FATIGUE TESTS OF HYBRID PLATE GIRDERS UNDER COMBINED MOMENT AND SHEAR

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The opinions, findings and conclusions expressed in this report are those of the authors and not necessarily those of the Bureau of Public Roads.

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ABSTRACT

Four hybrid plate girders were tested in combined bending and shear. The flanges of the girders were of ASTM A514 steel and the webs were of ASTM A36 steel. The test panel aspect ratio α of two girders was 0.5 while the same for the other two specimens was 1.5. For two of the specimens, (α = 0.5 and 1.5) the applied stresses fluctuated from 25 to 40 ksi, a stress range of 15 ksi. The remaining two girders were subjected to a stress range of 25 ksi with a minimum flange stress of 25 ksi. The test results indicated that hybrid plate girders, under combined bending and shear, have a shorter fatigue life for a stress range of 25 ksi than those subjected to pure bending.

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1. INTRODUCTION

1.1 General

A light and efficient plate girder can be fabricated by using constructional alloy steel (ASTM A514) flanges and a carbon steel (ASTM A36) web. Such a 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.

A program to study both the static and fatigue behavior of hybrid plate girders was started in 1960 at The University of Texas, Austin. Test results of girders investigated in this program have been published (Refs. 1 through 7, 9, 10). The results of the last tests carried out for the overall program are presented in this report.

1.2 Previous tests in Combined Bending and Shear

The significant conclusions derived from a previous study[7] on the fatigue behavior of hybrid plate girders under combined bending and shear are:

1. Fatigue life varies inversely with flange stress.
2. Fatigue cracks initiating at the toe of the transverse stiffener-to-web fillet weld at the stiffener cutoff, Type 2 cracks,[*] led to tension flange fracture.
3. Type 1 cracks[*] at the compression flange-to-web fillet weld propagated slower than Type 2 cracks.

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[*] See Fig. 4.

4. Girders with low web depth-to-web thickness ratio (β)[*] survived more cycles of load than those with higher web slenderness ratio.

1.3 Objectives of the Investigation

The objectives of this investigation were: (1) to study the behavior of hybrid plate girders with the panel aspect ratios of 0.5 and 1.5, (2) to compare with the previous test results of combined bending and shear specimens, and (3) to determine the influence of some of the factors, such as web-slenderness ratio, on the fatigue behavior of girders.

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[*] See Nomenclature.

2. TEST PROGRAM

2.1 Test Specimens

The details of the specimens are shown in Fig. 1. The girder designations are:

	32540F05,	32550F05,
and	32540F15	32550F15.

The first figure, in the above designation, indicates the web thickness in sixteenths of an inch. The next four numbers represent the minimum and maximum extreme fiber stresses, in ksi, to which the specimen is subjected during the fatigue test. The "F" is used to identify the test series. The last two numbers, either 05 or 15, indicate panel aspect ratio of 0.5 or 1.5 respectively.

Except the end bearing stiffeners, all stiffeners were cut two inches from the tension flange to reduce the possibility of premature fatigue cracks. The flanges were fillet welded to the web using submerged automatic arc welding, with full penetration required.

The measured plate dimensions are given in Table 1. The flange width and thickness were obtained from measurements made at 10 locations on the flanges of each girder. The web thickness was obtained from measurements made on a coupon plate cut from the same plate that was used for the web. The actual web-slenderness ratio, β (ratio of web depth to thickness) obtained from the measured dimensions is 192 for all the girders.

Physical properties determined by testing tensile coupons are also given in Table 1. Two tensile specimens were cut from each coupon plate; one perpendicular and one parallel to the direction of rolling of the web plate. Tensile specimens were cut parallel to the direction of the flange.

2.2 Test Setup and Instrumentation

The specimens were simply supported at their ends and subjected to equal loads applied through hydraulic jacks as shown in Fig. 2. A pulsator and hydraulic jacks were used to apply cyclic loads at 250 cycles per minute in the fatigue tests. Sufficient lateral bracing was provided to prevent lateral buckling of the compression flange. The locations of lateral bracing are indicated in Fig. 2.

Deflections were measured at the supports, load points, and centerline. Lateral web deflections 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. These gages were employed to apply the desired maximum and minimum stresses under cyclic loads.

The coordinate system for each panel is shown in Fig. 2. The origin is at the geometric center of each panel. The positive directions of this coordinate system is toward the right for X, upward for Y and normal to the web and out of the page for Z.

2.3 Reference Loads and Test Procedure

The material properties and the dimensions given in Table 1 were used to compute reference loads for each girder. The tests were designed so that at maximum load, P_{max}, the extreme fibers of the flange were stressed to 40 ksi or 50 ksi, and at the minimum load, P_{min}, to a stress of 25 ksi, resulting in the stress ranges of 15 ksi or 25 ksi.

The reference loads are given in Table 2. The critical web buckling stress in bending, σ_{cr}, listed in Table 2 was computed according to Reference 10 using 29, 600 ksi for the modulus of elasticity and 0. 3 for Poisson's ratio. The theoretical load that causes web buckling considering interaction between flexure and shear[11] are also shown in the same table as P_{cr}.

The test procedure for each girder was as follows:

1. Initial static test: The specimen was loaded first under static load to P_{max} in predetermined load intervals. It was then unloaded to P_{min} and finally to zero load. Pertinent readings were taken at each interval of loading.
2. Fatigue test: After the preliminary static test, fatigue testing was began. Visual inspections were made throughout the test to detect initiation of cracks and to record their propagation. For this purpose the girders were whitewashed prior to static test. The cracks were numbered according to the order of discovery.

3. TEST RESULTS

3.1 Static Test Results

Each girder was subjected to a preliminary static load test during which deflection data was taken. A typical load-centerline deflection curve (Girder 32540 F15) is shown in Fig. 3 in which a theoretical line based on elastic theory is also incorporated. For each girder, lateral web deflections were measured at zero load, P_{min} and at P_{max}.

3.2 Fatigue Test Results

The results of the fatigue tests are presented in Figs. 4, 5 and 6. The crack locations shown in Figs. 5 and 6 are on the positive Z side of each specimen. A short history of the propagation of the cracks is given in Fig. 7 for specimen 32550 F15.

3.2.1 Girder 32540 F05 -- This specimen was subjected to a stress range of 15 ksi with a minimum stress of 25 ksi. The girder sustained 2,123,770 cycles with no fatigue cracks.

3.2.2 Girder 32550 F05 -- Figure 5 shows crack No. 1 in test panel S4 after 669,700 cycles. This crack started at a discontinuity point in the flange edge caused by the flame cutting operation. Propagation of this crack was fast and the test was discontinued.

3.2.3 Girder 32540 F15 -- This girder, similar to girder 32540 F05, was subjected to a stress range of 15 ksi. No fatigue cracks were observed after 2,145,860 cycles.

3.2.4 Girder 32550 F15 -- Figure 6 shows four cracks in this specimen. Crack No. 1 originated at the toe of the compression flange-to-web fillet weld. Crack No. 2 was observed in the web at the transverse stiffener-to-web fillet weld. The above two cracks were noted in the test panel T3 (Fig. 6). The location of crack No. 3 was in the test panel T2. This crack was noted in the web at the transverse stiffener-to-web fillet weld. Crack No. 4 was in the panel between the load points and it formed in the web at the toe of the transverse stiffener-to-web fillet weld near the cut-off end of the stiffener as indicated in Fig. 6. No attempts were made to repair the cracks and testing was stopped after 360,490 cycles since crack No. 2 propagated to a considerable length in the test panel T3.

4. DISCUSSION

4.1 Fatigue Cracks

Typical fatigue cracks observed in combined bending and shear specimens are shown in Fig. 4. Three distinct types of fatigue cracks were defined in Reference 5 as Types 1, 2, and 3. The above fatigue cracks and as well as Types 4 and 5 were noted in combined bending and shear specimens.

Type 1 cracks form at the toe of the compression flange-to-web fillet weld. These cracks are found at those locations where the secondary bending stresses due to lateral web deflection are greatest. A Type 1 crack was noted only in specimen 32550 F15 as shown in Fig. 6. In the same figure, two web profiles show the deflected shape of the web at P_{max} and P_{min}. These profiles were selected because they are nearest to the point where Type 1 cracks would form. At P_{max}, as indicated in Fig. 6, the web reversed its curvature near the compression flange, indicating some fixity in the flange-web connection. Due to this fixity, secondary bending stresses were induced resulting in the formation of Type 1 crack. The propagation of this crack was slow.

Type 2 cracks form in the web at the toe of the transverse stiffener-to-web fillet weld near the cutoff end of the stiffener. These cracks are always located in an area of large flexural tensile stress and propagate fast. Type 2 cracks can lead to a fracture of the tension flange and so they are considered catastrophic. A Type 2 crack was noted only in specimen 32550 F15 (Fig. 7).

Type 3 cracks are those which occur in the tension flange. These cracks can form in the flange-to-web weld as a result of a discontinuity in and around the weld or they can start at a notch in the flange edges caused by the flame cutting operation. Girder 32550 F05 failed as a result of Type 3 crack which initiated at the edge of the flange. The length of the above crack at 670,710 cycles is shown in Fig. 8.

Type 4 cracks are U-shaped cracks around the bottom of the stiffeners with 8 in. cutoff.[7] These cracks, observed only in combined bending and shear specimens, and caused by the lateral deflection of the web and stiffener have been found to be non-catastrophic. No specimen reported here had Type 4 cracks.

Type 5 cracks, observed only in combined bending and shear specimens, began near middepth of the girder at the toe of the stiffener-to-web fillet weld. These cracks propagate along the stiffener and eventually reach the tension flange, and thus cause complete failure. In specimen 32550 F15, Type 5 cracks appeared at the toe of the loading stiffener-to-web fillet weld. Type 5 cracks like Type 1 cracks form where secondary bending stresses are maximum. The only difference between these two types is their location. The propagation of Crack No. 2 (Fig. 7), which is a Type 5 crack, is shown in Fig. 9.

4.2 Web Slenderness Ratio

The test results of thirteen specimens subjected to combined bending and shear are discussed in Reference 7. Those test data and the results of the four girders reported here are given in Table 3. The results show that one girder (33550 C2R) with β of 189 and two specimens (32540 F05, 32540 F15) with β of 192 had no cracks and they lasted more than two million cycles. However, the available information is not enough to suggest a limiting value of β for a fatigue life of two million cycles.

At present, a limiting β-ratio suggested in Reference 8 is recommended:

$$(\beta)_{\lim} = 100\sqrt{\frac{100}{\sigma_{yf}}} \qquad (4.1)$$

Where σ_{yf} is the yield stress of flange material in ksi. Since no consistent trend has been found in the test results, the same limiting β-ratio is recommended for a fatigue life of 500,000 cycles.

In Table 3 the characteristics of combined bending and shear specimens are given. A careful study of this table indicates that no crack was observed in any specimen prior to 100,000 cycles. The specimens studied had four different β-ratios, 139, 176, 189 and 192. A limiting β-ratio of 150 can be safely recommended for a fatigue life of 100,000 cycles. In general, the following equation can be used for a fatigue life of 100,000 cycles:

$$(\beta)_{\lim} = 150\sqrt{\frac{100}{\sigma_{yf}}} \qquad (4.2)$$

Where σ_{yf} is the yield stress of flange material in ksi. It is important to note that the above limiting β-ratio corresponds to hybrid plate girders with A36 steel webs.

4.3 Aspect Ratio

Only two girders with aspect ratio of 1.5 were tested in combined bending and shear. They were subjected to two different maximum stresses. Specimen 32550 F15 showed Type 1 crack after 210,000 cycles. Since sufficient data are not available, it is considered reasonable to limit the aspect ratio to 1.0 for combined bending and shear specimens.

5. RECOMMENDATIONS

Based on the fatigue test results of hybrid plate girders under combined bending and shear investigated at The University of Texas, the following are recommended:

1. The nature of Type 1 cracks in combined bending and shear specimens is not the same as in pure bending specimens. Type 1 cracks in combined bending and shear specimens appeared closer to the corners of the test panels, while in pure bending specimens they were detected closer to the middle of the test panels. For the prevention of Type 1 cracks in combined bending and shear more restrictive limitations are recommended. Additional test data are needed to impose precise limitations.
2. Until further information is available, the intial web lateral eccentricity should be limited to the thickness of the web.
3. The following limiting web slenderness ratios are recommended for a fatigue life of :

   a) 500,000 to 2,000,000 cycles,

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

   b) 100,000 cycles,

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

4. A panel aspect ratio of 1.0 is recommended as a limiting value for combined bending and shear specimens.

NOMENCLATURE

P_{cr}	load which produces buckling (kips).
P_{max}	maximum applied load during fatigue test (kips).
P_{min}	minimum applied load during fatigue test (kips).
P_y	load which produces general yielding in the web (kips).
α	aspect ratio, ratio of panel length to web depth.
β	slenderness ratio, ratio of web depth to web thickness.
$(\beta)_{lim}$	limiting slenderness ratio.
σ_{cr}	elastic buckling stress in bending.
σ_{max}	maximum stress at the extreme fiber of the flange at maximum load.
σ_{min}	minimum stress at the extreme fiber of the flange at minimum load.
σ_u	stress at ultimate load (coupons).
σ_y	static yield stress.
σ_{yw}	static yield stress of web material.

TABLE 1. PLATE PROPERTIES

Girder	Plate Dimensions (in.)		Material Properties					
	Web	Flanges	Web			Flanges		
			σ_y (ksi.)	σ_u (ksi.)	% Elong. (in 8'')	σ_y (ksi.)	σ_u (ksi.)	% Elong. (in 8'')
32540 F05	36 x 0.187	8.04 x 0.523	36.14	59.23	32	113.10	123.18	12
32550 F05	36 x 0.187	8.03 x 0.530	35.54	58.38	30	112.95	125.35	12
32540 F15	36 x 0.187	8.04 x 0.523	37.35	60.50	23	113.09	123.35	12
32550 F15	36 x 0.187	8.04 x 0.523	36.34	59.37	28	113.50	123.96	12

TABLE 2. REFERENCE LOADS

Girder	σ_{cr} (red.) (ksi)	P_{cr} (kips)	P_y (kips)	P_{max} (kips)	P_{min} (kips)	$\frac{P_{max}}{P_{cr}}$	$\frac{P_{min}}{P_{cr}}$
32540 F05	17.30	28.40	56.10	61.60	38.70	2.168	1.362
32550 F05	17.30	28.40	56.65	77.40	38.70	2.725	1.362
32540 F15	17.31	24.40	56.10	61.60	38.70	2.525	1.588
32550 F15	17.31	24.40	56.10	78.20	38.70	3.205	1.588

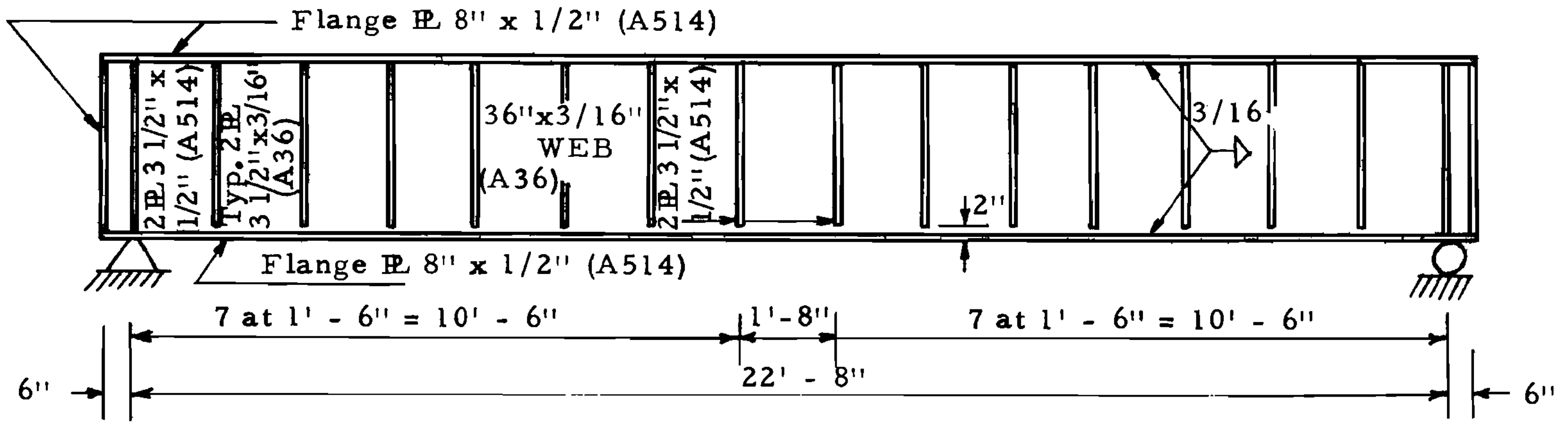
β = 192 for all specimens

TABLE 3. CHARACTERISTICS OF COMBINED BENDING AND SHEAR SPECIMENS

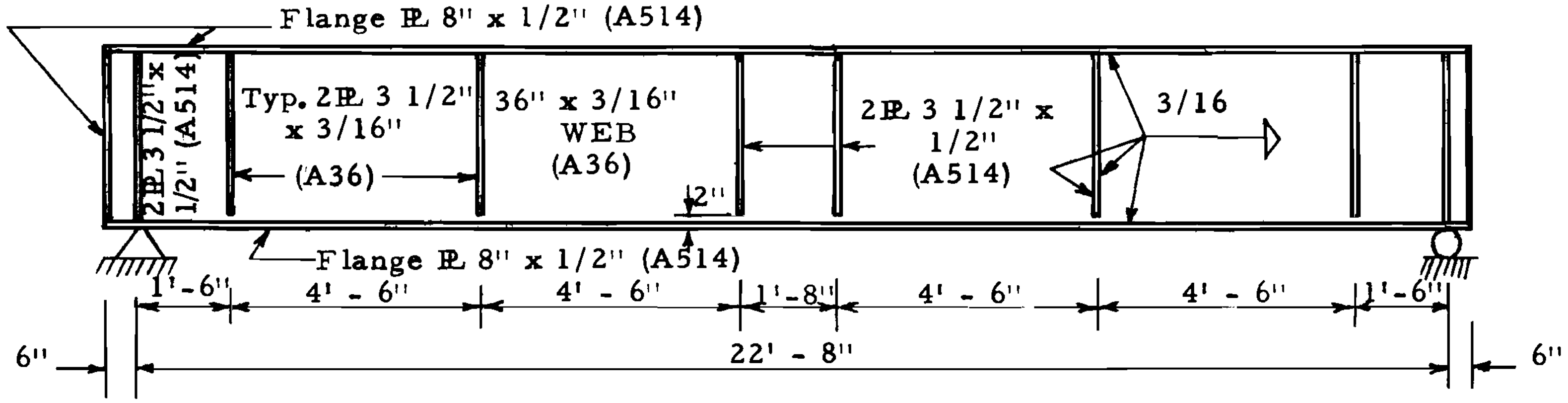
Girder	10^3 Cycles						σ_{max} (ksi)	σ_{min} (ksi)	σ_R (ksi)	σ_{yw}* (ksi)	β**	$\frac{P_{max}}{P_{cr}}$
	First Crack	Type 1	Type 2	Type 3	Type 4	Type 5						
32550C2	316	316 601	387				50	25	25	51.22	176	2.50
32550C2R	656	793	656 731				50	25	25	51.22	176	2.50
32550C2RR	326	326					50	25	25	42.94	189	2.50
33550C2	532	532	1,725				50	35	15	47.37	189	2.92
33550C2R	Run - Out Specimen						50	35	15	42.94	189	2.97
32150C2	622			622			50	21	29	42.94	189	2.96
32150C2R	277	277					50	21	29	42.94	189	2.96
32550C8	204	412 412	204		314 314	597 634	50	25	25	51.22	176	2.51
32550C8R	185	205 394	185 441		563 668	258 563	50	25	25	47.37	189	2.92
33550C8	299	299 317 318			386 728		50	35	15	47.37	189	2.93
42550C2	440	440	781			633	50	25	25	37.35	139	1.78
42550C2R	477			477 723			50	25	25	37.35	139	1.78
42550C2RR	1,896			1,896			50	25	25	37.35	139	1.78
32540F05	Run - Out Specimen						40	25	15	36.30	192	2.18
32550F05	671			671			50	25	25	36.30	192	2.73
32540F15	Run - Out Specimen						40	25	15	36.30	192	2.69
32550F15	210	210	329			225	50	25	25	36.30	192	3.37

* Based on coupon tests

** Based on actual dimensions

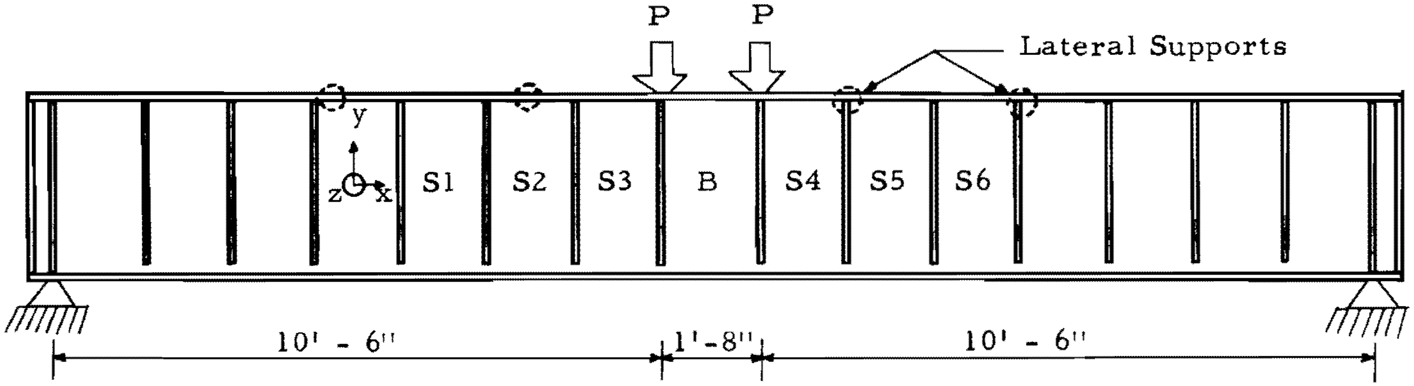


Specimens 32540 F05 and 32550 F05

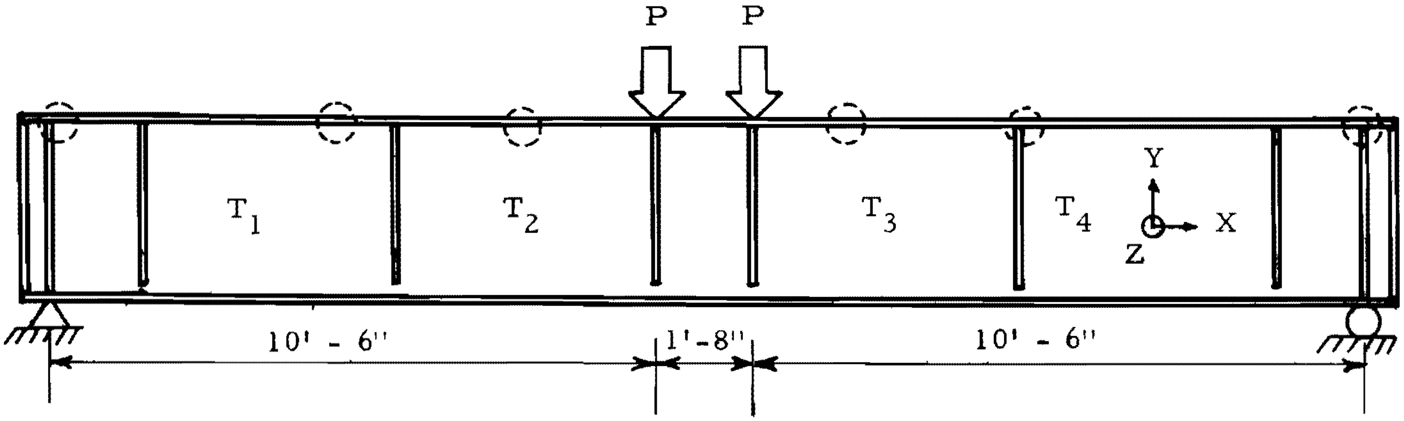


Specimens 32540 F15 and 32550 F15

FIG. 1. TEST SPECIMENS



a) Specimens 32540 F05 and 32550 F05



b) Specimens 32540 F15 and 32550 F15

FIG. 2. TEST SETUP

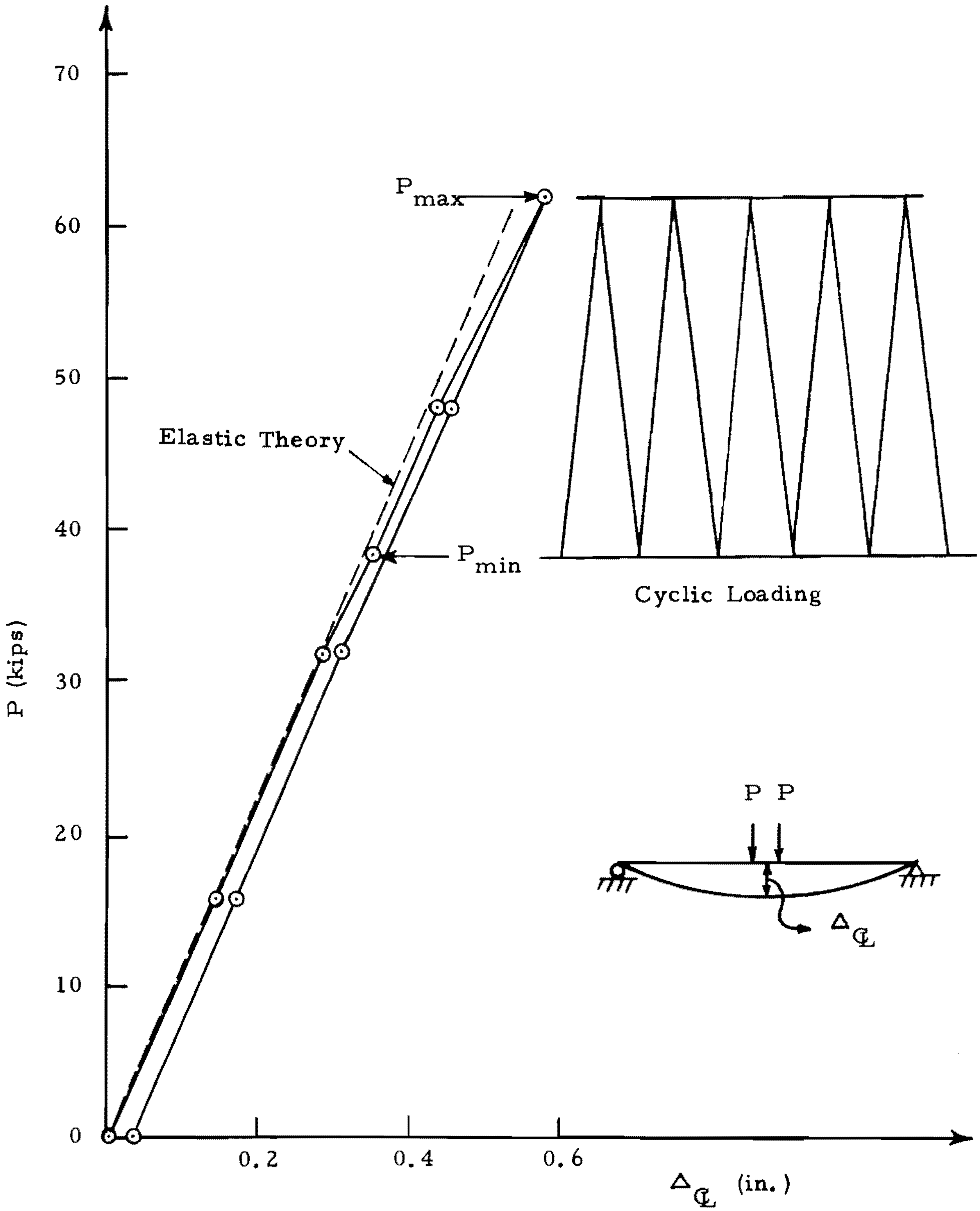
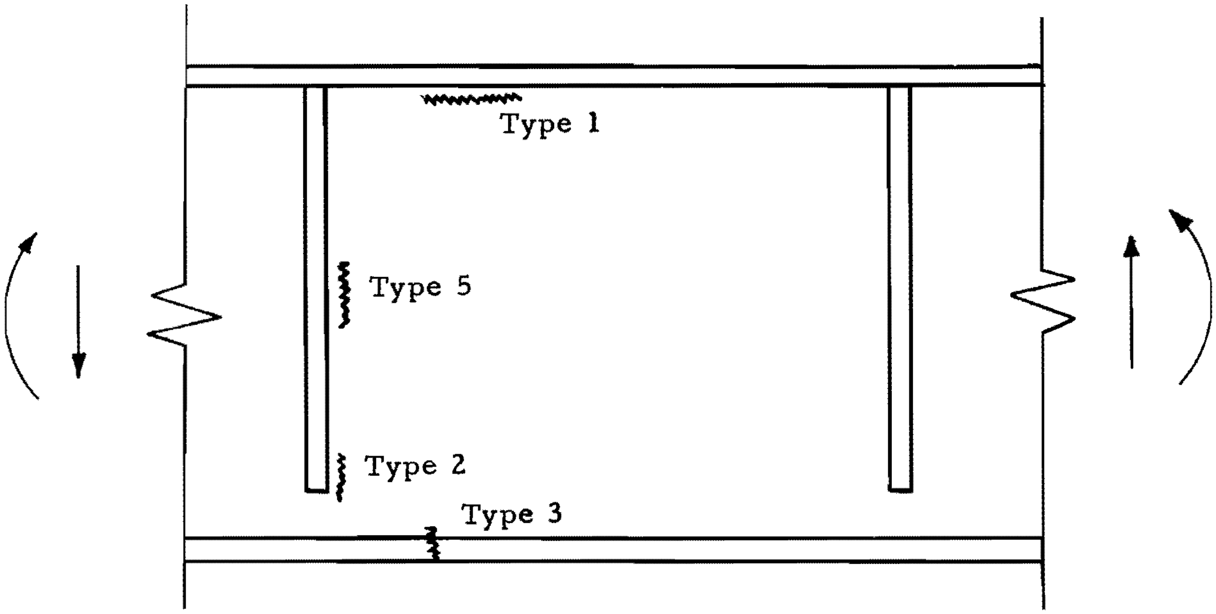
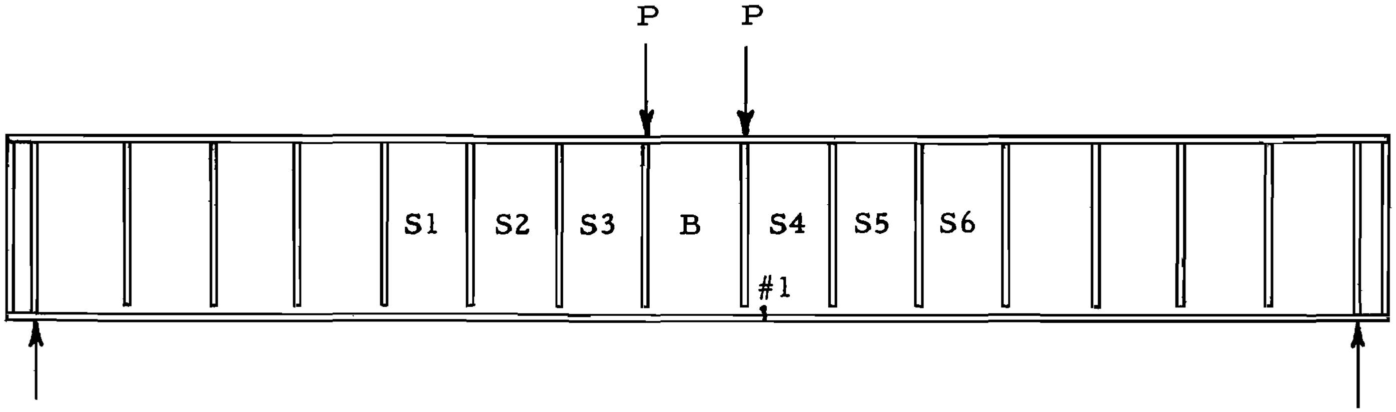


FIG. 3. LOAD-DEFLECTION CURVE FOR 32540 F15



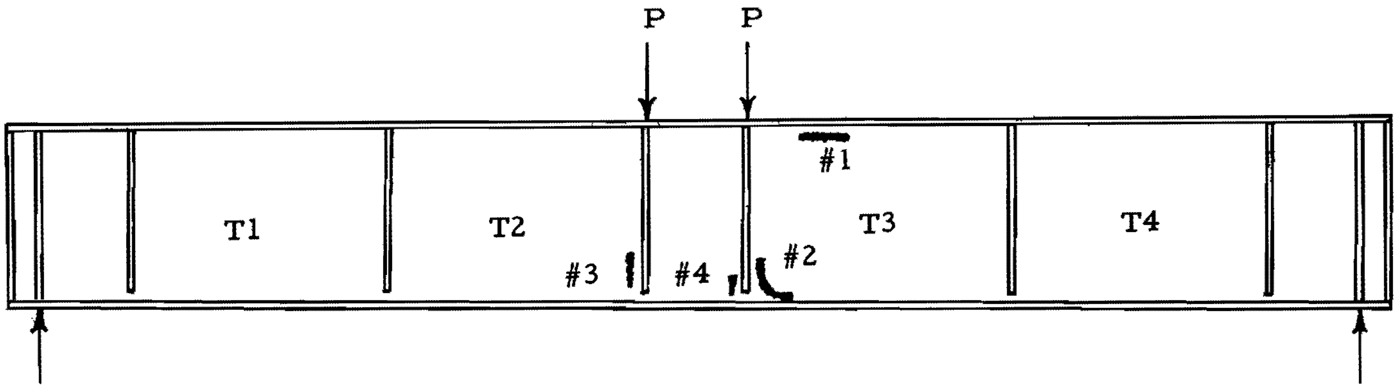
Girder Designation	Stress Levels	Remarks
32540 F05	25 - 40 ksi	N > 2 million cycles No cracks
32550 F05	25 - 50 ksi	See Fig. 6
32540 F15	25 - 40 ksi	N > 2 million cycles No cracks
32550 F15	25 - 50 ksi	See Fig. 7

FIG. 4. FATIGUE TEST RESULTS



Crack No.	Cycles at		Remarks
	Initiation	Propagation through web	
1	669,700	670,710	Type 3 crack

FIG. 5. CRACK LOCATIONS FOR 32550 F05



Crack No.	Cycles at		Remarks
	Initiation	Propagation through Web	
1	210,000	360,490	Type 1 Crack
2	225,000	360,490	Type 5 Crack
3	264,000	360,490	Type 2 Crack
4	329,300	346,000	Type 5 Crack

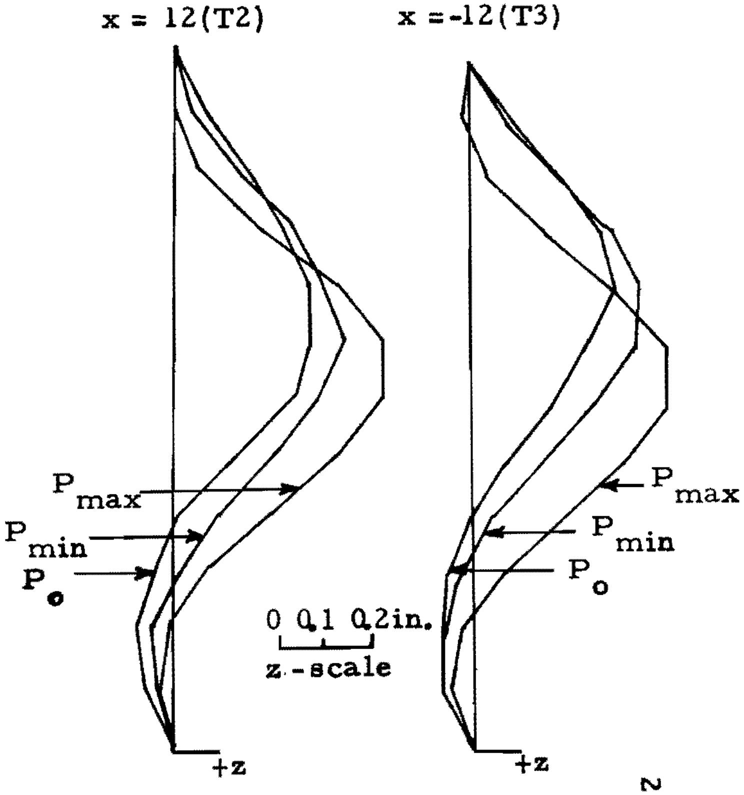


FIG. 6. CRACK LOCATIONS FOR 32550 F15

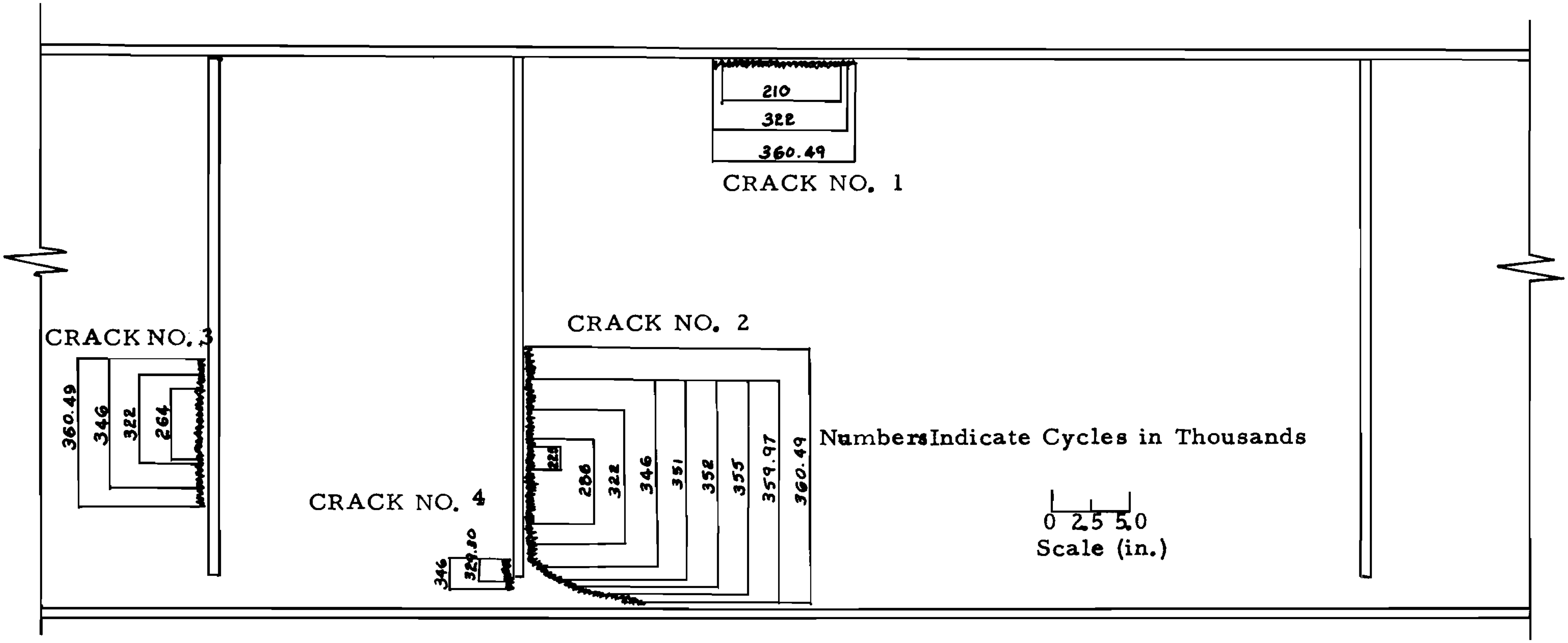
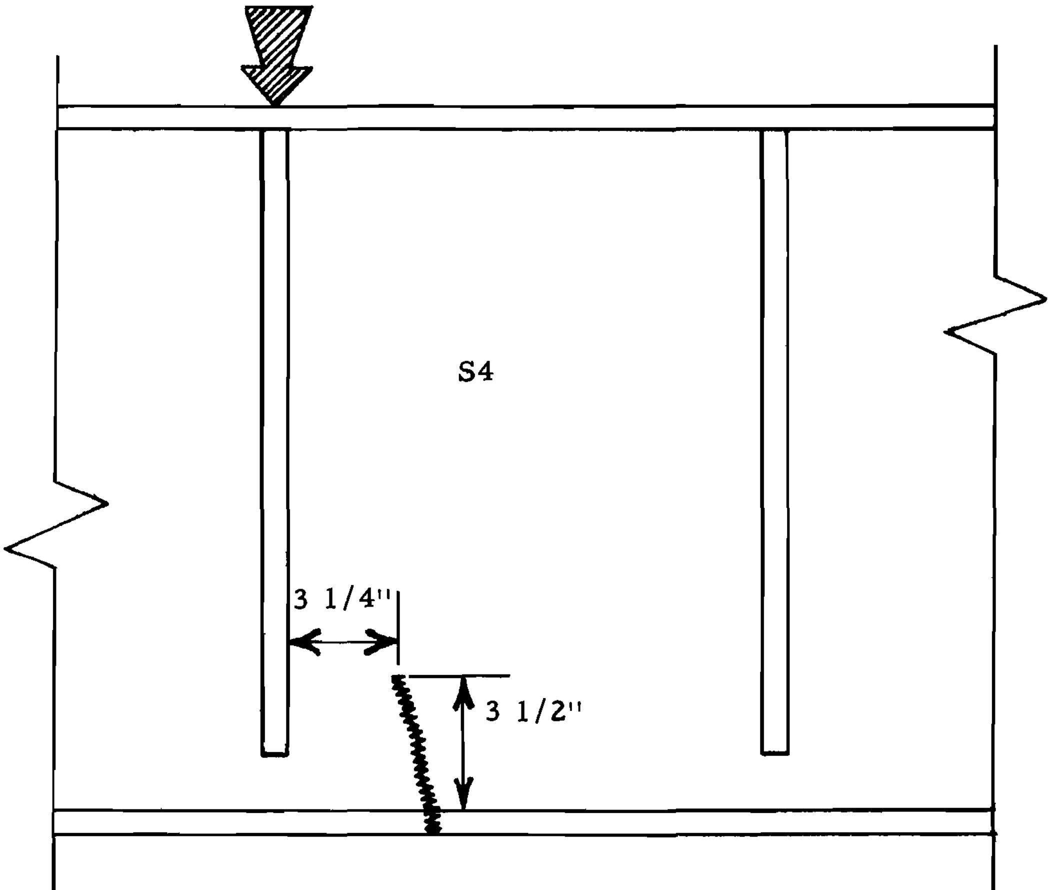
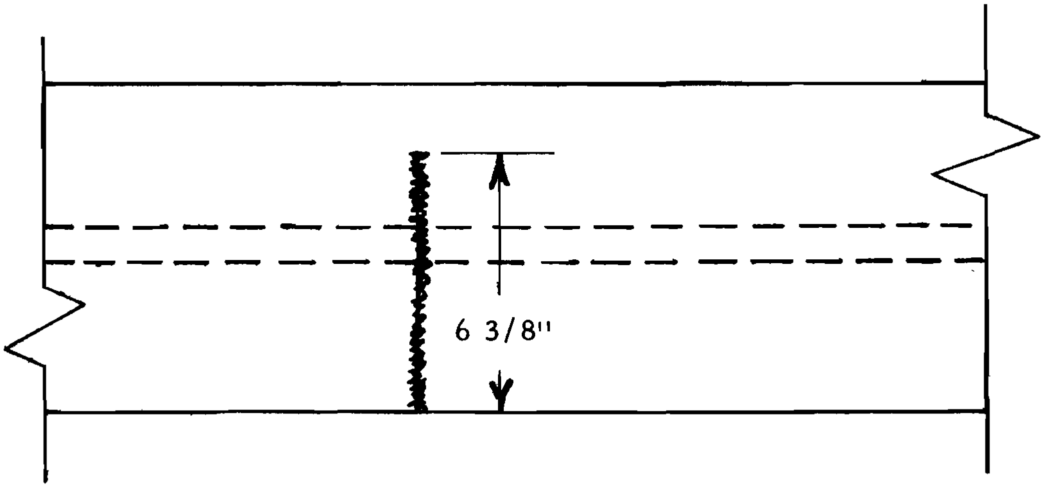


FIG. 7. CRACK GROWTH IN PANEL T3 (32550 F15)



a) Crack on Web and Bottom Flange



b) Crack on Bottom Face of Tension Flange

FIG. 8. TYPE 3 CRACK IN GIRDER 32550 F05

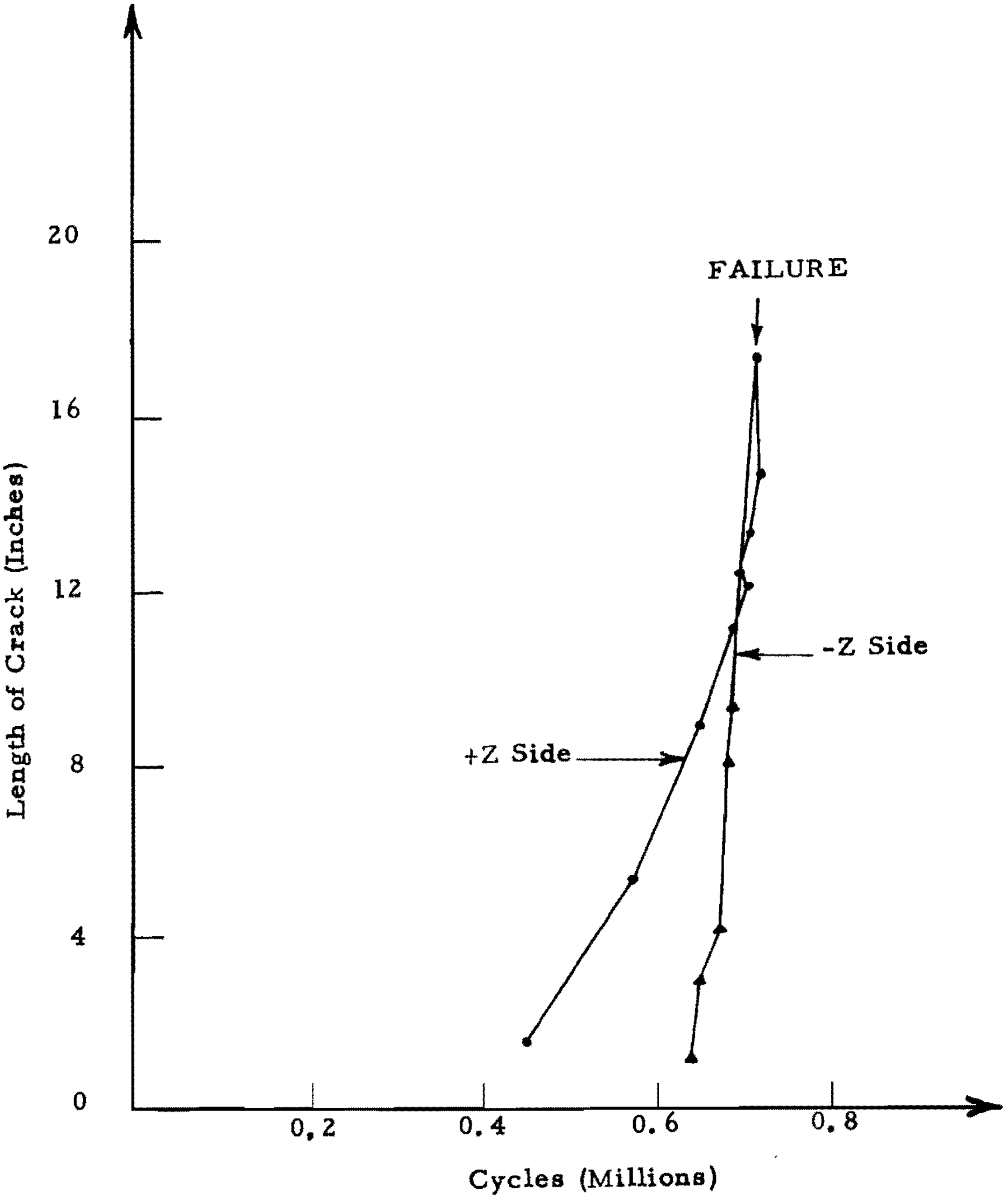


FIG. 9. CRACK PROPAGATION CURVE (32550 F15)

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