CIVIL ENGINEERING AND NUCLEAR POWER

September 15-17, 1980
Knoxville, Tennessee

VOL. I:
MATERIALS AND STRUCTURAL DESIGN, INCLUDING DESIGN AND ANALYSIS OF SUPPORTS FOR CABLE TRAY AND HVAC DUCTS

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PLASTIC CAPACITY OF RACEWAY SUPPORTS - EXPERIMENTAL EVIDENCE

by

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INTRODUCTION

Extensive dynamic tests of strut supported cable raceways indicate that both bolted and welded (horizontal leg of angles only) connections at the top of hanger struts undergo significant nonlinear rotation associated with a limited slippage between angle fittings and strut along the vertical leg of the angles. The mechanics of axial load and moment carrying capability of such angle connections is extremely complex. Thus, assumptions of complete fixity and subsequent stress analysis of the connection angles do not reflect the load carrying mechanism of these connections. However, despite the complexity of the connection deformation, these connections are characterized by stable hysteresis loops under cyclic loading. As a substitute to a sophisticated and possibly unmanageable nonlinear large-strain analysis, the decision was made to study the fatigue life of these connections and to base the design of similar connections on the resulting information. Data collected on fatigue life possessed wide data scatter which proved amenable to statistical analysis and interpretation. The methods and results of that analysis as well as recommended design parameters are presented in a companion paper by Hamilton and Hadjian.

A brief series of cyclic tests were performed on short sections of one-half inch threaded rod. Results indicate that large numbers of cycles at

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*ANCO Engineers, Inc.

deflections well above calculated elastic yield point values can be tolerated without rod failure. No statistical consideration was given to the data however, it was demonstrated that these components have high ductility (a factor of ten or greater above elastic limits) that results in seismic capacity significantly greater than predicted by analysis.

Subsequent sections present the experimental methods used, the test results and observations, and implications to the seismic capacity of these raceway supports.

TEST OBJECTIVES AND METHODS

Bolted and Welded Strut Anchor Connections

The experimental test program described herein was conducted to better define the failure modes and mechanisms of selected bolted and welded strut hanger anchor configurations used in typical strut supported cable tray systems. Of particular interest for each of the configurations tested in the current study was the determination of:

- the number of cycles to connection failure at selected values of angular rotation (N vs. θ);
- connection moment resistance as a function of the number of cycles achieved (m vs. N);
- the first cycle moment resistance - angular rotation hysteresis (m vs. θ_1); and
- the moment resistance as a function of angular rotation (m vs. θ).

A total of 85 specimens were tested (as summarized in Table 1). Approximately 35% of the test effort focused on standard bolted connections with the balance addressing the behavior of welded connections. The entire

test program was grouped into 12 tests, each determining data for a particular connection detail. Each test consisted of as few as 5 to as many as 20 runs (test specimens) as shown in Table 1. Briefly, the test program was performed as follows.

Test Sequences I and II were performed to determine the degrees of data scatter in the number of cycles to connection failure. Test Sequence I involved the use of "standard 4-hole angles" (B-104)* which were bolted to a simulated support strut whereas Test Sequence II used these same angles welded to a rigid support. For each test a "backbone" or moment vs. rotation curve was generated. At each of four preselected values of angular rotation four specimens were cycled until fracture of the angle occurred to provide a statistical base of data of failure rates of these connections. First cycle hystereses were also determined.

Test Sequence III provided data for the statistical determination of the sensitivity of test results to differences in workmanship. Backbone and failure rate data were collected and interpreted by a person other than the engineer responsible for previous testing. Bolted 4-hole angles were used here as in Test Sequence I. The same verbal work instructions were given to the engineers who performed Test Sequences I and III.

Test Sequences IV through VI and VIII through XII determined backbone, failure rate, and hysteresis data for a wide variety of commonly used bolted and welded anchor details. Moment resistance as a function of the number of cycles completed was determined. In addition, a special study (Test Sequence II, Runs 3.5 to 3.8) was performed to determine the effect of connection bolt

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*B-Line Systems part number.

torque on connection failure rate. This special test was conducted in lieu of Test Sequence VIII. In summary, the variables which were expected to influence test results were:

- type of strut;
- angle connection type;
- angle of rotation of the simulated hanger relative to the support point;
- welded angles vs. bolted angles;
- connection bolt torque; and
- workmanship.

Table 2 summarizes the components used in each sequence of the test program.

Two test fixtures were used: one for testing bolted anchor details and another for testing welded connection details. Both are illustrated in Figure 1. The objective of the first test fixture was to simulate a rigidly mounted strut support. The objective of the second test fixture was to simulate attachment of angle connections to structural steel members by welding. Other than the mode of support, both test fixtures are essentially identical.

After installation of a particular angle-strut configuration, a static load of 1,000 lbf was applied axially to the hanger to simulate the dead weight of typical raceway systems. Next a constant displacement rate was programmed into the actuator while the force and displacement at the point of load application were continuously recorded on a strip chart recorder. Load cell and LVDT signals were reviewed to determine the connection's moment resistance (from the zero position to full positive rotation permitted by stroke limits of the actuator) as a function of angular rotation of the strut hanger (m vs. θ curve).

Next all connection components were replaced, all connection bolts were torqued to their proper value (50 ft-lb), and the MTS actuator programmed to cycle the connection at a predetermined value of angular rotation until connection failure occurred. Cycle rates were 0.2 per second in most cases. Again force and deflection data were gathered on a strip chart recorder to determine (1) the first cycle hysteresis, (2) the connection moment resistance as a function of the number of cycles, and (3) the total number of cycles to connection failure.

Threaded Rod Hangers

As mentioned, an abbreviated test program using one-half inch threaded rod was performed to demonstrate that large margins of safety exist when failure levels of rod suspended raceways are predicted using linear elastic analysis techniques. To meet objectives, typical rod trapeze hangers (as shown in Figure 2) were cycled. Eight values of relative displacement (0.2, 0.5, 0.8, 1.0, 1.5, 1.88, and 2.0 inches) were selected. At each value the assembly was cycled until rod failure occurred or 1,000 cycles of full stress reversal was attained. Assembly bolts were torqued to 50 ft-lb with an axial load of 1,000 lb provided to simulate a heavily loaded raceway assembly.

Comparison of test results with hand calculations based on beam formulas (with and without stress concentration factors) was made to draw conclusions on apparent margins of safety.

SUMMARIZED TEST RESULTS

Bolted and Welded Strut Anchor Connections

Recall that the test variables were (1) type of strut, (2) angle connection type, (3) angle of rotation of the simulated hanger relative to the support point, (4) welded connections vs. bolted connections, (5) assembly bolt torque, and (6) differences in workmanship. To better understand the results, Table 3 gives relevant sectional properties of the three different types of strut used. Figure 3 illustrates the angle clips used. A better understanding of the different angle connectors is best obtained from manufacturers catalogues noting that the angle type given for a particular test is referenced by a B-Line System's part number. (Figure 4 illustrates the welding detail used in those tests [II, VIII through XII] calling for welded connections to the rigid support.) In tests other than those made to determine strength or "backbone" curves, angles of rotation were fixed at 0.067, 0.050, 0.042 and 0.020 radians. Fifty ft-lb assembly bolt torque (1/2 in. - 12 UNC bolts) was standard. Selected tests were made at 30 ft-lb and 75 ft-lb to determine the influence of assembly bolt torque on connection life.

Table 4 summarizes the number of cycles-to-connection failure determined for bolted B-104 angles using B-22A strut hangers. Here four separate specimens were cycled-to-connection failure of each of the four angles of rotation discussed above. Table 4 shows the test and run number, angular rotation in radians of the hanger relative to the support strut, and the number of cycles to failure. In general, testing was halted when the number of cycles exceeded 1,000.

Table 5 presents data similar to Table 4 but here the B-104 angles were welded to the simulated fixed support. Also given in Table 5 are the failure rates determined when assembly bolt torque was increased from 50 ft-lb to 75 ft-lb and decreased to 30 ft-lb. Comparison of Tables 4 and 5 will lead to an assessment of the relative merits of bolting vs. welding of the B-104 angles and will lead to an assessment of the effects of assembly bolt torques.

Table 6 gives the failure rates for bolted B-104 angles with B-22A strut hangers when testing was performed and data were reduced and summarized by another engineer.

Table 7 summarizes the failure rates determined for the balance of the test program. To compare the effect of strut type, Table 5 (Test II) should be compared with Table 7 (Tests IX and X). Here the strut dimensions (depth) were 3.25, 4.875, and 6.5 inches. Comparison of data in Table 7 (Tests VIII, IX and XII) illustrates the effect of strut dimensions in combination with welded B-144-L double angles rather than welded B-104 double angles. In addition, the relative merits of B-104 angles and B-144-L angles can be determined from the table. The effect of angular rotation on connection life can be seen throughout the tables.

A typical "backbone" or moment vs. angular rotation curve is illustrated in Figure 5. Here the moment resistance of the connection is plotted as the single amplitude rotation and increased linearly from zero to the maximum attainable due to stroke limits of the hydraulic actuator. Force and displacement data have been converted to moment and rotation values to present a consistent set of values so that direct comparisons can be made between tests. Similar curves for all tests were generated but are not shown.

A typical family of moment vs. number of cycles is shown in Figure 6. In this figure values determined at 0.067, 0.050, 0.042 and 0.020 radians are plotted as functions of the number of cycles achieved. As can be seen, higher values of rotation exhibit higher moment resistance initially but tend towards the same values as the number of cycles become large.

Lastly, typical first cycle hysteresis curves are shown as Figure 7. Here strip chart records were converted to moment-rotation values for the first cycle of loading, the first cycle being rotation from zero to full positive to full negative returning to zero. The figures are plotted for rotations of 0.067, 0.050, 0.042 and 0.020 radian rotations respectively.

Threaded Rod Hangers

Only one pair of one-half inch threaded steel rods (simulated trapeze hanger) was cycled to determine failure rates at each of the fixed values of relative displacement mentioned. Rod length was 12 in. with assembly bolt torque held constant at 50 ft-lb. Table 8 summarizes determined failure rates while Figure 8 presents this information graphically.

An interesting phenomenon was observed at the largest value of relative displacement ($d/\ell = 6$). Here the single nuts used to fix rod ends to the support and cross struts were observed to loosen during the first few cycles causing a decrease in maximum bending moment, hence reduced maximum stresses, which resulted in a reduced failure rate. It is doubtful that a double-nut connection would exhibit such behavior.

CONNECTION FAILURE MODES AND MECHANISMS

The principal failure mode for the ungussetted 4-hole angles (B-Line B-104) was found to be a fracture of the angle in the vicinity of its bend. This is illustrated in the first two photographs of Figure 9. This was observed in both bolted and welded connection tests. Some initial slippage of the hanger relative to the angle also occurred under the 1,000 lbf axial loading. In most cases (wide strut being the exception), axial slippage would progress rapidly through the first 20 or so cycles and then stop although movement between the hanger and angles persisted. While the hanger was being

rotated in one direction, movement was observed between the hanger and angle on the side of the connection opposite to the direction of rotation after the hanger passed through its zero rotation position. When the direction of rotation changed, the other side of the connection exhibited this behavior.

Failure mechanisms of gussetted angles were characterized by axial slippage of the hanger relative to the support angles. At large angular rotations, complete separation occurred. Here, as in the 4-hole angles discussed above, some abrasion of the hanger was observed at the twirl-nut-bolt connection which resulted in a decrease in assembly bolt torque. In one test with gussetted angles the hanger was fractured longitudinally along the line where the strut was engaged by the twirl nut (Test XII, Run 4.1).

In mixed pairs including a gussetted clip and a 2-hole clip, failure occurred as a combination of some axial slippage and fracture of the 2-hole clip at its bend. These tests (IV and VI) were not indicative of the ultimate capacity of this connection since the single gussetted angle can sustain considerably more cycles as shown by Test Sequence V.

In Test V, where single gussetted clips were tested, the connection maintained its integrity for each angular rotation despite partial fracture of the angle. A typical fracture is illustrated in the last photograph of Figure 9.

Failure mechanisms did not vary significantly when the hanger-strut was varied, but in tests where wider strut was used (B-11A and B-12A) generally higher applied moments were seen than for tests using the narrower (B-22A) strut.

IMPLICATIONS TO THE SEISMIC CAPACITY OF RACEWAY SUPPORTS

Laboratory testing of full scale raceway systems using anchor connection details similar to those investigated here has demonstrated that anchor rotation is a significant contributor to overall raceway dynamic response. Observed clip angle failure modes were similar on full systems to failure modes observed in these controlled bench tests--principally fracture of the angle at its cold formed bend.

Clearly assumptions of anchor fixity in linear elastic analysis are not justified and lead to erroneous conclusions about failure levels based on yield criteria. Further, it is doubtful that a sophisticated nonlinear large-strain analysis would be more appropriate due to the larger uncertainties introduced by the interaction between bolts, twirl nuts, and strut; how these strain relieving mechanisms function over time; hot those phenomena affect resulting strains at critical connection locations. These points are apparent in the large data scatter observed experimentally.

Perhaps design considerations should be based on a combination of fatigue consideration and ultimate anticipated load. By limiting possible rotation of these connections, fatigue effects can be limited to acceptable levels increasing the probability of survival under maximum anticipated loading. Statistical consideration of failure rate data, as presented by Hamilton and Hadjian, will demonstrate how the data presented was analyzed to determine acceptable values of connection rotation for any desired value of confidence in connection integrity.

It has been demonstrated that a one-half inch threaded rod can undergo large numbers of full stress reversal before fracture occurs. When linear elastic calculations (beam theory) based on yield criteria are compared with experimental data, huge ductility factors can be seen. Elastic limit calculations suggest that yield would be exceeded if the relative displacement of the test set-up (Figure 2) exceeded 0.07 in. without consideration of stress concentration. With consideration given to stress concentration due to threading, this value is reduced to 0.02 in. indicating as much as 50 times the elastic yield displacement may be tolerated with the expectation that the hanger would service in excess of 300 such cycles.

Recall that these data were collected on single samples. Undoubtedly, additional testing will be required to determine scatter of the data so that confidence levels on survivability can be determined. As in the case of anchor connections, there are a wide variety of rod connection details used within the industry that will have different failure rates than those given here. Variables which are expected to alter failure rates are:

- length and diameter of rod;
- rod splice location;
- connection details;
- anchor details;
- strut type;
- material mechanical properties;
- vertical load; and
- displacement vector orientation relative to the anchor and connection.

Additional research is warranted.

ACKNOWLEDGMENTS

The authors wish to extend thanks to Messrs. Asador Hadjian, Bruce Linderman and Edward Rose of Bechtel Power Corporation for their efforts and support in this project. Credit is also due to the utilities who funded the project and to Dr. C.W. Hamilton of the University of Southern California for his insight into the statistical nature of the data.

TABLE 1

TEST SEQUENCE
STRENGTH AND FATIGUE TESTING OF STRUT CONNECTIONS

Test No.	Run No.	Strut No.	Clip No.* (or Equiv.) B = Bolted, W = Welded	● = Data to be Recorded Force vs. Deflection	θ Radians	N = Cycles
I	1.1	B-22A	B104, B104, B	●		
I	2.1	"	" " "		0.067	●
I	2.2	"	" " "		0.067	●
I	2.3	"	" " "		0.067	●
I	2.4	"	" " "		0.067	●
I	3.1 thru 3.4	"	" " "		0.050	●
I	4.1 thru 4.4	"	" " "		0.042	●
I	5.1 thru 5.4	"	" " "		0.020	●
II	1.1	"	B104, B104, W	●		
II	2.1 thru 2.4	"	" " "		0.067	●
II	3.1 thru 3.4	"	" " "		0.050	●
II	3.5**	"	" " "		0.050	●
II	3.6†	"	" " "		0.050	●
II	3.7**	"	" " "		0.050	●
II	3.8†	"	" " "		0.050	●
II	4.1 thru 4.4	"	" " "		0.042	●
II	5.1	"	" " "		0.020	●
II	5.2 thru 5.4	"	" " "	Not Run	0.020	●
III	1.1	"	B104, B104, B	●		
III	2.1	"	" " "		0.067	●
III	3.1	"	" " "		0.050	●
III	4.1	"	" " "		0.042	●
III	5.1	"	" " "		0.020	●

*Note: B-Line Systems, Inc. strut and clips were used throughout testing.

**Torque = 75 ft-lb.

†Torque = 30 ft-lb.

TABLE 1

TEST SEQUENCE (cont'd)

Test No.	Run No.	Strut No.	Clip No.* (or Equiv.) B = Bolted, W = Welded	● = Data to be Recorded Force vs. Deflection	θ Radians	N = Cycles
IV	1.1	B-22A	B-144-L,B-101,B	●(1)		
IV	1.2	"	" " "	●(2)		●
IV	2.1	"	" " "		0.067	●
IV	3.1	"	" " "		0.050	●
IV	4.1	"	" " "		0.042	●
IV	5.1	"	" " "		0.020	●
V	1.1	"	(1) B-144-L, B	●(1)		
V	1.2	"	" "	●(2)		
V	2.1	"	" "	●(1)	0.067	●
V	3.1	"	" "	●(1)	0.050	●
V	4.1	"	" "	●(1)	0.042	●
V	5.1	"	" "	●(1)	0.020	●
VI	1.1	B-12A	B-144-L,B-101,B	●(1)		
VI	1.2	"	" " "	●(2)		
VI	2.1	"	" " "	●(1)	0.067	●
VI	3.1	"	" " "	●(1)	0.050	●
VI	4.1	"	" " "	●(1)	0.042	●
VI	5.1	"	" " "	●(1)	0.020	●
VII	1.1	B-22A	B104, B104, W	Not Run		
VII	2.1 thru 5.1	"	" " "	Not Run	0.067	●

*B-Line Systems, Inc. strut and clips were used throughout testing.

(1) Force applied towards B-101 or where there is no clip.

(2) Force applied towards B-144-L.

TABLE 1

TEST SEQUENCE (cont'd)

			Clip No.* (or Equiv.)	● = Data to be Recorded		
Test No.	Run No.	Strut No.*	B = Bolted, W = Welded	Force vs. Deflection	θ Radians	N = Cycles
VIII	1.1	B-22A	B-144-L,B-144-L,W	●		
VIII	2.1	"	" " "		0.067	●
VIII	3.1	"	" " "		0.050	●
VIII	4.1	"	" " "		0.042	●
VIII	5.1	"	" " "		0.020	●
IX	1.1	B-11A	B104, B104, W	●		
IX	2.1	"	" " "		0.067	●
IX	3.1	"	" " "		0.050	●
IX	4.1	"	" " "		0.042	●
IX	5.1	"	" " "		0.020	●
X	1.1	B-12A	" " "	●		
X	2.1	"	" " "		0.067	●
X	3.1	"	" " "		0.050	●
X	4.1	"	" " "		0.042	●
X	5.1	"	" " "		0.020	●
XI	1.1	B-11A	B-144-L,B-144-L,W	●		
XI	2.1	"	" " "		0.067	●
XI	3.1	"	" " "		0.050	●
XI	4.1	"	" " "		0.042	●
XI	5.1	"	" " "		0.020	●
XII	1.1	B-12A	" " "	●		
XII	2.1	"	" " "		0.067	●
XII	3.1	"	" " "		0.050	●
XII	4.1	"	" " "		0.042	●
XII	5.1	"	" " "		0.020	●

*B-Line Systems Inc. strut and clips were used throughout testing.

TABLE 2

FATIGUE TESTING SUMMARY

	Double Angle Connections				Single Angle Connection
Strut Type	B-104 Bolted	B-104 Welded	B-144-L B-101	B-144-L Welded	B-144-L Single
B-22A	I III	II+ (variable torque)	IV	VIII	V
B-12A	-	X	VI	XII	-
B-11A	-	IX	-	XI	-

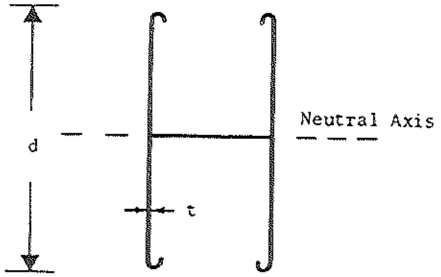
Note: Roman numerals designate test sequence number.

TABLE 3

STRUT SECTIONAL PROPERTIES

B-Line Systems, Inc.

Product No.	B-22A	B-12A	B-11A
A (in.^{2})	1.11	1.45	1.854
I (in.^{4})	0.954	2.86	6.616
S (in.^{3})	0.587	1.17	2.04
r (in.)	0.923	1.40	1.884
d (in.)	3.25	4.875	6.50
t (in.)*	0.105	0.105	0.105



*12 gauge.

TABLE 4

EXPERIMENTALLY DETERMINED NUMBER OF CYCLES TO CONNECTION FAILURE - B-22A STRUT WITH BOLTED DOUBLE B-104 ANGLES

Test No.	Run No.	θ (radians)	N_f (cycles)
I	2.1	0.067	137
	2.2	0.067	203
	2.3	0.067	275
	2.4	0.067	219
	3.1	0.050	398
	3.2	0.050	369
	3.3	0.050	560
	3.4	0.050	375
	4.1	0.042	710
	4.2	0.042	1,255
	4.3	0.042	579
	4.4	0.042	926
	5.1	0.020	>1,151
	5.2	0.020	>1,198
	5.3	0.020	>1,073
	5.4	0.020	>1,070

TABLE 5

DETERMINED NUMBER OF CYCLES TO FAILURE - B-22A STRUT WITH WELDED DOUBLE B-104 ANGLES

Test No.	Run No.	θ (radians)	N_f (cycles)
II	2.1	0.067	212
	2.2	0.067	269
	2.3	0.067	495
	2.4	0.067	235
	3.1	0.050	030
	3.2	0.050	794
	3.3	0.050	1,194
	3.4	0.050	1,315
	3.5*	0.050	454
	3.6**	0.050	743
	3.7*	0.050	475
	3.8**	0.050	450
	4.1	0.042	1,603
	4.2	0.042	2,223
	4.3	0.042	2,650
	4.4	0.042	1,023
	5.1	0.020	>1,156
	5.2	Not Run	
	5.3	Not Run	
	5.4	Not Run	

*Assembly bolt torque = 75 ft-lb.

**Assembly bolt torque = 30 ft-lb.

TABLE 6

DETERMINED NUMBER OF CYCLES TO FAILURE, B-22A STRUT WITH BOLTED DOUBLE B-104 ANGLES, PERFORMED TO DETERMINE THE SENSITIVITY OF TEST RESULTS TO DIFFERENCE IN WORKMANSHIP STANDARDS

Test No.	Run No.	θ (radians)	N_f (cycles)
III	2.1	0.067	375
	3.1	0.050	662
	4.1	0.042	1,080
	5.1	0.020	2,700

TABLE 7

DETERMINED NUMBER OF CYCLES TO FAILURE FOR THE REMAINDER OF THE TEST SEQUENCE

Test No.	Run No.	θ (radians)	N_f (cycles)
P1001 strut with bolted B-144-L and B-101 angles			
IV	2.1	0.067	114
	3.1	0.050	301
	4.1	0.042	274
	5.1	0.020	>1,182
P1001 strut with single B-144-L angle, bolted			
V	2.1	0.067	1,150
	3.1	0.050	1,110
	4.1	0.042	1,097
	5.1	0.020	>1,155
P5501 strut hanger with bolted B-144-L and B-101 angles			
VI	2.1	0.067	160
	3.1	0.050	443
	4.1	0.042	310
	5.1	0.020	>1,267
B-22A strut with welded B104 angles Substituted by Test III (Runs 3-5 to 3.8)			
VII			
B-22A strut with welded double B-144-L angles			
VIII	2.1	0.067	8
	3.1	0.050	158
	4.1	0.042	>1,183
	5.1	0.020	>1,139
B-11A strut with welded B104 double angles			
IX	2.1	0.067	>1,141
	3.1	0.050	>1,194
	4.1	0.042	>1,145
	5.1	0.020	>1,223
B-12A strut with welded B104 double angles			
X	2.1	0.067	367
	3.1	0.050	891
	4.1	0.042	1,083
	5.1	0.020	>1,400
B-11A strut with welded B-144-L double angles			
XI	2.1	0.067	27
	3.1	0.050	127
	4.1	0.042	156
	5.1	0.020	>1,133
B-12A strut with welded B-144-L double angles			
XII	2.1	0.067	90
	3.1	0.050	244
	4.1	0.042	1,149
	5.1	0.020	>1,105

TABLE 8

SUMMARY OF THREADED STEEL ROD FATIGUE TEST

(Tension load = 1,000#, bolt torque = 50 ft-lb)

Displacement (inches)	Cycles to Failure*
0.20	>1,000**
0.50	>1,000**
0.80	1,103
1.00	363
1.50	202
1.88	42
2.00	53†

*All failures were fatigue fractures of steel rod at bottom connection.

**Test concluded if failure not reached within 1,000 cycles.

†Severe loosening of locking nuts causes stress relaxation, thereby increasing cycles to fatigue at large displacements.

FIGURE 1: FIXTURES FOR TESTING BOLTED AND WELDED ANCHOR CONNECTIONS

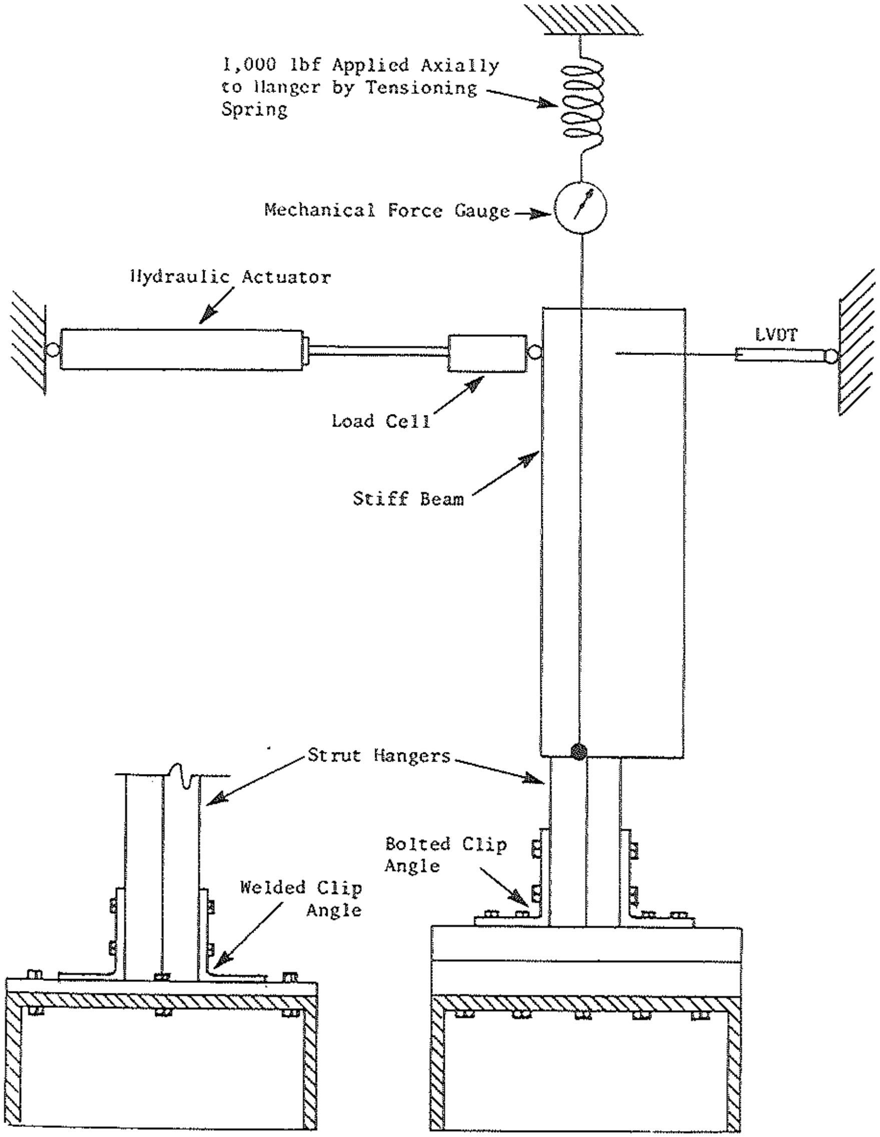


FIGURE 2: FIXTURE FOR CYCLING SIMULATED ONE-HALF INCH ROD TRAPEZE HANGER

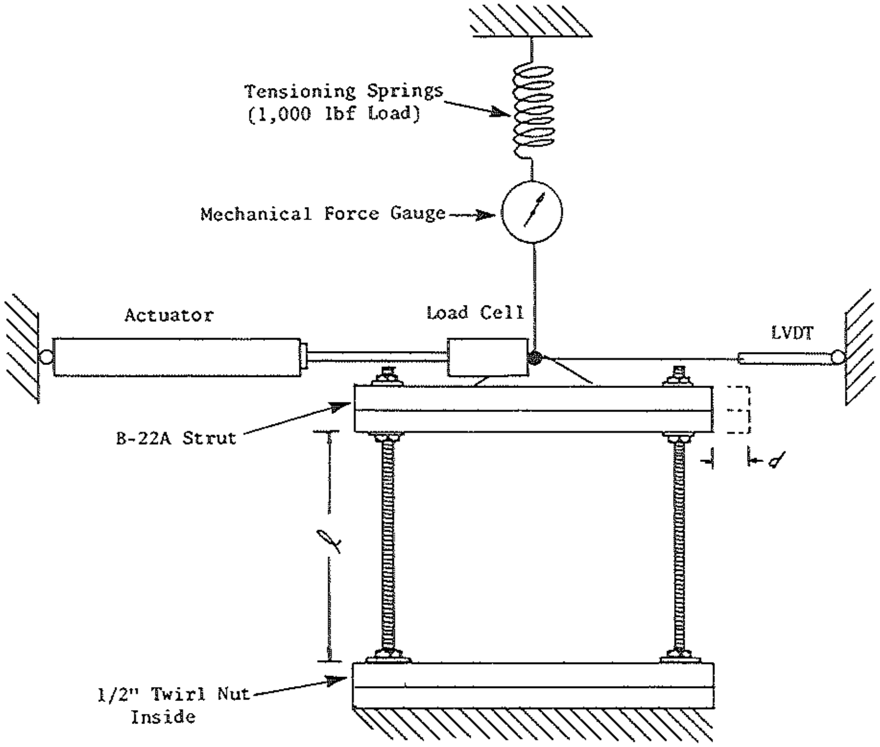


FIGURE 3: ANGLE CLIPS USED IN TEST PROGRAM (B-Line Systems Components)

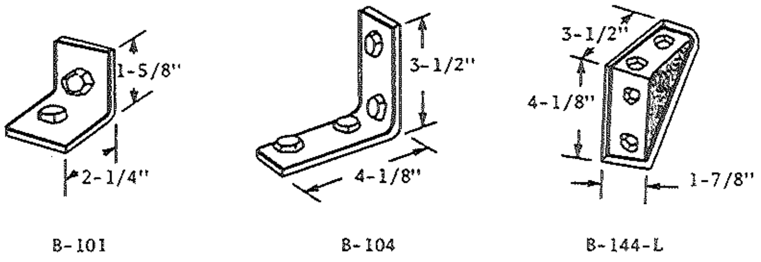


FIGURE 4: CONNECTION WELDING DETAIL

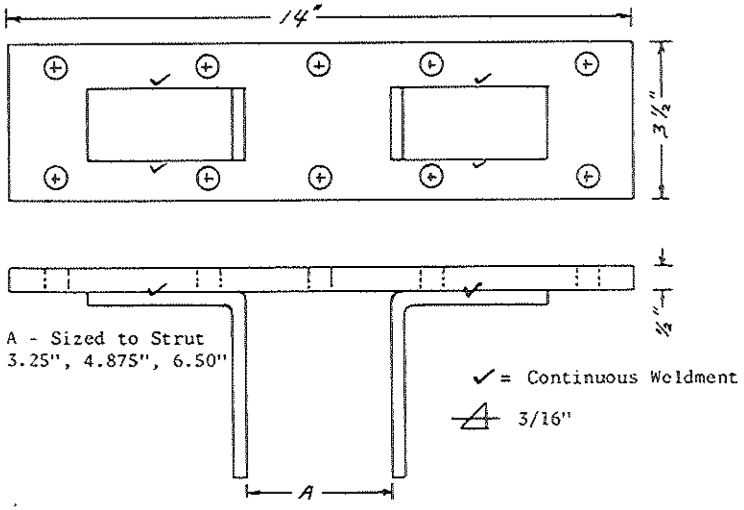


FIGURE 5: APPLIED MOMENT VS. ANGULAR ROTATION
TEST XI, RUN 1.1
DOUBLE B-144-L ANGLES, WELDED TO FIXED
SUPPORT WITH B-11A STRUT HANGER

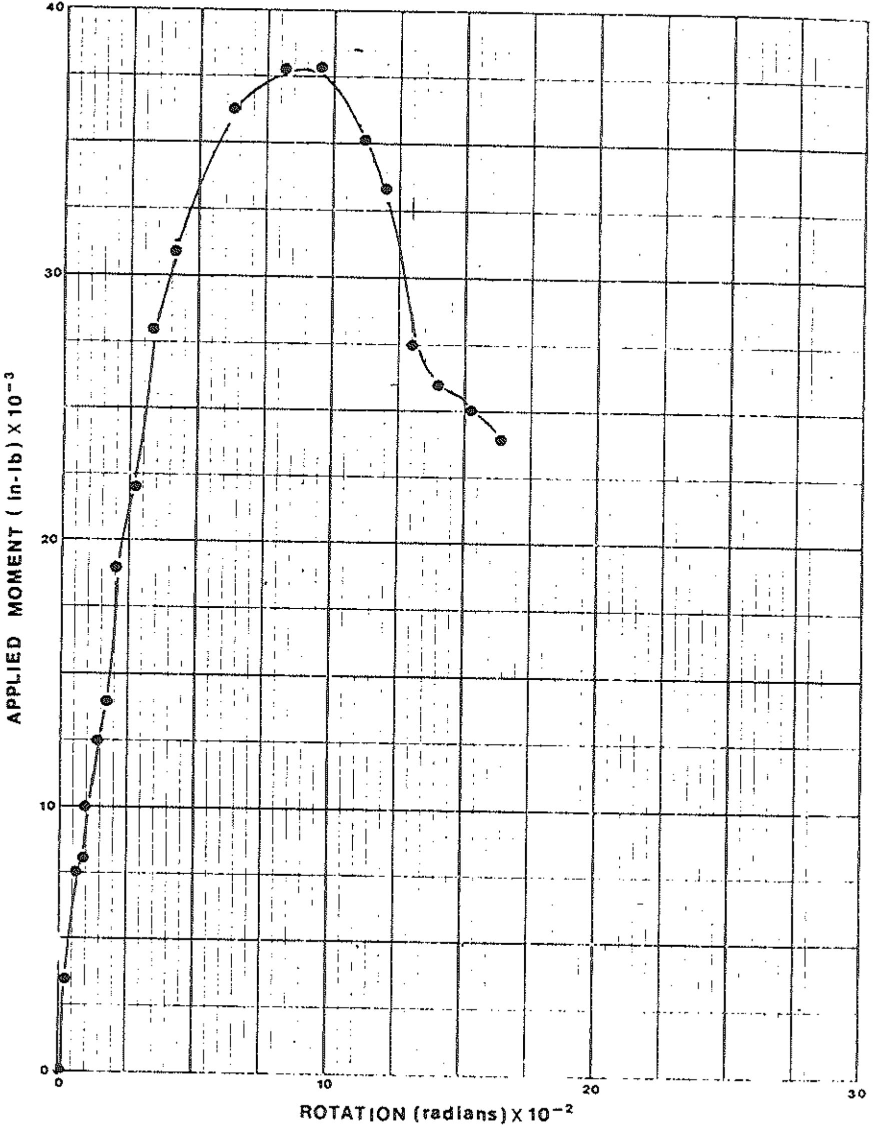


FIGURE 6: APPLIED MOMENT VS. NUMBER OF CYCLES
FOR TEST SEQUENCE III
DOUBLE B104 ANGLE CLIPS
BOLTED WITH B-22A STRUT HANGERS

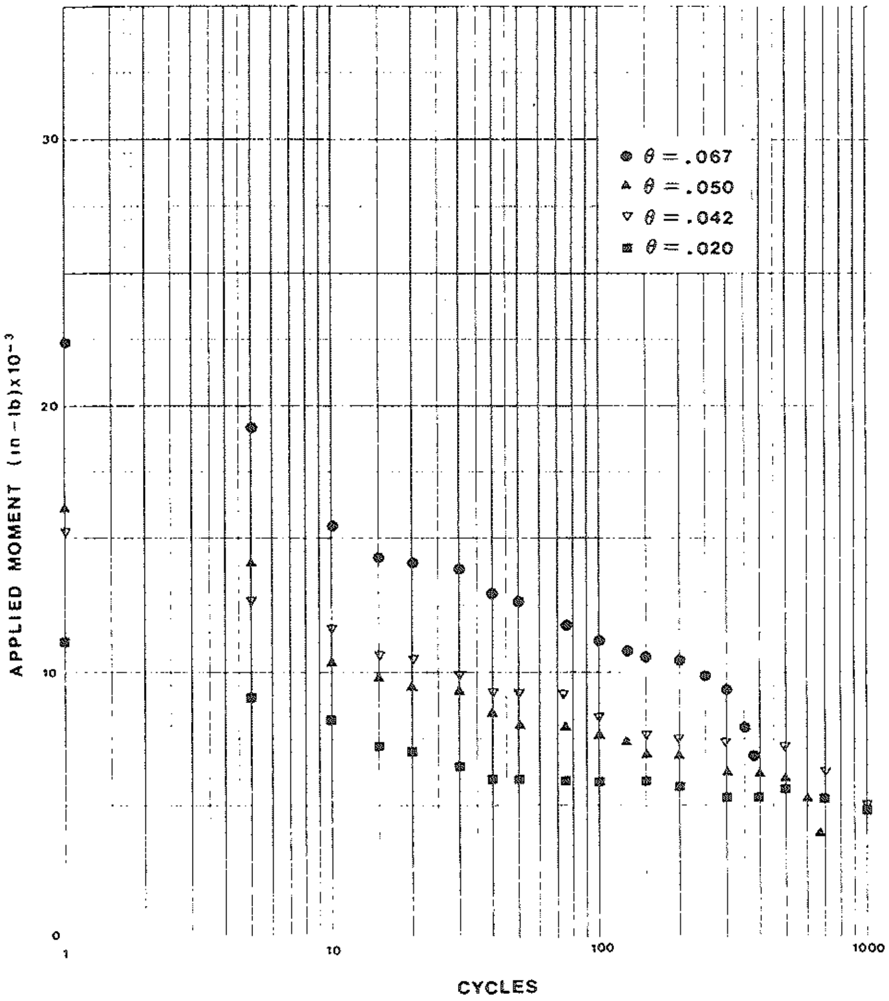


FIGURE 7: FIRST CYCLE HYSTERESIS
TEST III, RUNS 2.1 THRU 5.1
DOUBLE B104 ANGLE CLIPS, BOLTED
WITH B-22A STRUT HANGERS

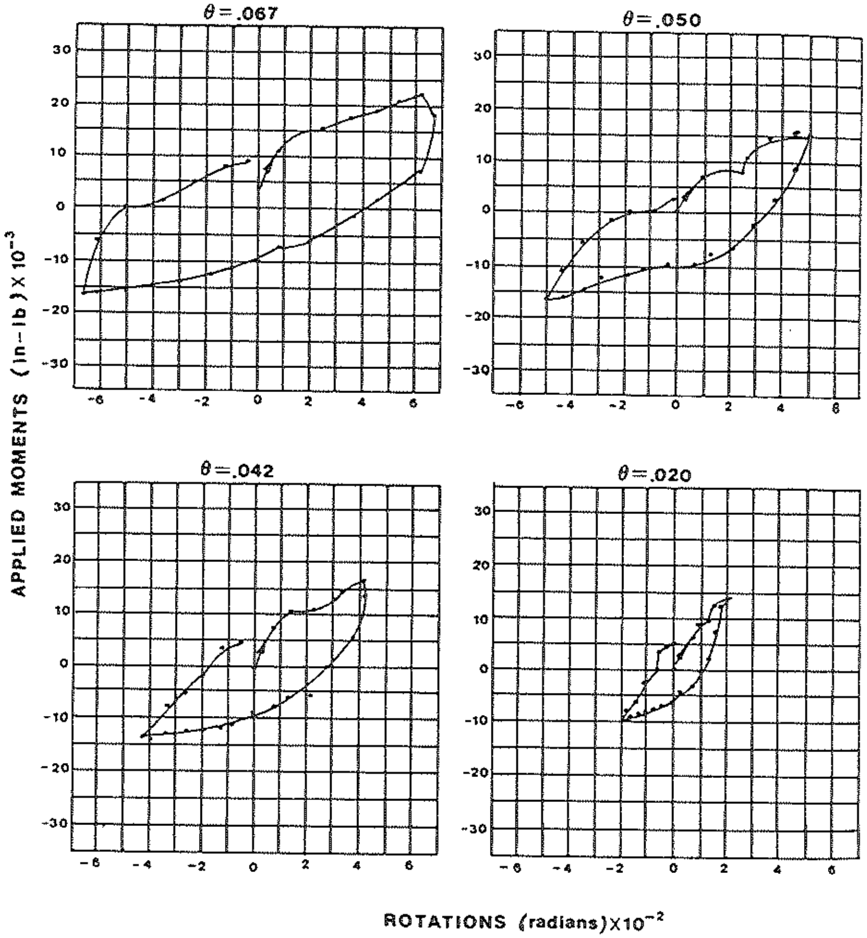


FIGURE 8: THREADED STEEL ROD FATIGUE RATES
AT SELECTED RELATIVE DISPLACEMENTS

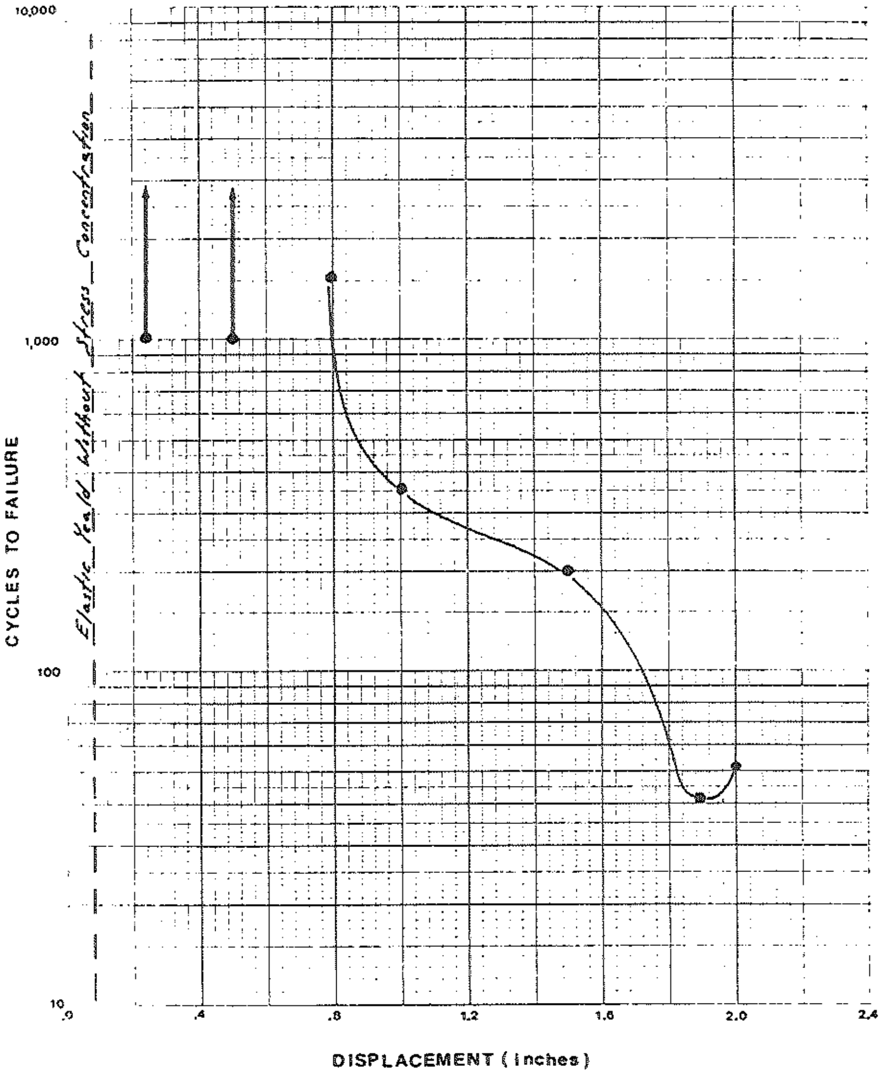
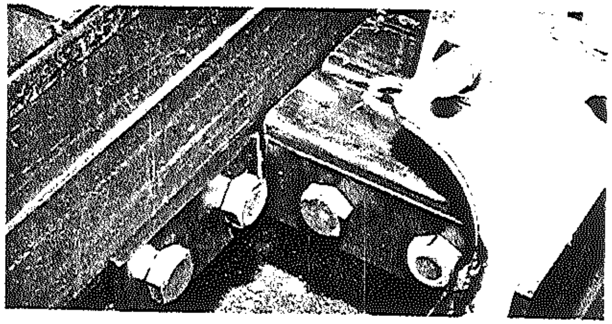
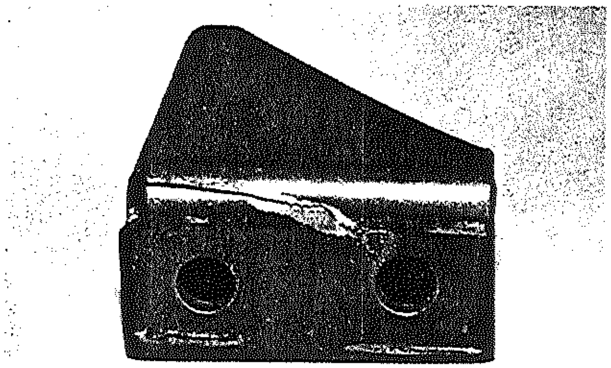


FIGURE 9: TYPICAL CONNECTION FAILURE MODES



Fracture of 4-hole
Angle (B-104)
Test 1, Run 4.1

Fracture 4-hole Angle
(B-104)
Test 1, Run 3.1



Fracture Propagating in
Gussetted Angle (B-144-L)
Test V, Run 3.1