Plastic behavior of WF beams, January 1948

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The Plastic Behavior of Wide Flange Beams

by

W. William Luxion* and Bruce G. Johnston°

FOREWORD

The Welding Research Council, through its Structural Steel Committee, directed in December of 1945 that the resumption of its work at Lehigh University should be on the subject of fully continuous welded frame construction. Prior to interruption by the war, a number of projects at Fritz Laboratory had been sponsored on flexible beam-to-column building connections and the possibilities of the "semi-rigid" connections also had been explored.

In suggesting the new program it was thought that the advantages of welding could best be realized if the fully continuous type of construction were used, thereby leading to the greatest ultimate or collapse strength of the structure.

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The work was to commence with simple beam tests of wide flange sections and lead to tests of continuous beams, welded connections, and welded continuous frames. In Great Britain, J. F. Baker and his associates have had under way a similar investigation, utilizing tests of small models, the results of which have been presented in a number of reports of the British Welding Research Association.

In 1946 the American Institute of Steel Construction also resumed sponsorship of research at Fritz Engineering Laboratory, continuing its prewar investigation of steel columns. Emphasis was placed on the behavior of the column as part of a continuous frame. This naturally led to the suggestion (in 1947) to unite the W. R. C. and A. I. S. C. work under a single coordinated program. This move was later approved by the Structural Steel Committee which also expedited the work by increasing the allotted annual budget. The Bureau of Yards and Docks and the Bureau of Ships of the U. S. Navy, through the Office of Naval Research, undertook the sponsorship of specific features of the overall program. The American Iron and Steel Institute added their financial support and at the time of writing this report all phases of the work are now underway.

Acknowledgment is due Mr. William Spraragen, Director of the Welding Research Council, Mr. LaMotte Groover, Chairman of the Structural Steel Committee, and Mr. T. R. Higging, Chairman of the Lehigh Project Subcommittee for their continued
guidance and assistance. Mr. A. Amirikian, of the Bureau of Yards and Docks, was also particularly helpful in providing the initial impetus to the work and advising as to its detailed direction.

**INTRODUCTION**

This report presents results of wide flange sections tested as simple beams. Third point loading was used to provide a central section wherein pure moment (no shear) would be obtained and the basic bending behavior at initial yielding and in the plastic range could be studied. An extensive exploration of elastic and plastic strains was made throughout each of the beams in the regular test series.

The tests reported on herein were as follows:

<table>
<thead>
<tr>
<th>Pilot Test No. 1</th>
<th>SWF31 As delivered</th>
<th>12'-0&quot; Span</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;</td>
<td>No. 2 SWF40</td>
<td></td>
</tr>
<tr>
<td>Regular Test No. 1</td>
<td>SWF40</td>
<td>14'-0&quot;</td>
</tr>
<tr>
<td>&quot;</td>
<td>No. 2 SWF40</td>
<td></td>
</tr>
<tr>
<td>&quot;</td>
<td>No. 3 SWF67</td>
<td></td>
</tr>
<tr>
<td>&quot;</td>
<td>No. 4 SWF67</td>
<td></td>
</tr>
</tbody>
</table>

The bending behavior at a particular location along a beam may be depicted by means of an "M-ϕ" graph, in which the moment, M, is the ordinate, and ϕ plotted as the abscissae is the rate of change of slope of the beam axis at the point in question. ϕ is inversely proportional to the radius of curvature of the
beam axis. \( \phi = 1/R \). Within the elastic range, the bending moment is proportional to the curvature and the \( M-\phi \) curve is a straight line, the elastic constant of proportionality being equal to \( EI \).\(^{(1)} \) If the bending moment is constant over any length of the beam, as in the central third of the test beams, \( \phi \) is also constant within this region and the beam bends into a circular arc. Within this section \( \phi \) may be determined by deflection readings at three different locations along the beam.

Some of the factors influencing the bending behavior will be discussed herein under the following headings:

1. Stress-strain properties of structural steel
2. Shape of cross section
3. Local buckling
4. Residual stresses

**Stress-strain properties of structural steel**

The well-known tensile stress-strain properties of structural steel are illustrated in Figure 1A. A proportional limit (not shown) is usually observed somewhat below the upper yield point. The upper yield point represents a condition of instability, affected by rate of loading, surface condition, and other factors. The lower yield point is the more stable and

\(^{(1)} \) See any book on Strength of Materials, for example, Timoshenko, Volume 1, page 134.
well defined of the two being the nearly constant stress at which continued slow average strain rate is maintained while zones of yielded material spread from their points of inception. The total plastic strain during the constant lower yield point stress is usually ten to twenty times as large as the initial elastic strain. (See Fig. 1A). The yielded regions finally become more or less general, the material starts to strain harden, and the stress increases.

One of the objects of these tests was to compare experimental M-Ø curves with those calculated from the tensile and compressive stress-strain diagrams of the same material. General procedures for calculating M-Ø curves for any shape section from any given stress-strain data, or the reverse, have long been available.²,³ These procedures assume that the longitudinal strain in the elastic, plastic, and intermediate stages of bending varies linearly across the beam section and that the strain in the most stressed fiber is uniformly the same along any region of constant moment at all stages of yielding. These conditions may be approximately realized in the case of a non-ferrous alloy with a continuously increasing stress-strain curve. In the case of structural steel, yielding commences intermittently along the most stressed fibers and proceeds

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downward in localized planes into less stressed regions, as well as along the beam. An extensive investigation of this process has recently been reported by the University of Illinois.(4) The "theoretical" curves reported herein are nevertheless based on the usual assumption of uniform yielding. It will also be assumed as is commonly the case that the web material has a different yield point than the flange.

Calculation of a "theoretical" $M-\phi$ curve is extremely simple if the stress-strain curve is as shown in Figure 1A and is assumed the same in tension as in compression. The calculation of 3 pairs of $M$ and $\phi$ values plus a fourth limiting $M$ value will satisfactorily determine the curve for a WF section at various states of yielding as follows:

$M_1$, $\phi_1$ at initial plastic yielding of outer fibers of beam.

$M_2$, $\phi_2$ after yielding has progressed through the flange to the juncture of web and fillets (to $y_2$ in Fig. 1B)

$M_3$, $\phi_3$ after yielding has progressed into the web any appreciable amount (to $y_3$ in Fig. 1B)

$M_4$ -- the limiting moment assuming the entire section to be plastic.

It will be assumed that initial yielding takes place when the most stressed fibers in bending reach a stress equal to the

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(4) Morkovin, D. and Sidebottom, O. "The Effect of Non-Uniform Distribution of Stress on the Yield-Strength of Steel" University of Illinois Experiment Station, Bulletin No. 372, 1947.
upper yield point of the flange material $\sigma_{UYF}$ as determined by a tension or compression test. As soon as yielding has commenced it is questionable whether the upper yield point should be assumed as maintained on the elastic side of the theoretical elastic-plastic boundary. The material used in this investigation had an upper yield point not much larger than the lower and no conclusions could be drawn as to the foregoing matter. The two different procedures would give nearly identical curves and in the absence of conclusive evidence it will be assumed that the upper yield point is maintained at the elastic plastic boundary, and that the lower yield point obtains throughout the plastic region, as shown in Fig. 1B.

In Appendix A the formulas are developed for calculating $M$ and $\phi$ at the four stages of plastic yielding and an illustrative example is presented of the $M$-$\phi$ curve of the 8 WF 67 section having handbook dimensions and a minimum specification yield point of 33 ksi.

Figure 2 shows this $M$-$\phi$ curve along with the $M$-$\phi$ curve for a rectangular section having the same depth and the same section modulus as the 8 WF67, 9" deep by 4.474" wide.

**Shape of Cross-Section**

The ratio of the limiting moment with the whole section assumed plastic, $(M_4)$ divided by the moment at initial yield$(M_1)$,
is sometimes called the "shape factor" of the section. This
is an index of the plastic reserve strength of a particular
cross section, being 1.50 for the rectangular shape and 1.15
for the 8 WF67 section, both of which have the same moment at
initial yield.

As typified in Figure 2, the I beam or WF shape has an
M- curve with a sharp knee at moments 5 to 15% larger than
the maximum elastic moment. Thereafter, \( \phi \) increases very rapidly
at nearly constant moment and the beam becomes, in effect, a
"plastic hinge". The computation of ultimate or collapse loads
of continuous frames is simplified by assuming the development
of "plastic hinges" at successive locations of maximum elastic
moment in the structure.

**Local buckling**

If the outstanding parts of the flange buckle before
reaching the yield point, or, if plastic buckling occurs shortly
after the section yields, the full contribution of the plastic
hinge to the ultimate strength of the continuous frame will not
be realized. However, all currently rolled structural shapes
as listed in the A. I. S. C. Handbook have a flange thickness
sufficient to insure against elastic buckling, and will develop
the full yield strength of structural steel. However if higher
strength alloys, or non-ferous alloys, are used, or if thin
sections are built up by welding, the problem of local buckling
should be given consideration as has been done in a recent
Residual Stresses

Residual stresses are generally thought to have little or no effect on the static strength of structural steel members. In many instances this has been demonstrated, however, at least one investigator (6) has reported a lowering of buckling strength due to internal stresses caused by welding. After completing pilot tests of this investigation, the suggestion was made that residual stresses caused by rolling might be responsible for the non-uniform strain distribution that was observed. Therefore, the regular tests included specimens that were stress-relief annealed after rolling and welding of test fixtures.

PILOT TESTS

The initial pilot test was made on an 8WF40 beam of 12' span, simply supported and loaded at the third points (see Fig. 3). Around the center section of the beam were located 18 electric strain gages as shown in Fig. 4. The load was applied to the beam through bearing blocks resting on the top flange and the web was stiffened under the load with 3/8" plates welded perpendicular to the web.

Upon testing this specimen it was observed (5) that when the elastic


(6) Madsen, I. "Box Girder Buckling Tests", Iron and Steel Engineer volume 18, No. 11, p. 95, November, 1941.
limit of the beam was passed the strain across the center section no longer followed a straight line variation. The strain in the compression flange remained relatively constant from the 46 to 52 kip load while the strain in the web and tension flange progressed and the neutral axis moved towards the tension flange. This phenomenon can be observed in Fig. 4. This figure also shows that the neutral axis moved back towards the centroidal axis of the beam at higher percent strains. The pilot test developed less plastic strength than that calculated. This fact together with the non-linearity observed in the strain distribution led to the decision by the committee to carry out a more detailed study of additional beam tests.

**PROGRAM OF TESTS**

The four "regular tests" had as objectives (1) to thoroughly study the strain pattern throughout the beam for increasing degrees of plastic development, and (2) to compare the M-ψ curves obtained from tests with theoretical curves predicted from tension and compression tests.

Two variables were incorporated into the four tests, namely: (1) the effect of residual stress, and (2) the effect of the weight of the section on its behavior. To obtain these variables two 8WF40, and two 8WF67 beams were tested and in each weight one beam was tested in the as-delivered condition and the other was stress-relief annealed prior to testing.
The method of load application was made to simulate a beam to girder connection by bringing the load directly into the web as is depicted in Fig. 5. This method of applying the load to the beam differed from the flange bearing block method used in the pilot tests, as previously described and as shown in Fig. 3.

PREPARATION OF SPECIMENS

Initial Preparations

Except for the stress-relief annealing process each beam was prepared for testing in the same manner. Upon receiving the beams in the laboratory they were weighed and measured. The cross-sectional area was determined from the weight and length and used to check the direct measurements by micrometer calipers. The dimensions and calculated properties of the sections are shown in Fig. 6.

The load-carriers and stiffeners over the supports (Fig. 5 and Fig. 7) were welded in position and then the beams to be stress-relief annealed were delivered to the shop for this process. The next step was to determine the residual strains in the beams.

Residual Strain Measurements

The specimens had been ordered in 19 ft. lengths, 4 ft. longer than required for the beam tests. This four extra feet had the two-fold purpose of being used for residual strain tests
and also as coupons for physical property tests. The following procedure was used in determining the residual strains in the beams.

On the 19 ft. length the 15 ft. required for the beam test was laid out from one end. Adjacent to this (see Fig. 8) the desired number of 10" gage lengths were laid out around the beam section and the Whittemore strain gage holes were drilled, prepared, and a complete set of readings taken around the section. The portion A in Fig. 8 was then sawed out of the 19 ft. length, and finally all the gage lengths were isolated by sawing 1/4" on either side of each pair of holes. Readings were then taken on these isolated lengths and relaxation of strain computed. Although the accuracy of the method was not perfect, the results obtained gave a good indication of the magnitude of the residual strains in the beams.

In the first beam tested for residual strains (8WF40 as-delivered), measurements were taken only for one half of the section with a few check points on the other half. However, it was decided after this test that more points for measurements were required, and therefore in the specimens that followed either 44 or 46 points of measurement were used.

Physical Property Tests

The remaining 3 ft. of the original 19 ft. length was used to make physical property coupons which would be, of course, representative of each beam. Seven coupons were taken from
each section located as shown in Fig. 9 to 14, which present all stress strain curves. The upper and lower yield points of the web and flange were used in Equations 4 to 10 to determine the theoretical curves. Table 1 gives a summary of the average physical properties of all the coupon specimens. As shown by Fig. 9 to 14, tension and compression tests were usually in close agreement and the overall average of the 6 flange-coupons was used to determine $\sigma_{UYF}$ and $\sigma_{LYF}$ as used in calculating the theoretical $M-\theta$ curves.

An O. S. Peters strain gage of 2" gage length was used for tension tests and two Huggenberger tensometers were used for compression specimens. A modulus of elasticity of 30,000 kips per in.² was used in all calculations and was representative of the test results.
Electrical Strain Gages

The next step in the preparation of the beams prior to testing was to lay out the electrical (SR-4) strain gage locations.

In order to thoroughly study the strain pattern developed around the loading point and the region of pure bending, 141 electrical strain gages were mounted on each beam specimen in the pattern shown in Figure 15. Gages were mounted only on one half of the beam since due to symmetry the results obtained should be similar in both sides. AX-5 gages were used along with uniaxial gages in the vicinity of the load carrier to allow a complete study of strain that might develop from bending, shear, or be the result of the concentration of load in the area. Uniaxial gages were mounted along the beam at various points to permit measurement of the longitudinal strain across different sections in the pure bending region, and to enable a study to be made of any change in strain pattern along the beam which might be attributed to the position of the section in this pure bending region.

After completing the mounting of SR-4 gages and their wiring the specimens were ready for testing and were set up in the 300,000lb Baldwin-Southwark hydraulic testing machine. A Baldwin Southwark Type K Strain Indicator was used to measure strains in conjunction with switch boxes made at the Fritz Laboratory. Figures 16 and 17 are photographs of the complete setup before and after one of the tests.
Deflection Gages

As illustrated in Figures 5 and 16 deflections were measured at nine points along the beam by means of dial gages. Three of these dial gages were mounted in the pure bending region of the beam to enable calculations to be made of the rotation or angle change due to the applied moment in the section and to allow plotting of observed M-θ curves for all the beams.

Lateral Bracing

In the pilot tests considerable lateral deflection as well as twisting developed as the beam progressed into the plastic range. Lateral bracing was supplied to the regular test specimens by forming an adjustable, vertical passageway for the beams as is illustrated in Fig. 5. The distances between the guide plates at the bottom and top were carefully measured to be sure that the plates were parallel, as well as vertical, to insure against pinching of the beam as it deflected. These plates were also greased so that friction between the vertical slides and the beam would be a minimum.

Whitewash

The final preparation prior to test was to paint slaked lime whitewash on the beams. This whitewash served as an aid in studying the progression of yielding throughout the specimens.

TEST PROCEDURE

The testing procedure for all the specimens was as similar
as possible. However, Regular Test No. 1 (SWF40, as delivered) was run at perhaps a slower rate than was justified. This factor, along with unavoidable interruptions in the test, and the length of time involved in recording the 141 strain gage and 9 deflection readings, caused the test to extend over a period of approximately two weeks. Beyond the yield point there were observed numerous discontinuous increases in strength of the member which are attributed to strain aging.

The remaining three beam tests were planned so that it would not be necessary to interrupt the early stages of plastic development, thereby reducing strain aging as much as possible. To accomplish this the tests were carried to within a safe margin of the calculated elastic limit on the first day of testing and the entire second day was used to carry the test well into the plastic region. In comparison to the first test the other three extended over the following lengths of time: SWF40 Annealed, two days; SWF67 As-Delivered, 3 days; SWF67 Annealed, 4 days.

In all the tests readings were recorded when the deflection of the beams stopped or the rate of deflection became a negligible amount for a particular load.* Strain and deflection were also recorded at intervals before these values were reached to indicate the progression of yielding under a constant load. To obtain

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* An equilibrium condition was assumed when the deflection in the center did not increase more than .02" in 30 minutes.
readings which would give the strain and deflection pattern for the entire beam at a particular instant even though the beam was in the process of yielding, the load was dropped slightly to stop yielding. Then a complete set of readings was recorded. The amount that the load had to be dropped to accomplish this was small and the reduction in strain, at the elastic rate, was a negligible value which could not be seen on the plotted curves.

When it became necessary to interrupt the testing for a considerable length of time, overnight for example, the hydraulic testing machine was shut down with the load left on the specimen. This was done to keep as much load on the specimen as possible to prevent any recovery that might tend to occur. However, over a period of 12 hours the load would drop to about 2/3 of the original value, due to gradual seepage of oil from the hydraulic testing machine loading cylinder.

All tests were carried far enough so that the beams should have developed nearly all of their ultimate plastic hinge value prior to general strain hardening.

**TEST RESULTS**

Results of the moment-curvature relation, or M-\( \phi \) diagrams are presented in Figures 18, 19, and 20 for the pilot tests, SWF40 tests, and SWF67 tests respectively. Actual test curves are compared with curves determined theoretically by the procedure outlined in the introduction. These curves illustrate the bending behavior of the specimens and determine their plastic hinge value.
Longitudinal strain gage data at various loads are presented graphically for typical test results as follows:

Fig. No.
21 Strain across flanges of 8WF67 as delivered beam
22 " " " " " annealed "
23 Strain on various cross sections along as-delivered 8WF40 beam
24 Strain on various cross sections along annealed 8WF40 beam
25 Strain distribution along tension flange of 8WF40 beam
26 " " " " compression " " " "

In each of the three foregoing categories the data from one beam size is omitted, but is available in the original report at Fritz Laboratory. Fig. 21 and 22 show the strain distribution on the flanges of the 8WF67 beams at various loads and degrees of plastic development. The 46,300 lb. load is approximately equivalent to a maximum fiber stress in the beams of 20,000 p.s.i. while the subsequent loads for plotting curves were chosen at or above the apparent elastic limit of the material. There appears to be little if any difference in the curves for the stress-relief annealed and the as-delivered beams which might be attributed to residual stress, except around the load carrier, where residual stresses of apparently greater magnitude than elsewhere existed because of welding. (Note the surface yield lines shown in Fig. 27.)
The strain distribution at points along the 8WF40 beams for different loads and degrees of plastic development are shown in Fig. 23 and 24. The values plotted in these figures are averages of all the gages occupying the same position vertically on the section. These curves show no appreciable difference which might be attributed to the variables studied, except as mentioned before there is initial yielding around the load points at a much lower load in the as-delivered beams than the annealed beams. It can be observed in these figures also that the strain distribution even in the vicinity of the load point is linear through the elastic ranges but that once the yielding starts there is considerable deviation from linearity. These figures also illustrate the change of strain pattern or flow of the material under a particular load. For example, in Fig. 23 there are shown two sets of curves for the load of 50,500 lb. (1) while another set of strain reading taken sometime later are identified by the curve for the load 50,500 lb. (4). As can be seen from these curves, yielding at section J did not occur until yielding at Sections B, C, E, and G had very nearly stopped. Progression of yielding under one particular load is also illustrated for the annealed 8WF40 in Fig. 24. (See also Fig. 32 and 33.)

A study of the degree of yielding along the beams is depicted by Fig. 32 and 33. These figures show the average strain developed in the flanges of the 8WF67 beams under increasing loads. Here also is shown that the point of maximum plastic strain does not occur at the loading point but rather that
that yielding seems to be retarded in this section and the region of maximum yielding occurs from about 6" inside the loading point to the center of the beams. However, there was appreciably more yielding at the load point in the as-delivered beams than in the annealed beams.

The residual strains caused by rolling and handling in the as-delivered and stress relief annealed beams as determined by the method previously described are presented in Fig. 34 and 35. The sections at the top of these figures are oriented so that referring to the test setup the person is looking at the left end of the beam towards the far end. Subsequently the views labeled B are taken looking into the near side of the beams as shown in various figures illustrating the test setup. All figures portraying strain are oriented in this way so that the strain measured under load may be studied and compared directly with the residual strain patterns.

Progression of Yielding Indicated from Whitewash

Since in a general manner the progression of yielding in all the specimens was similar, a complete discussion of the progression of yielding observed in one of the beams will be representative of all.

The following is the complete history of yielding in the 8WF 67 stress-relief annealed beam (Test No. 4) as observed by cracking of the whitewash on the beam.
At a load of 90,300 lb., the first sign of yielding appeared on the compression flange at the loading point of the beam. When the load was increased to 94,300 lb., indications of yielding occurred on both the top and bottom of the compression flange in the vicinity of the load point, and initial yielding appeared in the compression flange inside of this region as is shown by Fig. 31A. These yield lines appeared simultaneously on the bottom and top of the compression flange. Fig. 30B shows the yield lines in the compression flange one hour after applying 96,300 lb. to the beam, and Fig. 30C gives the same view several hours later at the same load. Fig. 31A shows the condition in the region of the load carrier at the same time. Both Fig. 30C and 31A were taken after the beam had stopped yielding under the applied load. One hour after the application of 98,300 lb. the beam appeared as is shown by Fig. 31B, 32A, and 33A.

After a lapse of 5 hours, the final yielded condition under the load of 98,300 lb. is shown by Fig. 32B and 33B. Fig. 32C and 33C show the beam 1/2 hour after application of the ultimate load of 100,300 lb. Finally Fig. 34, 35, and 36 show the beam at the completion of the test.

The similarity of the progression of yielding in the different tests is shown by Fig. 37 to 40. Figure 37 shows initial yielding and Fig. 38 the final appearance in Test No. 1 of the 8WF40 As-Delivered Beam. Fig. 39 shows the final
appearance of the SWF40 Stress-Relief Annealed beam, and although no pictures are available it can be stated that yielding first appeared in the form of flaking whitewash at the same location as it occurred in the As-Delivered beam of this weight, and as shown by Fig. 37 initial yielding in Test No. 3 of the SWF67 As-Delivered beam, as observed from the whitewash, occurred at the junction of the web, bottom flange and load carrier. Final appearance of this beam is shown in Figure 40.

In general with regard to the yielding of these beams it can be said that yielding first occurred in the vicinity of the load point, although it did not spread into the pure bonding region from this point. Secondly yielding would appear at some point on the top flange inside the loading points and spread throughout the top flange and into the web to some degree before indication of yield lines would appear on the bottom flange. This progression would continue, then, until it reached the final condition as shown in previously mentioned figures.

Not all of the studies to be made of these tests results have been completed for this first progress report. A study of the local stresses near the load bearing stiffeners and the complete deflection curve results are omitted.

**SUMMARY AND CONCLUSIONS**

The agreement between the experimental and calculated M-ϕ curves is as good as could possibly be expected in the case of Tests 2 and 4, of the annealed SWF40 and 67 beams, respectively,
as shown in Fig. 19 and 20. The test $M-\phi$ curves for the two pilot tests are somewhat lower than the curves calculated from the stress-strain diagrams; however, the pilot tests differed from Tests 2 and 4 in the following respects:

(1) Pilot test beams were not annealed,

(2) were not laterally supported, and

(3) were loaded with bearing blocks through the top flange whereas the regular tests were loaded by web stiffeners as shown in Fig. 7.

Any or all of these factors might have contributed to the less-than-theoretical strength of the pilot tests, hence, no definite conclusion can be given from the foregoing comparison.

Test No. 1 may be compared with Test No. 2, the principal difference between the two being that No. 2 was annealed and No. 1 was not. As shown in Fig. 19, the agreement between Test No. 1 and the theoretical curve is good, but as previously discussed, Test No. 1 consumed over a two week period and there are evidences of strain-aging at locations marked A to E on Fig. 19. Had Test No. 1 been run at the same speed as No. 2, the agreement with the theoretical probably would have been poorer.

Tests No. 3 and 4 in Fig. 20 may be compared on the basis that only one difference existed between the tests, that of residual stress levels. The strength of the as delivered beam in test No. 3 was definitely less than that predicted from the stress-strain data. As shown in Fig. 29 the residual stresses had maximum values of about 12 ksi in both flanges and in the web of this beam.
The apparent effect of residual stresses in producing less-than-theoretical plastic moment capacity in the case of Test No. 3 is largely discounted in practical importance by the fact that, in Test No. 4, in spite of the excellent theoretical agreement, the strength is nevertheless lower than the strength of the "As Delivered" beam of Test No. 3. This is due to the fact that the annealing generally lowered the yield strength of the material at the same time that it reduced the residual stresses.

The observed and calculated moments at initial yield (based on upper yield point) and after general yielding (influenced primarily by lower yield point) are presented in Table 2.

TABLE 2
SUMMARY OF TEST RESULTS

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Section</th>
<th>Internal Stress Condition</th>
<th>Initial Yield Moment-Kip-in</th>
<th>Ratio Obs. LyM</th>
<th>Plastic Moment*</th>
<th>Ratio Obs. P.M.</th>
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<td>8WF31</td>
<td>As Delivered</td>
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<td>1012 0.91</td>
<td>1182</td>
<td>1145 0.97</td>
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<td>1330</td>
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<td>&quot;</td>
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<td>1258 0.97</td>
<td>1430</td>
<td>1405 0.98</td>
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<td>Annealed</td>
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<td>1243 0.99</td>
<td>1366</td>
<td>1340 0.98</td>
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<td>3</td>
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<td>As Delivered</td>
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<td>2285 0.83</td>
<td>3104</td>
<td>2900 0.93</td>
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<td>2441</td>
<td>2585 1.06</td>
<td>2783</td>
<td>2780 1.00</td>
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</tbody>
</table>

* Arbitrarily taken as moment when yielded region had theoretically progressed to within 2 inches of neutral axis.
Although the "observed" initial yield moment cannot be evaluated with much precision from the M-\( \phi \) curve, the agreement with the calculated value is good for the annealed beams. The "plastic moment", arbitrarily evaluated when the yielding had come within 2 inches of the neutral axis, was practically constant after this amount of yielding. The poorest agreement was in Test No. 3 of the as-delivered 8WF67, where the plastic moment determined by test was 93\% of the calculated moment. In no case was the observed plastic moment appreciably greater than the calculated value.

As explained in the introduction, the theoretically calculated curves were based on the assumption that the upper yield point was maintained in the elastic region adjacent to the theoretical plastic boundary. However, in view of the small difference between the upper and lower yield points and therefore the inappreciable effect on the theoretically calculated M-\( \phi \) curves, no conclusion on this question can be based on these test results. The fact that surface yield lines developed simultaneously on both surfaces of the upper flange would indicate that the upper yield point is not maintained after initial yielding, for, if it were, one would expect yielding to progress slowly from the outer to the inner surfaces of the flanges.

Another factor that according to some investigators\(^7\) might be expected to influence the test results is a supposed increase

---

in yield point attributed to a non-uniform elastic stress
distribution. Others have disputed the foregoing proposition
and have sought to demonstrate\(^{(4)}\) that the phenomenon is primarily
due to an unstable upper yield point which may be increased to
an exaggerated degree under unusual conditions of smooth surface
finish, precise loading, etc. obtained in specially machined
specimens. Certainly the tests reported herein give no evidence
of an appreciably increased yield point due to non-uniform stress
distribution or to any other cause and the question appears to
be of academic interest.

The gradual spread of intermittent zones of yielding has
been fully discussed under "Test Results".

Of importance to the calculation of ultimate or collapse
strength of frames is the graphic illustration in Figures 18
to 20 of the fact that the "plastic moment" or "hinge moment"
of the beams was practically constant over a range of deflection
and unit angle change (\(\phi\)) of more than eight times the elastic
range of the beams. The tests herein reported indicate that a
satisfactory approximation for the "hinge moment" would be the
mean value between the moment at initial yielding (\(M_0\)) and the
maximum limiting moment at complete plastic yield (\(M_{YZ}\)), or,
denoting the "hinge moment" as \(M_H\)

\[
M_H = \frac{M_0 + M_{YZ}}{2} \tag{2}
\]

For approximate design estimates since the AISC handbook
gives the section modulus (\(S\)) of sections but does not give the

\(\) Loc. cit.
section static moment \( (Z) \), it might be satisfactory to use \( 1.1S \) in place of \( \frac{S+Z}{2} \). \( 1.1S \) will in many cases be a few percent larger than \( \frac{S+Z}{2} \), but if the minimum specification yield point of 33 ksi is used for design purposes the resulting formula for the hinge moment would simply be \( M_H = 36S \). \( (3) \)

As shown by the following Table No. 3, Eq. 2, modified as

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Plastic Moment (Observed)</th>
<th>Plastic Moment (Calculated)</th>
<th>Plastic Moment (Calculated)</th>
<th>Ratio (Observed/Equation 2)</th>
<th>Ratio (Observed/Equation 3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pilot-1</td>
<td>1145 (from Table 2)</td>
<td>1140</td>
<td>986</td>
<td>1.00</td>
<td>1.16</td>
</tr>
<tr>
<td>Pilot-2</td>
<td>1260</td>
<td>1280</td>
<td>1278</td>
<td>0.99</td>
<td>0.99</td>
</tr>
<tr>
<td>1</td>
<td>1405</td>
<td>1370</td>
<td>1278</td>
<td>1.02</td>
<td>1.10</td>
</tr>
<tr>
<td>2</td>
<td>1340</td>
<td>1310</td>
<td>1278</td>
<td>1.02</td>
<td>1.05</td>
</tr>
<tr>
<td>3</td>
<td>2900</td>
<td>2920</td>
<td>2174</td>
<td>0.99</td>
<td>1.33</td>
</tr>
<tr>
<td>4</td>
<td>2780</td>
<td>2600</td>
<td>2174</td>
<td>1.07</td>
<td>1.28</td>
</tr>
</tbody>
</table>

was done herein to take account of the variation in yield point between the web and flange, is in reasonably good agreement with test results and at most only 1% on the unsafe side. Eq. 3, because it does not incorporate the variation in yield point characteristic of structural steel, is not in good general agreement with the test results but is on the safe side in all except one case, wherein it is only 1% low. Since the actual yield point cannot be taken advantage of in ordinary design,
which is necessarily based on a minimum specification value, Eq. 3 should be satisfactory for design purposes.

Some of the more important conclusions in the foregoing remarks are summarized as follows:

(1) The M-Δ curve for annealed structural steel beams, laterally supported, can be predicted accurately from the stress-strain curves and the usual theory of plastic bending based on the assumptions of uniform distribution of yield and strains proportionate to the distance from the neutral axis.

(2) The existence of residual stress may result in actual yield strengths in plastic bending being lower than calculated from the test coupon strength.

(3) The advantages of annealing in giving better agreement between calculated and actual static bending strength may be more than offset by the general reduction in yield point that may be caused by the annealing process.

(4) The tests give no evidence of increased upper yield point or increased bending strength due to the non-uniform stress distribution in bending.

(5) For design purposes the plastic hinge moment of a laterally supported structural steel section of the proportions herein tested could be assumed as not appreciably less than 363, in kip inches.
APPENDIX

Calculation of M-Ø Curve

As stated in the Introduction, the calculated moment at initial yield of the beams was assumed as corresponding to the load at which the extreme fibers of the beam reached the upper yield point of the flange material. As shown diagramatically by Fig. 41, the angle change per unit length, Ø, is simply the maximum longitudinal strain divided by the distance from the neutral axis and may be expressed conveniently in terms of stress at the boundary of the elastic region of the beam.

\[ M_1 \text{ and } \Phi_1 \text{ at initial yield, therefore, are calculated to be:} \]

\[ M_1 = S \frac{\sigma_{UYF}}{\epsilon_c} \quad (4) \]

\[ \Phi_1 = \frac{\epsilon_c}{c} = \frac{\sigma_{UYF}}{\epsilon_c} \quad (5) \]

where

- \( S = \text{Section modulus (in handbook)} \)
- \( E = \text{Modulus of elasticity} \)
- \( \epsilon_c = \text{longitudinal strain at extreme fiber} \)
- \( c = \text{distance from neutral axis to extreme fiber} \)

The second pair of coupled M and Ø values is most conveniently determined after yielding has progressed to the juncture of the fillets and the web, a distance \( y_2 \) from the neutral axis as shown in Figure 1B. At this stage it is assumed that the region between the distances \( y_2 \) and \( c \) from the neutral axis are uniformly stressed to the lower yield point of the flange material, \( \sigma_{LYF} \).
The contribution of this region to the resisting moment is simply equal to the product of the stress times the static moment of the uniformly stressed area about the neutral axis. Then, after yielding reaches the web, the static moment of the plastic region equals that of the whole section less that of the rectangular web section that is still elastic.

Letting \( Z = \) static moment of whole section

\[ Z_2 = \text{wy}_2^2 = \text{static moment of web between fillets} \]

The contribution of the plastic portion to \( M_2 \) is

\[ \sigma_{\text{LYF}} (Z-Z_2) \]

And the contribution of the elastic portion is

\[ \frac{\sigma_{\text{UYW}} I_2}{y_2} \]

but \( I_2 = \frac{2}{3} \text{wy}_2^3 = \frac{2}{3} Z_2 y_2 \)

Hence the total resisting moment is

\[ M_2 = \frac{2}{3} \sigma_{\text{UYW}} Z_2 + \sigma_{\text{LYF}} (Z-Z_2) \]  \hspace{1cm} (6)

and \( \phi_2 = \frac{\sigma_{\text{UYW}}}{E y_2} \)  \hspace{1cm} (7)

After yielding has progressed into the web to any distance \( y_3 \) from the neutral axis similarly computed \( M \) and \( \phi \) values would be given by:

\[ M_3 = \frac{2}{3} \sigma_{\text{UYW}} Z_3 + \sigma_{\text{LYF}} (Z-Z_2) + \sigma_{\text{LYW}} (Z_2-Z_3) \]  \hspace{1cm} (8)

\[ \phi_3 = \frac{\sigma_{\text{UYW}}}{E y_3} \]  \hspace{1cm} (9)

The limit of \( M \), as \( \phi \) increases, and the whole section is assumed plastic, would be

\[ M_4 = \sigma_{\text{LYF}} (Z-Z_2) + \sigma_{\text{LYW}} Z_2 \]  \hspace{1cm} (10)
Since most of the plastic strength of the section is realized as soon as the flanges have entirely yielded, the value of \( M_4 \) by Eq. 10 is closely approached at \( \phi \) values for which the maximum plastic strains are within the lower yield point range.

In the simply supported beam the deflections for usual span lengths will be far beyond permissible values before strain hardening commences in the outer fibers.

Equations 4 to 10 illustrate the procedure used in this report in obtaining "theoretical" \( M-\phi \) curves. An illustrative example will now be given in which the procedure will be further simplified though slightly less accurate. Consider an 8 WF67 section, for which the AISC handbook gives:

- \( S = 60.4 \)
- \( w = 0.575 \) (web thickness)
- \( t = 0.933 \) (flange thickness)
- \( b = 8.287'' \) (flange width)
- \( d = 9.00'' \) (overall depth)

Assume both upper and lower yield points equal to the specification minimum of \( \sigma_y = 33 \) kips per sq. in. and assume \( E = 30,000 \) kips per in\(^2\). Neglect fillets, since these radii are not given in the handbook and the error will be about 1% on the safe side.

Equations 4 to 10 for these assumptions, simplify to:

\[
\begin{align*}
M_1 &= 33S \\
M_2 &= 33S - 11E_2 \\
M_3 &= 33S - 11E_3 \\
M_4 &= 33E \\
\phi_1 &= \frac{0.0011}{c}
\end{align*}
\]
Neglecting fillets, the static moments are given by

\[ Z = bt (d-t) + w \frac{(d-2t)^2}{4} \]

and

\[ Z_2 = \frac{w(d-2t)^2}{4} \]

\[ Z_3 = 4w \text{ (assuming } Y_3 = 2'') \]

or, for the 8 WF67

\[ Z = (8.287)(0.933)(8.067) + (0.575)(7.134)^2 \]

\[ = (62.37)(7.32) = 69.69 \text{ in}^3 \]

\[ Z_2 = 7.32 \text{ in}^3 \]

\[ Z_3 = 3.73 \text{ in}^2 \]

Substituting these values in the expression for \( M \) and \( \phi \)

\[ M_1 = 1993.2 \text{ kip in.} \quad \phi_1 = 0.000244 \text{ radians per inch} \]

\[ M_2 = 2219.3 \quad \phi_2 = 0.000308 \]

\[ M_3 = 2258.8 \quad \phi_3 = 0.000550 \]

\[ M_4 = 2299.8 \]

Figure 2 shows these calculated values and the curve that they define.
FIG. 1a  TYPICAL SHAPE OF STRESS-STRAIN DIAGRAM FOR STRUCTURAL STEEL.

FIG. 1b  ASSUMED STRESS DISTRIBUTION IN STEEL BEAM STRAINED BEYOND ELASTIC RANGE.
M - \phi CURVE FOR 8WF67 and for equivalent rectangular section having the same depth and same section modulus \( \sigma_{y} \) assumed 33KSI.

FIG. 2
FIG. 4 STRAIN PATTERN AT CENTER OF 8WF40 BEAM (Pilot Test)

Gages mounted around centerline of beam as shown on the left
Pilot Test Beams

Main Program Beams

DIMENSIONS AND PROPERTIES OF CROSS SECTION OF BEAMS

FIG. 6
Fig. 7. Load carriers and S-R 4 gages prior to connecting.
FIG. 8 REPRESENTATION OF HOW RESIDUAL STRAIN MEASUREMENTS WERE OBTAINED
FIG. 9 STRESS-STRAIN CURVES FOR PHYSICAL PROPERTY COUPONS OF 8WF 3I PILOT TEST BEAM

NOTE:
1, 4, 5, 6 Tension
2, 7 Compression
FIG. 10 STRESS-STRAIN CURVES FOR PHYSICAL PROPERTY COUPONS OF 8WF40 PILOT TEST BEAM

Note:
1,3,4,5,6 Tension
2,7 Compression
FIG. 11 STRESS-STRAIN CURVES FOR PHYSICAL PROPERTY COUPONS OF 8WF40 AS-DELIVERED BEAM
FIG. 12 STRESS-STRAIN CURVES FOR PHYSICAL PROPERTY COUPONS OF 8WF40 STRESS-RELIEVED BEAM

Note:
1, 3, 4, 5, 6 tension
2, 7 compression
FIG. 13 STRESS–STRAIN CURVES FOR PHYSICAL PROPERTY COUPONS OF 8WF67 AS-DELIVERED BEAM

Note:
1, 3, 4, 5, 6, tension
2, 7 compression
FIG. 14 STRESS-STRAIN CURVES FOR PHYSICAL PROPERTY COUPONS OF 8WF67 STRESS-RELIEVED BEAM

Note:
1,3,4,5,6 Tension
2,7 Compression
LOCATION OF ELECTRICAL STRAIN GAGES
FIG. 15
Fig. 16. General view of typical test set up prior to testing.

Fig. 17: Same as Figure 16, after testing.
NOTE: Letters A, B, C, D, & E designate discontinuities in testing varying in length from \( \frac{1}{2} \) to 2 days.

![Graph showing theoretical and experimental moment-\( \phi \) curves for 8WF40 beams.]

**THEORETICAL AND EXPERIMENTAL MOMENT-\( \phi \) CURVES**

**FOR**

8WF40 BEAMS

**FIG. 19**

\( \phi \) IN RADIANS PER INCH
THEORETICAL AND EXPERIMENTAL MOMENT - $\phi$ CURVES FOR 8WF 67 BEAMS

FIG. 20
FIG. 21 STRAIN ACROSS FLANGES OF 8 WF67 AS DELIVERED BEAM
FIG. 22 STRAIN ACROSS FLANGES OF 8WF67 ANNEALED BEAM
FIG. 23

STRAIN ON VARIOUS CROSS SECTIONS ALONG AS-DELIVERED 8WF40 BEAM
FIG 24: STRAIN ON VARIOUS CROSS SECTIONS ALONG STRESS-RELIEF ANNEALED 8WF40 BEAM
Sections showing location at which strain measurements used in the curves below were made.

FIG. 25 STRAIN DISTRIBUTION ALONG TENSION FLANGE OF 8WF67 BEAMS
FIG. 26 STRAIN DISTRIBUTION ALONG COMPRESSION FLANGE OF 8 WF67 FLANGE
Fig. 27. Surface yield lines produced by welding load carrying stiffeners.
FIG28 RESIDUAL STRAIN IN 8WF40 BEAM

- - Near Side
- - Far Side
FIG 29
RESIDUAL STRAIN
IN 8 WF67 BEAM
Fig. 30A. Test No. 4, 6WF67, annealed, compression flange, after initial yielding at 94 kips.

Fig. 30B. Same view as 30A, after one hour of yielding at 96 kips.
Fig. 30C. Same view as 30A, after several hours at 96 kips. Yielding had virtually stopped.
Fig. 31A. Test No. 4, underside of compression flange at load carrier, 96 kip load, after yielding had stopped.

Fig. 31B. Test No. 4 same view as 31A, after one hour of yielding at 98 kips.
Fig. 32A. Test No. 4, top of compression flange after one hour of yielding at 97 kips.

Fig. 32B. Test No. 4, same view as Fig. 32A, after five hours yield at 93 kips.
Fig. 32C. Test No. 4, same view as Fig. 32A, 1/2 hour after applying maximum load of 100 kips.

Fig. 33A. Test No. 4, side view after one hour of yielding at 98 kips.
Fig. 33B. Test No. 4, same view as Fig. 33A, after five hours yield at 98 kips.

Fig. 33C. Test No. 4, same view as Fig. 33A, 1/2 hour after applying maximum load of 100 kips.
Fig. 34. Test No. 4 after completion. Upper surface of top and bottom flange.

Fig. 35. Test No. 4 after completion of test.
Fig. 36. Test No. 4 after completion of test. Lower surface of top and bottom flanges.
Fig. 37. Test No. 1, 8WF40 as delivered, initial yield in compression flange at load carrier.

Fig. 38. Test No. 1 after completion of test.
Fig. 39. Test No. 2, 8WF40, annealed, after completion of test.

Fig. 40. Test No. 3, 8WF67, as-delivered, after completion of test.
\( \phi = \text{Angle change per unit length.} \)

Unit length of beam.

Before bending

After bending

\( \epsilon = \frac{\sigma}{E} \) in elastic region

FIG. 41

DEFORMATION OF UNIT LENGTH OF BEAM DURING BENDING