FATIGUE TESTS OF HYBRID PLATE GIRDERS

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Plate Girders Under Shear

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The present report is the final under Project 3-5-66-96 "Fatigue Strength of Hybrid Plate Girders Under Shear." The first, second, third and fourth reports under this project are entitled

1. "Additional Fatigue Tests of Hybrid Plate Girders Under Pure Bending Moment."
2. "Fatigue Tests of Hybrid Plate Girders Under Combined Bending and Shear."
3. "Study on Fatigue of Hybrid Plate Girders Under Constant Moment."
4. "Fatigue Tests of Hybrid Plate Girders Under Combined Bending and Shear."

ABSTRACT

The results of sixty-three hybrid girders tested at The University of Texas at Austin are presented. The girders were subjected to three different fatigue loading conditions: a) bending, b) shear, and c) combined bending and shear. The results of each loading condition are discussed in separate sections of this report.

The fatigue tests data were analyzed statistically. Based on the analysis of available data, the relationships between the parameters were established. The correlation study of statistical analysis aided: a) in distinquishing the significant parameters to consider, and b) in recommending the limiting values for those parameters.

SUMMARY

This experimental investigation presents results from 63 fatigue tests of hybrid plate girders with A36 steel webs and A441 or A514 steel flanges. The objectives of this project were (1) to determine the manner in which thin web hybrid girders fail and (2) to determine what factor influences the fatigue strength.

Since 1961 the response of hybrid plate girders were studied both when subjected to static and fatigue loading. The fatigue tests indicated that there are certain areas in a plate girder where cracks may develop depending on the type of stress, the aspect ratio, and the slenderness of the web. These girders when subjected to cyclic loads developed five types of fatigue cracks.

Type 1 cracks occur in the heat-affected zone along the fillet weld connecting the web to the compression flange as a result of lateral movements of the web under cyclic loading. These cracks propagate slowly and do not cause a significant reduction in the bending strength of the girder because they are parallel with the direction of the bending stresses. Type 2 cracks occur near concentration caused by the stiffener. Type 3a cracks occur in the flange-web fillet welds in the tension region due to unavoidable imperfections in these welds. Both Type 2 and Type 3a cracks propagate rapidly into the tension flange and cause a large reduction in bending strength. All three types of cracks have been observed both in homogeneous and in hybrid plate girders. Type 4 and Type 5 cracks are observed in specific and unusual situations. They are discussed in the report.

No Type 1, 2, or 3a cracks occurred in any of the tested specimens (without longitudinal stiffeners) in less than 140,000 stress cycles even though many of the specimens had web slenderness ratios or transverse stiffener spacings, or both, up to three times those presently allowed by AASHO. Many of the test panels in the girders were subjected to bending stresses varying between 25 ksi and 50 ksi; some of these were simultaneously subjected to shear stresses varying between 6 ksi and 12 ksi.

No Type 1 crack occurred in any of the tested specimens in less than 2,000,000 stress cycles when the web was less than $120\sqrt{100/\sigma_{yf}}$ in which σ_{yf} = the minimum specified yield strength of the flange steel in kips per square inch. The web slenderness ratio of $180\sqrt{100/\sigma_{yf}}$ is proposed for a fatigue life of 100,000 cycles.

No Type 1 crack occurred in any of the tested specimens in less than 2,000,000 cycles when the stress range was 10 ksi regardless of the magnitude of the web slenderness ratio.

Under bending stresses varying between 25 ksi and 50 ksi, the average life for transverse stiffeners (Type 2 cracks) in the tested A514/A36 hybrid girders exceeded 650,000 cycles. Under bending stresses varying between 15 ksi and 30 ksi, no Type 2 crack occurred in the tested A441/A36 hybrid girders. In some of these tests, high shear stresses, in addition to bending stresses, were present at the transverse stiffeners. These results are consistent with the present AASHO fatigue provisions.

IMPLEMENTATION STATEMENT

Previous studies showed that the proper use of the various structural steels available to the designer will result in more economical structures. This is because the relative increase in price of higher strength steels is less than the relative increase in yield point. Thus the application of higher strength steels results in lighter weight structures accompanied usually by cost savings. Hybrid steel girders with A36 steel web and A514 steel flanges show a 14-percent cost savings.

It is for this reason that a hybrid plate girder project was started at The University of Texas in 1961. Final recommendations for the design of such girders are given in this final report. It is believed that girders designed according to these recommendations will result in economical bridges.

TABLE OF CONTENTS

ACKNOWLEDGMENTS ii

ABSTRACT iii

SUMMARY iv

IMPLEMENTATION STATEMENT vi

NOMENCLATURE ix

1. INTRODUCTION

1.1 General 1
1.2 Background and Scope 1
1.3 Objective 2

2. TEST PROGRAM AND TESTS RESULTS

2.1 Test Program 3
2.2 Specimen Designations 5
2.3 Test Procedure 6
2.4 Test Results 6

3. DISCUSSION OF RESULTS - BENDING TESTS

3.1 General 8
3.2 Fatigue Cracks 8

3.2.1 Type 1 Cracks 8
3.2.2 Type 2 Cracks 9
3.2.3 Type 3 Cracks 9

3.3 Crack Locations as Compared with Homogeneous Girders . . . 10
3.4 Initial Web Eccentricity 10
3.5 Slenderness Ratio 10
3.6 Stress Level 13
3.7 Transverse Stiffeners 13
3.8 Longitudinal Stiffeners 14
3.9 Aspect Ratio 14
3.10 Series H Specimens (with A441 Flanges) 14
3.11 Regression Analysis 15

4. DISCUSSION OF RESULTS - SHEAR TESTS

4.1 General 18
4.2 Fatigue Cracks 18

5. DISCUSSION OF RESULTS - COMBINED BENDING AND SHEAR TESTS

5.1 General 19
5.2 Fatigue Cracks 19
5.3 Type 4 Cracks 19
5.4 Type 5 Cracks 20
5.5 Type 1 Cracks - A Comparison 20
5.6 Web Slenderness Ratio 20
5.7 Stress Range 21

6. RECOMMENDATIONS 23

REFERENCES 24

TABLES 26

FIGURES 41

NOMENCLATURE

Symbol	Definition
A_f	Area of flange, inches
A_w	Area of web, inches
$C, C_1, C_2 \ldots$	Coefficients of regression equation.
E	Modulus of elasticity (Young's modulus), ksi
h	Clear depth of web between flanges, inches
N	Number of cycles
P_{cr}	Theoretical web buckling load, ksi
P_{max}	Maximum applied load during fatigue test, kips
P_{min}	Minimum applied load during fatigue test, kips
t	Web thickness, inches
$X_1, X_2 \ldots .$	Parameters considered in regression equation
α	Aspect ratio, ratio of panel length to web depth
β	Slenderness ratio, ratio of web depth to web thickness
$(\delta_o)_{max}$	Maximum initial lateral web eccentricity, inches
ζ	σ_{yw}/σ_{yf}
ρ	A_w/A_f
σ	Stress, ksi

Symbol	Definition
σ_{af}	Allowable (static) flange stress, ksi
σ_{cr}	Theoretical web buckling stress, ksi
σ_{f}	Basic allowable bending stress for flange steel (0.55 σ_{yf}), ksi
σ_{max}	Maximum stress at the extreme fiber of the flanges at maximum applied load in a stress cycle, ksi
σ_{min}	Minimum stress at the extreme fiber of the flanges at maximum applied load in a stress cycle, ksi
σ_{R}	Stress range, the algebraic difference between the maximum and minimum stresses in a stress cycle, ksi
σ_{u}	Ultimate tensile strength of a coupon specimen, ksi
σ_{y}	Static yield stress of a coupon specimen, ksi
σ_{yf}	Static yield stress of the material of the flange, ksi
σ_{yw}	Static yield stress of the material of the web, ksi
σ_{w}	Allowable web stress
τ_{max}	Average maximum shear stress in a test panel, ksi
τ_{min}	Average minimum shear stress in a test panel, ksi
ϕ	Curvature of a member (girder) due to an applied moment, σ/Ey.

1. INTRODUCTION

1.1 General

A light and efficient plate girder can be fabricated by using high strength constructional alloy steel (ASTM A514) flanges and a carbon steel (ASTM A36) web. Such a structural member, called a hybrid plate girder, is efficient because higher stress is permitted in the alloy steel flanges than is possible in the flanges of homogeneous carbon steel girders. Hybrid plate girders are light because, for a given flexural stress, a smaller size flange is necessary with high strength steel than with carbon steel.

The advantage and principal difference of hybrid plate girders over the homogeneous carbon steel girders can be easily seen in Figs 1a and 1b. In the elastic region (stage a), the behavior of both types of plate girders is the same. The difference between the two types of girders is noticeable at stage b (Fig 1a). Although the web is partially yielded, the flanges are elastic and provide enough overall strength to the member to support the applied loads. Eventually, as the loads increase, the flanges will also yield (stage c). At this stage a small central part of the web is still elastic. Finally the whole member will be plastified as indicated in stage d.

1.2 Background and Scope

An extensive research program of hybrid plate girders was initiated at the Structures Fatigue Research Laboratory of The University of Texas, Austin, in 1961. The earlier studies at The University of Texas were concentrated on the investigation of the static behavior of hybrid girders. Extensive documentation in that respect can be found in References 1 through 6 listed at the end of this report. For all practical purposes, the available data on the static behavior of hybrid plate girders is sufficient to incorporate in design procedures. However, for bridge construction, information on the fatigue strength of hybrid plate girders was important.

In 1963, a pilot study[7] was initiated at The University of Texas to investigate the fatigue strength of hybrid girders. As a results of this pilot study, an elaborate research program was planned to investigate fatigue behavior of hybrid plate girders. At present, all the fatigue tests have been completed and this report describes the results.

1.3 Objective

The objective of this report is to present the tests results obtained when hybrid plate girders were subjected to three different loading conditions: a) bending, b) shear, and c) combined bending and shear. The discussion of each loading condition is given in a separate section for purposes of clarity and consiseness. The maximum stress levels and the stress ranges were the important variables of the tests program.

The fatigue tests data was analyzed statistically. Based on the analysis, various relationships between the parameters were established. The correlation study of statistical analysis aided in distinquishing the significant parameters to consider in design practice.

2. TEST PROGRAM AND TEST RESULTS

2.1 Test Program

The test program consisted of sixty-three specimens. The fatigue tests were carried out under three different loading conditions: a) bending, b) shear, and c) combined bending and shear. The data for shear loading condition was obtained from the end panels of bending tests specimens. In Table 1 the test program is shown with a brief description of each specimen and its loading condition.

The girders tested under bending consisted of two types of specimens: a) panel specimens and b) full-length specimens. At the beginning of the test program, fourteen panel specimens (Series A) were tested under bending. The details of panel type specimens are shown in Fig. 2. The loading fixtures were bolted to the panel specimen as shown in Fig. 3. The economy of using panel specimens was offset by the complexity of the connections between the specimen and the loading fixtures. Therefore, full-length specimens were used for the rest of the program. A total of twenty-nine full-length specimens were tested in bending. These specimens were divided into two groups:

1. Twenty-three specimens with A514 steel flanges and A36 steel webs (Series B, D, and G).

2. Six specimens with A441 steel flanges and A36 steel webs (Series H).

In the first group, three specimens had both transverse and longitudinal stiffeners. The rest of the specimens of the above two groups had transverse stiffeners only. Figure 4 shows the details of one of Series B (full-length) specimens. The specimens of Series D and H were essentially the same, as those of Series B except for some minor details. The details of specimens G1, G5 and G5A of Series G are shown in Fig. 5. The girders G3 and G4 were similar to specimens G5 and G5a. The only difference was the web slenderness ratio, β (ratio of web depth to web thickness). The girders G3 and G4 had a web slenderness ratio of 198 while specimens G5 and G5A had a β-ratio of 242. It is also important to note that except for Series G specimens, which had 48-inch web depth, all other specimens had 36-inch web depth.

Girders G6, G7, and G8 were tested under shear loading. The loading arrangement for these girders is shown in Fig. 6. The details of the above three specimens are shown in Fig. 7. Specimen G8 had transverse stiffeners. The data from panels closest to the end supports of six bending specimens were also used in the analysis for shear loading condition because such end panels were subjected mainly to shear with negligible bending moment.

A total of seventeen specimens were tested under combined bending and shear. According to the panel aspect ratio, α (panel length/web depth), the specimens were divided into three groups:

1. Two specimens with α of 0.5.
2. Thirteen specimens with α of 1.0.
3. Two specimens with α of 1.5.

The details and loading arrangements for each group of specimens are shown in Fig. 8.

Out of sixty-three specimens tested, three specimens (combined bending and shear with α of 1.0) had 8-inch stiffener cut-offs. In other words, the distance from the tension flange to the end of the stiffeners was 8 inches. The rest of the specimens had a standard 2-inch stiffener cut-off except for Series G specimens which had 3/4-inch cut-off. Except for the six girders in bending, which had A441 steel flanges and A36 webs, all others had A514 steel flanges and A36 steel webs. In the remainder of this report, if a girder or a specimen is not mentioned specifically as having A441 flanges, it should be understood that it refers to a hybrid plate girder with A514 steel flanges.

Physical properties of plate materials were determined by tensile coupon tests. The static yield stress, σ_y , ultimate stress, σ_u , and percent elongation are given in Table 2 for each series of specimens tested.

2.2 Specimen Designations

Eight specimens (Series G)[7,8,9] were designated as G1, etc. as given in Tables 3 and 4. These specimens were subjected to a maximum and minimum stresses of 45 and 25 ksi. All other specimens were so labeled that characteristic information can be read from their designations as follows:

a) The first number indicates the thickness of the web plate in sixteenths of an inch.

b) The next two numbers represent the minimum flange stress in ksi under fatigue loading.

c) The following two numbers denote the maximum flange stress in ksi under fatigue loading.

d) The following letter represents the series to which the specimen belongs. If a letter R (or RR) follows a girder name, this indicates that a second (or third) tests was performed on a specimen with parameters identical to those of the original specimen.

For example, girder 32050DR had a web thickness of 3/16-inch and was subjected to minimum and maximum stresses of 20 and 50 ksi respectively. This girder, one of Series D specimens, has parameters identical to specimen 32050D. It is a duplicate test. In Series C, the number after the letter "C" is the stiffener cut-off, the distance between the tension flange and the bottom end of transverse stiffener, in inches. In Series F, the numbers after the letter "F" represents aspect ratio. For example, 32540F05 and 32540F15 denote girders with α-values of 0.5 and 1.5 respectively.

2.3 Test Procedure

The girders were simply supported and were subjected to repeated loads by a pulsator and two hydraulic jacks of 120 kips dynamic capacity each, at a constant speed of about 250 cycles per minute. Sufficient lateral supports were used to prevent any tilting of the specimen during the tests.

Each specimen was loaded first statically to P_{max} in predetermined load intervals. It was then unloaded to P_{min} and finally to zero load. P_{max} and P_{min} are the applied loads which produce the desired fatigue loading.

During the static load tests, deflections were measured at the supports, load points, and centerline. Lateral web deflections of the tests panels were measured with a movable head dial rig. Two uniaxial strain gages were installed at the top and bottom flanges of each girder at midspan to check the desired maximum and minimum stresses.

During the fatigue tests, a visual inspection of all welds and the heat affected areas due to welding was made with the aid of a magnifying glass at 3 hour intervals. For this purpose the girders were whitewashed prior to static tests. However, a more frequent observation was made after the first crack was noted and continued until the end of the fatigue testing. The growth of cracks was marked and measured at each inspection period.

2.4 Test Results

The results are presented in tablular form. In Tables 3,4, and 5, the number of cycles at which cracks were initiated is given for each girder. The specimens were subjected to at least two million cycles if no fractures appeared.

Table 3 shows the results of specimens tested in bending. It includes panel specimens of Series A and full-length specimens of Series B, D, G, and H.

The last column of Table 3 refers to the types of cracks noted. The typical fatigue cracks observed in bending specimens are shown in Fig. 9.

Table 4 summarizes the results of the girders of Series B and G which showed typical shear cracks (Fig. 10a). Since hybrid plate girders tested under shear can be related to homogeneous plate girders subjected to shear, pertinent tests results of five homogeneous plate girders[10] are also included in Table 4.

Table 5 contains the results of combined bending and shear girders (Series C and F). Typical fatigue cracks noted in the above girders are shown in Fig. 10b. Type 4 cracks were observed only in specimens with 6-inch stiffener cut-offs.

3. DISCUSSION OF RESULTS - BENDING TESTS

3.1 General

The results of forty-three specimens tested [11,12,13] under bending are discussed in the following sections. Although the test program of bending specimens consists of girders with A514 and A441 steel flanges (see Table 1), the investigation is entirely concentrated on the web behavior of these girders. This is due to the fact that it is the thin web behavior which distinguishes welded plate girders from rolled beams.

3.2 Fatigue Cracks

Test panels of hybrid plate girders subjected to a constant moment condition showed three distinctive types of fatigue cracks. These cracks are classified as Type 1, 2, or 3 depending on their locations and nature. Figure 9 shows these cracks in a test panel. In Fig. 11 the photographs of the above cracks as observed in a test specimen are shown.

3.2.1 Type 1 Cracks

These cracks appear at the top of the compression flange-to-web fillet weld, in the heat affected zone of web. Formation of this type of crack can be attributed to excessive lateral movements of the web under cyclic loading. The lateral web movements induce secondary bending stresses which cause the initiation of Type 1 cracks.[9,13]

Large initial web lateral deflections (eccentricity) and a considerable movement of the web during the fatigue cycling will result in Type 1 cracks. To avoid the formation of this type of crack the interaction of these two factors should be considered.

3.2.2 Type 2 Cracks

These cracks start below the neutral axis at the stiffener-to-web juncture and close to the cut-off end of the transverse stiffeners. The local stress concentration due to the abrupt termination of stiffeners and the longitudinal bending stresses are responsible for the initiation of this type of crack. Because they are located in the tension side of the girder, they propagate faster than Type 1 cracks. Type 2 cracks are difficult to repair and they produce complete failure after reaching the tension flange.

3.2.3 Type 3 Cracks

Type 3 cracks are those which start in the tension flange and are divided into three groups according to point of origin.

The first group, Type 3a, includes those cracks which initiated at the flange to web juncture. Such a crack is mainly due to incomplete penetration of the fillet weld leaving an internal stress concentration point or to discontinuities on the weld surface as a result of manual welding operation.

The second group, Type 3b, includes those cracks which inititiated at the edge of the tension flange due to the presence of notches. Such notches are formed, as a result of the flame cutting process, by a sudden increase in oxygen pressure to the cutting torch or an uneven travel speed of the cutting torch.

The third group, Type 3c, was detected in panel specimens at the re-entrant corners of the tension flange. Type 3 cracks, similar to Type 2 cracks, propagate faster than Type 1 cracks. Attempted repairs of these cracks proved to be unsuccessful because they reappeared in the same place after a small number of additional cycles. It is important to note that the formation of Type 3 cracks is not related to hybrid feature of the girders tested.

3.3 Crack Loactions as Compared with Homogeneous Girders

In Fig. 12a, the crack locations for hybrid and homogeneous plate girders under constant moment are shown. Type 2 cracks were found in both hybrid and homogeneous girders. This is due to the fact that stress concentration induced by the transverse stiffeners is unavoidable in both cases. Type 1 cracks were found in the hybrid girders tested under constant moment. At those places (on the compression side) where the calculated secondary bending stresses were higher than the static yield stress (σ_{yw}) of the material of the web, Type 1 cracks were noted.[13]

3.4 Initial Web Eccentricity

The initial deflected shape of the web and its magnitude have a considerable influence on the fatigue behavior of plate girders. The maximum initial web eccentricities [$(\delta_o)_{max}$] were measured for Series A, B, and D specimens and are given in Table 3. These measured values are compared with the limiting values recommended by AWS Specifications[14] in Figs. 13 and 14. The data for girders with $\beta > 150$ are shown in Fig. 13. Figure 14 shows the data corresponding to girders with $\beta < 150$. The measured $[\delta_o]_{max}$ values were less than the limiting values recommended by AWS Specifications.

3.5 Slenderness Ratio

Web slenderness ratio, β, is one of the factors to consider in design practice. The limiting β-ratio suggested in Reference 18, Formula 19a is obtained by equating the theoretical web bucking stress to the allowable stress:

$$\frac{b}{t} = 4.6\sqrt{\frac{E}{\sigma_w}}$$

$$= 4.6\sqrt{\frac{30,000}{60}}$$

$$= 100+$$

This represents max β for hybrid beams with flanges of 100 ksi yield.

For hybrid beams with flanges of less than 100 ksi yield, a higher β ratio is calculated as suggested in Ref 15 as follows:

$$(\beta)_{lim} = 100\sqrt{\frac{100}{\sigma_{yf}}} \quad (3.1)$$

where σ_{yf} is in ksi. For a girder with a flange steel of 100 ksi yield stress the limiting web slenderness ratio, according to equation 3.3 will be 100.

Table 6, to be used later for the discussion of regression analysis, shows that only one specimen (32550B) having 3/16-inch web thickness showed Type 1 crack. No other specimen with web thickness of more than 3/16-inch had Type 1 crack. Further, it is important to mention that specimen 32550B had the largest maximum initial web eccentricity among 3/16-inch web girders.

Since all the girders reported in Table 6 had 36 inches web depth, the 3/16-inch web thickness corresponds to a web slenderness ratio of 192. Also, it should be noted that the specimens having 3/16-inch web thickness or more have been stressed up to 50 ksi, close to the allowable value given in Reference 15:

$$\sigma_{af} = \sigma_f \left[\frac{12 + \rho(3\zeta - \zeta^3)}{12 + 2\rho} \right] \quad (3.2)$$

where

$$\rho = A_w/A_f$$

$$\zeta = \sigma_{yw}/\sigma_{yf}$$

and

$$\sigma_f = 0.55\sigma_{yf}$$

The maximum value of the allowable stress, σ_{af}, obtained from equation 3.2, for the girders tested is 54 ksi. Thus, the lmmiting β-ratio of 100 suggested[15] for hybrid plate girders with flange steel of 100 ksi steel seems to be too conservative.

Based on the experimental results, a limiting β-ratio of 150 can be suggested for the design purpose for hybrid girders with A36 web steel. Thus, equation 3.1 would be:

$$(\beta)_{lim} = 150\sqrt{\frac{100}{\sigma_{yf}}} \tag{3.3}$$

where σ_{yf} is in ksi. This equation indicates that for a flange with 100 ksi yield stress, the limiting β-ratio is 150. AASHO Specifications[16] suggest a maximum β of 165 for girders with A36 steel webs not stiffened longitudinally.

For 500,000 and 100,000 cycles considered by AASHO Specifications[16] limiting β-ratios of 180 and 190 respectively can be used safely for flange steels of 100 ksi yield stress. It can be seen from Table 6 that even for specimens with β-ratio of 295, no Type 1 cracks were found before 100,000 cycles. Limit values of 180, 230, and 280 for β are suggested for fatigue life of 2,000,000 cycles, 500,000 cycles and 100,000 cycles respectively. For β-ratios, Table 7 shows three equations together with their limiting values for the three different number of cycles mentioned above. It is important to note that the above limiting values correspond to the hybrid girders with A36 web steel.

3.6 Stress Level

An approach based on a statistical study is recommended to include the influence of stress range, σ_R. An equation derived from the regression analysis, which relates the number of cycles with the stress range, can be used for design purposes. The statistical analysis is presented at a later part of this report. The limiting values for maximum stress, σ_{max}, can be based on the static strength given by equation 3.2.

3.7 Transverse Stiffeners

The abrupt termination of the transverse stiffeners in the tension side, as mentioned earlier, produces stress concentration resulting in the formation of Type 2 cracks. The results in Table 3 indicate that only two specimens, 42550B and 32050DR, had Type 2 cracks before 500,000 cycles. These two specimens were loaded to a maximum stress of 50 ksi, the highest σ_{max} value tested so far at The University of Texas, add closer to the allowable stress suggested in Reference 15.

The results permit the statement that girders with transverse stiffeners are adequate for bridges designed to a fatigue of 500,000 cycles or less. The above statement is true for both A514 and A441 steel flanges. However, special provisions are necessary to design for a fatigue life of two million cycles. Reference 15 indicates that the fatigue strength of girders with transverse stiffeners can be related to that of a transverse butt weld on two plates. Thus, designs for a fatigue life of more than 500,000 cycles can be based on the fatigue tests results of butt welds on steel plates having the same properties of those used for the flanges of hybrid plate girders.

3.8 Longitudinal Stiffeners

Test results[7,8,9] indicated that longitudinal stiffeners reduce the lateral web movements and thus prevent Type 1 cracks. Two specimens of Series G (see Table 1) had both transverse and longitudinal stiffeners. Specimen G3 was first tested without longitudinal stiffeners and Type 1 cracks were noted. When this specimen was retested after repairing Type 1 cracks and adding longitudinal stiffeners, no Type 1 cracks were observed. Specimen G4 had longitudinal stiffeners prior to testing. Type 1 cracks did not form in this specimen during the test.

For both specimens G3 and G4, the longitudinal stiffeners were placed at a distance h/5, where h is web depth, from the compression flange (Ref. 15). The longitudinal stiffeners can be preferrably placed at a distance h/5 from the compression flange so that the resulting reduced web slenderness ratio will be lower than the β-ratio recommended in Section 3.5.

3.9 Aspect Ratio

Except for Series G specimens, all others tested in bending had an aspect ratio, α, of 1.0. The available test data are not sufficient to make any conclusions about the limiting value for α.

3.10 Series H Specimens (with A441 flanges)

All the specimens of this series, with A441 steel flanges, were subjected to a maximum stress of 30 ksi. This maximum stress is above the allowable stress ($0.55\sigma_{yf}$) for a homogeneous girder of A441 steel, without the reduction of the allowable stress suggested in Reference 15 for hybrid plate girders.

Table 3 shows that no Type 1 cracks were noted in these girders. The web slenderness ratios of these specimens were 144 and 192, both higher than the limiting β-ratio of 141 obtained by using equation 3.1. For the limiting values of β, equation 3.3 can be used also for A441/A36 girders with proper value for σ_{yf}.

3.11 Regression Analysis

The relationships between various variables and fatigue life of girders can be obtained mathematically by multiple regression analysis. The dependent variable throughout the analysis was the number of cycles, N, that a specimen withstood before a crack was first observed. A mathematical model of the following form has been used to correlate the available data:

$$\log N = C + C_1 \text{ Log } X_1 + C_2 \log X_2 \; . \; . \; . \; . \; . \; . \; . \qquad (3.4)$$

where

N	=	number of cycles to first crack
$X_1, X_2 \ldots$	=	different parameters considered
$C, C_1, C_2 \ldots$	=	coefficients to be evaluated by the analysis.

The regression analysis was carried out in a stepwise manner using a Fortran Computer program as described in Reference 13. The method[17] essentially consists of a stepwise analysis using an "F" distribution to test for significance. F-distribution or the analysis of variance permits a check on the possibility of a relationship between the variables considered. If there is a relationship, the computed values would be expected to be closer to the observed values, and the variation measured by the standard error of estimate would be relatively small.

A sequence of multiple regression equations was obtained. At each step one variable was added to the regression equation and its effect was checked. A level of significance of 0.01 was considered sufficient to include a variable and a 0.005 significance level was used for the removal of a variable. These limits were considered sufficient for any practical application of the equations obtained.

The data presented in Table 6 for bending specimens were used in the regression analysis. The number of cycles, given in terms of kilocycles for computational conveniences, is related to the following parameters:

1. $(\delta_o/T)_{max}$
2. σ_{max}
3. σ_R
4. β, and
5. σ_{max}/σ_{cr}.

It is necessary to point out that Table 6 includes the data of the test panels which had an actual crack and those with no cracks after two million or more cycles (run-out specimens).

In the second column of Table 6, the number of kilocycles to observation of first crack, irrespective of its type, is given for each girder. Following this, cycles corresponding to the initiation of different types of cracks are included. The ratio σ_{max}/σ_{cr} was obtained using the minimum theoretical critical buckling stress, σ_{cr}, as given by Basler.[18]

Sybstituting the recorded number of cycles for the run-out specimens and the number of cycles to first crack for the rest of the specimens, it was found that the important parameter among those considered in the analysis is the stress range, σ_R. The equation thus obtained relating the stress range and the number of cycles is:

$$\log(N \times 10^{-3}) = 5.5166 - 1.9222 \log \sigma_R \tag{3.5}$$

The correlation coefficient and the standard error of estimate of equation 3.5 are 0.8835 and 0.1689 respectively

Equation 3.5 is based on the test data of twnety-eight girders (Table 6). Three specimens (22550A, 42540A, and 42550A) had Type 3c cracks and were not included in the analysis to obtain equation 3.5. This equation can be used to limit the stress range to be applied in a hybrid plate girder under constant moment. Table 8 shows the values of stress range, obtained by means of equation 3.5, that are recommended for 2,000,000 cycles and 500,000 cycles. For a fatigue life of 100,000 cycles, equation 3.5 would give a stress range of 67.5 ksi which is above the allowable recommended for homogeneous plate girders. Equation 3.5 cannot be used for a fatigue life of 100,000 cycle since the test data did not include any specimen for this fatigue life.

A similar approach was used for the specimens with A441 steel flanges to obtain the following relationship between the number of cycles and the stress range:

$$\log (N \times 10^{-3}) = 5.9376 - 2.1064 \log \sigma_R \tag{3.6}$$

The correlation coefficient and the standard error of estimate of this equation are 0.9375 and 0.0871 respectively.

The test results of A514/A36 and A441/A36 girders are shown in Fig. 15. The plots of equations 3.5 and 3.6 are also shown in Fig. 15. Since equation 3.6 is obtained from the data of six specimens, it is recommended that equation 3.5 be used for hybrid girders with either A514 or A441 steel flanges and A36 steel webs.

4. DISCUSSION OF RESULTS - SHEAR TESTS

4.1 General

The test results of shear specimens are given in Table 4. The shear loading condition is not considered in detail in this research program. This is due to the fact that the behavior of hybrid plate girders under shear is exactly the same as that of homogeneous plate girders. It is known that shear is carried almost completely by the web of a plate girder. Thus, no advantage is gained by using hybrid plate girders for members subjected mainly to shear.

4.2 Fatigue Cracks

A limited series of tests on hybrid plate girders under predominantly shear loading were performed in order to compare their behavior with that of homogeneous girders. The results given in Table 4 show that both hybrid and homogeneous girders behave in the same way under shear. This can also be seen from Fig. 12b. The fatigue cracks produced by shear in hybrid plate girders are located at the same places and are similar in nature as those observed in homogeneous girders tested at Lehigh University.[10]

Fatigue cracks due to shear loading were mainly due to tension field action. These cracks propagate along the toe of the web-fillet weld and eventually branch into the web. The load carrying capacity of the girder is reduced considerably due to this propagation and extent of the cracks.

The design method to be followed for this loading condition is similar to that for homogenous plate girders.

5. DISCUSSION OF RESULTS - COMBINED BENDING AND SHEAR TESTS

5.1 General

Seventeen girders[19,20,21] were tested under combined bending and shear. Test results of these specimens are given in Table 5. The specimens had three different aspect ratios, 0.5, 1.0, and 1.5. Among the thirteen specimens of Series C, three had 8-inch transverse stiffener cut-offs. Figure 8 shows the details of combined bending and shear specimens.

5.2 Fatigue Cracks

Typical cracks observed in combined bending and shear specimens are shown in Fig. 12c. A comparison of Figs. 12b and 12c reveals that fatigue cracks of Types 1, 2, and 3 observed in bending specimens were also noted in combined loading specimens. Fatigue cracks of Types 4 and 5 were found only in combined bending and shear specimens.

5.3 Type 4 Cracks

These cracks were noted in Series C specimens with 8-inch transverse stiffener cut-offs. Type 4 cracks were U-shaped cracks around the bottom end of short stiffeners caused by the lateral deflection of the stiffener. These cracks, which were observed in specimens 32550C8 and 32550C8R (see Table 5), grew very slowly.

Due to the fact that the transverse stiffeners (8-inch cut-off) are shorter, the web lateral movements are not controlled and hence Type 4 cracks are induced. These cracks being closer to the neutral axis do not propagate fast and eventually stabilize. Type 4 cracks are noncatastropic and can be prevented by using transverse stiffeners with 2-inch cut-offs.

5.4 Type 5 Cracks

Type 5 cracks began near middepth of the girder at the toe of the transverse stiffener-to-web fillet weld. These cracks propagate along the transverse stiffener, eventually reaching the tension flange, and cause complete failure. In four specimens, 32550C8, 32550C8R, 42550C2, and 32550F15, the crack appeared at the toe of the loading stiffener-to-web fillet weld. Type 5 cracks like Type 1 cracks form where secondary web bending stresses are maximum.

5.5 Type 1 Cracks - A Comparison

The nature of Type 1 cracks in combined bending and shear specimens is not the same as in bending specimens. The effect of shear is apparent from the locations of Type 1 cracks for the above two loading conditions. By comparing Figs. 9 and 10b, it can be seen that Type 1 cracks in combined bending and shear specimens appeared closer to the corners of the test panels, at the tension field anchorages, while in bending specimens they were usually detected closer to the middle of the test panels.

5.6 Web Slenderness Ratio

The results show (Table 9) that one specimen (32550C2R) with β of 189 and two girders (32540F05, 32540F15) with β of 192 had no cracks and they were runout specimens. The test data are scattered and no specimen with $\beta < 139$ was tested in combined bending and shear at The University of Texas at Austin. The specimens were subjected to three different stress ranges: 15, 25, and 29 ksi. Since the limiting web slenderness ratio has to be considered in conjuction with the limiting stress range (Section 5.7), the following equation is recommended for a fatigue life of 2,000,000 cycles:

$$(\beta)_{lim} = 120\sqrt{\frac{100}{\sigma_{yf}}} \qquad (5.1)$$

where σ_{yf} is in ksi. Since no consistent trend has been found in the test results, the above equation can be used also for a fatigue life of 500,00 cycles.

From a careful study of the data presented in Table 9, which shows the different characteristics of the combined bending and shear specimens, it can be seen that no Type 1 cracks were observed before 100,000 cycles. So a limiting β value of 180 can be safely recommended for hybrid girders with A514 steel flanges and A36 steel webs. In general, the following equation is recommended for a fatigue life of 100,000 cycles:

$$(\beta)_{lim} = 180\sqrt{\frac{100}{\sigma_{yf}}} \qquad (5.2)$$

where σ_{yf} is in ksi. Table 10 shows the suggested allowable values of β for combined bending and shear specimens.

5.7 Stress Range

Regression analysis, similar to that described in Section 3.11, resulted in the following equation relating the stress range and the first crack:

$$\log (N \times 10^{-3}) = 5.172 - 1.812 \log \sigma_R \qquad (5.3)$$

The correlation coefficient and the standard error of estimate of equation 5.3 are 0.5305 and 0.3324 respectively.

Equation 5.3 is based on the test data of seventeen girders (Table 9). The test data are compared with the plots of equations 3.5 and 5.3 in Fig. 16. Equation 3.5 corresponds to bending specimens. However, in reality the test panels of the girders tested under bending had to sustain shear stresses also. From Table 11 it can be seen that the test panels of combined bending and shear specimens were not subjected to high shear stress range (τ_{max} - τ_{min}). Further, the correlation coefficient and standard error of estimate of equation 5.3 indicate a poor relationship between the number of cycles and the stress range. The following table shows the values of stress range obtained by means of equation 3.5 and 5.3 and those recommended for 2,000,000 cycles and 500,000 cycles.

	σ_R (ksi)		
Number of Cycles	Eq. 3.5	Eq. 5.3	Recommended Values
2,000,000	14.0	11.0	12.5
500,000	29.0	23.0	25.0

Equation 5.3 cannot be used for a fatigue life of 100,000 cycles since the test data did not include any specimen for this fatigue life.

6. RECOMMENDATIONS

The results of sixty-three hybrid plate girders tested at The University of Texas are discussed. These girders were subjected to three loading conditions: a) bending, b) shear, and c) combined bending and shear. Based on the test results and References 14 and 15, some design recommendations are suggested. The recommendations for combined bending and shear specimens are given in Table 12.

It is recommended that further study in combined bending and shear loading condition is necessary. This further investigation will aid a) in recommending more suitable limiting values for web slenderness ratio and for stress range, and b) in understanding the influence of shear of the fatigue behavior of hybrid plate girders subjected to combined bending and shear.

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TABLE 1 TEST PROGRAM

Loading Condition	Description of Specimens	Number of Specimens	Remarks
Bending	1. Series A specimens	14	Total Bending Specimens: 43
	2(a). Series B, D and G specimens		
	(i) with transverse stiffeners only	20	
	(ii) with transverse and longitudinal stiffeners	3	
	2(b). Series H specimens	6	
Shear	Series G specimens		Total Shear Specimens: 3
	(i) with transverse stiffeners only	1	
	(ii) with transverse and longitudinal stiffeners	2	
Combined Bending and Shear	Series C specimens (aspect ratio of 1.0)		Total Combined Bending and Shear Specimens: 17
	(i) with 2" stiffener cut-off	10	
	(ii) with 8" stiffener cut-off	3	
	Series F		
	(i) with aspect ratio of 0.5	2	
	(ii) with aspect ratio of 1.5	2	
	Total Number of Specimens	63	

NOTE:
1. Series A specimens were panel specimens. All others were full-length specimens.
2. Series H specimens had A441 flanges and A36 web. All others had A514 flanges and A36 web.
3. Three specimens in Series C had 8" stiffener cut-off. Series G specimen had 3/4" cut-off. All other specimens had 2" stiffener cut-off.

TABLE 2. PHYSICAL PROPERTIES OF PLATE MATERIALS

Series	ASTM Designation	Nominal Thickness (in.)	σ_y (ksi)	σ_u (ksi)	% Elong. in 8"
A	A514	1/2	104.71	116.37	11.91
	A36	3/8	41.54	64.68	33.71
	A36	1/4	36.66	59.04	29.52
	A36	1/8	33.87	45.90	30.43
B	SSS 100A	1/2	104.00	110.40	13.68
	A36	1/4	40.88	66.06	27.84
	A36	1/8	32.35	45.00	31.20
C	A514	1/2	111.55	121.48	12.46
	A36	3/16	49.29	67.56	23.50
	A283C[1]	3/16	42.94	61.21	30.00
	A283C[2]	1/4	37.35	62.32	30.00
D	A514	1/2	111.08	123.45	-----
	A36	3/16	51.68	62.15	-----
	A36	10 gage[3]	32.18	47.79	-----
F	A514	1/2	113.16	123.96	12.00
	A36	3/16	36.34	59.37	28.25

TABLE 2 (Cont'd)

Series	ASTM Designation	Nominal Thickness (in.)	σ_y (ksi)	σ_u (ksi)	% Elong. in 8"
G	SSS-100	5/8	109.10	122.85	31.0[4]
	A36	5/16	35.70	------	-----
	A36	1/4	38.60	------	-----
	A36	3/16	41.24	------	-----
H	A441	1/2	52.70	74.20	24.00
	A36	3/16	40.40	54.70	28.00
	A36	1/4	43.30	66.30	29.00

[1] For specimens 32550C2RR, 33550C2R, 32150C2, and 32150C2R.

[2] For specimens 42550C2, 42550C2R, and 42550C2RR.

[3] For specimens 22050D and 22050DR.

[4] Percent elongation in 2".

TABLE 3. TEST RESULTS OF BENDING SPECIMENS

Specimen Designation	β	Cycles to Initial Crack	Type of Crack	$(\delta_o)_{max}$ (in.)
21020A	295	2,927,000	No Crack	0.196
21530A	295	2,000,000	No Crack	0.189
21540A	295	294,000	1	0.206
22540A	295	1,318,700	3c	0.197
		1,722,400	1	
22550A	295	617,800	1,2	0.255
21020B	269	2,233,000	No Crack	0.230
21530B	269	2,137,300	No Crack	0.095
21540B	269	277,400	Testing Discontinued	-----
22540B	269	1,588,000	1	0.181
22550B	269	672,000	1	0.201
31020B	190	4,700,900	No Crack	0.168
31530B	190	2,104,360	No Crack	0.187
31540B	190	890,000	2	0.263
		919,000	2	
		1,132,100	2	
32540B	190	2,440,000	No Crack	0.164
32550B	190	815,300	1	0.274
		911,530	3	
41020A	141	2,311,200	No Crack	0.062
41530A	141	2,000,000	No Crack	0.038
41540A	141	630,000	3a	0.074
42540A	141	947,200	3c	0.054
42550A	141	639,500	3c	0.036
41530B	147	2,052,800	No Crack	0.043
41540B	147	974,000	2	0.120
		974,000	2	
42540B	147	3,643,000	No Crack	0.130
42550B	147	421,000	2	0.142
61530A	93	2,000,000	No Crack	0.093
61540A	93	1,394,800	2, 3a	0.135

TABLE 3 (Cont'd)

Specimen Designation	β	Cycles to Initial Crack	Type of Crack	$(\delta_o)_{max}$ (in.)
62540A	93	2,530,000	No Crack	0.131
62550A	93	479,000	3b	0.085
22050D	267	230,000	1	0.255
		544,000	3a	
22050DR	267	532,000	1	0.235
		546,000	3a	
		615,000	2	
32050D	197	566,000	3a	0.121
32050DR	197	439,000	2	0.150
		527,000	2	
		560,000	2	
G1	154	2,974,000	1	
G3*	198	576,000	1	
		665,000	1	
G4**	198	962,500	3b	
G5	242	141,000	1	
		270,000	1	
		800,000	1	
G5A**	242	2,504,100	No Crack	
31030H	192	1,842,000	2	
31530H	192	2,941,000	No Crack	
31530HR	192	2,360,000	No Crack	
41030H	144	2,041,000	2	
40530H	144	888,000	2	
40530HR	144	862,000	2	

* G3 was retested with added longitudinal stiffeners.

** G4 and G5A had both transverse and longitudinal stiffeners.

NOTE:

1. Only cracks in bending region are reported.
2. σ_{max} and σ_{min} for Series G specimens were 45 and 25 ksi respectively.
3. Except for Series G specimens, which had 48 in. web depth, all others had 36 in. web depth.
4. Series H had A441 flanges and A36 webs. All other specimens had A514 flanges and A36 webs.
5. See Fig. 10 for types of fatigue cracks in bending specimens.

TABLE 4. TEST RESULTS OF SHEAR SPECIMENS

Specimen Designation	β	Cycles to Initial Crack
G6	265	282,000
G7	195	690,000
G8	151	1,626,000
21020B	269	2,000,000
21530B	269	615,000
31020B	190	2,000,000
31530B	190	2,000,000
31540B	190	299,000
32540B	190	2,000,000
F1*	264	330,000
F2*	263	2,000,000
F3*	287	800,000
F4*	260	430,000
F5*	256	2,000,000

*Homogeneous plate girder tests reported in Reference 10 (ASTM A373 steel).

TABLE 5. TEST RESULTS OF COMBINED BENDING AND SHEAR SPECIMENS

Specimen Designation	β	Cycles to Initial Crack	Type of Crack
32550C2	176	316,000	1
		387,000	2
32550C2R	176	656,000	2
		731,000	2
		793,000	1
32550C2RR	189	326,000	1
32550C2	189	532,000	1
		1,725,000	2
33550C2R	189	2,539,000	No Crack
32150C2	189	622,000	3a
32150C2R	189	277,000	1
32550C8	176	204,000	2
		314,000	4
		314,000	4
		412,000	1
		597,000	5
		634,000	5
32550C8R	189	185,000	2
		205,000	1
		258,000	5
		394,000	1
		442,000	2
		563,000	4,5
		668,000	4
33550C8	189	299,000	1
		317,000	1
		386,000	4
		728,000	4
42550C2	139	440,000	1
		633,000	5
		781,000	2
42550C2R	139	477,000	3b
		723,000	3a
42550C2RR	139	1,896,000	3a

TABLE 5 (Cont'd)

Specimen Designation	β	Cycles to Initial Crack	Type of Crack
32540F05	192	2,123,770	No Crack
32540F15	192	2,145,860	No Crack
32550F05	192	670,710	3b
32550F15	192	210,000	1
		225,000	5
		329,300	2

TABLE 6. MULTIPLE REGRESSION ANALYSIS DATA (BENDING TESTS)

Specimen	Number of Cycles (10^3 Cycles) to				σ_{min} (ksi)	σ_{max} (ksi)	σ_R (ksi)	β	$\frac{\sigma_{max}}{\sigma_{cr}}$
	1st Crack	Type 1	Type 2	Type 3					
21020A	2,927 *				10.0	20.0	10.0	295.0	0.32
21530A	2,000 *				15.0	30.0	15.0		0.47
21540A	294				15.0	40.0	25.0		0.63
22540A	1,318.7	1,722.4		1,318.7	25.0	40.0	15.0		0.61
22550A	617.8	617.8	617.8		25.0	50.0	25.0		0.78
21020B	2,233 *				10.0	20.0	10.0	269.0	0.27
21530B	2,137.3*				15.0	30.0	15.0		0.40
22540B	1,588	1,588			25.0	40.0	15.0		0.53
22550B	672	672			25.0	50.0	25.0		0.67
31020B	4,700.9*				10.0	20.0	10.0	190.0	0.21
31530B	2,104.4*				15.0	30.0	15.0		0.32
31540B	890		890		15.0	40.0	25.0		0.43
	919		919		15.0	40.0	25.0		0.43
32540B	2,440 *				25.0	40.0	15.0		0.43
32550B	911.5			911.5	25.0	50.0	25.0		0.53
	815.3	815.3			25.0	50.0	25.0		0.53
41020A	2,311.2*				10.0	20.0	10.0	141.0	0.21
41530A	2,000 *				15.0	30.0	15.0		0.32
41540A	630			630	15.0	40.0	25.0		0.42
42540A	947.2			947.2	25.0	40.0	15.0		0.42
42550A	639.5			639.5	25.0	50.0	25.0		0.53

TABLE 6 (Cont'd)

Specimen	Number of Cycles (10^3 Cycles) to				σ_{min} (ksi)	σ_{max} (ksi)	σ_R (ksi)	β	$\frac{\sigma_{max}}{\sigma_{cr}}$
	1st Crack	Type 1	Type 2	Type 3					
41530B	2,052.8*				15.0	30.0	15.0	147.0	0.32
41540B	974.0		974		15.0	40.0	25.0		0.43
	974.0		974		15.0	40.0	25.0		0.43
42540B	3,643.0*				25.0	40.0	15.0		0.43
42550B	421.0		421.0		25.0	50.0	25.0		0.53
61530A	2,000.0*				15.0	30.0	15.0	93.0	0.32
61540A	1,394.8		1,394.8	1,394.8	15.0	40.0	25.0		0.42
62540A	2,530.0*				25.0	40.0	15.0		0.42
62550A	479.0			479.0	25.0	50.0	25.0		0.53
22050D	230.0	230.0		544	20.0	50.0	30.0	267.0	0.65
22050DR	546.0			546.0	20.0	50.0	30.0		0.65
	532.0	532.0			20.0	50.0	30.0		0.65
32050D	566.0			566.0	20.0	50.0	30.0	197.0	0.51
32050DR	439.0		439.0		20.0	50.0	30.0		0.52
	527.0		527.0		20.0	50.0	30.0		0.52

* Run-out specimens. Specimens with A514 flanges are shown. Specimens had no longitudinal stiffeners.

TABLE 7 LIMITING WEB SLENDERNESS RATIOS (β) FOR BENDING SPECIMENS

(σ_{yw} = 36 ksi)

Number of Cycles	$(\beta)_{lim}$
2,000,000	$150 \sqrt{100/\sigma_{yf}} \leq 180$
500,000	$180 \sqrt{100/\sigma_{yf}} \leq 230$
100,000	$190 \sqrt{100/\sigma_{yf}} \leq 280$

σ_{yf} in ksi.

TABLE 8 LIMITING STRESS RANGES (σ_R) FOR BENDING SPECIMENS

(σ_{yw} = 36 ksi)

Number of Cycles	σ_R (ksi)
2,000,000	14.0
500,000	29.0

TABLE 9 DATA OF COMBINED BENDING AND SHEAR SPECIMENS

** Based on actual dimensions

Girder	10^3 Cycles						σ_{max} (ksi)	σ_{min} (ksi)	σ_R (ksi)	β**	$\frac{P_{max}}{P_{cr}}$
	First Crack	Type 1	Type 2	Type 3	Type 4	Type 5					
32550C2	316	316 601	387				50	25	25	176	2.50
32550C2R	656	793	656 731				50	25	25	176	2.50
32550C2RR	326	326					50	25	25	189	2.50
33550C2	532	532	1,725				50	35	15	189	2.92
33550C2R	Run - Out Specimen						50	35	15	189	2.97
32150C2	622			622			50	21	29	189	2.96
32150C2R	277	277					50	21	29	189	2.96
32550C8	204	412 412	204		314 314	597 634	50	25	25	176	2.51
32550C8R	185	205 394	185 441		563 668	258 563	50	25	25	189	2.92
33550C8	299	299 317 318			386 728		50	35	15	189	2.93
42550C2	440	440	781			633	50	25	25	139	1.78
42550C2R	477			477 723			50	25	25	139	1.78
42550C2RR	1,896			1,896			50	25	25	139	1.78
32540F05	Run - Out Specimen						40	25	15	192	2.18
32550F05	671			671			50	25	25	192	2.73
32540F15	Run - Out Specimen						40	25	15	192	2.69
32550F15	210	210	329			225	50	25	25	192	3.37

TABLE 10 LIMITING WEB SLENDERNESS RATIOS (β) FOR COMBINED BENDING AND SHEAR

(σ_{yw} = 36 ksi)

Number of Cycles	$(\beta)_{lim}$
2,000,000	$120\sqrt{100/\sigma_{yf}}$
500,000	$120\sqrt{100/\sigma_{yf}}$
100,000	$180\sqrt{100/\sigma_{yf}}$

σ_{yf} in ksi.

TABLE 11 AVERAGE MAXIMUM AND MINIMUM SHEAR STRESSES

(Combined Bending and Shear Specimens)

Girder	τ_{max} (ksi)	τ_{min} (ksi)	$(\tau_{max} - \tau_{min})$ (ksi)
32550C2	12.34	6.16	6.18
32550C2R	12.34	6.16	6.18
32550C2RR	13.24	6.58	6.66
33550C2	12.77	8.92	3.85
33550C2R	13.32	9.30	4.02
32150C2	13.31	5.55	7.76
32150C2R	13.27	5.52	7.75
32550C8	12.39	6.20	6.19
32550C8R	12.78	6.40	6.38
33550C8	12.80	8.96	3.84
42550C2	12.60	6.17	6.43
42550C2R	12.66	6.20	6.46
42550C2RR	12.70	6.21	6.49
32540F05	9.16	5.75	3.41
32550F05	11.52	5.75	5.77
32540F15	9.16	5.75	3.41
32550F15	11.65	5.75	5.90

TABLE 12 RECOMMENDED LIMITING VALUES

Parameter	Number of Cycles	Loading Condition Combined Bending and Shear
$(\delta_o)_{max}$		AWS Specifications (Reference 14)
β	2,000,000	$120 \sqrt{100/\sigma_{yf}}$
	500,000	$120 \sqrt{100/\sigma_{yf}}$
	100,000	$180 \sqrt{100/\sigma_{yf}}$
σ_R	2,000,000	12.5
	500,000	25.0
σ_{max}	2,000,000 500,000 100,000	$\sigma_{af} = \sigma_f \left[\frac{12+\rho(3\xi-\xi^3)}{12+2\rho}\right]$ (Reference 15)

NOTE: For symbols and units, see Nomenclature.

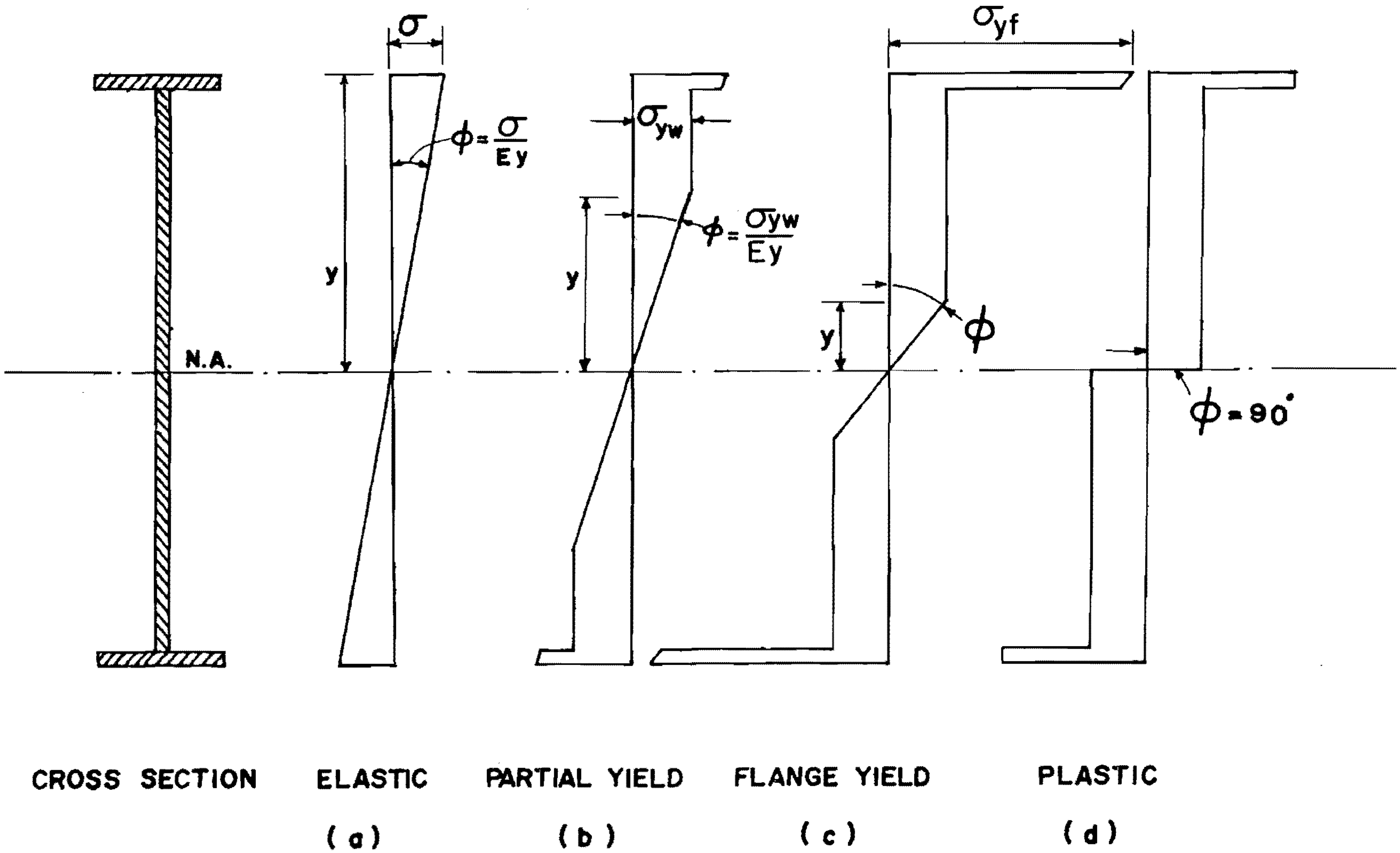


Fig. 1a. Stress conditions in hybrid girders.

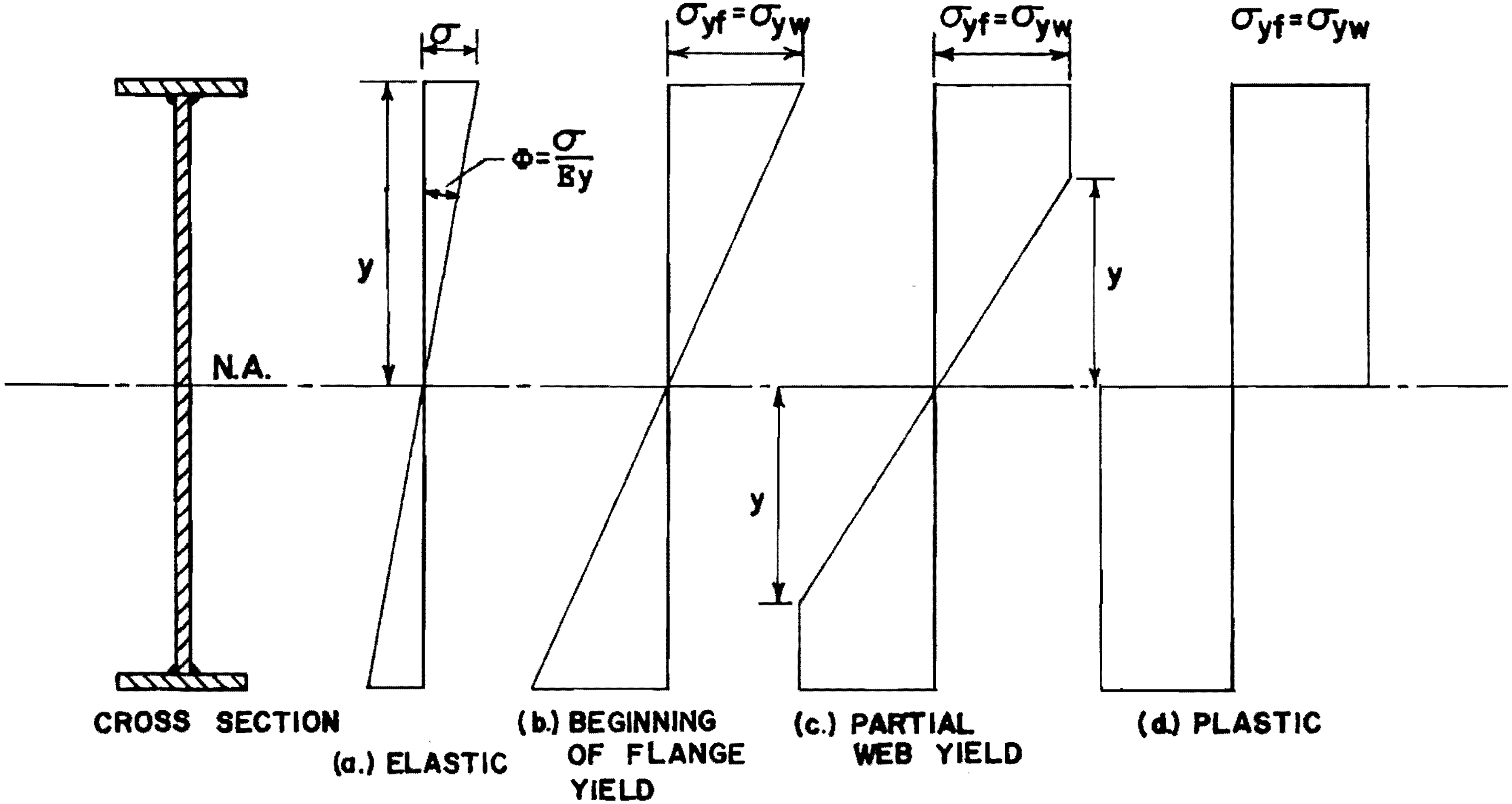


Fig. 1b. Stress conditions in homogeneous girders.

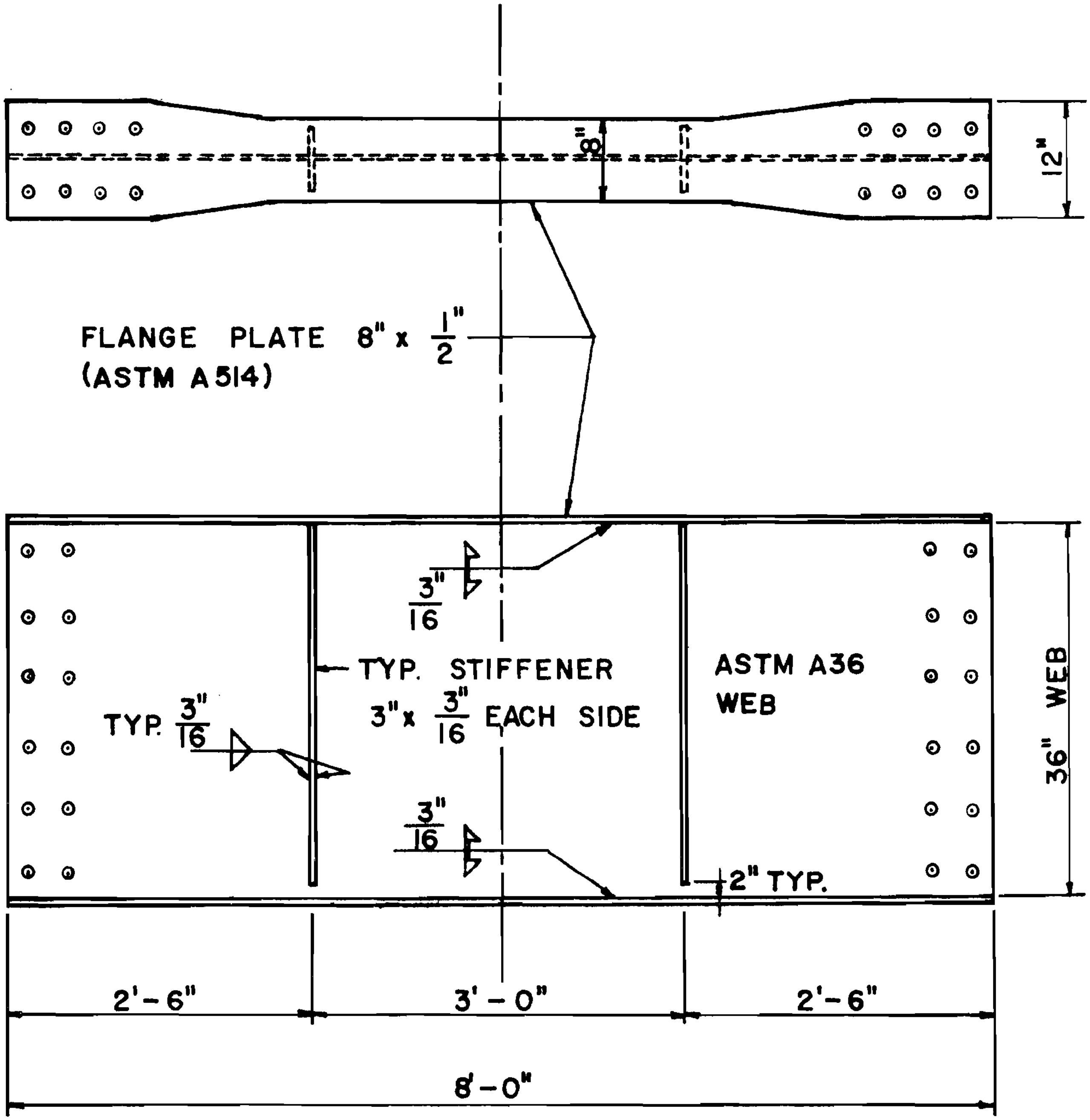


Fig. 2. Details of panel specimens.

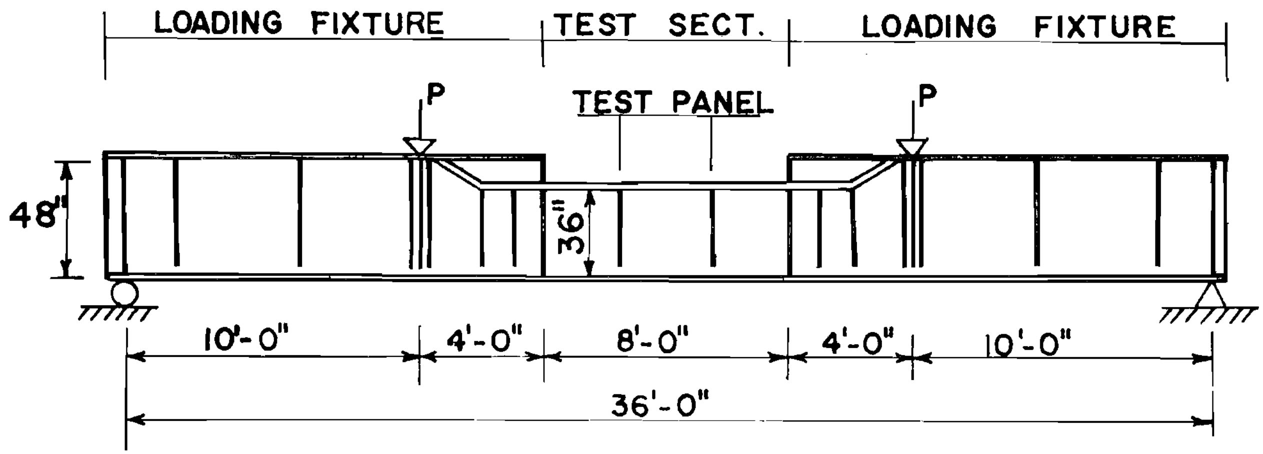


Fig. 3. Test setup for panel specimens.

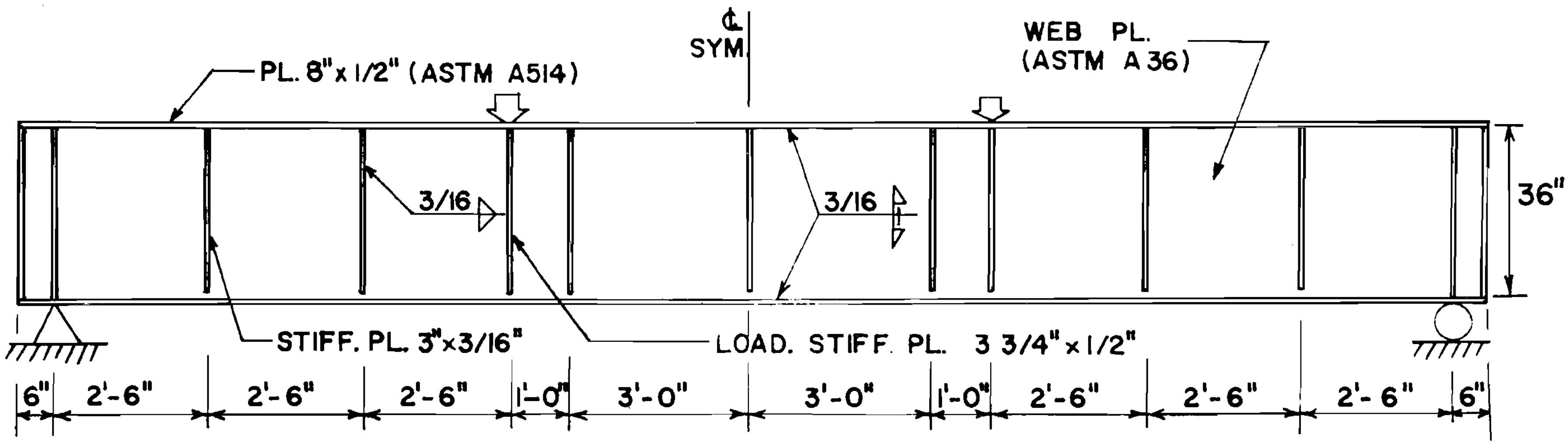


Fig. 4. Details of Series B specimens.

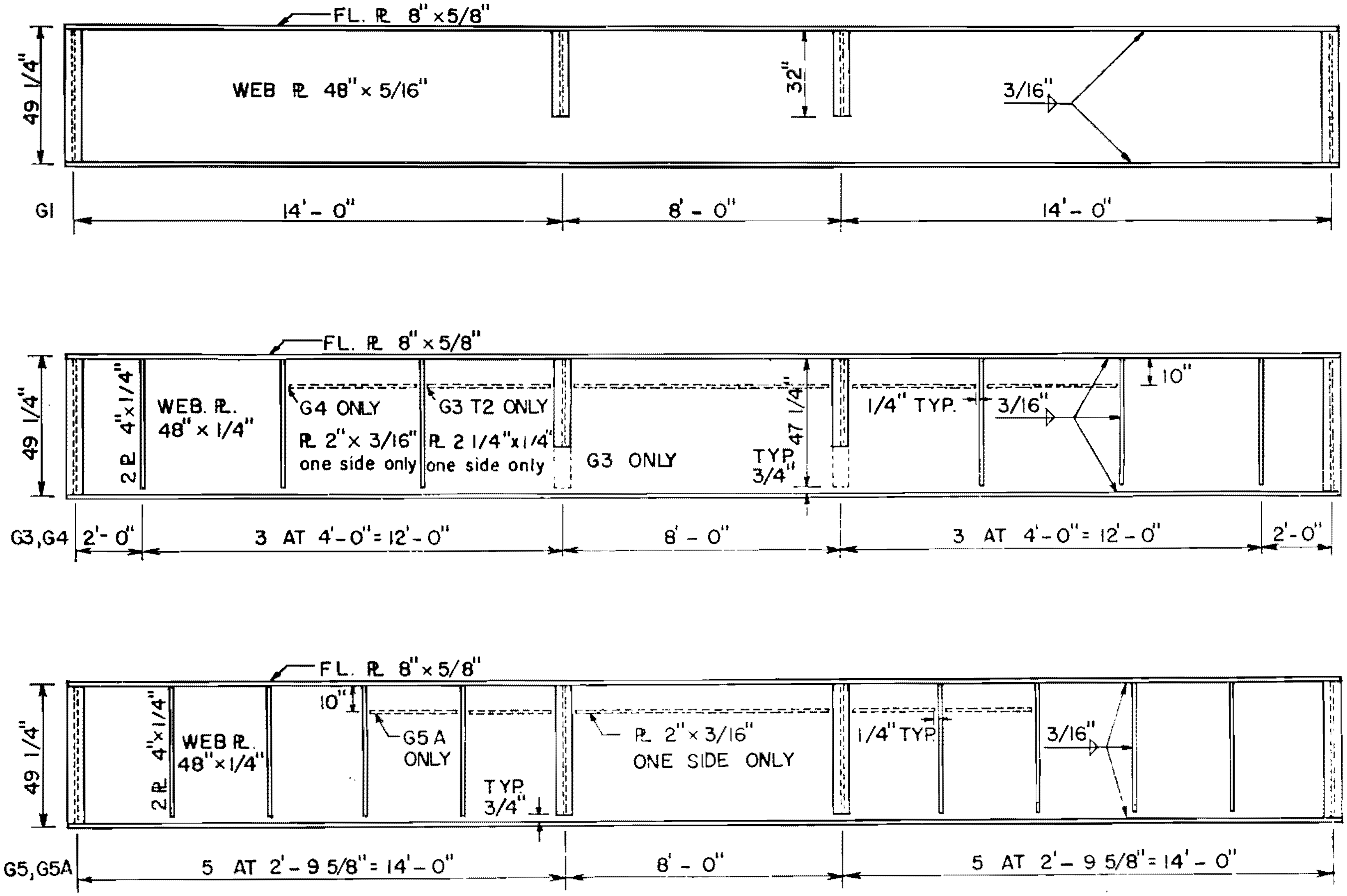


Fig. 5. Details of specimens G1, G3, G4, G5, and G5a.

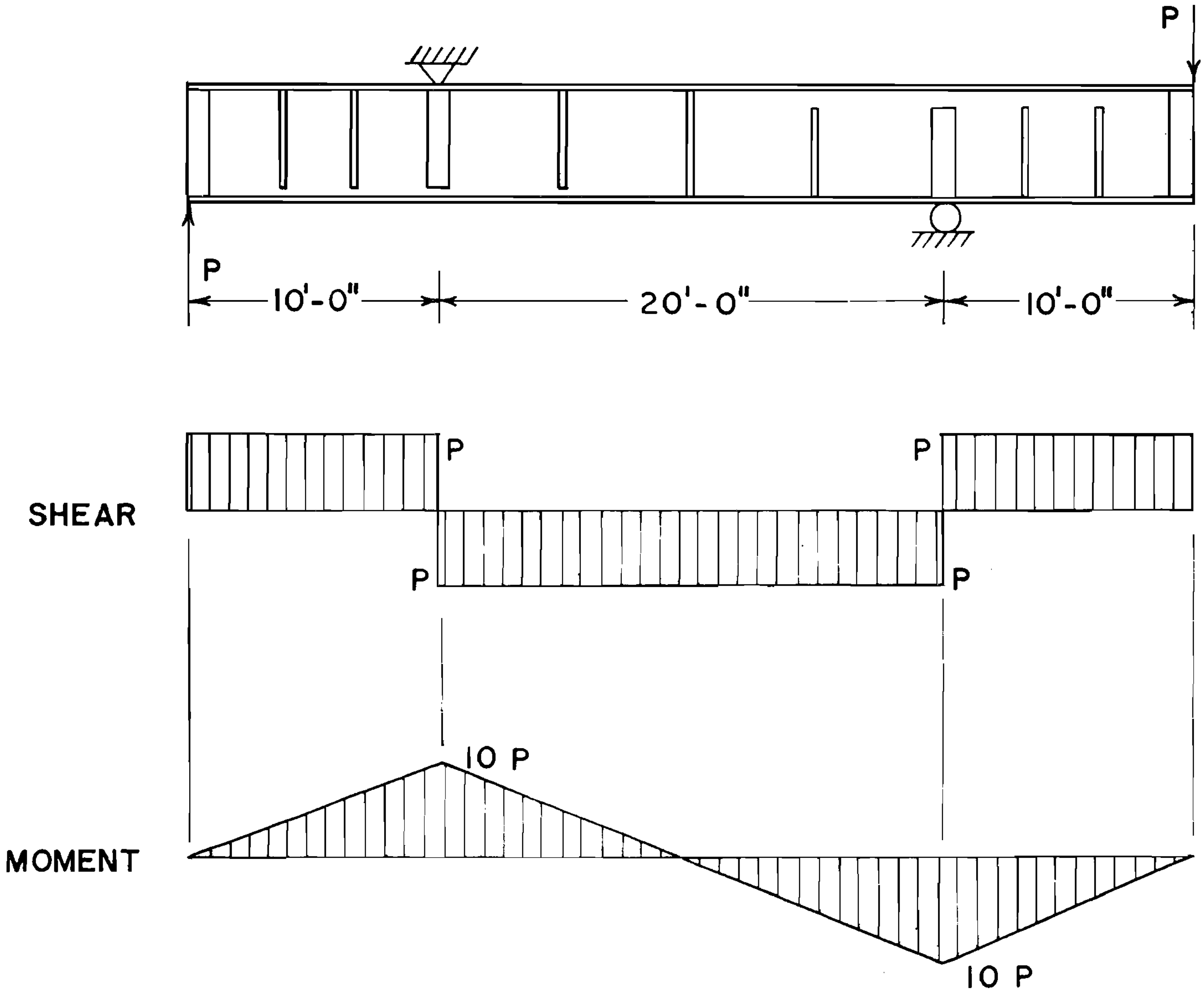


Fig. 6. Loading for shear girders (G-Series).

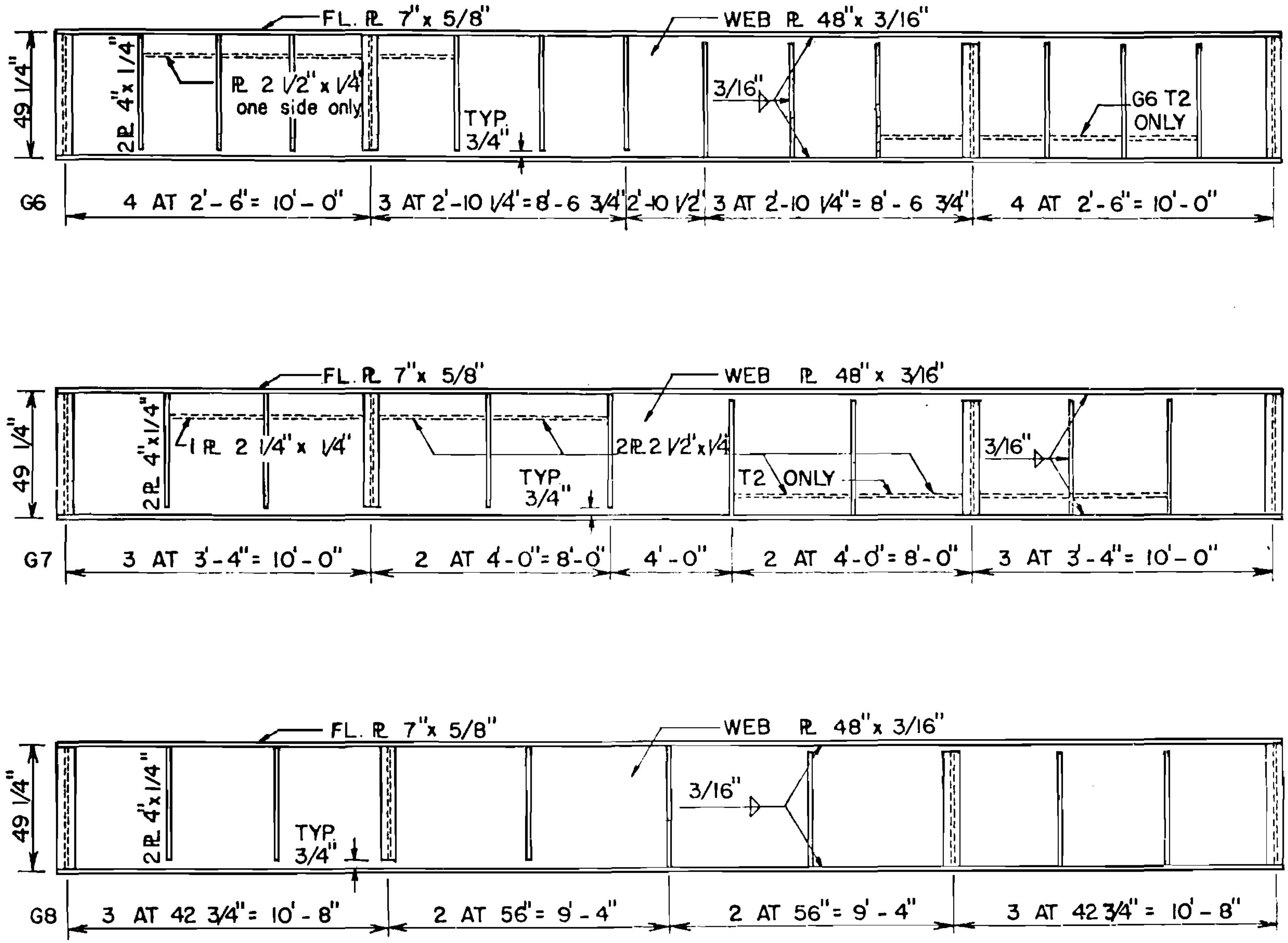


Fig. 7. Details of specimens G6, G7, and G8.

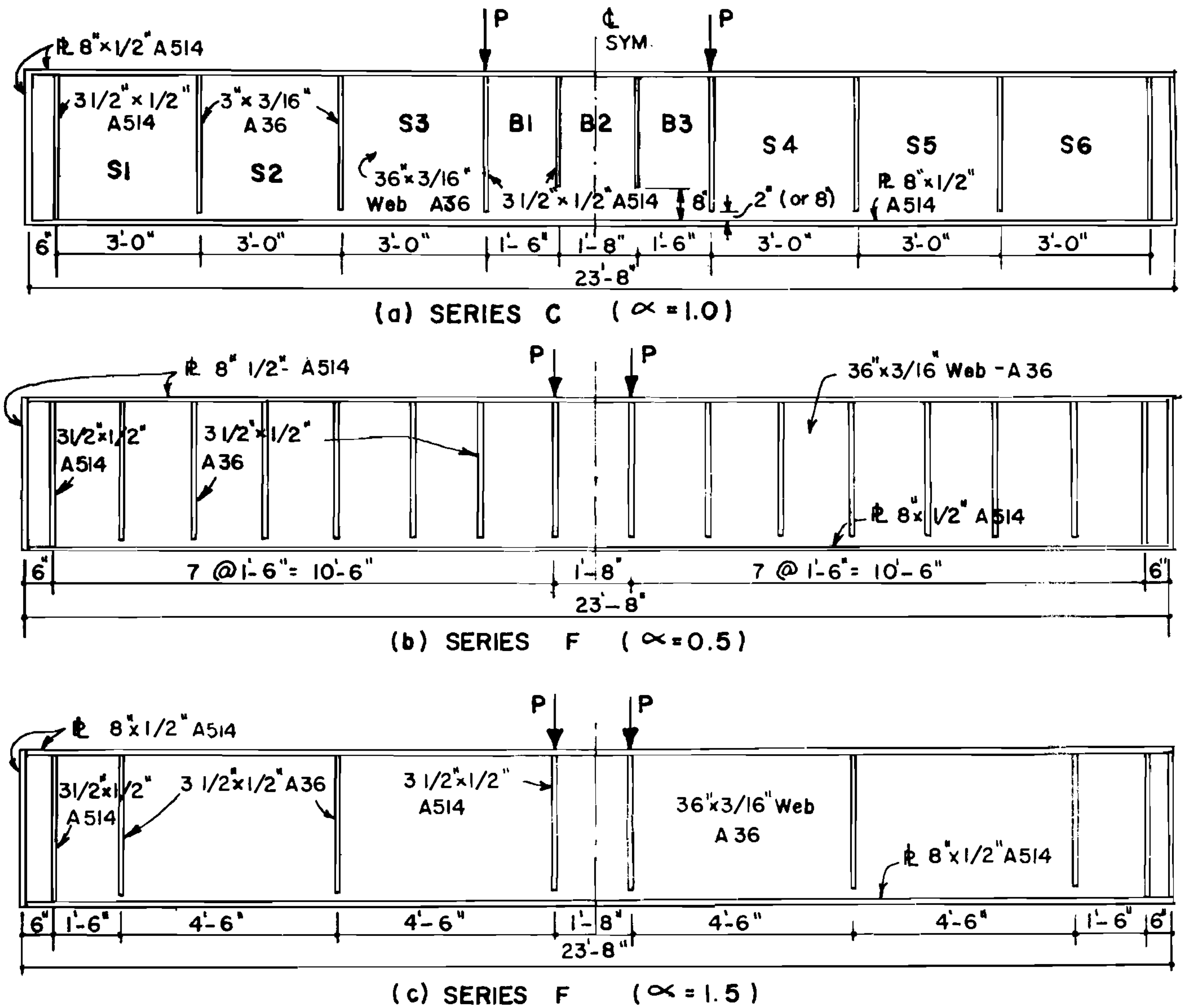


Fig. 8. Details of combined bending and shear specimens.

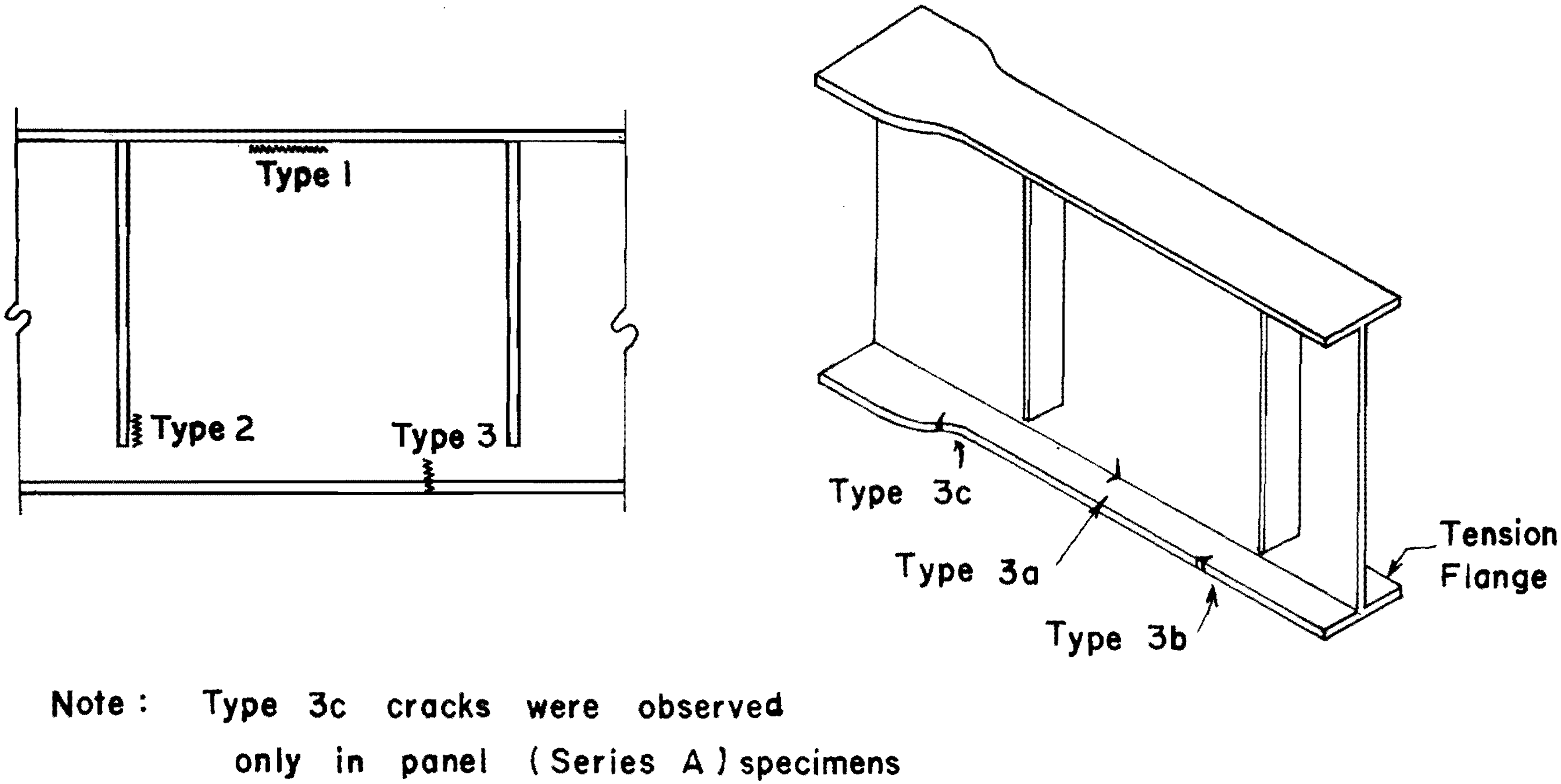


Fig. 9. Fatigue cracks in bending specimens.

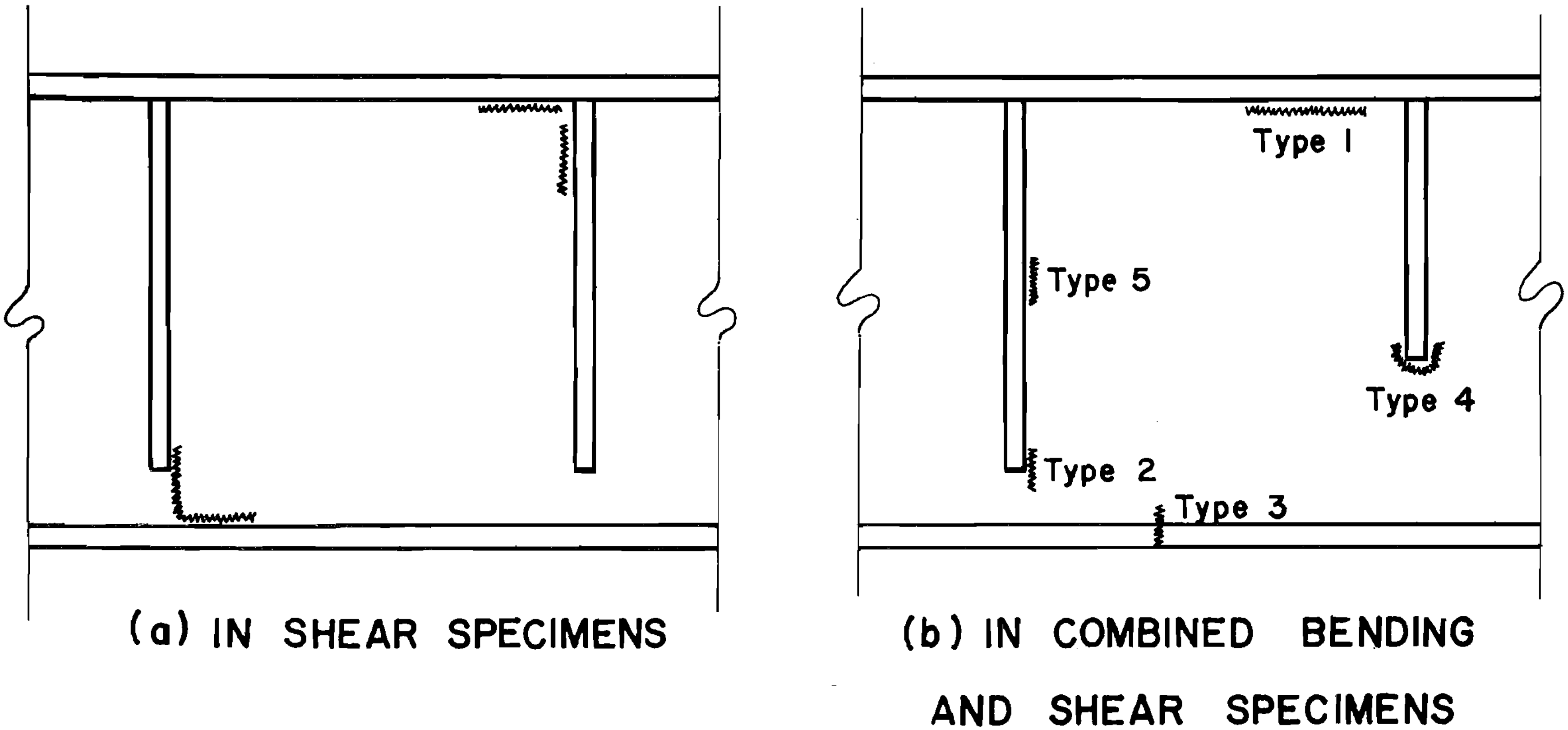
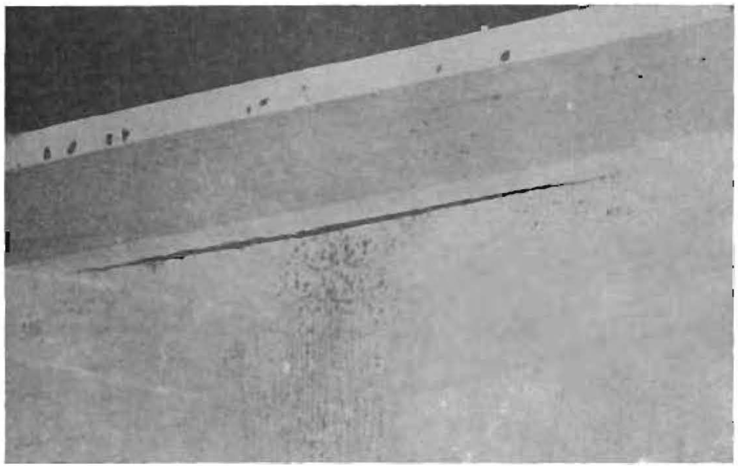
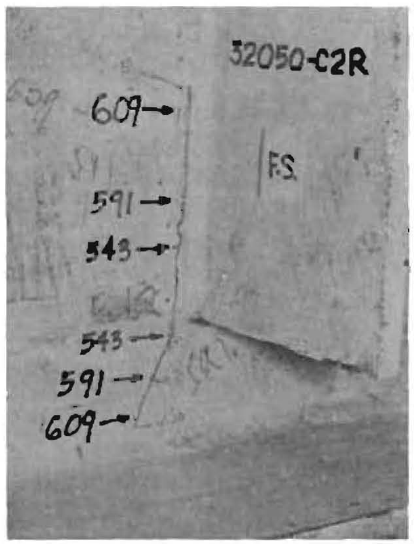


Fig. 10. Typical fatigue cracks.



(a) Type 1.



(b) Type 2.

(c) Type 3.

Fig 11. Typical cracks in bending specimen.

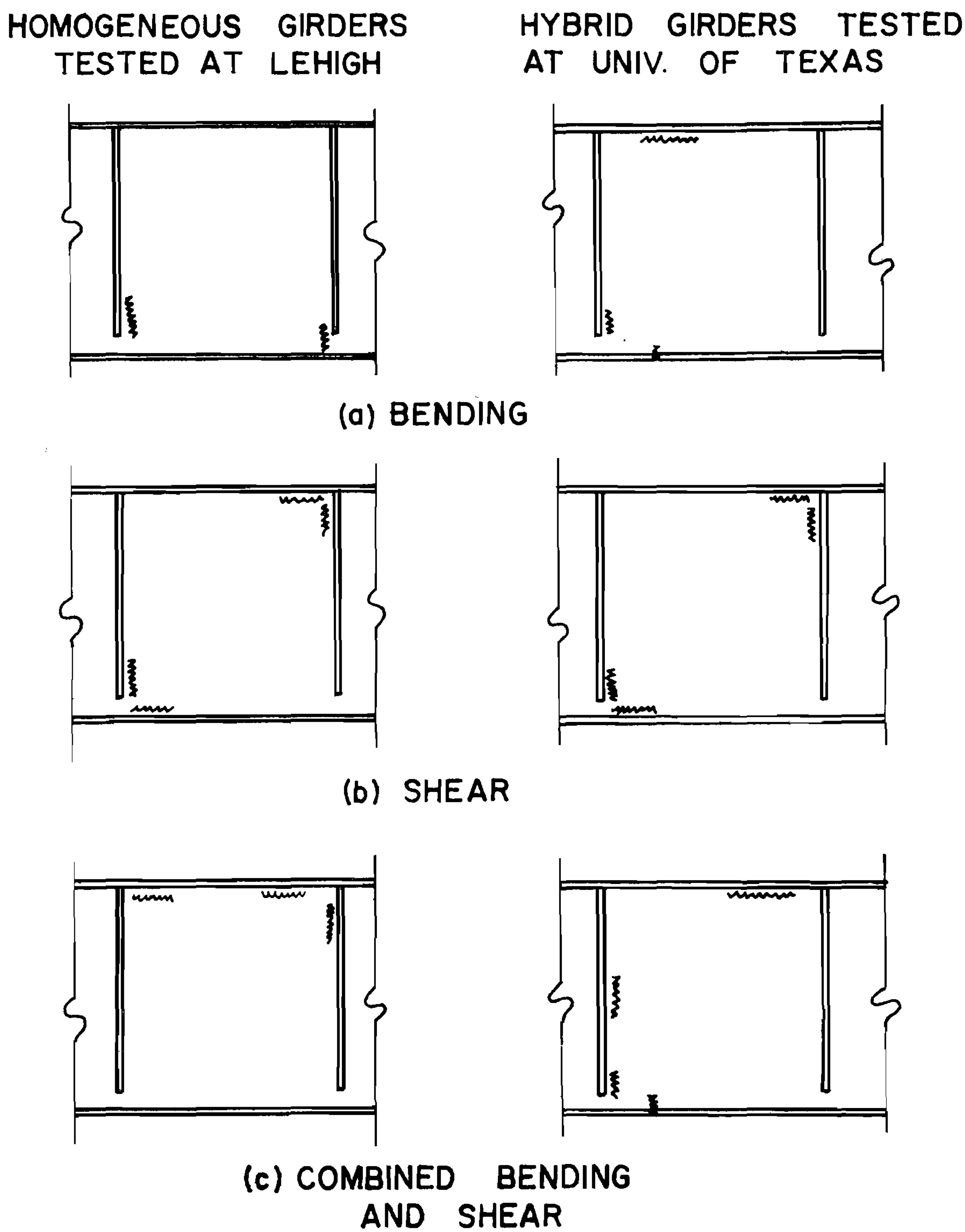


Fig. 12. Crack locations in homogeneous and hybrid girders.

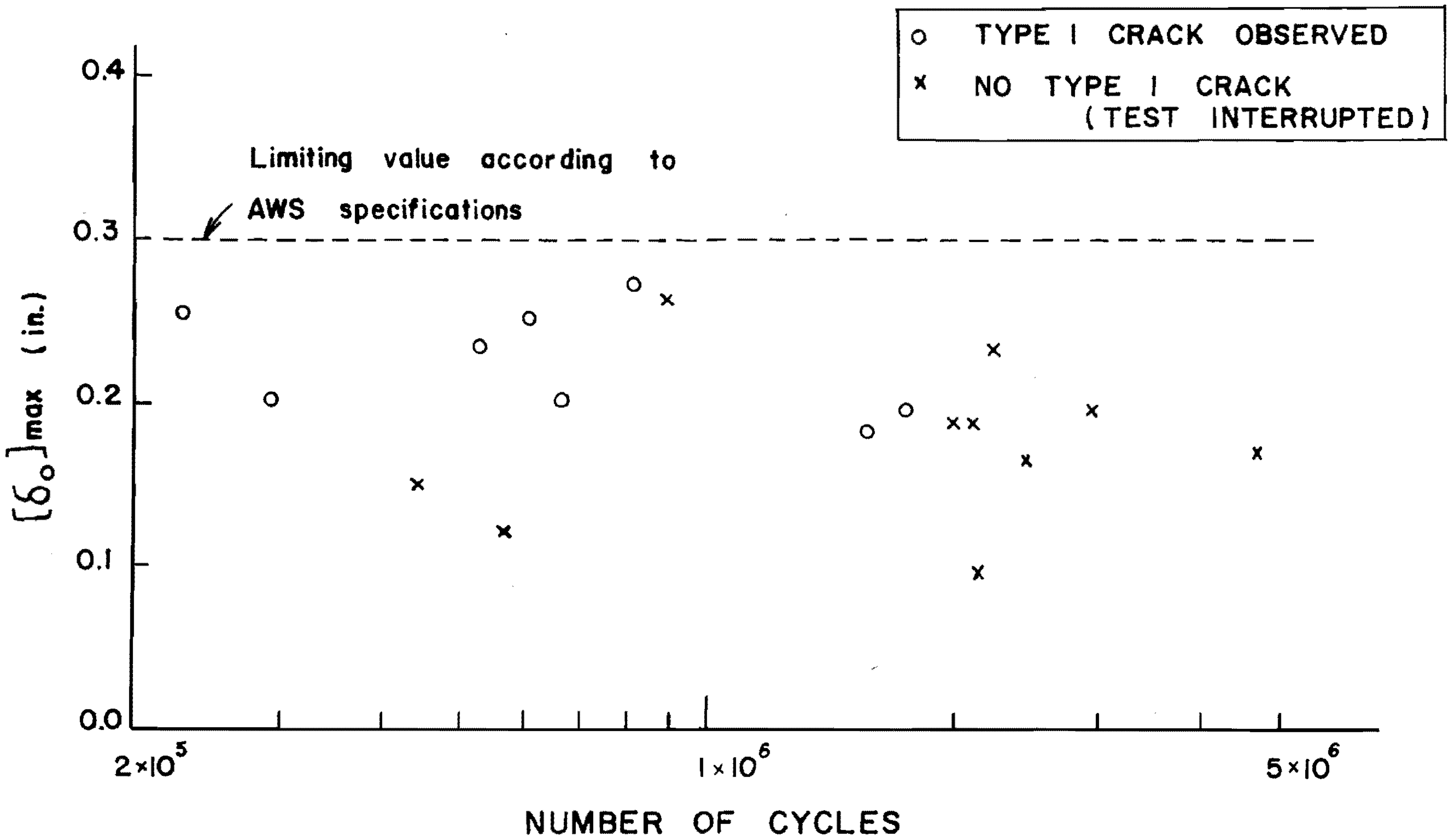


Fig. 13. Comparison of measured $[\delta_o]$max with AWS specifications ($\beta > 150$).

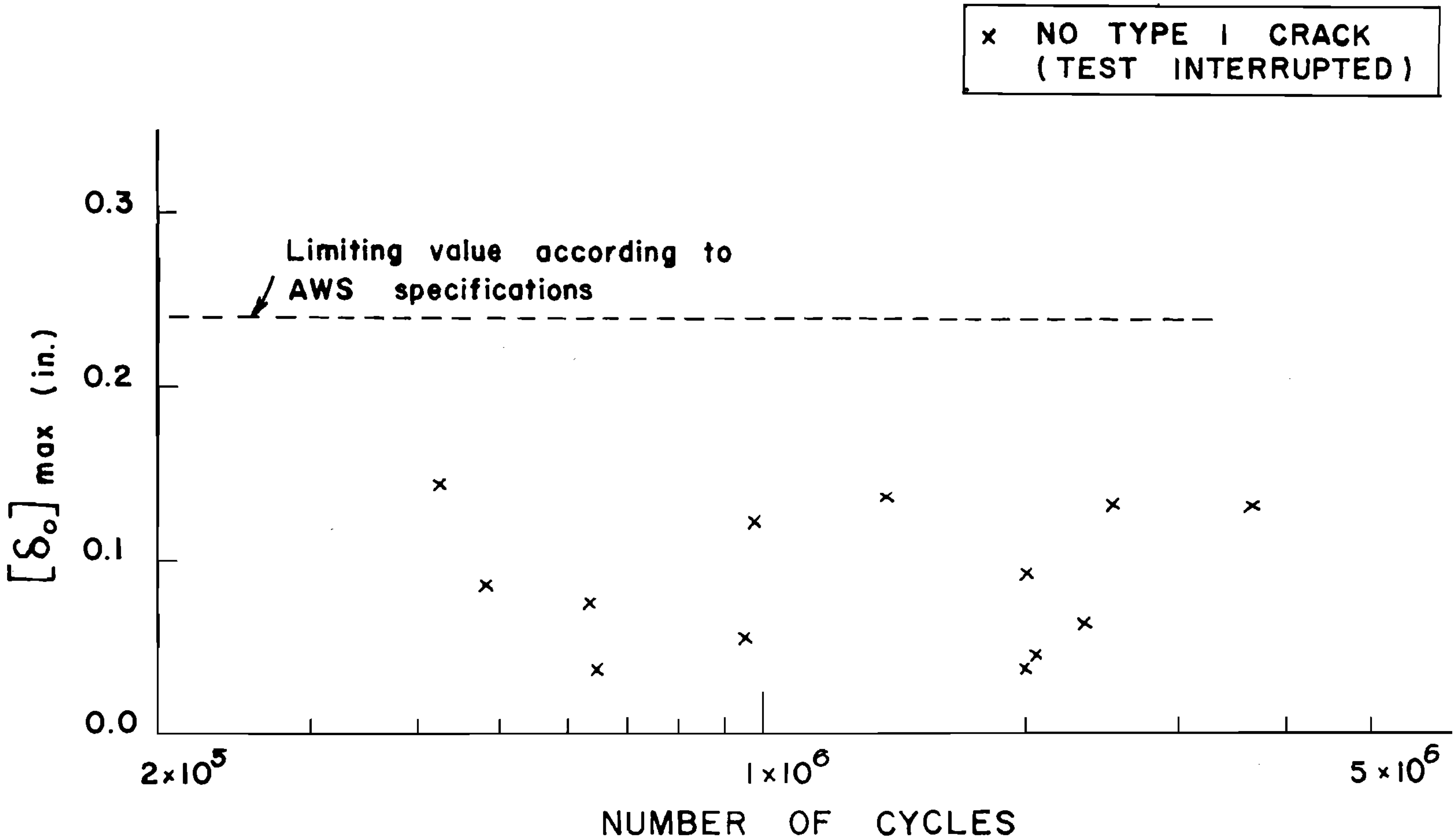


Fig. 14. Comparison of measured $[\delta_o]$max with AWS specifications ($\beta < 150$).

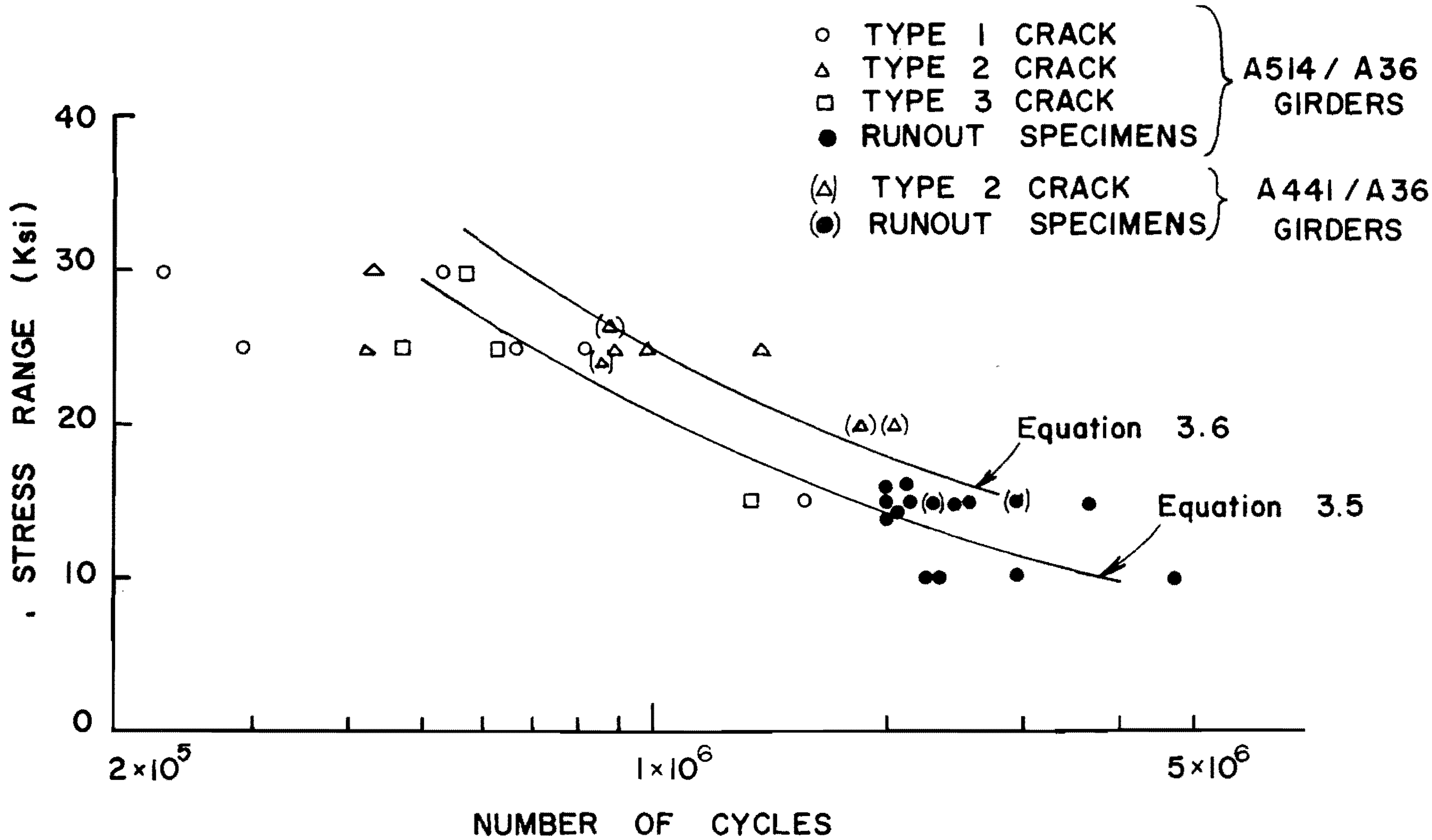


Fig. 15. Comparison of Eqs. 3.5 and 3.6 with test results (bending).

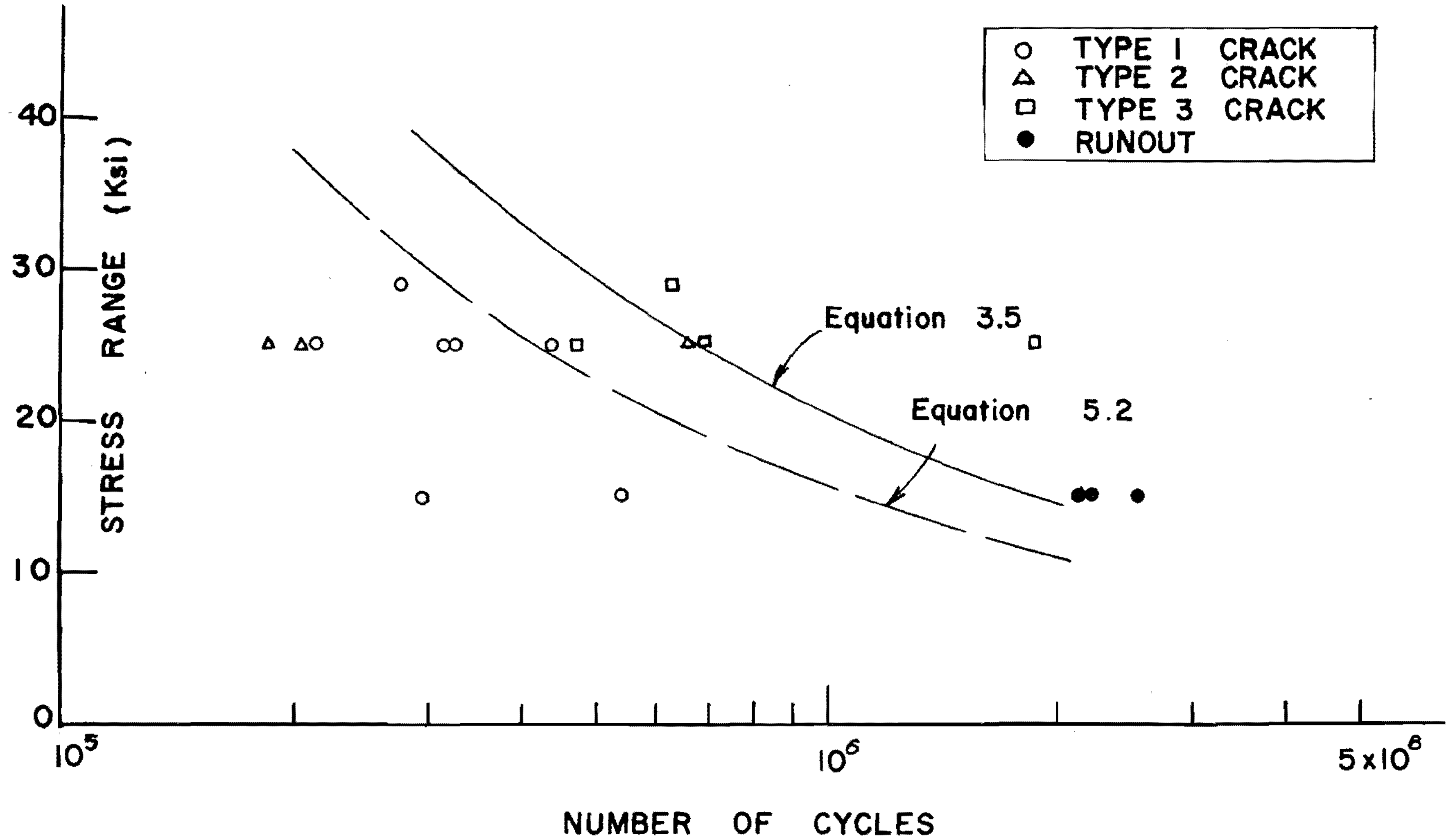


Fig. 16. Comparison of Eq. 5.2 with test data.