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COMPRESSION TESTS OF STRUCTURAL STEEL AT ELEVATED TEMPERATURES

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ABSTRACT

The strength in compression and the stress-strain relations are given for structural-steel shapes and for round bars at temperatures up to 945° C (1,733° F), the slenderness ratio (l/r) for the bars being in the general range 20 to 150. One group of tests with cast-iron specimens is included for comparative purposes. Two general methods of testing are included, one in which the specimen is heated to a given temperature and then loaded to failure, and the other in which the load is maintained constant and the temperature increased until failure occurs. The results are given in tables and graphs.

For structural steel tested at temperatures of 250° C (482° F) or higher, and for cast iron at all temperatures, no well-defined yield point or yield region was developed. A strength higher than that obtained at room temperature was developed at temperatures near 250° C (482° F) in all tests except in those with the light-angle, pressed-steel, and cast-iron sections, and with round bars of smaller diameter than three-fourths inch (45 l/r). From the standpoint of variation of strength with slenderness ratio, the results are consistent with those derived from column theory. They are also in agreement with results from two series of fire tests of building columns.

CONTENTS

I. INTRODUCTION

The test conditions for the compression tests reported herein include some of those to which full-size building columns are subjected during fires. The rise in temperature of the structural-metal parts varies with the fire exposure and the protection applied on them, while the load remains constant or increases depending upon the restraint imposed on the particular member. Although the fire-protective material in the construction may take part of the load, the steel core usually is designed to carry all the load, and the protection is relied upon solely to retard temperature rise in the steel during a possible fire exposure.

Long-time creep tests have no direct application to ultimate performance of members subjected to these changing exposure conditions of relatively short duration. Representative temperature, expansion, load, and deformation measurements can be made to yield under laboratory-controlled conditions more definite data than those obtainable from full-size tests of columns conducted in accordance with the usual procedure, where the object is to obtain information on particular constructions, inclusive of the protective coverings.

A series of tests on rolled structural shapes is included to give information on local compressive buckling. Tests of round bars having slenderness ratios (l/r) in the general range 20 to 150 are included to cover the performance for a wide range of temperatures and loads.

The results of these short-time tests have been compared with data available from fire tests of columns [1] [2] for those results that were relatively free from effects of load-assistance from the protective coverings. The total number of tests reported herein is 281. Of this number, 63 were tension tests and 50 compression tests at room temperature 159 were compression tests at elevated temperatures, and 9 were expansion tests.

"Stress" as used in this paper indicates load per unit of area, P/A, where P denotes the total load and A the original cross-sectional area of the test specimen. "Strain" indicates the deformation per unit of original gage length.

II. MATERIALS AND TEST SPECIMENS

1. SHAPE SPECIMENS

The structural elements and the compression properties at room temperature for the shape specimens are given in table 1 and tensile properties and chemical analyses in table 2. Groups 1 to 9 refer to shape tests. The numbers designating the specimens used in the cold tests are the first in the individual groups, those following being for specimens used in the tests at elevated temperatures. All tension tests were made at room temperature with 2 in. by ½ in. round specimens for the round stock and with representative flat coupons from the structural-steel shapes.

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[1] S. H. Ingberg, H. K. Griffin, W. C. Robinson, and R. E. Wilson, *Fire tests of building columns*, BS Techn. Pap. T184 (1921).

[2] N. D. Mitchell, *Fire tests of columns protected with gypsum*, BS J. Research 10, 737(1933); RP563.

TABLE 1.—*Elements of structural shapes and compression properties at room temperature*

STRUCTURAL STEEL SHAPES

Reference			Elements of structural shape					Compression properties at room temperature					
Group	Shape	Specimen no.	Area	Thickness [1]	Least radius of gyration, *r*	Length, *l*	Slenderness ratio, *l*/*r*	Proportional limit	Modulus of elasticity	Yield point [2]	Strain at yield point	Ultimate strength	Strain at ultimate
			*In.*²	*In.*	*In.*	*In.*		*Lb/in.*²	*Million lb/in.*²	*Lb/in.*²		*Lb/in.*²	
1	3 in. I-beam, 5½ lb/ft (Mn 1.15%)	1	1.63	0.17	0.53	10.5	19.8	40,000	31.0	43,500	0.0019	67,300	0.0601
2	3 in. I-beam, 5½ lb/ft (Mn 0.81%)	25	1.67	.17	.50	10.5	19.8	--------	30.0	42,000	.0019	62,000	.0530
3	3 in. I-beam, 5½ lb/ft (Mn 0.81%) annealed	26	1.67	.17	.53	10.5	19.8	--------	30.0	33,000	.0016	53,000	.0532
4	4 in. channel, 7¼ lb/ft	40	2.13	.32	.46	2.4	5.2	35,000	--------	37,500	.0030	67,000	.1167
		41	--------	--------	--------	10.5	22.8	35,000	28.0	38,700	.0019	56,800	.0532
		42	--------	--------	--------	--------	22.8	35,000	30.0	37,000	.0017	52,200	.0497
5	4 in. channel, 5¼ lb/ft	51	1.55	.18	.45	10.5	23.4	--------	30.0	39,600	.0018	42,640	.0427
		59	--------	--------	.45	1.8	4.1	--------	--------	28,500	.0043	60,000	.1094
6	2½ by 2½ by ½ in. angle, 7.7 lb/ft	61	2.25	.50	.47	10.5	22.3	33,000	31.0	37,000	.0018	52,800	--------
7	3 by 3 by ¼ in. angle, 4.9 lb/ft	71	1.44	.25	.59	10.5	17.8	--------	31.0	37,500	.0017	39,200	.0083
		72	--------	--------	--------	--------	17.8	36,000	30.0	39,000	.0018	39,000	.0016
		73	--------	--------	--------	--------	17.8	34,000	--------	38,900	.0018	40,600	.0020
8	Pressed steel joist, 3.13 lb/ft	90	.92	.06	.75	10.5	14.0	39,000	28.0	40,200	.0022	40,500	.0024
		91	--------	--------	--------	--------	--------	34,000	30.0	37,800	.0019	38,500	.0026

CAST IRON, OUTSIDE DIAMETER 1½ IN.; INSIDE DIAMETER ½ IN., WITH FLANGES

Group	Shape	Specimen no.	Area	Thickness [1]	Least radius of gyration, *r*	Length, *l*	Slenderness ratio, *l*/*r*	Proportional limit	Modulus of elasticity	Yield point [2]	Strain at yield point	Ultimate strength	Strain at ultimate
9	Hollow round, 5.5 lb/ft	100	1.61	.50	.395	9.25	23.4	40,000	16.60	50,000	.0041	86,710	.0350
		100	--------	--------	--------	--------	--------	--------	--------	--------	--------	[3] 87,500	.0428

[1] Nominal web thickness for groups 1 to 5, leg thickness for groups 6 and 7, sheet thickness for group 8, wall thickness for group 9.

[2] Yield point selected at 0.0005 strain from initial modulus line, for structural steel; at 0.001 strain from initial modulus line, for cast iron.

[3] Reloaded at later date.

TABLE 2.—*Chemical analysis and tensile properties at room temperature for shapes and round specimens*

STRUCTURAL STEEL SHAPES

Reference		Chemical analysis						Tensile properties at room temperature [1]						
Group number	Shape and stock	C	Mn	P	S	Si	Other elements	Proportional limit		Modulus of elasticity	Yield point [2]	Tensile strength	Elongation in 2 in.	Reduction of area
		%	%	%	%	%	%		*Lb/in.²*	*Million Lb/in.²*	*Lb/in.²*	*Lb/in.²*	*Percent*	*Percent*
1	3 in. I-beam, 5½ lb/ft	0.21	1.15	0.016	0.034	0.025	Cr 0.06 Cu .18	Max	38,500	29.5	45,200	70,200	42.0	71.8
								Min	28,000	27.0	41,900	65,200	32.0	57.8
								Avg of 6	35,000	28.3	43,700	68,700	36.6	63.4
2	do	.21	.81	.020	.052	.030		Max	38,500	29.5	44,200	68,700	48.5	52.5
								Min	30,000	29.0	38,500	63,900	44.5	47.7
								Avg of 3	33,200	29.2	42,000	66,900	46.3	50.3
3	3 in. I-beam, 5½ lb/ft, annealed.	.21	.81	.020	.052	.030		Max	29,500	34.5	35,900	61,000	43.5	47.8
								Min	17,500	26.5	32,080	58,800	34.0	44.3
								Avg of 3	22,300	29.8	34,200	60,200	38.3	45.9
4	4 in. channel, 7¼ lb/ft	.21	.58	.011	.044	.050		Max	35,500	31.0	41,500	62,400	36.0	67.0
								Min	27,500	29.0	38,500	60,100	29.0	53.2
								Avg of 5	32,200	29.8	39,700	61,700	35.2	62.2
5	4 in. channel, 5¼ lb/ft	.17	.56	.036	.055	.040		Max	45,500	30.5	50,350	64,400	29.0	58.5
								Min	29,000	28.5	46,200	62,300	26.5	46.8
								Avg of 4	37,300	29.6	48,700	63,800	28.3	53.9
6	2½×2½×½ in. angle, 7.7 lb/ft	.20	.34	.018	.063	.050		Max	36,700	32.5	42,100	62,600	39.0	63.0
								Min	23,500	30.0	34,800	57,800	27.0	61.3
								Avg of 7	32,900	31.0	38,100	59,800	33.8	62.1
7	3×3×¼ in. angle, 4.9 lb/ft	.21	.57	.014	.035	.020		Max	35,000	30.0	43,000	62,400	47.5	64.2
								Min	24,000	27.0	37,300	55,800	29.0	57.8
								Avg of 12	32,100	28.7	39,900	58,400	37.5	60.3
8	Pressed steel joist, 3.13 lb/ft	.09	.39	.010	.020	.002	Cu .085	Max	36,500	29.1	42,500	52,900	34.0	57.0
								Min	29,200	24.0	34,200	46,800	29.0	49.6
								Avg of 5	33,900	27.4	40,100	51,500	31.0	54.1

CAST IRON, OUTSIDE DIAMETER 1½ IN.; INSIDE DIAMETER ½ IN., WITH FLANGES

9	Hollow round, 5.5 lb/ft	[3] 3.42 [4] 3.10	.37	.715	.115	1.580		Transverse test, 60,000 lb/in.[2], extreme fiber stress.						

STRUCTURAL STEEL, ROUND RODS

10 to 13	2 in. round, lot A	.20	.38	.013	.032	.010		Max	30,500	31.0	33,800	61,400	42.5	58.6
								Min	27,000	28.5	32.100	58,900	35.5	54.4
								Avg of 4	29,300	29.5	33,000	60,000	38.3	56.1
14 to 19	2 in. round, lot B	.18	.43	.008	.033	.010		Max	29,500	28.8	32,750	55,500	43.0	65.0
								Min	25,500	27.3	29,750	53,900	41.0	63.0
								Avg of 6	28,000	28.1	31,550	54,800	42.5	64.5
20	do.[5]	.18	.43	.008	.033	.010		1 test	28,000	31.0	62,650	63,550	25.0	63.3
21	1 in. round, lot C	.10	.83	.107	.106	.04		1 test			64,000	80,000	17.0	60.3
22 and 23	1 in. round, lot D	.20	.41	.014	.048	.10		Max	38,000	29.5	41,500	63,000	37.5	62.4
								Min	37,000	29.0	41,100	62,900	37.5	61.6
								Avg of 2	37,500	29.3	41,300	63,000	37.5	62.0
24	1½ in. round, lot E	.22	.36	.01	.041	.07		Max	32,700	30.6	33,000	57,300	41.0	63.8
								Min	27,400	28.7	30,900	57,200	39.0	62.9
								Avg of 3	30,200	29.8	32,200	57,250	39.7	63.3

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[1] For groups 1 to 8, tension specimens were rectangular flats from ½ to 1¾ in. wide at the reduced section and were cut from webs and flanges. Rounds from ¼ to ½ in. in diameter were cut from the junction of flange and web. The length of the reduced section was about 4 in. for the flats and 2½ inches for the rounds. For groups 10 to 20 and 22 to 24, standard .505 inch diameter specimens with threaded ends were used. For group 21 the ⅜-inch round compression specimen was retested in tension.

[2] Yield point determined by "drop of beam" method.

[3] Combined carbon.

[4] Graphitic carbon.

[5] Cut from specimen no. 159 after its regular test.

The diagrams in figure 1 give the compressive stress-strain records for the specimens indicated by the underlined numbers. Duplicates and lengths shorter than the normal 10.5 in. test lengths are excluded here. These diagrams illustrate the performance for short struts. It is noted that the cast-iron specimen no. 100 exhibits no yielding without increase in load except at ultimate, while the remaining structural-steel shapes of varying symmetry yield at stresses from 45,000 to 32,000 lb/in². Ultimate strengths higher than the yield point are indicated, however, for all specimens except the least symmetrical and relatively thin angle section no. 72. Generally, yielding of a member beyond a certain limit disturbs seriously the distribution of stresses in the structure of which the member is a part, so an arbitrary yield point, applicable for cold tests only, has been selected from the stress-strain diagrams, as indicated in table 1, footnotes 2 and 3. The proportional limit and modulus of elasticity were estimated from plottings of the

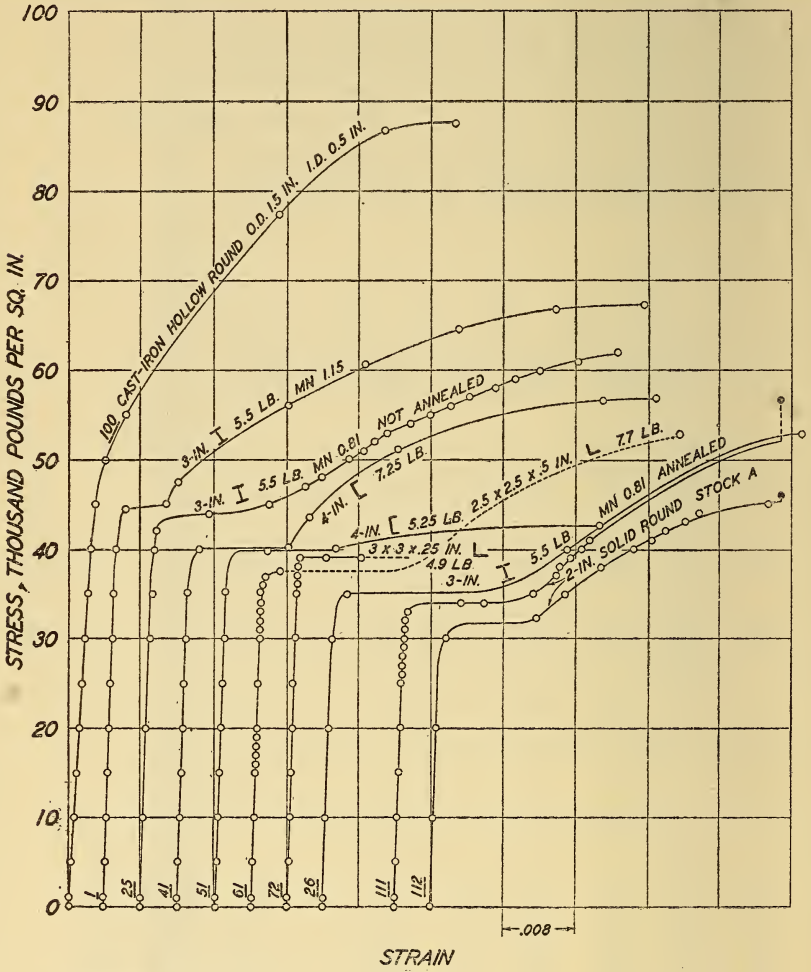

Figure 1.—*Stress-strain data from the shape tests at room temperature.*

stress-strain data to a large scale, giving due consideration to experimental errors involved. They are listed in table 1 insofar as they were obtained.

2. ROUND STEEL SPECIMENS

The round specimens were made from five lots of structural steel designated as A to E, the chemical analyses and tensile properties of which are given in table 2. The one tension test for each of groups 20 and 21 is for strain-hardened material, while the remaining tension tests identify the materials as grades of structural steel such as would be normally included by specifications for this class of material.

Table 3 gives the structural elements and compression properties at room temperature for the round specimens. The specimens, except as noted, were of 10.5 in. total length with slenderness ratios as indicated. Group 19 includes only half-length specimens and group 20 half-length strain-hardened specimens. The group values of slenderness ratio, l/r, approximate 22, 35, 45, 70, 95, and 145, where l equals the effective length of the specimen and r the least radius of gyration.

TABLE 3.—*Elements and compression properties of structural rounds at room temperature*

[Structural steel round rods, all flanged ends and reduced sections, except groups 10 and 14 and specimen no. 159 in group 19]

Reference			Elements of structural shape					Compression properties at room temperature					
Group number	Stock	Specimen number	Area	Diameter	Least radius of gyration, *r*	Effective length	Slenderness ratio, *l:r*	Proportional limit	Modulus of elasticity	Yield point [1]	Strain at yield point	Ultimate strength	Strain at ultimate
			Sq/in.	*In.*	*In.*	*In.*		*Lb/in.*^{2}	*Million lb/in.*^{2}	*Lb/in.*^{2}		*Lb/in.*^{2}	
10	2 in. round, lot A	111	2.763	1.88	0.470	10.50	22.4	28,000	30.0	34,000	0.0030	56,700	0.0702
		112							30.0	32,300	.0030	46,000	.0462
		113						29,000	30.0	35,000	.0030	43,000	.0203
11	do	118	.784	1.00	.250	8.61	34.4	28,000	28.0	28,000	.0010	42,000	.0375
		119						26,000	28.0	34,000	.0030	42,000	.0294
12	do	125	.440	.75	.187	8.50	45.5	26,000	28.0	30,500	.0014	35,000	.0097
		126						20,000	30.0	30,000	.0018	32,500	.0138
13	do	134	.196	.50	.125	8.53	68.3	29,500	31.0	30,000	.0017	32,500	.0034
		135						25,000	31.0	29,000	.0018	31,000	.0109
14	2 in. round, lot B	141	2.763	1.88	.470	10.50	22.4	17,000	29.0	27,000	.0037	47,000	.0584
15	do	144	.785	1.00	.250	8.91	35.6	26,000	30.0	27,000	.0015	34,700	.0292
		145						26,000	30.0	27,500	.0016	35,000	.0278
16	do	148	.442	.75	.187	8.84	47.2	26,000	30.0	27,500	.0015	28,100	.0122
17	do	152	.196	.50	.125	8.71	69.7	25,000	25.0	26,000	.0012	28,000	.0036
18	do	155	.110	.375	.094	9.26	99.0	26,000	25.0	29,000	.0016	No increase beyond yield point.	
		156						26,000	27.5	28,000	.0013		
		157	.099	.250	.062	9.29	149.1	22,000	27.5	28,000	.0011		
		158						24,000	26.5	26,000	.0016		
19	Shorts, lot B	159	2.88	1.915	1.479	5.50	11.5	15,000	25.0	28,500	.0020	69,500	.1213
		160	.196	.50	.125	4.17	33.4	20,000	29.0	28,000	.0011	37,450	.0400
		161	.110	.375	.094	4.12	43.9	25,000	31.0	29,500	.0011	30,400	.0050
		162	.049	.249	.062	4.04	64.9	25,500	31.0	29,000	.0011	29,500	.0027
		163	.049	.249	.062	4.06	65.2	25,000	29.5	28,000	.0012	28,500	.0025
20 [2]	do	164	.196	.50	.125	3.90	31.2	64,000	30.0	65,000	.0025	No increase beyond yield point.	
		165	.110	.375	.094	3.87	41.4	66,000	31.0	66,000	.0022		
		166	.049	.251	.063	3.87	61.8	66,500	31.0	66,500	.0021		

21	1 in. round, lot C	168	.109	.373	.093	8.90	95.4	61,000	31.5	61,400	.0020	do	
22	1 in. round, lot D	171	.110	.374	.093	8.92	95.5	48,900	30.2	48,900	.0016	do	
23	do	181	.049	.249	.0622	8.92	143.4	43,000	30.0	43,000	.0015	do	
		182	.049	.249	.0623	9.00	144.5	42,000	30.0	42,000	.0015		
24	1½ in. round lot E	195	.196	.499	.125	9.21	73.8		30.0			36,500	.0012
			Load dropped to 30,000 lb/in.^{2}, reloaded					33,500				34,400	.0018
		196	.191	.493	.123	8.80	71.5		28.5			34,500	.0012
			Load dropped to 30,100 lb/in.^{2}, reloaded					32,000				33,000	.0012
		197	.109	.373	.093	9.02	96.7		30.6			33,500	.0011
			Load dropped to 29,100 lb/in.^{2}, reloaded					34,000		34,000	.0012	34,260	.0014
		198	.049	.250	.0625	8.78	140.0		28.3			38,000	.0014
		199	.048	.247	.0618	8.91	144.2	33,000	29.6			33,500	.0011
			Load dropped to 30,800 lb/in.^{2}, reloaded					31,000	31.0			32,800	.0026

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[1] Yield point selected at 0.0005 strain from initial modulus line.

[2] Shorts cut from specimen number 159 after its regular test.

The larger specimens of about 1.9 inch diameter had no flanged ends, while all smaller sizes were reduced from 2-, 1½-, or 1-inch stock to the desired diameters over the effective length, with rounded fillets at the end flanges, which were slightly smaller in diameter than the original stock. The ends were faced flat and perpendicular to the axis of the turned specimens and drilled at the center of the ends for alinement in testing.

The compression properties at room temperature given in table 3 were obtained from stress-strain records as illustrated in figures 2 and 3. Development of a yield region at nearly constant load is shown followed by increase in load for specimens of slenderness ratio less than 45, while little or no load increase is shown for specimens of greater slenderness.

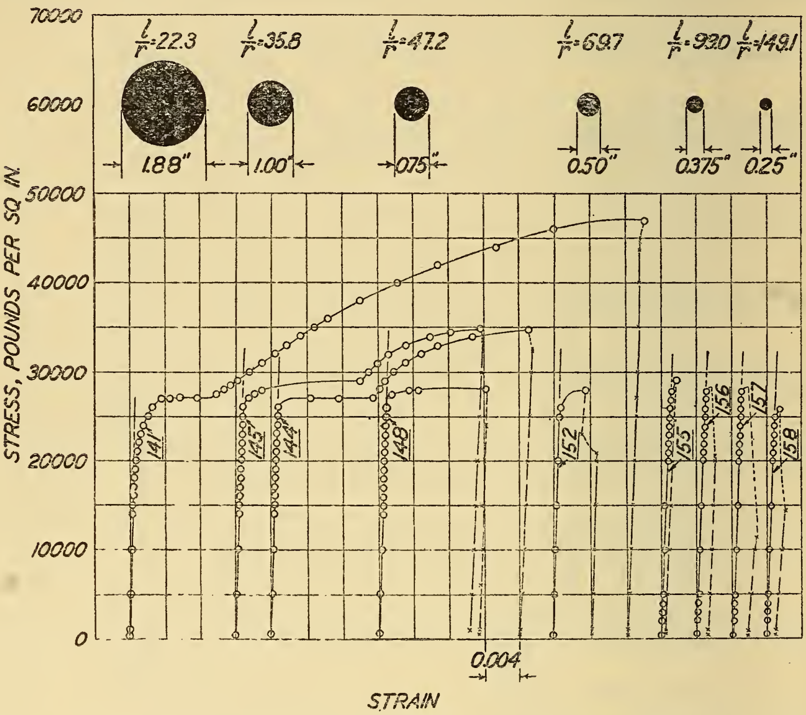

FIGURE 2.—*Stress-strain data from compression tests at room temperature of lot B specimens 141, 144, 145, 148, 152, and 155 to 158, inclusive.*

Figure 3 gives results of compression tests at room temperature using half-length specimens from lot B. The first 5 tests, nos. 159 to 163, inclusive, check the performance for a given slenderness ratio with the 10.5-inch length specimens covered in figure 2. Specimens nos. 164, 165, and 166 were also from lot B, strain-hardened by compression in test no. 159, which specimen after this test was quartered to make 3 short compression specimens and 1 standard tension specimen. The stress-strain diagrams show the extent to which the strength and yield characteristics are modified due to the strain-hardened condition of the material. The properties of lots C and D might be due to some strain-hardened conditions occurring in ordinary structural steel. Lot C was discarded as too hard for inclusion in these tests while D was retained as representative of that allowable by the upper strength limits of structural-steel specifications (see tensile properties, table 2, lots C and D). Lot E was included to supply a number of slender specimens for high-temperature tests to supplement the B series.

III. EQUIPMENT AND METHODS OF TESTING

All compression tests, except several at room temperature, were made in the machine shown in figure 4 or in the Emery testing machine shown in figure 6 equipped at the compression end for testing at elevated temperatures. Tests on shapes and the larger bars were made in the former machine, and all tests with slender specimens of lots B, C, D, and E were made in the Emery machine. All compression tests were planned for flat- or fixed-end test conditions although these conditions may not have been realized in all cases, as later indicated.

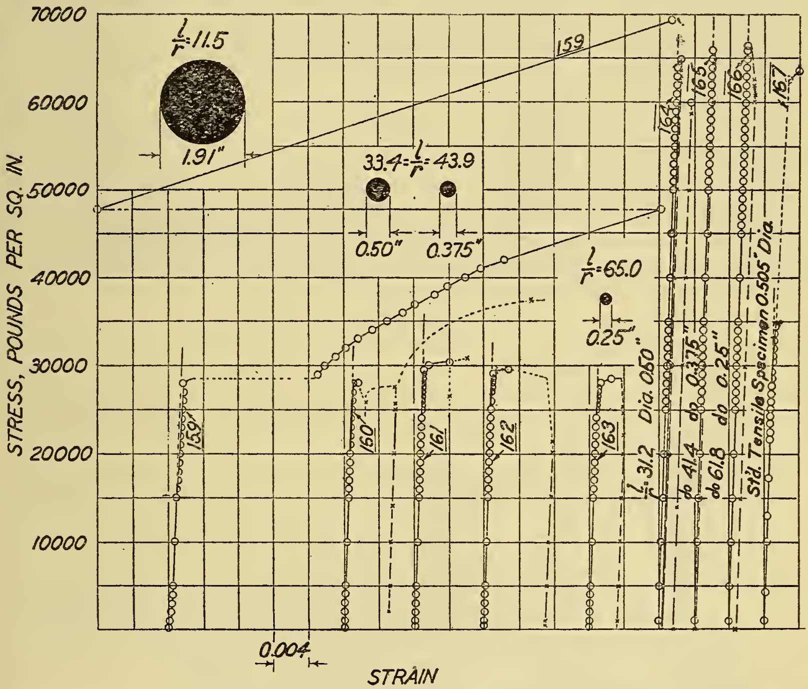

FIGURE 3.—*Stress-strain data from compression tests at room temperature of lot B specimens 159 to 167, inclusive.*

In figure 4 the main furnace, A, is shown rolled back with the specimen, B, in position for test. The load is applied from the left by the hydraulic press, C, which carries an adjustable spherical-seated block, D. Rigidly attached to the press, C, is a 1¼ in. diameter steel rod which projects through the block, D. The specimen can be positioned by means of three radial screws engaging this rod. These parts are placed in a 260,000-pound capacity restraining frame, below which a shelf supports a mounting for two microscopes used for deformation measurements. All the movable parts, including the main furnace, are counterweighted to obviate bending stresses. Hydraulic pressure is obtained with the pump, E, and is measured by a fluid pressure scale, F. This loading equipment was calibrated before and after the series of tests by means of elastic springs and bars, which indicated an accuracy of about ±0.2 percent for full-capacity loads and ±5 percent for the lowest load producing failure of specimens tested in this equipment.

Uniform heating of the test specimen is obtainable by the use of three pairs of end-compensating heaters placed symmetrically with respect to the middle of the specimen. Two of the heaters at one end are shown, one at G projecting 2 inches over the end of the specimen, and one at H wound over the cast-iron bearings outside of the heat-insulating blocks, I. A third pair of separately controlled heaters is wound over the outer portions of the main furnace tube, A.

Eight iron-constantan thermocouples, insulated with flexible asbestos tubing and with hot ends peened into small drilled holes in the specimens, were used for measuring temperatures of the shapes and the larger round specimens. They were systematically distributed along the length of the specimen. For the smaller round specimens, the hot ends of the thermocouples were wrapped around the bar and the junctions bound in position with iron wire. Sufficient depth of immersion in the furnace was provided for these wires and the cold-junctions were iced and connected with a potentiometer. A temperature uniform within ±3° C or better was obtainable over the 6-inch gage length of the specimen. The accuracy of temperature measurements was possibly limited to ±5° C, due to the use of lot calibrations of the base-metal thermocouples and in some of the tests to the use of a portable potentiometer.

At the ends of the 6-inch gage length small metal pegs were screwed into the angle and the channel shapes for attaching wires at the centroids of the end sections. At these two points, fine annealed alloy wire were hung through tubes in the furnace wall. The lower ends of the wires were weighted and were submerged in cups of oil to dampen vibrations. For some round specimens each of the wires was supported by a wire yoke suspended from a pair of pegs screwed into the specimen at opposite ends of a horizontal diameter at each end of the gage length. For specimens of smaller diameter the loops of wire were located in shallow vertical V grooves that marked the gage length. The freely suspended but taut wires were brought into focus for observations in the microscopes K shown below the furnace.

A view of the part of the apparatus used for obtaining deformation measurements is shown in figure 5. It consists of 2 microscopes mounted in micrometer slides that are secured to 1 transverse pivoted slide, J which may be rotated by screws, R, moved laterally with the screw, L, and in the line of sight with the screw, S. This permits refocusing the microscopes on the gage wires without moving the microscopes in their tubes. During readings only one microscope was moved in its micrometer slide, the other being set on the wire by bodily movement of the supporting slide, J. The micrometer head, M, is graduated to 0.005 mm and readings were estimated to the nearest 0.001 mm.

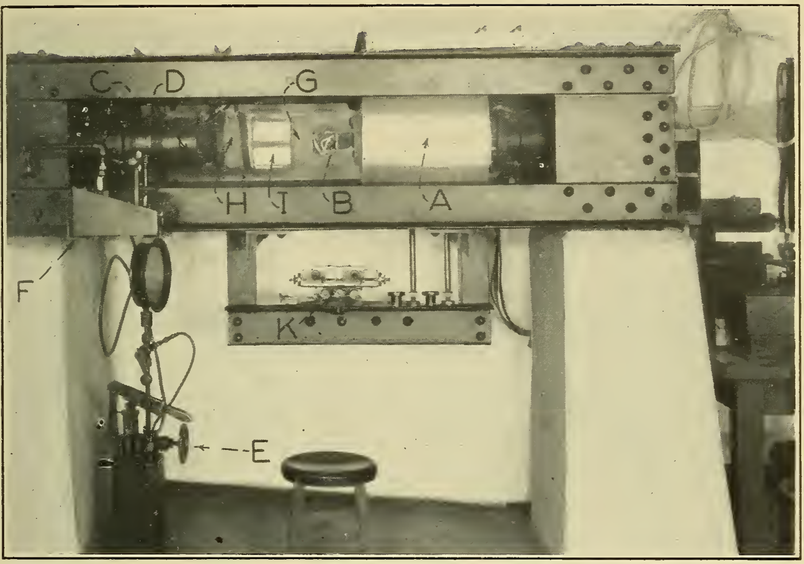

Figure 4.—*Equipment used for tests of shapes and of round bars of lots A and B.*

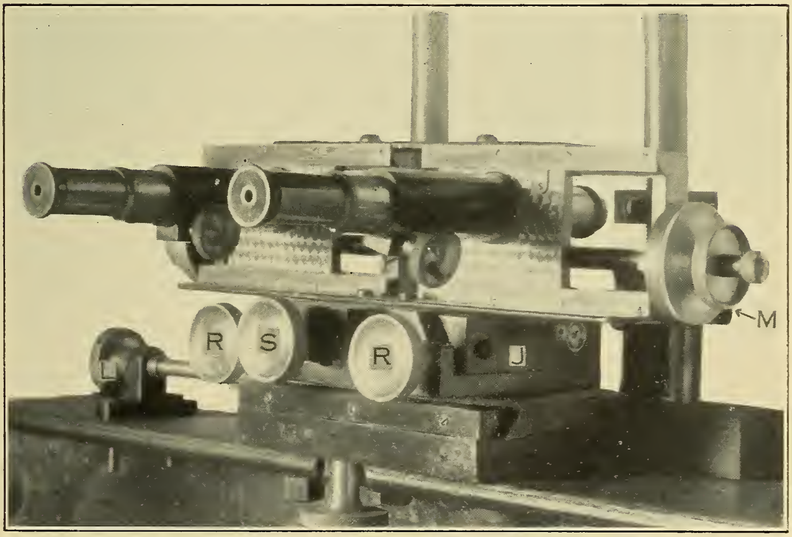

Figure 5.—*Apparatus for obtaining deformation measurements.*

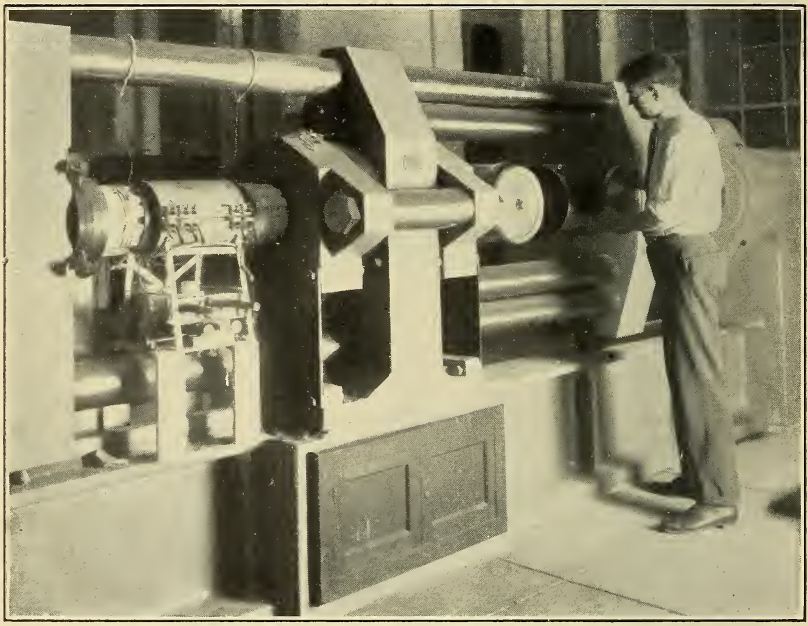

Figure 6.—*Equipment used for tests of slender bars of lot B and all tests of lots C, D, and E.*

The Emery testing machine, figure 6, was used for making compression tests of specimens of the higher slenderness ratios and smaller areas since greater accuracy in loading and facility of load control were desirable. In this machine use was made of the deformation equipment and some other parts employed in the original equipment. The bearing blocks were counterweighted, as before, to avoid bending stresses in the test specimen, which was supported on small pins projecting from the centers of the faces of the cast-iron bearing blocks. By use of a split furnace in this equipment the alignment of the test specimen was readily checked and the attachment of thermocouple and gage wires was greatly facilitated. The gage wires were annealed by electric heating in places after attachment in this set-up, and gave almost perfect line targets for deformation measurements. The accuracy of loading with the Emery machine was at least equal to that obtained for the larger specimens with the loading equipment previously described.

Generally, two separate testing procedures were adopted which are referred to as "constant-load" tests and "constant-temperature" tests, although these were combined in a few tests on shapes where some information on the time effect was desired.

In the constant-load test the specimen was set up as previously described and the load was applied before heating was commenced. As heat was applied and the temperature rose, the specimen expanded until the rate of expansion just equaled the rate of compressive deformation of the specimen for the load and temperature obtaining, which occurrence was termed "maximum expansion". Finally a temperature was reached beyond which full load could no longer be maintained, and further compression caused severe buckling of the specimen under decreasing load. Deformation and temperature measurements were made at intervals approximating 5 minutes and more often at critical stages of the test. Thirty tests, which included only four round specimens, were made by the constant-load method.

Most of the remaining tests were made by loading the specimen while the temperature was maintained constant. Measurements of deformation and temperature were made simultaneously for each increment of load.

IV. TEST RESULTS AT ELEVATED TEMPERATURES

Stress-strain records for all tests at elevated temperatures were obtained, but are only given in part here for the several materials tested,[3] figures 7 to 15. The specimen numbers are underlined in the diagrams to distinguish them from the indicated temperature of the test.

The performance of the shapes illustrates local bending and detail failures of columns, while that of the round bars may indicate, within limitations to be noted, primary column action for the temperature, shape, and end conditions imposed.

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[3] Further data from the tests with shapes are given in "*Compressive strength and deformation of structural steel and cast iron shapes at temperatures up to 950° C (1,742° F)*", by S. H. Ingberg and P. D. Sale, Proc. ASTM, *26*, part II, 33(1926).

1. RESULTS WITH STEEL SHAPES AND CAST IRON

(a) CONSTANT-TEMPERATURE TESTS

General results of these tests are given in table 4 and figure 9, and typical stress-strain diagrams in figures 7 and 8.

TABLE 4.—*Compression properties of structural shapes at elevated temperatures from constant-temperature tests*

[All specimens are 10.5 in. long except where noted]

GROUP 1.—3 IN. I-BEAM, MANGANESE CONTENT 1.15 PERCENT

Specimen number	Elements of structural shape			Proportional limit		Modulus of elasticity		Ultimate strength		
	Thickness	Least radius of gyration (*r*)	Slenderness ratio *l*/*r*	Temperature	Stress	Temperature	Million lb/in.^{2}	Temperature	Stress	Strain
	In.	*In.*		°*C*	*Lb/in.*^{2}	°*C*		°*C*	*Lb/in.*^{2}	
2	0.17	0.53	19.8	141	35,000	144	23.1	149	72,500	0.0486
3				--------	--------	--------	--------	248	77,500	.0488
4				--------	--------	--------	--------	306	74,000	.0540
5				348	20,000	347	22.2	360	68,500	.0513
6				463	15,000	462	17.4	468	54,500	.0525
7				514	15,000	512	17.4	521	44,500	.0600
8				553	10,000	553	24.2	560	33,650	.0399
9				601	7,000	600	11.9	608	24,400	.0990
10				--------	--------	--------	--------	705	11,000	.0538
11				--------	--------	--------	--------	797	7,500	.0598
12				--------	--------	--------	--------	916	4,800	.0670

GROUP 3.—3 in. I-BEAM, ANNEALED, MANGANESE CONTENT 0.81 PERCENT

27	0.17	0.53	19.0	183	25,000	182	24.2	190	71,500	0.0621
28				--------	--------	--------	--------	343	58,500	.0621
29				--------	--------	--------	--------	403	56,500	.0625
30				--------	--------	--------	--------	503	39,000	.0590
31				--------	--------	--------	--------	592	23,250	.0497
32				591	8,000	589	8.7	593	[2]14,000	[3].0692
32a [1]				--------	--------	--------	--------	594	23,000	.1142
33				603	6,000	604	10.7	595	[2]12,000	.0751
34				--------	--------	--------	--------	702	[2]9,000	.1222
35				709	3,000	709	5.3	705	[2]7,000	.1342
36				691	3,500	691	4.0	702	[2]5,000	.0961
37				--------	--------	--------	--------	732	9,000	.0484
38				--------	--------	--------	--------	828	7,800	.0577
39				--------	--------	--------	--------	910	6,900	--------

GROUP 4.—4 IN. 7¼ LB CHANNEL, WITH END ANGLES

43	0.32	0.46	22.8	231	20,000	231	26.3	225	63,050	0.0328
43a [1]				--------	--------	--------	--------	255	68,000	.0279
44				--------	--------	311	22.0	304	62,000	.0499
45				--------	--------	--------	--------	380	53,000	.0522
46				501	10,000	501	21.0	497	32,150	.0567
47				--------	--------	599	11.7	601	17,650	.0711
48			5.34	--------	--------	--------	--------	603	19,750	.1667
49			22.8	721	2,000	721	4.5	722	7,700	.0467
50			22.8	--------	--------	--------	--------	848	7,150	.0589

GROUP 5.—4 IN. 5¼ LB CHANNEL, WITH END ANGLES

54	0.18	0.45	23.4	99	30,000	100	31.5	99	47,000	0.0384
55				188	30,000	191	28.0	187	53,400	.0420
56				--------	--------	--------	--------	288	45,300	.0463
57				--------	--------	--------	--------	402	38,050	.0395
58				505	10,000	505	17.0	510	26,250	.0413
59a			11.83	585	4,000	584	12.7	588	17,300	.0300
59b			5.62	--------	--------	--------	--------	613	17,500	.1011
60			23.4	--------	--------	--------	--------	699	7,600	--------

See end of table for footnotes.

TABLE 4.—*Compression properties of structural shapes at elevated temperatures from constant-temperature tests*—Continued

GROUP 6.—2½ BY 2½ BY ½ IN. ANGLE

Specimen number	Elements of structural shape			Proportional limit		Modulus of elasticity		Ultimate strength		
	Thickness	Least radius of gyration (*r*)	Slenderness ratio *l*/*r*	Temperature	Stress	Temperature	Million lb/in.²	Temperature	Stress	Strain
	In.	*In.*		°*C*	*Lb/in.²*	°*C*		°*C*	*Lb/in.²*	
63	0.50	0.47	22.3	-------	-------	223	26.5	198	68,000	0.0381
63a [1]				-------	-------	-------	-------	275	59,500	-------
63b [1]				-------	-------	-------	-------	327	45,500	-------
64				-------	-------	-------	-------	406	37,500	.05
65				-------	-------	-------	-------	453	33,600	.0402
66				-------	-------	-------	-------	494	29,000	.0456
67				-------	-------	-------	-------	556	19,670	.0762
68				-------	-------	-------	-------	593	15,500	.0540
69			11.2	-------	-------	-------	-------	589	20,000	.0754
70			22.3	-------	-------	-------	-------	689	8,500	.0450

GROUP 7.—3 BY 3 BY ¼ IN. ANGLE

Specimen number	Thickness	Least radius of gyration (*r*)	Slenderness ratio *l*/*r*	Temperature	Stress	Temperature	Million lb/in.²	Temperature	Stress	Strain
80	0.25	0.59	17.8	104	35,000	105	29.2	105	37,400	0.0132
81				-------	-------	-------	-------	149	37,000	.0113
82				-------	-------	250	21.5	248	32,400	.0155
83				-------	-------	308	20.2	310	29,000	.0188
84				-------	-------	-------	-------	362	27,500	.0119
85				399	10,000	399	18.0	407	27,000	.0116
86				-------	-------	-------	-------	499	20,000	.0328
87				-------	-------	-------	-------	519	19,750	.0118
88				-------	-------	-------	-------	605	11,200	.0155
89				-------	-------	-------	-------	738	5,000	.0129

GROUP 8.—3 IN. PRESSED-STEEL JOIST

Specimen number	Thickness	Least radius of gyration (*r*)	Slenderness ratio *l*/*r*	Temperature	Stress	Temperature	Million lb/in.²	Temperature	Stress	Strain
94	0.069	0.75	14.0	259	23,000	258	19.4	263	37,000	0.0088
95				399	20,000	399	16.0	410	31,500	.0072
96				546	8,000	545	14.9	549	16,100	.0099
97				654	2,000	655	7.2	648	7,000	.0104
98				787	750	786	2.8	793	4,000	-------

GROUP 9.—CAST-IRON HOLLOW ROUND

Specimen number	Thickness	Least radius of gyration (*r*)	Slenderness ratio *l*/*r*	Temperature	Stress	Temperature	Million lb/in.²	Temperature	Stress	Strain
103	0.50	0.395	[4] 23.4	-------	-------	-------	-------	250	80,000	0.0320
104				-------	-------	-------	-------	312	66,000	.0225
105				-------	-------	-------	-------	411	72,000	.0300
106				516	15,000	516	14.5	515	49,650	.0642
107				-------	-------	-------	-------	636	22,900	.0730
108				-------	-------	-------	-------	757	7,850	.0995

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[1] Retest after cooling of specimen of corresponding number.
[2] Constant load and temperature maintained during these tests to obtain effect of time on yield.
[3] Maximum load and deformation not obtained.
[4] Group 9, effective length of specimen is 9.25 in.

(1) *Structural-Steel Shapes.*—Figure 7 gives results for 3-inch I-sections having manganese content of 0.81 percent, the stock having been annealed before test. In this condition the cold tensile properties, table 2, are comparable with those for a medium grade of structural steel, while in the original unannealed condition this stock was somewhat hard with properties comparable with those recorded for the higher (1.15 percent) manganese content. The symmetrical I-sections exhibited a decided yield region for test temperatures below about 250° C. The end points, indicated by solid points, are plotted

at the ultimate load obtained and the dotted connecting line indicates that the deformation is beyond the scale of the chart, but the values are given in the tables for each specimen.

Although it is generally recognized that short-time tests more closely simulate the conditions met in fire exposure of building members, some time data were obtained as indicated in figure 7, tests 31 to 37, which were run for a portion of the test at the constant loads and temperatures indicated. These come within the range of conditions that cause failure of building columns in fires.

(2) *Cast-Iron Specimens.*—In figure 8 the results of seven tests of cast-iron specimens are given for temperatures up to 757° C. These diagrams indicate the usual lower modulus of elasticity and greater

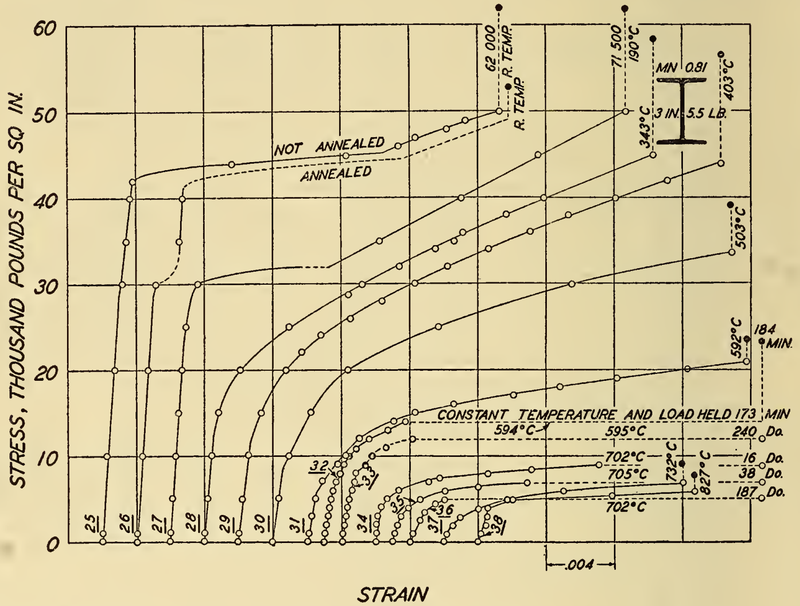

FIGURE 7.—*Stress-strain data from compression tests at elevated temperatures, of 3-in., 5.5-lb* I*-sections, annealed, manganese content of 0.81 percent.*

compressive strength at the lower temperatures for this gray cast iron compared with what is shown in the diagrams for steel.

(3) *Discussion.*—Table 4 gives the compression properties for all of the structural shapes tested at elevated temperatures by the constant-temperature method. The ultimate-strength values given cannot be taken as indicative of the properties of the metal but rather show the individual performance for shapes which differ in symmetry and stability.

Figure 9 gives the variation of compressive strengths with temperature for the 8 steel shapes and the 1 cast-iron shape tested. Here it will be noticed that an increase in strength is shown in the blue-heat range of temperature over that at room temperature, except for the cast-iron and the less stable steel sections (7 and 8). At 300 to 400° C the strength for steel sections nos. 1, 3, 4, 5, and 6 just about equals that at ordinary temperature. For higher temperatures the strength decreases regularly as the temperature increases, the several shapes maintaining generally the same relative positions established at about 400° C. At about 750° C the symmetrical or heavy sections have nearly the same ultimate strength and the light sections, nos. 7 and 8, show only about half the strength obtained with the more stable sections. For a given stress, say 15,000 lb/in.^{2}, the temperature at failure varies from about 550° C for thin-angle and pressed-steel sections (7 and 8) to 650° C for the annealed **I**-section having manganese content of 0.81 percent.

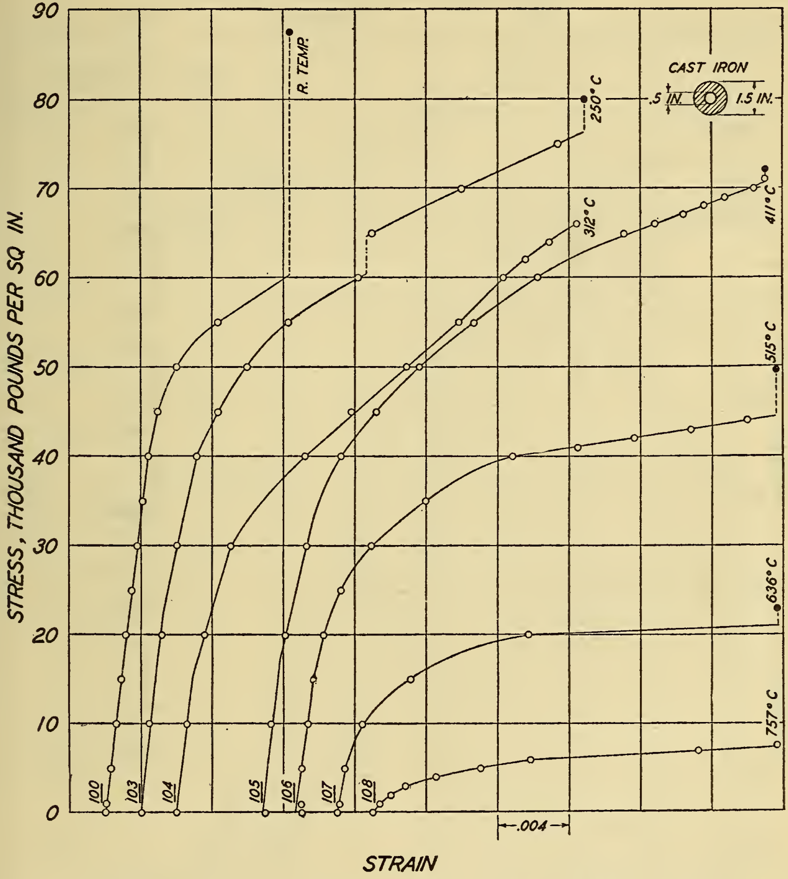

Figure 8.—*Stress-strain data from compression tests of hollow round cast-iron specimens at elevated temperatures.*

It will be noticed from the group headings in table 4 that the channel sections had end angles forming a part of the bearings which may have contributed some additional end restraint. The remaining sections except specimen no. 87 had no end angles and all were tested with flat ends subject to the restraint afforded by the testing equipment.

(b) CONSTANT-LOAD TESTS

The main results from the constant-load tests with shapes are given in table 5 and by the dashed lines in figure 9. Typical stress-strain-temperature relations are given in figure 10. The strain shown below the zero line at the start is due to the application of the constant load for the test. For group 1, I-sections (fig. 10), this load was below the yield point for applied stresses up to 40,000 lb/in². From this initial condition of stress and deformation the specimen expanded under the load as the temperature was raised at the approximate rate of 2 to 3° C per minute. Maximum expansion occurred at the temperatures indicated by the construction line drawn to connect

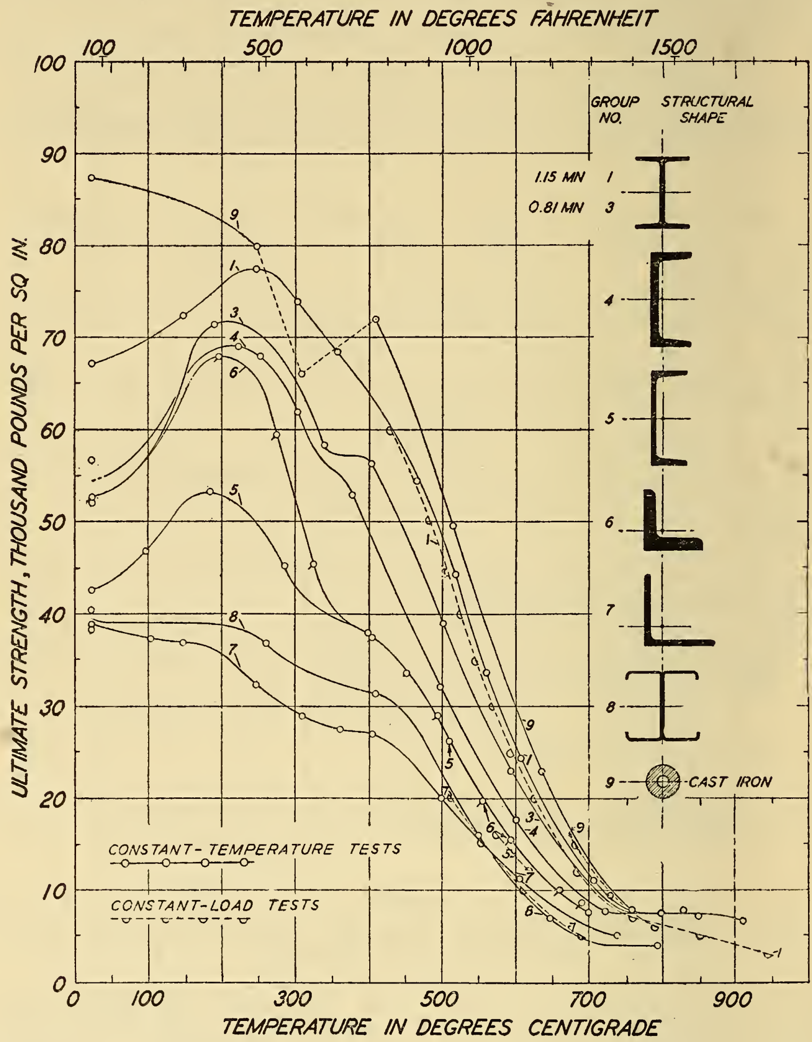

FIGURE 9.—*Compressive strength of cast-iron and structural-steel shapes at elevated temperatures.*

these points in the diagram, beyond which the rate of yielding exceeded the expansion. Finally failure occurred at the temperature and strain indicated by the arrows and figures. In general, the temperature at failure in the constant-load tests of **I**-sections was about 10° C below that for the constant-temperature test at the same load, equivalent to a difference of about 1,000 lb/in.^{2} for a given temperature of failure (fig. 9). For the less symmetrical shapes and for slender bars these differences are about half the values given above. This close agreement between results obtained by the two methods of testing constitutes evidence of the reliability of the de-

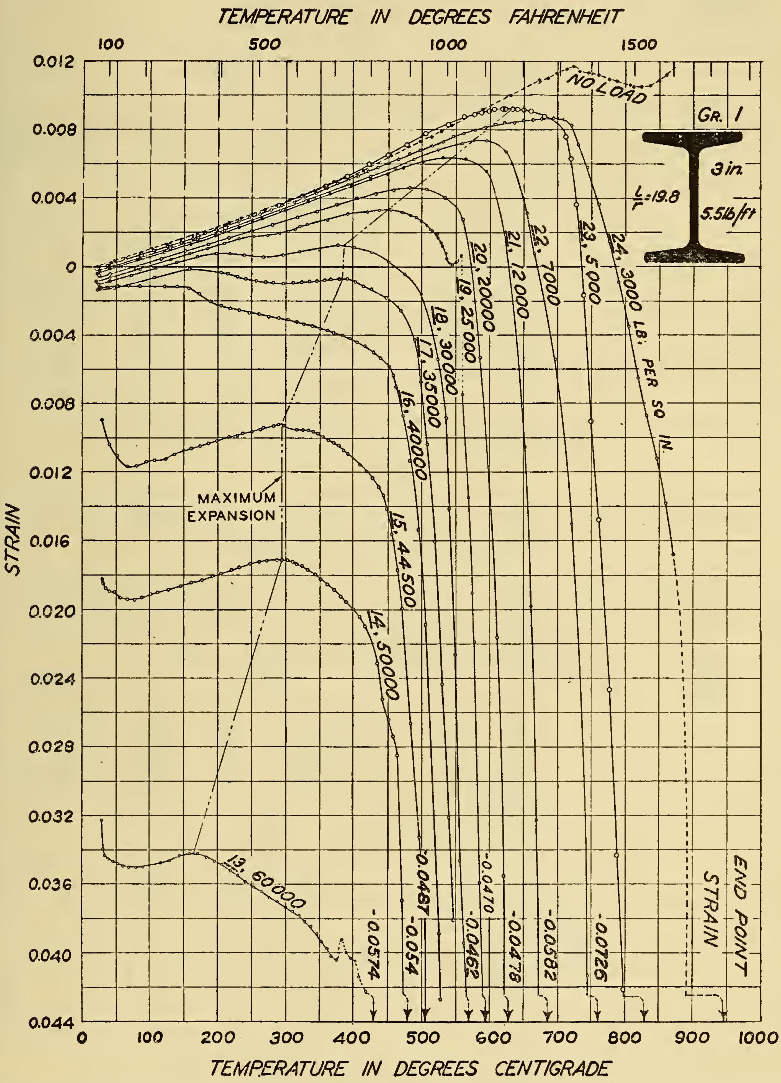

Figure 10.—*Data from constant-load tests of group 1,* **I**-*sections, 1.15 percent manganese content.*

terminations. The slightly lower results obtained in the constant-load tests can be attributed to the longer time of application of the load causing failure.

TABLE 5.—*Results from constant-load tests*

Group number	Specimen number	Slenderness ratio l/r	Sustained stress	Maximum expansion		Ultimate	
				Temperature	Compressive strain	Temperature	Compressive strain
3-IN. I-BEAM, MN 1.15 PERCENT							
			Lb/in.²	°C		°C	
1	13	19.8	60,000	165	0.03617	428	0.06308
	14		50,000	295	.02073	480	.06125
	15		44,500	295	.01292	502	.05550
	16		40,000	352	---------	527	.05000
	17		35,000	382	.00551	546	.04565
	18		30,000	385	.00368	569	.05422
	19		25,000	448	.00271	593	.05530
	20		20,000	490	.00207	627	.05670
	21		12,000	545	.00128	685	.06800
	22		7,000	575	.00077	758	.07255
	23		5,000	633	+.00017	851	(1)
	24		3,000	693	.00113	945	(1)
4-IN. CHANNEL, 5¼ LB, WITH END ANGLES							
5	52	23.4	16,000	458	0.00160	572	0.03451
	53	23.4	12,000	500	.00098	617	.05270
2½ BY 2½ BY ½ IN. ANGLE							
6	62	22.3	10,000	513	0.00134	659	0.06227
3 BY 3 BY ¼ IN. ANGLE, WITH END ANGLES							
7	74	17.8	20,000	440	0.00230	513	0.01838
	75		15,000	494	.00146	553	[2] .01089
	76		10,000	510	.00070	583	.04055
	77		10,000	510	.00120	608	(2)
	78		5,000	600	.00090	698	(1)
	79		2,500	719	.00055	922	(1)
3 IN. PRESSED STEEL JOISTS							
8	92	14.0	16,000	465	0.00170	531	0.01889
	93	14.0	7,000	553	.00165	646	.01965
CAST IRON, HOLLOW ROUND, FLANGED ENDS							
9	101	23.4	15,000	485	0.00285	681	0.05905
	102	23.4	6,000	610	.00088	790	(1)
LOT D, ⅜ IN. DIAMETER, FLANGED ENDS							
22	175	95.2	15,000	481	0.00126	506	0.01001
	177	95.2	9,500	523	.00105	584	.01161
LOT D, ¼ IN. DIAMETER, FLANGED ENDS							
23	185	143.2	15,000	392	0.00090	397	0.00923
	188	143.2	5,900	583	.00045	629	.01378

[1] Deformation not obtainable, wires broke or touched tubes.

[2] Preliminary loading on specimen reduced strain otherwise available.

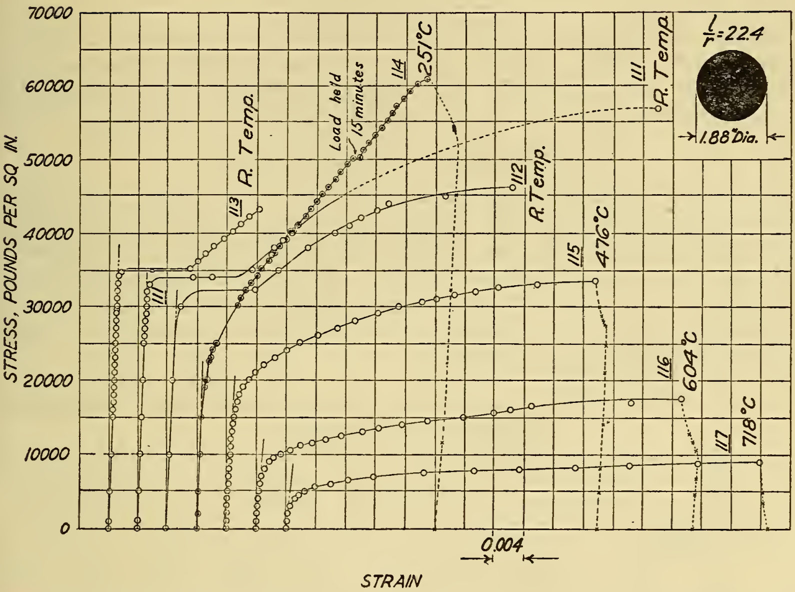

FIGURE 11.—*Stress-strain data from compression tests of 1.88 in. diameter lot A specimens at elevated temperatures.*

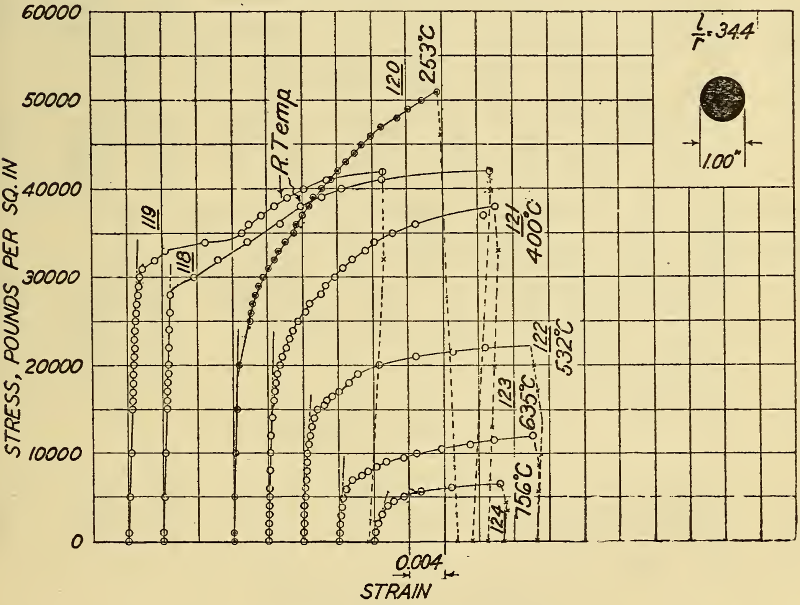

FIGURE 12.—*Stress-strain data from compression tests of 1 in. diameter lot A specimens at elevated temperatures.*

2. RESULTS WITH ROUND-BAR SPECIMENS

For the round-bar specimens the main difference in shape consisted in change in diameter of the test bars with corresponding variations in slenderness ratios. Most of the tests were made by the constant-temperature method, only four being made by the constant-load method, the results with the latter being given in table 5.

(a) CONSTANT-TEMPERATURE TESTS

Results of constant-temperature tests with round bars are given in table 6. In figures 11 and 12 for bars of 22.4 and 34.4 l/r of lot A, the results of tests at room temperature are included for comparison with those at elevated temperatures. In these diagrams tests made at "blue heat" temperatures, which develop an ultimate strength and stiffness superior to those for cold tests, are indicated by a special plotting point (dot and circle).

Table 6.—*Compression properties of structural rounds at elevated temperatures*

Group number	Specimen number	Elements of structural shape		Proportional limit		Modulus of elasticity		Ultimate strength		
		Length, l	Slenderness ratio l/r	Temperature	Stress	Temperature	Million lb/in.^{2}	Temperature	Stress	Strain
LOT A, 1⅞ IN. DIAMETER										
		In.		° *C*	*Lb/in.*^{2}	° *C*			*Lb/in.*^{2}	
10	114	10.5	23.4	254	15,000	254	27.0	251	60,600	0.0308
	115	10.5	22.4	--------	--------	--------	--------	476	33,500	.0497
	116	10.5	22.4	603	4,000	602	14.5	604	17,500	.0574
	117	10.5	22.4	715	2,000	715	10.9	718	9,000	.0638
LOT A, 1 IN. DIAMETER										
11	120	8.65	34.6	255	15,000	255	28.3	253	51,000	0.0235
	121	8.64	34.6	398	12,000	397	30.0	400	38,000	.0261
	122	8.60	34.4	533	9,000	533	17.0	532	22,000	.0260
	123	8.60	34.4	635	4,500	634	8.9	635	12,000	[2] .0222
	124	8.60	34.4	745	2,500	747	3.3	756	6,500	.0143
LOT A, ¾ IN. DIAMETER										
12	127	8.48	45.3	226	22,000	226	26.7	225	28,000	0.0036
	[1] 127a	8.48	45.3	243	22,000	243	30.0	243	39,000	.0140
	129	8.50	45.4	--------	--------	--------	--------	398	30,000	.0096
	130	8.50	45.4	498	7,000	499	21.1	500	22,000	.0166
	[1] 130a	8.50	45.4	--------	--------	--------	--------	502	20,000	.0063
	132	8.50	45.4	--------	--------	--------	--------	631	11,750	.0153
	133	8.50	45.5	--------	--------	--------	--------	713	6,700	[2] .0105
LOT A, ½ IN. DIAMETER										
13	136	8.64	69.2	199	24,000	196	--------	200	28,750	0.0021
	137	8.48	67.8	401	12,000	402	19.7	400	23,000	.0046
	138	8.50	67.9	--------	--------	--------	--------	559	15,000	.0063
	[1] 136a	8.64	69.2	--------	--------	--------	--------	633	8,750	.0074
	140	8.46	67.7	--------	--------	--------	--------	711	6,500	.0067
LOT B, 1⅞ IN. DIAMETER										
14	142	10.50	22.4	--------	--------	--------	--------	238	57,250	0.0393
	143	10.50	22.4	704	2,500	704	6.8	694	9,750	.0685

---

[1] Retest after cooling of specimen of corresponding number.
[2] Deformation apparently not maximum obtainable.

TABLE 6.—*Compression properties of structural rounds at elevated temperatures*—Continued

LOT B, 1 IN. DIAMETER

Group number	Specimen number	Elements of structural shape		Proportional limit		Modulus of elasticity		Ultimate strength		
		Length, *l*	Slenderness ratio *l/r*	Temperature	Stress	Temperature	Million lb/in.²	Temperature	Stress	Strain
		In.		° *C*	*Lb/in.²*	° *C*			*Lb/in.²*	
15	146	8.84	35.5	241	20,000	241	26.1	245	44,500	0.0301
	147	8.90	35.6	599	3,000	600	14.5	601	15,000	.0343
LOT B, ¾ IN. DIAMETER										
16	149	8.87	47.4	239	17,000	240	24.5	240	33,000	0.0178
	150	8.85	47.2					309	31,750	.0200
	151	8.84	47.2	601	4,000	602	11.3	604	13,150	.0219
LOT B, ½ IN. DIAMETER										
17	153	8.72	69.9	299	12,000	297	25.6	300	21,350	0.0082
	154	8.70	69.7	603	5,000	604	9.4	602	11,000	.0092
LOT C, ⅜ IN. DIAMETER (LOW CARBON CONTENT, COLD-ROLLED)										
21	169	8.90	95.4	351	45,000	356	25.2	352	48,350	0.0026
	170	8.88	95.0	606	10,000	606	15.1	607	21,500	.0080
LOT D, ⅜ IN. DIAMETER										
22	172	8.99	96.2	251	25,000	253	25.0	251	28,750	0.0039
	173	8.91	95.4	304	14,000	302	27.8	306	20,000	.0047
	174	8.90	95.2	403	11,000	401	25.0	405	19,100	.0045
	176	8.91	95.3	511	7,000	505	20.3	512	15,650	.0052
	178	8.92	95.4	599	4,500	599	12.8	597	10,850	.0092
	179	8.85	94.7	597	4,000	597	12.8	600	10,950	.0096
	180	8.91	95.4	704	1,750	702	8.0	707	5,500	.0096
LOT D, ¼ IN. DIAMETER										
23	183	8.94	143.7	175	38,500	175	28.5	175	39,300	0.0017
	184	8.94	143.6	296	15,000	293	27.5	296	18,500	.0012
	186	8.94	144.0	402	11,000	402	21.0	401	16,000	.0015
	187	8.93	143.5	560	5,000	560	14.5	561	10,300	.0030
	189	8.94	143.4	640	3,750	640	6.8	643	6,750	.0030
	190	8.85	142.4					716	4,350	.0047
LOT E, ½ IN. DIAMETER										
25a	200	9.32	75.3	495	6,000	498	16.0	501	16,500	0.0072
	201	9.14	74.2					545	14,400	.0077
	202	9.06	71.9	601	3,500	601	11.0	602	10,340	.0061
LOT E, ⅜ IN. DIAMETER										
25b	203	8.98	96.3	499	4,000	505	20.0	501	14,500	0.0030
	204	9.08	99.8	550	5,500	548	15.3	552	11,000	.0026
	[1] 204a	9.08	99.8					556	11,500	.0041
	205	9.20	103.5					550	11,500	.0051
LOT E, ¼ IN. DIAMETER										
25c	206	9.13	157.5					501	12,000	0.0012
	207	9.10	151.0	552	6,000	552	11.7	554	9,500	.0019
	208	9.15	151.5	605	3,000	605	11.7	602	7,000	.0012

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[1] Retest after cooling of specimen of corresponding number.

Figures 13 and 14 give some results for lot B, which is a slightly milder grade of structural steel than lot A as indicated by tension and compression tests at room temperature.

In figure 15 is shown the variation with temperature of the ultimate compressive strength for the several qualities of steel and sizes of bars, as based on data given in table 6.

From table 6 there is seen to be a marked decrease of the strain attained at maximum load with increase of slenderness ratio, proportionately greater than the decrease in strength, as would be expected from the stress-strain relations for the material. With regard to effect of temperature, for the lower slenderness ratios, the strain developed at maximum load is somewhat smaller for tests made in the temperature range 250 to 300° C (482 to 572° F) than for lower or higher temperatures. Otherwise, in general, the strain at ultimate increases with the temperature of test.

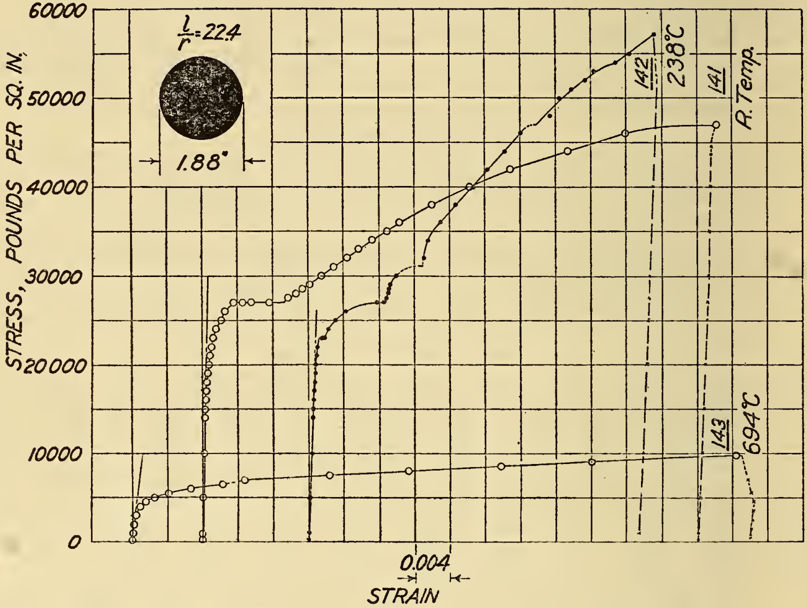

Figure 13.—*Stress-strain data from compression tests of 1.88 in. diameter lot B specimens at elevated temperatures.*

The strains given in table 6 include the shortening between gage points due to the bending of the specimen near failure. Computations based on the deflections of the specimens, indicate this to be within 15 percent of the reported strain for most of the tests, although with slender specimens, where relatively small strains were developed, the percentage is larger.

(b) CONSTANT-LOAD TESTS

In this series tests of the four round bars, nos. 175 and 177 of 95.2 (l/r), and nos. 185 and 188 of 143.2 (l/r), were made of lot D by the constant-load method previously discussed, and the data included in table 5. In the constant-load tests for the slender bars of lot D failure occurred at an average stress of 1,000 lb/in.^{2} less than that obtained in the constant-temperature test for the same temperature. This corresponds with the difference found for **I**-sections, discussed in section IV–1(b).

(c) COMPARISON OF RESULTS WITH THOSE DERIVED FROM THEORY AND TESTS OF BUILDING COLUMNS

The test results with round specimens have been analyzed to determine the extent to which they conform with rational column theory. Since all of these specimens failed at stresses higher than the proportional limit, the modifications of Euler's treatment that have been developed [4] to take into account the yield preceding failure, were applied, use being made of the formulas presented by Southwell for solid round sections. No results of these comparisons will be given except to state that such a degree of agreement was found between experimental results and those derived from theory as to indicate from the standpoint of temperature effects that extraneous conditions such as eccentricity of load application, uneven bearings, inhomogeneity of material, and initial bends in the specimens, did not seriously affect the results.

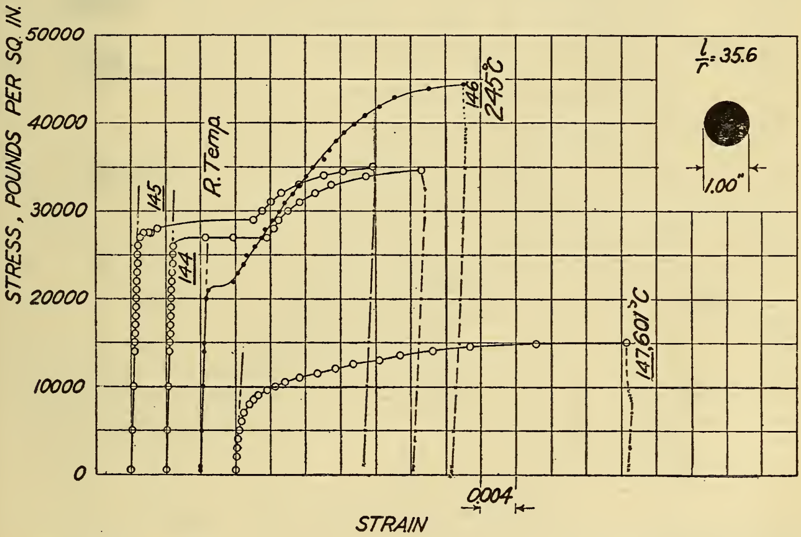

FIGURE 14.—*Stress-strain data from compression tests of 1 in. diameter lot B specimens at elevated temperatures.*

Comparisons are made in table 7 with results from two series of tests of building columns reported in BS Technologic Paper T184 and BS Research Paper RP563, respectively. The columns included were either tested unprotected or had coverings that contributed very little to their load-carrying capacity. The temperature in the column steel was measured at 1 or more locations at each of 4 levels. In

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[4] Engesser, Zeitschrift des Hannov. Arch. und Ing.—Ver., 35, 455(1889); Schweizerische Bauzeitung, 26, 24(1895); Zeitschrift des Vereines deutscher Ingenieure, p. 927(1898).
Considère, Résistance des Pièces Comprimées, Congrès International des Procédés de Construction, Annexe a comptes rendus, p. 382(1891).
Theo. v. Kármán, Mitteilungen über Forschungsarbeiten, Verein deutscher Ingenieure, Heft 81, Berlin, Julius Springer, 1910.
R. V. Southwell, Strength of struts, Engineering, London, 94, 249(Aug. 23, 1912).

computing the average temperature for a section at a given level, the temperature for given locations in the section was weighted in proportion to the tributary metal area. The average of the three hottest sections is taken as the effective temperature of the column. The end restraints in the second series of tests, columns nos. *1*, *3*, *4*, *5*, and *6*, approximated the condition of 1 fixed and 1 round end, as compared with the fixed-end condition it was aimed to attain in the earlier series.

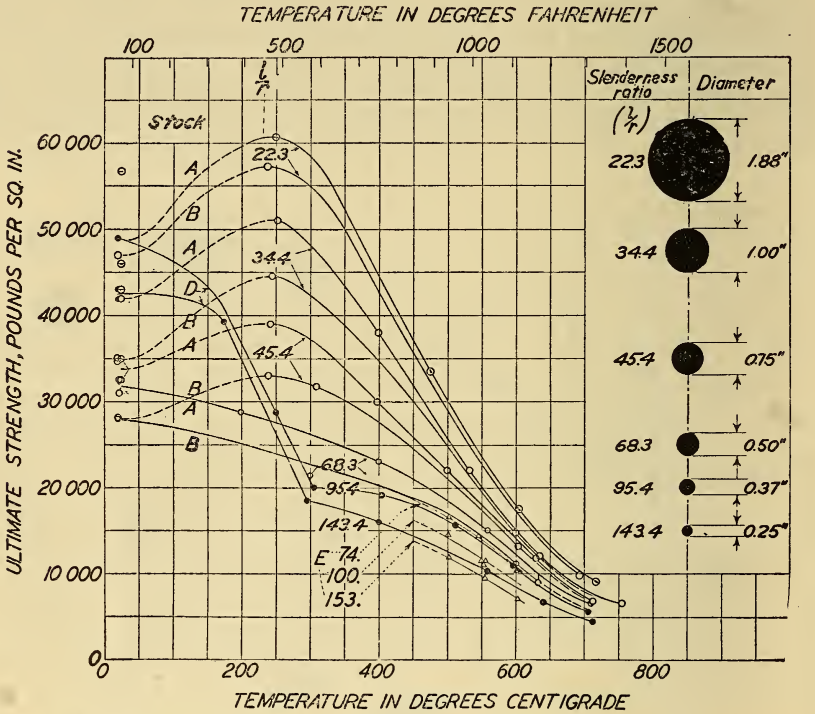

FIGURE 15.—*Compressive strength of solid round bars at elevated temperatures.*

TABLE 7.—*Temperature at failure in fire tests of full-size columns and comparable data from tests of round bars*

COLUMNS 12 FT, 8 IN. LONG WITH FLAT RESTRAINED ENDS [1]

Column number	Column section and protection	Slenderness ratio, l/r	Average load	Time of failure	Temperatures at failure					
					Maximum indicated temperature	Average for hottest section	Average of 3 hottest sections	Round bars for same P/A and l/r as columns		
								Lot A	Lots B & E	Lot D
			Lb/in.^{2}	*HrMin*	°C	°C	°C	°C	°C	°C
1	Solid rolled H, unprotected	75.6	11,750	0:11¼	624	620	588	603	580 B; 585 E	------
2	Plate and angle, unprotected	111.8	8,900	0:19¼	672	646	624	------	590 E	619
23	Plate and angle, 2 layers plaster on metal lath	111.8	8,900	2:52	650	634	621	------	590 E	619

[1] Eight unprotected and 4 protected columns selected from Techn. Pap. BS **15**, (1921); T184.

TABLE 7.—*Temperature at failure in fire tests of full-size columns and comparable data from tests of round bars*—Continued

COLUMNS 12 FT, 8 IN. LONG WITH FLAT RESTRAINED ENDS—Continued

Column number	Column section and protection	Slenderness ratio, *l/r*	Average load	Time of failure	Temperatures at failure					
					Maximum indicated temperature	Average for hottest section	Average of 3 hottest sections	Round bars for same *P/A* and *l/r* as columns		
								Lot A	Lots B & E	Lot D
			Lb/in.^{2}	*HrMin*	*°C*	*°C*	*°C*	*°C*	*°C*	*°C*
3	Plate and channel, unprotected	64.7	12,650	0:14	632	634	622	597	582 B	------
24	Plate and channel, 2 layers of plaster on wire lath	64.7	12,650	2:24	618	615	581	597	582 B	------
4	Latticed channel, unprotected	44.0	14,250	0:11	629	602	595	600	591 B	------
5	Z-bar and plate, unprotected	81.7	11,250	0:14¼	670	613	605	602	582 B; 585 E	------
25	Z-bar and plate, 1 layer of plaster on metal lath	81.7	11,250	1:07¾	658	614	598	602	582 B; 585 E	------
6	I-beam and channel, unprotected	72.1	12,050	0:17	658	644	634	598	580 B; 579 E	------
7	Latticed angle, unprotected	40.7	14,550	0:14	620	611	587	600	593 B; 598 E	------
26	Latticed angle, 1 layer of plaster on metal lath	40.7	14,550	1:23½	605	600	583	600	593 B; 598 E	------
8	Starred angle, unprotected	108.5	9,350	0:21½	620	607	579	------	588 E	610
	COLUMNS 10 FT, 4 IN. LONG WITH 1 FIXED AND 1 ROUND END[2]									
1	Plate and angle, 2 in. gypsum concrete, plastered	91.2	14,100	6:54	700	620	554	------	518 E	550
3	Plate and angle, 2 in. solid gypsum block, filled and plastered	91.2	12,800	5:47	575	558	554	------	542 E	571
4	Plate and angle, 3 in. hollow gypsum block, no fill, no plaster	91.2	12,800	2:52	558	546	514	------	542 E	571
5	Plate and angle, 2 in. solid gypsum block, plastered, no fill	91.2	12,800	4:21	574	565	543	------	542 E	571
6	Plate and angle, 2 in. solid gypsum block, no fill, no plaster	91.2	12,800	2:33	587	559	508	------	542 E	571

[2] Five protected columns selected from BS J.Research **10**, 737 (1933); RP563.

The last columns in table 7 give for round bars temperatures at failure interpolated for the same load and slenderness ratio as those obtaining in the building-column test with which the comparison is made. The differences between the temperatures compared are within the limits within which the effective temperature of the columns can be considered as known. It may be of interest to note the comparison between the average temperature of 601° C (1,114° F) for the 12 columns in the first group, tested with flat ends, and the average of 594° C (1,101° F) for the round bars. In the second group the average temperature for the 5 columns, tested with end restraint approximating 1 fixed and 1 round end, is 535° C (995° F) and that for the round bars in the comparison, 552° C (1,026° F). As previously indicated, the end restraint in the tests of round bars was probably intermediate between those obtaining for the two respective column groups.

The results with round bars in point of ultimate strength in the temperature range 450 to 600° C can be expressed approximately by the empirical formula,

$$P/A=10{,}000\left(\frac{1870}{T}\right)^2\left(\frac{r}{l}\right)^{1/2},$$

where P/A is the average stress in pounds per square inch and T the average temperature at failure in degrees C. The deviation of ultimate strength obtained with the formula from individual test results is within ± 15 percent of the latter, while the maximum deviation of individual results from the general trend of results at given temperatures is about 14 percent. As applied to the results of tests with the building columns given in table 7, approximately the same maximum percentage deviations from the individual and average of test results obtains.

3. EXPANSION TESTS

The materials tested included structural steel, cast iron, and 42-percent nickel steel. Expansion bars ⅜ to 1½ inches in diameter were cut from specimens 2, 99, 127, 142, and 171 after the regular compression tests with them were completed. Expansion bars of three diameters (1½, 1, and ½ inch) were also cut from the remaining 1½-inch diameter stock of lot E. The apparatus for measuring deformation and the split furnace employed in some of the compression tests were used for the expansion tests. In all these tests expansion observations were made with fine alloy wires hung from V-grooves spaced 6 inches apart on the specimen. The wires were weighted at the free ends and annealed in place as previously described to assure the required degree of straightness.

In figure 16 the average expansion per unit length is plotted against temperature. The annealed condition was obtained by heating above the thermal critical temperature for structural steel, followed by slow cooling. The difference between data from the first run and those obtained in the subsequent annealed condition is not large. It appears that slightly larger expansion obtains for the annealed condition. The usual growth for the first runs on cast-iron specimens was obtained as shown at a temperature near 700° C. It is of interest to note the relatively low expansion of the 42 percent nickel steel.

In figure 17 the average data for all expansion tests of structural steel are given for both total expansion and corresponding average coefficient of expansion from 20° C to higher temperatures.

The expansion data indicate that structurally restrained members would bend or give evidence of initial failure after a moderate temperature rise in the steel above that of the restraining members. Fortunately structural frames do not give full restraint because of their normal elasticity, nonrigid connections, and their own expansion from the fire that causes expansion of the restrained member. Even so, the stresses thus induced, particularly in floor members, may become relatively high. For building columns, axial stresses from expansion would be induced only by differences in average temperature between columns within a building story or portion thereof.

V. CONCLUSIONS

1. MATERIAL, SPECIMENS, AND TEST CONDITIONS

The different stocks of steel included in the tests, while presenting a considerable range in properties, were identified as coming within the general range of material acceptable under current specifications for structural steel.

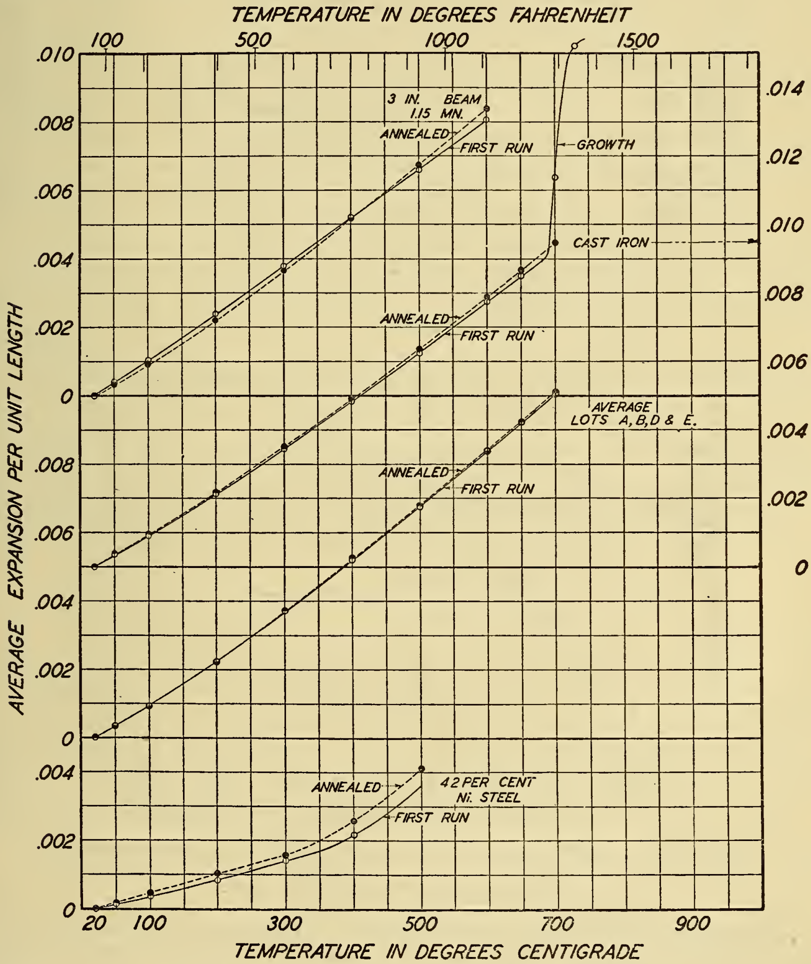

FIGURE 16.—*Average expansion per unit length above 20° C for structural steel, cast iron, and nickel steel.*

Since the compressive strength is influenced greatly by the shape of cross section and the slenderness ratio, a range in both was introduced. In point of stability, the range in specimens extended from those of relatively thin material and unsymmetrical section that failed by local buckling, to fully symmetrical sections proportioned to act as homogeneous units under load application.

The test conditions were designed in part to simulate those to which building columns are subjected when exposed to fire. While the effect of duration of load and temperature were determined from this standpoint, the results should not be taken as applicable to the design of columns to be subjected to load and high temperature for longer periods.

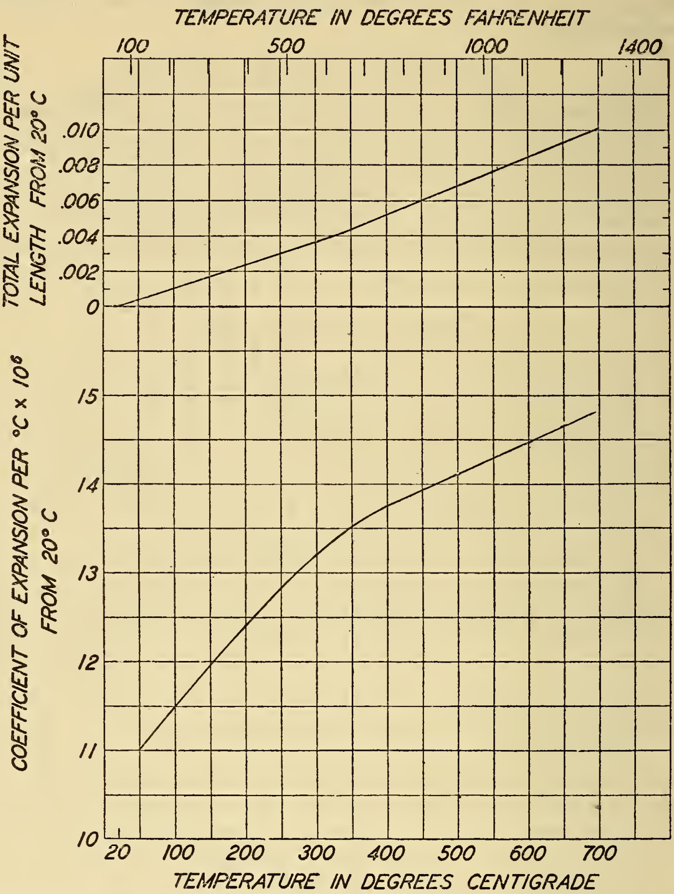

FIGURE 17.—*Total expansion and coefficient of expansion above 20° C.*

Average values for all structional-steel tests.

The good agreement between results from the constant-temperature and the constant-load tests and the general consistency of results in point of ultimate strength at given temperatures indicate that applied load and temperature were measured with the requisite accuracy.

While no great refinement is claimed for the strain measurements, the long range of the instruments permitted determinations of deformation up to the ultimate in nearly all tests.

2. GENERAL CONCLUSIONS

The variation of the compressive strength of structural steel with temperature was determined within the limits defined by the temperature range included the methods of testing, and the range in shape and proportions of specimen outlined above.

One group of tests with cast-iron specimens of low slenderness ratio was included for comparative purposes, the strength developed being a little higher than any obtained with structural steel for the same temperature and slenderness ratio.

At room temperature an ultimate strength appreciably higher than the yield point was obtained except with the light-angle and pressed-steel sections and with round bars of smaller diameter than three-fourths inch (45 l/r).

In tests with structural steel at temperatures of 250° C (482° F) or higher, and with cast iron at all temperatures, no well-defined yield point or yield region was developed.

In all tests except with the light-angle and pressed-steel sections and round bars of smaller diameter than three-fourths inch (45 l/r), an increase in strength above that obtained at room temperature was developed at temperatures near 250° C (482° F).

For specimens of the same material having symmetry and proportion of parts such that local or detail failure did not occur, the main element affecting strength at a given temperature was found to be the slenderness ratio, as would be expected with properly controlled test conditions.

Agreement in point of ultimate strength at given temperatures and slenderness ratios was also found with results of fire tests of building columns.

The variation with temperature and slenderness ratio of the ultimate strength of round, structural-steel bars in the temperature range 450 to 600° C (842 to 1,113° F) and of building columns in the range 500 to 635° C (932 to 1,175° F) is given approximately by the formula

$$P/A=10{,}000\left(\frac{1870}{T}\right)^2\left(\frac{r}{l}\right)^{1/2}$$

where P/A is the average stress in pounds per square inch and T the temperature at failure in degrees C.

The results of the expansion determinations taken in conjunction with the stress-strain relations defined for given temperatures, indicate that if a building member is restrained by the surrounding construction and heated to a higher temperature, stresses induced by the restraint may become higher than those due to the supported load.

Acknowledgment is made to L. R. Sweetman of the engineering-mechanics section for assistance on the tests made in the Emery testing machine, and to R. M. Hamilton and F. M. Hoffheins, members of the fire-resistance section of the National Bureau of Standards, for aid in conducting the tests and reducing and verifying experimental data. The author expresses his appreciation to S. H. Ingberg, chief of the fire-resistance section, for constructive suggestions during the progress of the research project.

WASHINGTON, August 25, 1934.