture some distance away from the weld line even though the cross-sectional area was a minimum at the weld line.

Table 1. Tension Tests for Steel Specimens

Test No.	Description	Area (in.) x (in.)	Annealing	Yield Stress (psi)	Ultimate Strength (psi)	Elongation One Inch (%)
			SAE C1020 Hot Rolled			
1	Plain specimen from stock	0.063 x 0.434	1100°F 40 min.	46.1	63.9	34
2	Plain specimen from stock	0.063 x 0.434	1100°F 40 min.	46.6	66.0	32
3	Plain specimen from stock	0.063 x 0.434	1100°F 40 min.	46.1	65.3	36
4	TIG butt welded	0.113 x 0.430	1100°F 40 min.	49.4	70.4	14
5	TIG butt welded	0.113 x 0.429	1100°F 40 min.	48.8	71.0	12
6	Cut from web of 1/15 scale 21WF62	0.028 x 0.375	None	48.4*	64.0	27
7	Cut from web of 1/15 scale 21WF62	0.028 x 0.431	None	45.7*	65.2	25
8	Cut from web of 1/15 scale 21WF62	0.028 x 0.435	None	47.4*	64.6	23
9	Cut from web of 1/15 scale 21WF62	0.028 x 0.436	1000°F 45 min.	42.3	61.5	32
10	Cut from web of 1/15 scale 21WF62	0.028 x 0.436	1000°F 45 min.	45.3	61.5	29
11	Cut from web of 1/15 scale 21WF62	0.028 x 0.437	1000°F 45 min.	46.3	62.0	34
12	Cut from web of 1/15 scale 14WF103	0.033 x 0.435	None	34.4*	60.0	38
13	Cut from flange of 1/15 scale 14WF103	0.053 x 0.436	None	35.8*	60.2	23
14	Cut from flange of 1/15 scale 14WF103	0.052 x 0.436	1000°F 45 min.	37.4	58.4	26
15	Cut from flange of 1/15 scale 14WF103	0.052 x 0.436	1000°F 45 min.	37.8	59.1	39
			SAE C1010 Hot Rolled			
16	Plain specimen from stock	0.090 x 0.423	None	41.2*	45.3	36
17	Plain specimen from stock	0.090 x 0.424	None	39.1*	48.4	40
18	Plain specimen from stock	0.090 x 0.423	800°F 60 min.	37.8	47.4	40
19	Plain specimen from stock	0.089 x 0.425	800°F 60 min.	44.5	47.6	40
20	Plain specimen from stock	0.024 x 0.426	800°F 60 min.	43.5	45.6	38
21	Plain specimen from stock	0.024 x 0.426	800°F 60 min.	31.8	44.3	36
22	Plain specimen from stock	0.090 x 0.427	1000°F 60 min.	42.2	47.6	40
23	Plain specimen from stock	0.090 x 0.427	1000°F 60 min.	43.0	48.4	40
24	Plain specimen from stock	0.024 x 0.427	1000°F 60 min.	44.2	45.7	36
25	Plain specimen from stock	0.024 x 0.427	1000°F 60 min.	43.4	45.8	36
26	Plain specimen from stock	0.063 x 0.434	1100°F 40 min.	35.8	43.9	40
27	Plain specimen from stock	0.062 x 0.434	1100°F 40 min.	35.3	42.0	38
28	Plain specimen from stock	0.061 x 0.435	1100°F 40 min.	32.6	42.6	34
29	TIG butt weld	0.023 x 0.431	None	40.8*	47.4	8
30	TIG butt weld	0.027 x 0.422	None	34.7*	40.5	10
31	TIG butt weld	0.057 x 0.426	None	35.0*	41.0	O.G.†
32	TIG butt weld	0.055 x 0.424	None	39.1*	47.4	O.G.†
33	TIG butt weld	0.061 x 0.434	None	31.6*	42.6	O.G.†
34	TIG butt weld	0.061 x 0.435	None	31.6*	43.4	O.G.†
35	TIG butt weld	0.057 x 0.425	1100°F 45 min.	31.7	41.7	O.G.†
36	TIG butt weld	0.055 x 0.426	1100°F 45 min.	37.4	44.0	26
37	TIG butt weld	0.057 x 0.427	1100°F 45 min.	37.6	44.9	30
38	TIG butt weld	0.055 x 0.432	1100°F 45 min.	38.9	46.5	28
39	TIG butt weld	0.030 x 0.427	1100°F 45 min.	34.7	40.5	O.G.†
40	TIG butt weld	0.026 x 0.425	1100°F 45 min.	38.8	40.5	12

* *0.2% offset method.*

† *Failed outside 1 in. gage length.*

This fact would indicate a strength buildup in the heat affected zone. Subsequent behavior in the joint tests confirmed these suspicions.

FABRICATION OF WIDE-FLANGE SHAPES

Five techniques have been considered for fabrication of small scale wide-flange steel beams. These are hot rolling, die extrusion, electron beam welding of three plates, resistance welding of three plates and milling of rectangular bar stock. At the one-eighth to one-fifteenth scales envisioned for the model work, minimum thicknesses down to about 0.025-in would be required. Rolling facilities for such sections are not available and no economic justification can be presented for developing them. If large quantities would be anticipated for each section, the high initial cost of dies for die extrusion could be amortized. However, experience indicates that the occasions demand small quantities of a large number of different sections rather than large quantities of a few sections. The use of electron beam welding to fuse flange and web plates of appropriate width and thickness was investigated. Although the process produced reliable welds, test specimens showed occasional weld skips or incomplete welds due to imperfect alignment of the plates or due to "wandering" of the electron beam. These occurrences, coupled with the physical size limitations of existing vacuum chambers which house the electron beam equipment, caused rejection of this technique. Resistance welding of flange and web plates was also investigated. The AMF Thermotool equipment which currently will do this job for prototype size members does not accommodate the size members envisioned here. While it appears that a suitable machine could be built, its development and cost was beyond the scope of this work.

Although the cost of milling wide-flange shapes is much higher than one would wish, it seems at the present time to be the most appropriate technique. Tables 2 and 3 indicate the dimensional tolerances that can be maintained. The maximum deviation from that specified is 0.005-in. with the average in all cases being within 0.002-in. Finished sections are delivered in 6- to 10-ft lengths at a cost of about $28 per foot.

FABRICATION OF JOINTS AND FRAMEWORKS

Both MIG (metallic inert gas) and TIG (tungsten inert gas) welding were considered for the joining of two or more wide-flange members. With 0.030-in. diameter consumable electrodes it was found that the MIG welds were extremely heavy and with the thin material it was difficult to prevent burnthrough and spatter. The TIG process allowed for greater control and smoother cleaner welds were obtained. In the TIG process the tungsten electrode is not consumed, but rather a filler wire is fed into the arc, melted, and propelled toward the joint being formed. Shielding is provided by an inert gas, this gas commonly being argon or argon mixed with a small percentage of helium.

In order to establish proper techniques, a one- by two-bay three-story space framework was fabricated using one-fifteenth scale 14WF103 members as columns and one-fifteenth scale 21WF62 members as beams. TIG welding with 0.032-in Industrial Stainless 410 filler wire was used throughout. The nominal framework dimensions are shown in Fig. 1, and in Table 4 the measured dimensions on the finished frame (not annealed) are listed. The maximum deviations from specified dimensions occur in the bottom story column heights where in one place the column is 0.08-in. too short. The second- and third-story column heights and all bay widths are everywhere within 0.04-in. A brief description of the course of the framework fabrication follows.

Table 2. Dimensions of Milled One-Fifteenth Scale 14WF103 Beams

Beam No.	Section	Overall Depth (in.)	Flange Width (in.)	Top Flange Thickness (in.)	Bot. Flange Thickness (in.)	Web Thickness (in.)
Specified to	Manufacturer	0.950	0.972	0.054	0.054	0.036
1	1	0.949	0.975	0.050	0.050	0.034
	2	0.948	0.974	0.051	0.052	0.034
	3	0.949	0.972	0.050	0.052	0.036
2	1	0.950	0.973	0.052	0.054	0.034
	2	0.951	0.974	0.052	0.054	0.034
	3	0.949	0.973	0.052	0.054	0.034
	4	0.950	0.972	0.051	0.052	0.034
3	1	0.950	0.973	0.053	0.054	0.033
	2	0.951	0.974	0.053	0.053	0.033
	3	0.952	0.974	0.052	0.054	0.033
	4	0.952	0.973	0.052	0.055	0.033
4	1	0.950	0.975	0.053	0.053	0.034
	2	0.951	0.975	0.052	0.054	0.035
	3	0.951	0.973	0.053	0.053	0.032
	4	0.950	0.975	0.052	0.054	0.032
5	1	0.950	0.971	0.052	0.054	0.034
	2	0.950	0.972	0.052	0.053	0.034
	3	0.950	0.971	0.050	0.053	0.034
	4	0.950	0.972	0.051	0.053	0.034
6	1	0.950	0.974	0.051	0.053	0.034
	2	0.950	0.973	0.052	0.052	0.034
	3	0.950	0.974	0.051	0.052	0.034
	4	0.947	0.973	0.053	0.050	0.034
7	1	0.951	0.971	0.053	0.053	0.034
	2	0.950	0.972	0.052	0.053	0.034
	3	0.949	0.972	0.052	0.053	0.035
	4	0.950	0.972	0.051	0.052	0.035

The 14WF103 columns and 21WF62 beams were cut to proper length on a band saw and the beam seats, stiffeners and plates milled to size. Before welding all parts were cleaned to remove dust, oil and oxides.

First the beam seats and top plates were tacked to the bottom and top flanges of the beams. During tacking, a beam was secured in a jig with the seats and plates held by small clamps. After tacking the clamps were removed and the seats and top plates welded all around (Fig. 2). Each beam was then vapor-honed (mixture of compressed air, water and a very fine grit of clay-like texture) to remove any oxidation on the finished weld.

The 14WF103 columns were marked off at the proper floor levels and the web stiffeners lightly tapped into position. The web stiffeners were milled slightly oversize to compensate for weld shrinkage. The web stiffeners were tacked, welded all around and the affected area vapor-honed (Fig. 3).

A special jig consisting of a flat steel plate with small right angles welded to its surface at each floor level was used in the fabrication of each of the three portal frames in the framework. The columns were clamped to the flat steel plate and then, with the beam seats and top plates snugly against the web of the column, the beams were clamped against the small angles (Fig. 4). The beam seats and top plates were first tacked and then welded all around. The filler beams were jigged and welded as shown in Figs. 5 and 6. Figure 7 shows the completed framework.

Table 3. Dimensions of Milled One-Fifteenth Scale 21WF62 Beams

Beam No.	Section	Over-all Depth (in.)	Flange Width (in.)	Top Flange Thickness (in.)	Bot. Flange Thickness (in.)	Web Thickness (in.)
Specified to	Manufacturer	1.400	0.548	0.041	0.041	0.027
1	1	1.403	0.548	0.042	0.041	0.028
	2	1.404	0.548	0.042	0.040	0.029
	3	1.404	0.548	0.042	0.040	0.028
	4	1.405	0.548	0.042	0.040	0.028
2	1	1.401	0.546	0.042	0.042	0.028
	2	1.400	0.548	0.041	0.040	0.028
	3	1.401	0.548	0.039	0.041	0.028
	4	1.400	0.549	0.040	0.040	0.029
3	1	1.404	0.545	0.040	0.041	0.030
	2	1.402	0.548	0.040	0.042	0.028
	3	1.404	0.547	0.041	0.041	0.029
	4	1.403	0.548	0.041	0.042	0.028
4	1	1.403	0.549	0.041	0.041	0.028
	2	1.402	0.549	0.040	0.040	0.029
	3	1.400	0.548	0.041	0.039	0.029
	4	1.402	0.548	0.040	0.040	0.029
5	1	1.399	0.548	0.039	0.039	0.030
	2	1.400	0.548	0.040	0.039	0.030
	3	1.400	0.549	0.041	0.040	0.030
	4	1.400	0.549	0.040	0.041	0.028
6	1	1.401	0.548	0.041	0.041	0.028
	2	1.402	0.547	0.041	0.041	0.028
	3	1.402	0.549	0.041	0.041	0.029
	4	1.402	0.549	0.042	0.041	0.028
7	1	1.402	0.548	0.041	0.041	0.026
	2	1.401	0.548	0.041	0.041	0.026
	3	1.401	0.548	0.041	0.041	0.026
	4	1.402	0.547	0.042	0.041	0.025

Table 4. Geometry of Completed Space Framework
Refer to Fig. 1

Frame	Section	Floor Distance		
		1–2 (in.)	2–3 (in.)	3–4 (in.)
A	1	14.77	10.62	10.59
	2	14.76	10.59	10.57
	3	14.74	10.61	10.58
	4	14.72	10.62	10.59
	5	14.74	10.62	10.61
B	1	14.74	10.62	10.61
	2	14.83	10.62	10.59
	3	14.81	10.62	10.59
	4	14.81	10.61	10.60
	5	14.74	10.62	10.59
C	1	14.73	10.62	10.58
	2	14.73	10.62	10.59
D	1	14.80	10.62	10.59
	2	14.81	10.61	10.59
E	1	14.74	10.62	10.60
	2	14.73	10.62	10.59

Bay Width	Floor Level		
	2 (in.)	3 (in.)	4 (in.)
DE_0	32.02	32.02	32.03
DE_1	32.04	32.00	32.04
DE_2	32.00	32.01	32.00
DE_3	32.00	32.01	32.00
CD_0	16.00	16.00	16.00
CD_1	16.00	15.99	16.00
CD_2	16.00	15.98	16.00
CD_3	16.00	15.99	16.00
AB_0	15.09	15.09	15.09
AB_1	15.09	15.09	15.09
AB_2	15.07	15.06	15.07
AB_3	15.07	15.09	15.07
AB_4	15.08	15.07	15.08
AB_5	15.09	15.09	15.09

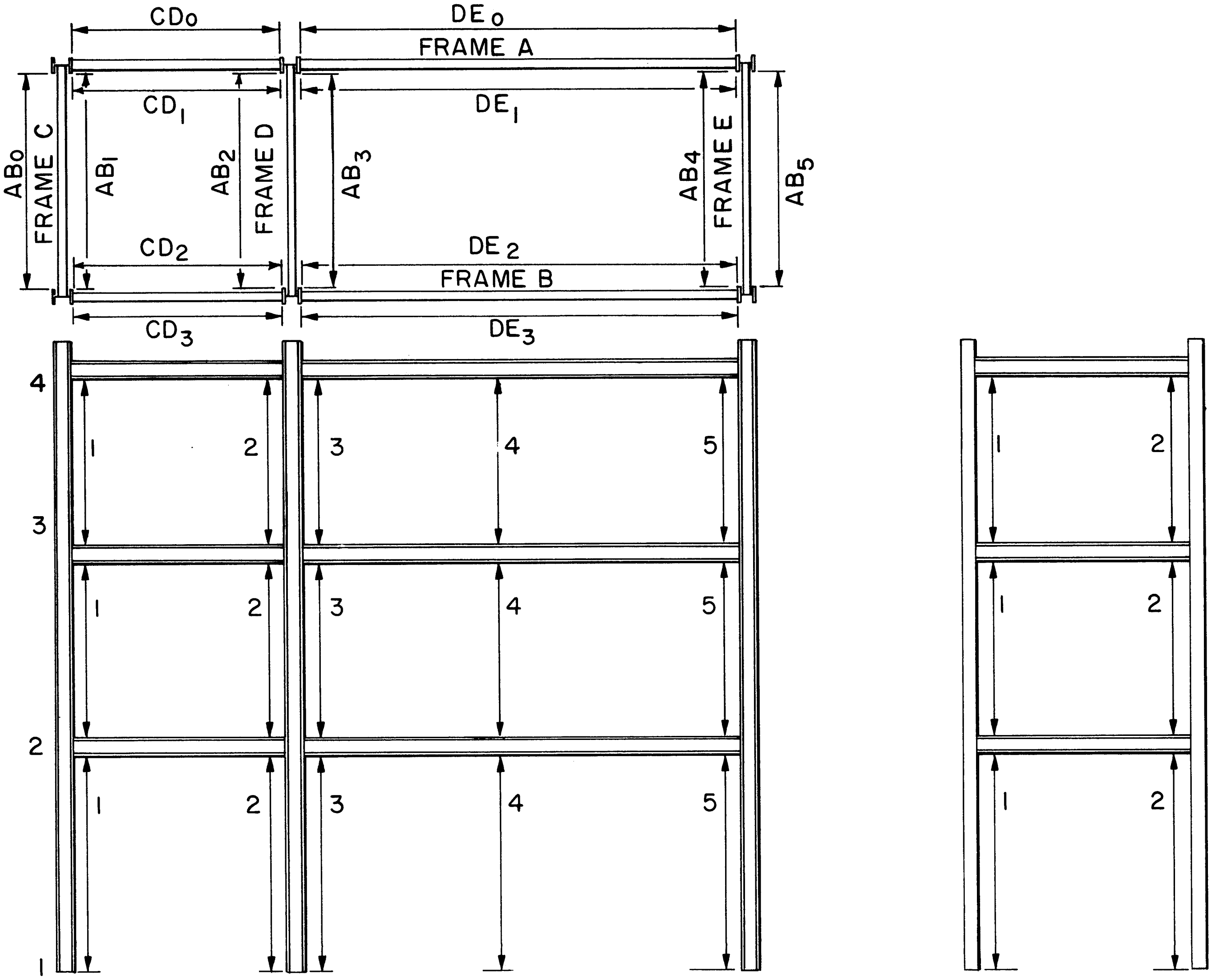

Fig. 1. Geometry of fabricated framework

The cost for the framework assembly was $700. This cost was due to the fact that a highly skilled operator was required and he had to proceed through each situation in a carefully controlled way.

In this framework each seat, plate and stiffener was welded all around on both sides, but this practice is not recommended except where it is necessary from a strength point of view. It may well be suitable for stiffeners to have only intermittent welds on one side only, etc. Clearly, the less welding to be done, the less the cost and the less the troubles with shrinkage, distortion and burnthrough. Alternatively, one might consider silver solder for connecting secondary elements.

BEAM TESTS

Third point loaded 14WF103 and 21WF62 beams were tested to determine the influence of annealing on the behavior of milled wide-flange sections. With the test

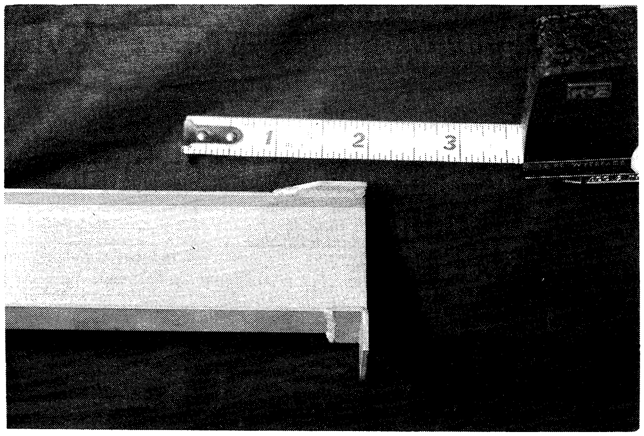

Fig. 2. Beam with seat and top plate

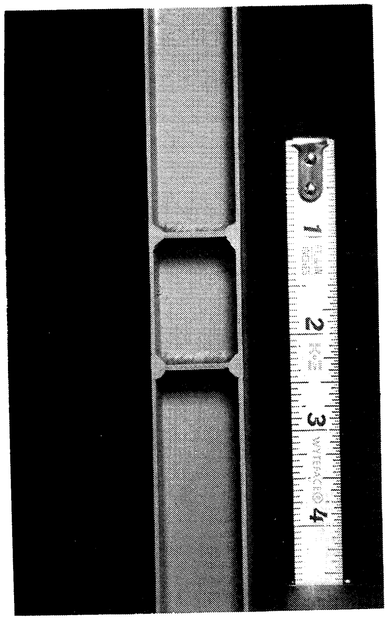

Fig. 3. Column with web stiffeners

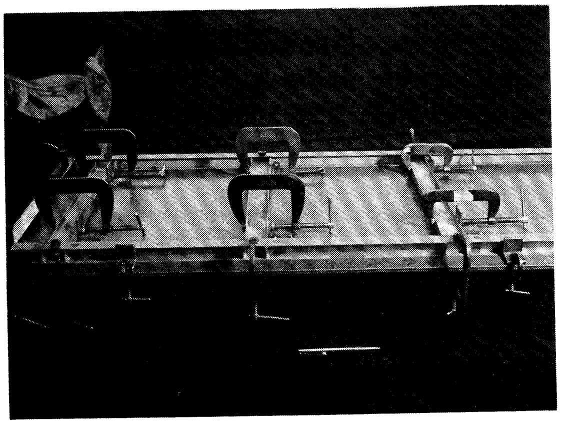

Fig. 4. Assembly of portal frame

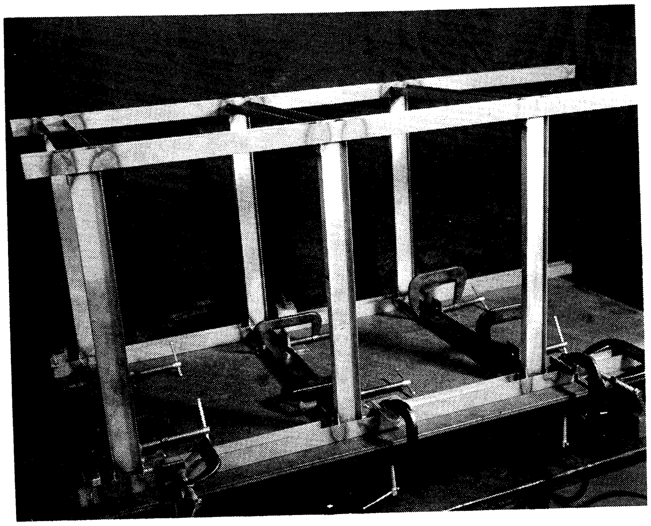

Fig. 5. Space frame subassembly

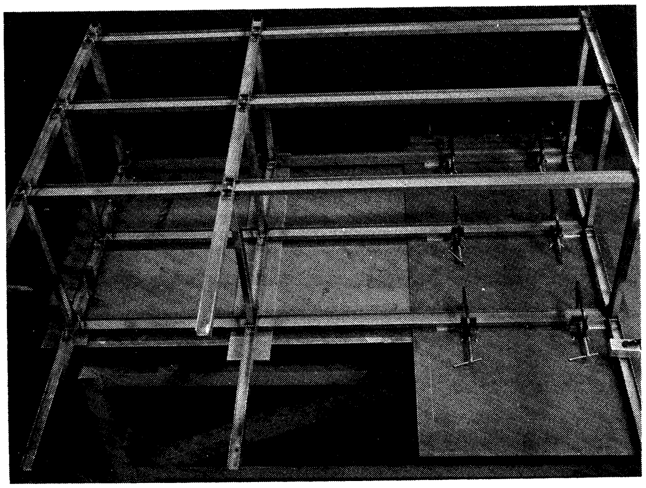

Fig. 6. Addition of last beams

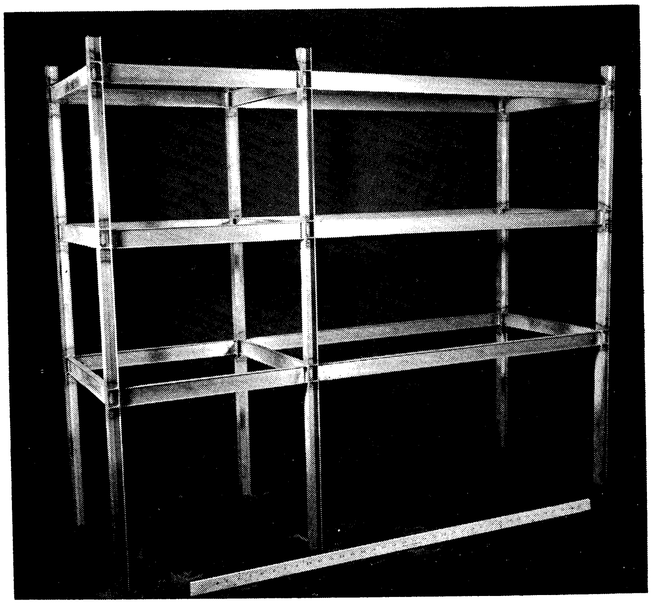

Fig. 7. Completed framework

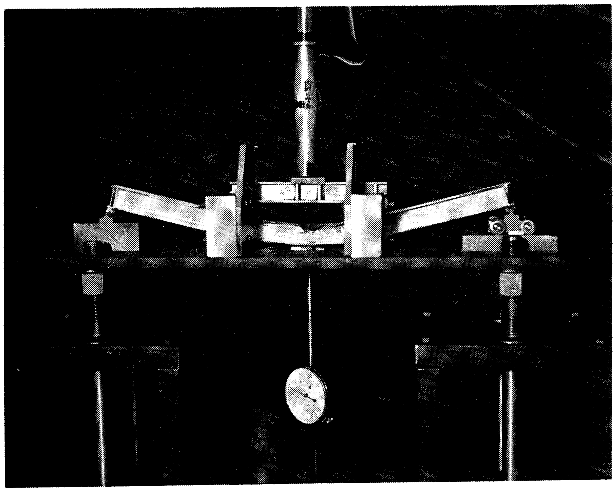

Fig. 8. 14 WF 103 beam test setup

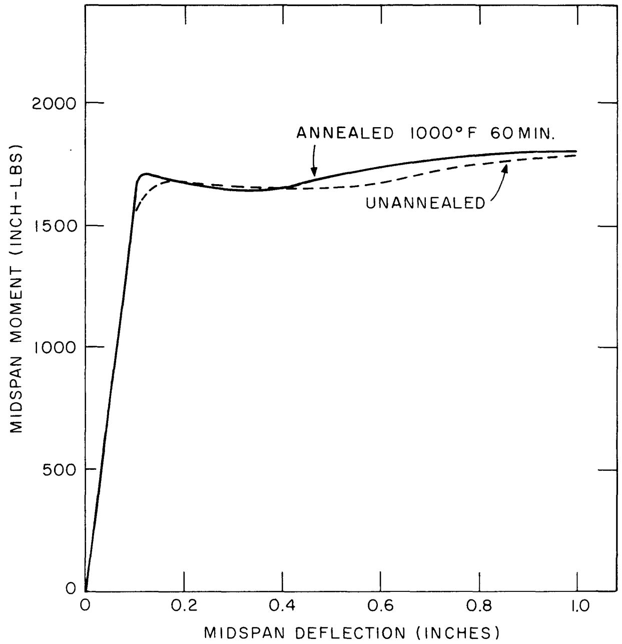

Fig. 9. 1/15 scale 14 WF 103 beam tests

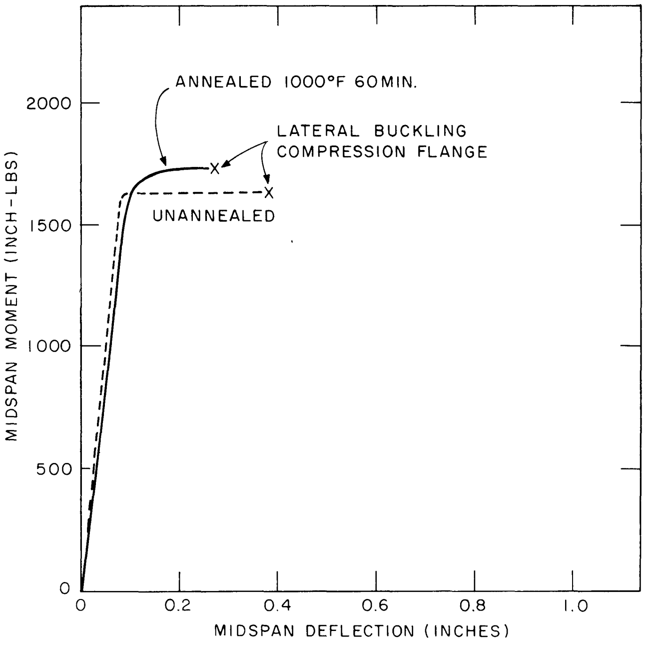

Fig. 10. 1/15 scale 21 WF 62 beam tests

setup shown in Fig. 8, lateral bracing was provided just inside the third points of the 18-in. long beams.

Two beams were cut from a length of 14WF103 and two from a length of 21WF62. One of each was annealed at 1000°F for 60 min. while the other received no heat treatment. The results shown in Figs. 9 and 10 confirm that the stresses induced by milling do not significantly influence the bending strength of beam members.

JOINT TESTS

The joint tests have three purposes. The first is to determine the strength of the weld in a joint connection, the second is to determine the effect and necessity of annealing welded members and the third is to compare actual ultimate moments to predicted ones. Eight tests are included:

1. 14WF103-14WF103 knee joint, no annealing
2. 14WF103-14WF103 knee joint, annealing after welding 1000°F 60 min. with oven cool
3. 14WF103-21WF62 knee joint, no annealing
4. 14WF103-21WF62 knee joint, annealing before welding 1000°F 60 min. with oven cool
5. 14WF103-21WF62 knee joint, annealing after welding 1000°F 60 min. with oven cool
6. 21WF62 cantilever joint, no annealing
7. 21WF62 cantilever joint, annealing before welding 1000°F 60 min. with oven cool
8. 21WF62 cantilever joint, annealing after welding 1000°F 60 min. with oven cool

The joints were fabricated using the TIG welding process discussed earlier. To determine stress vs. strain characteristics of the lengths of material from which the joints came, four tension samples were taken from the flange and web of the 14WF103 section and six from the web of the 21WF62 section. Two of the 14WF103 and three of the 21WF62 specimens were annealed at 1000°F for 60 min. and oven cooled. The results of these tests are indicated in Table 1 as Test Numbers 6 through 15. Taking the average of the annealed specimens as a control value and the average of the measured section geometries in Tables 2 and 3 one obtains for the one-eighth scale 14WF103 values of yield stress equal to 37.6 ksi and plastic moment capacity equal to 1,940 lb-in., while for the 21WF62 section the same values are 44.6 ksi and 1,920 lb-in. (Note that these plastic moment values do not agree closely with the beam test values, but one must recognize that the beam test specimens came from separate lengths of material.)

Figures 11, 12 and 13 show the details of the three joint configurations. Figures 14 and 15 illustrate the test setup.

Figure 16 gives results for the 14WF103-14WF103 joints. The bending moment at the intersection of the beam centerlines is plotted. Theoretically predicted moments are extrapolated from the plastic moment at the face of the joint to a larger value at the centerline intersection. No modification for the presence of axial load is made since P/P_y maximum is only about 0.13.

Flange buckling became quite pronounced before web buckling occurred and the sections continued to carry

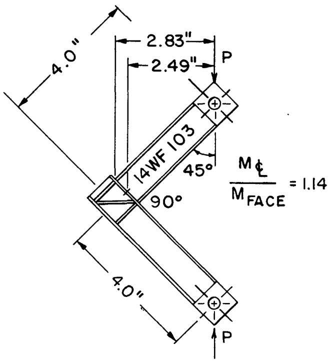

Fig. 11. 14 WF 103—14 WF 103 knee joint

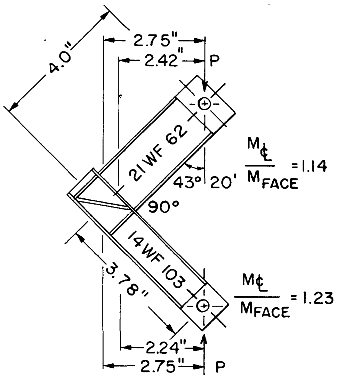

Fig. 12. 14 WF 103—21 WF 62 knee joint

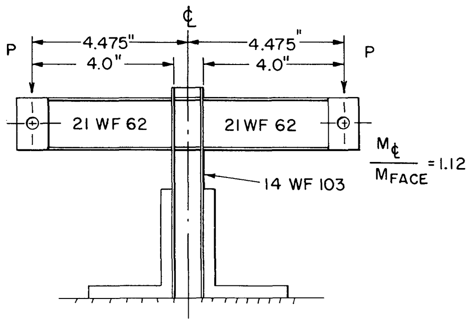

Fig. 13. Cantilever joint

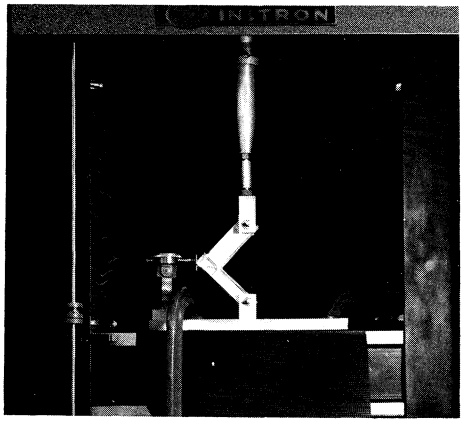

Fig. 14. 14 WF 103—21 WF 62 knee joint test setup

additional load after flange buckling. The welds were strong and evidenced no signs of distress.

Figure 17 gives results for the 14WF103-21WF62 joints. The 21WF62 beam failed in each test. Unloading began as soon as web buckling occurred. Again the welds showed no sign of failure.

Results for the cantilever tests are given in Figs. 18, 19 and 20. The theoretical moment vs. deflection curve includes the effect of shear distortions. Unloading of all the sections takes place shortly after flange and web buckling. Again no weld showed any sign of distress.

Two distinct conclusions can be drawn from the joint test results. First, the behavior of the joints that were annealed after welding followed very closely that which was predicted. Second, the welding process employed definitely influenced the strength characteristics in the welded zone. Even though the heat affected zone would extend no more than about one-half-in. along any member, that distance is significant for the scale of the models. Considering the present uncertainty in determining or predicting beforehand the moment capacity in the heat affected zone, it is recommended at this time that model frames be annealed after welding.

CONCLUSION

1. The mechanical properties and weldability of SAE C1020 hot rolled steel permit its use as an ultimate strength model material for ASTM A36 steel structures.

2. Milling wide-flange sections from hot rolled bar stock is a reliable and accurate process for fabricating small scale sections with element thicknesses down to 0.025-in.

3. The machining process used to fabricate the wide-flange sections destroys the sharp break at the yield

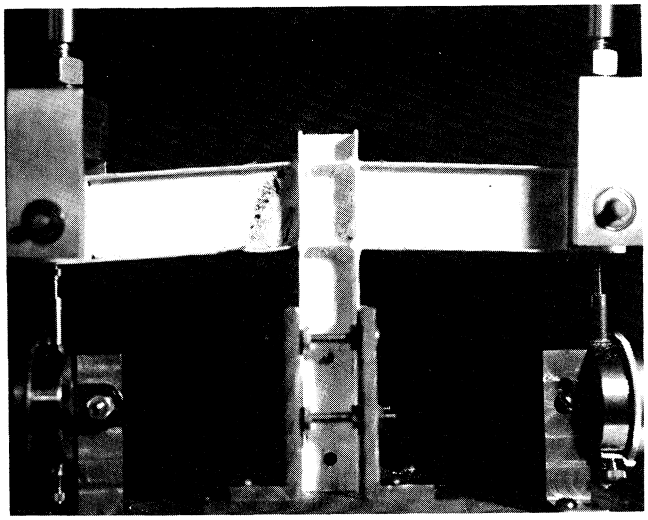

Fig. 15. Cantilever joint test setup

plateau but does not significantly influence the yield or ultimate strength.

4. Tension and joint tests show that the Heliarc welding process (TIG) with Industrial Stainless 410 filler wires provides joints with more than adequate strength and ductility.

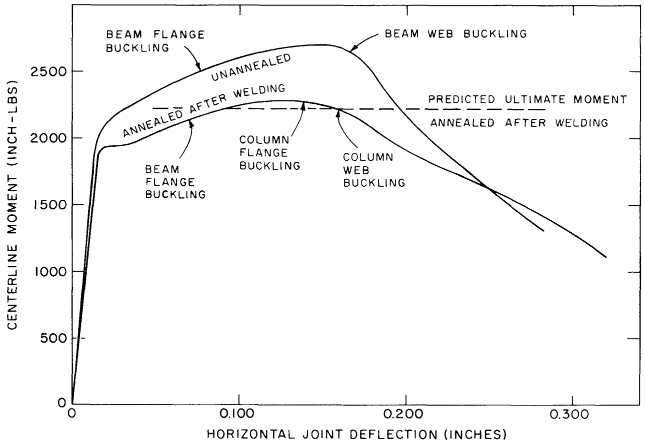

Fig. 16. 14 WF 103—14 WF 103 joint test results

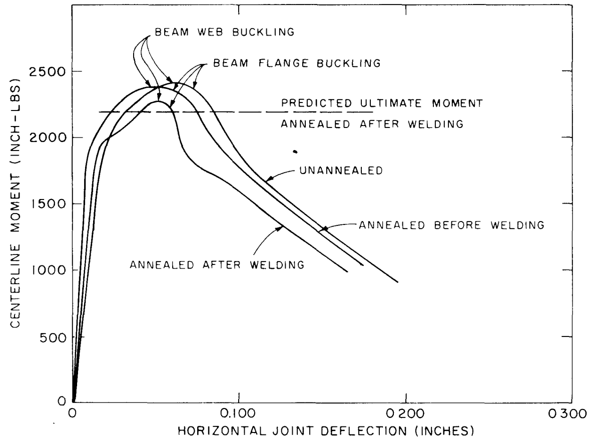

Fig. 17. 14 WF 103—21 WF 62 joint test results

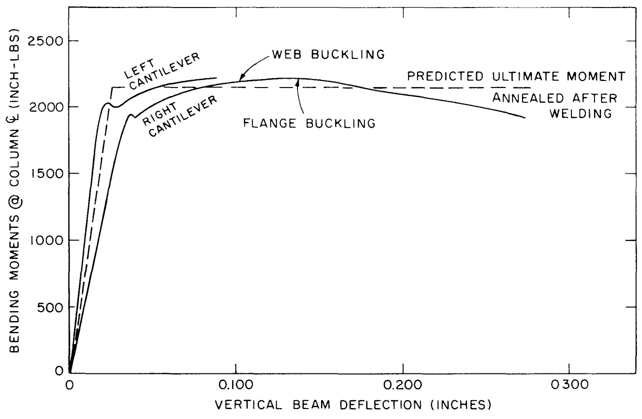

Fig. 18. Annealed after welding cantilever joint results

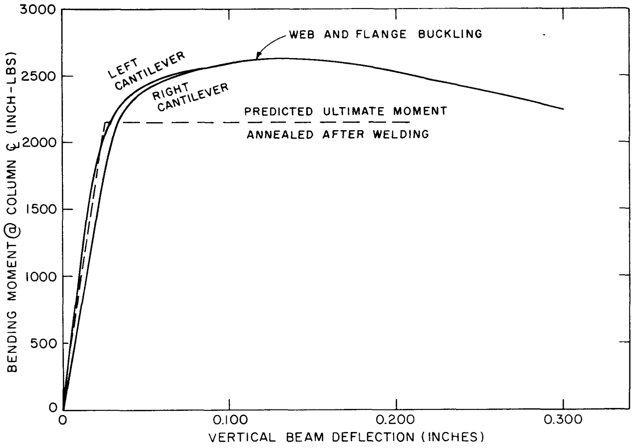

Fig. 19. Annealed before welding cantilever joint results

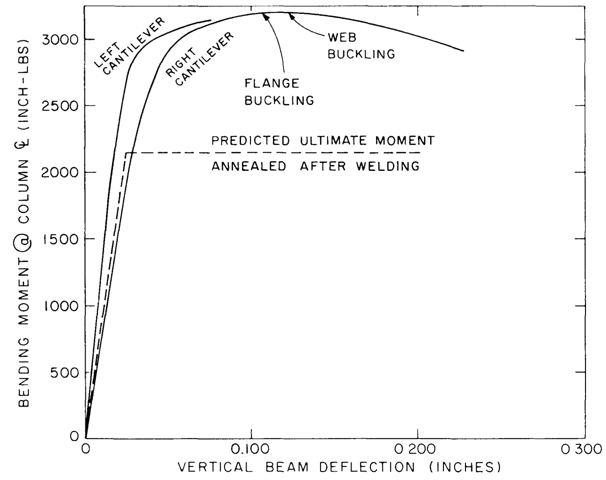

Fig. 20. Unannealed cantilever joint results

5. Due to an unpredictable strength increase in the heat affected zones of non-annealed welded joints it is desirable to anneal whole frameworks before testing.

ACKNOWLEDGMENTS

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