

**THE EVALUATION OF DISCONTINUITIES
IN COMMERCIAL STEEL CASTINGS BY
DYNAMIC LOADING TO FAILURE
IN FATIGUE**

**A RESEARCH PROJECT AT CASE INSTITUTE
OF TECHNOLOGY**

Sponsored by

Steel Foundry Research Foundation

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Director of Research

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STEEL FOUNDRY RESEARCH FOUNDATION

THE EVALUATION OF DISCONTINUITIES IN COMMERCIAL STEEL CASTINGS BY DYNAMIC LOADING TO FAILURE IN FATIGUE

SCOPE OF THE RESEARCH REPORT

Previous studies reported on 12 commercial steel castings tested under simulated service static loads carried to casting destruction determined the influence that four factors had on the castings performance. The factors studied were: (1) discontinuities in the steel castings; (2) relation between castings properties and test bar properties; (3) stress distribution and concentrations within the castings and (4) safety design factors.

The present research studied 7 commercial steel castings in dynamic loading by fatigue and to determine the effect of discontinuities and location of stress concentration on the position of fatigue failure and the reduction in endurance limit as the result of casting design and discontinuities. Static loading of the steel castings to failure and a study of the fatigue properties of the steel and steel castings were undertaken.

SUMMARY OF THE RESEARCH REPORT CONCLUSIONS

Stress analysis and destructive testing of 7 steel castings of different commercial applications in fatigue provided information on design and discontinuities on casting failure. Conclusions are as follows:

1. A comparison of the results of the simulated service fatigue tests and static load-to-failure tests with the stress analysis data on the 7 cast steel parts indicated that failure occurred in the areas of maximum stress resulting from design. The fatigue and static failures occurred at locations of maximum stress regardless of the presence of discontinuities in other sections.

2. Failure of the 7 cast steel parts under static testing occurred at loads well in excess of the maximum designed service loads. The static

failure was influenced by design rather than by the presence of discontinuities. Extensive deformation occurred prior to failure.

3. The endurance limit for all of the steel castings under simulated service fatigue stresses was greater than the cyclic service loads. The safety factors for the steel castings in fatigue varied from 1.4 to 3.0.

4. The tensile and fatigue properties determined for these cast steels were typical for the types of steel utilized.

5. The research proved conclusively that steel castings with discontinuities of considerable magnitude will perform satisfactorily in fatigue loading. Accordingly, the presence of discontinuities may not require casting rejection.

RECOMMENDATIONS FOR DESIGNERS

It is recommended that steel castings designed for dynamic loading (fatigue service) be given the following considerations :

1. Use the notched (.015 in notch radius) R. R. Moore endurance strength properties of the cast steel without further casting safety factors.

2. If the notched endurance strength value for the steel is not available employ the unnotched R. R. Moore strength value multiplied by .70 to give a good approximation of the notched fatigue.

3. If endurance strength values of the cast steel are not available use 40 percent of the tensile

strength of the cast steel to approximate the endurance limit and multiply this value by .70 to give a good approximation of the notched endurance strength. This value will be conservative and will not require further casting safety factors.

It is appreciated that additional design safety factors are often utilized which are necessary because of incomplete information concerning actual service conditions of the part regardless of the material of construction. However, it is hoped that the above guide lines will reduce the tendency of applying excessive safety factors to cast steel parts.

PREFACE TO THE RESEARCH PROJECT

The research studies presented in this report are another in the series of studies that have been published or are underway on the Evaluation of Discontinuities in Steel Castings.

Steel Casting Sections

The first published report is on the "Effect of Shrinkage Porosity on Mechanical Properties of Steel Casting Sections." This research taught that:

1. Shrinkage of Class 2 ASTM E-71 will decrease the tensile strength of cast steel sections by only 4 percent when compared to the strength of radiographically sound cast steel sections. A decrease of 8 percent in strength resulted for sections having very severe Class 5 to 6 shrinkage.

2. The strength of steel casting sections tested in bending is not significantly influenced (1 percent) by the presence of considerable shrinkage at the center of the section where shrinkage discontinuities are normally found. If the shrinkage is brought to the surface by machining at the area of maximum tensile stress concentration in bending, the loss in strength is about 20 percent.

Steel castings are primarily employed as dynamically loaded parts rather than statically loaded. Therefore, it was advisable to carry on studies in fatigue testing. This need was fulfilled by the publication of the report on "The Effects of Surface Discontinuities on the Fatigue Properties of Cast Steel Sections." Tests were made on cast steel sections under dynamic loading conditions of bending and torsion fatigue. The cast steel sections contained surface discontinuities of a severity greater than that permitted by ASTM E-125, "Reference photographs for magnetic particle indications on commercial steel castings," for its most severe class. This research taught the following:

1. Severe surface discontinuities lowered the endurance strength of cast steels 8 to 20 percent but to less extent than the presence of the notch in the standard (R. R. Moore) fatigue test which is responsible for a 35 percent reduction.

2. Surface discontinuities in cast steel were more damaging in reverse bending than in reverse torsion.

3. Severe discontinuities in welds in cast steel lower the endurance strength of the weld from 3 to 20 percent depending on the heat treatment condition and type of fatigue testing.

Testing of Entire Steel Castings

It was the opinion of some design engineers that the testing of cast steel sections could not be related to the testing of entire castings. Therefore, stress analysis and destructive testing of 12 different commercial steel castings were undertaken. These studies provided significant information on the safety factors being employed by design engineers in steel casting design and the relation of casting properties and discontinuities on simulated service failure. Castings were selected for testing with a size limitation of a maximum testing load of 600,000 pounds, the capacity of the large testing machine at Case Institute of Technology. The castings selected were taken directly out of production runs and from those casting orders which did not require nondestructive testing. This later was done since castings produced to nondestructive testing specifications are corrected after pilot casting tests and repaired by welding.

Static Loading Studies . . . Studies on the 12 commercial castings were published as a research report on "Correlation of Destructive Testing of Steel Castings with Stress Analysis and Mechanical Properties." This research taught that:

1. The commercial steel castings were loaded to failure by applying loads that were from four to over twenty times the designed maximum service load. This clearly indicated that unreasonably large safety factors are being applied in the preparation of steel casting design.

2. Brittle lacquer and strain gage analyses showed that the positions of stress concentration on the castings were also the positions of casting failure upon destructive testing. The positions of stress concentration in all cases resulted from inadequacies of casting design and not from the presence or location of discontinuities.

3. The castings with discontinuities of even considerable magnitude performed satisfactorily under the high loads of destructive testing which were in considerable excess of service requirements.

It was very evident from these studies that design and materials engineers have been pointing at steel casting discontinuities with a great emphasis to cover up their inadequacies in stress concentration caused by casting design. However, comments were received from engineers that it was very possible that different results would be

found if the castings were destructively tested by dynamic loading. It was also pointed out by them that in service most steel castings are loaded dynamically such as bending fatigue, torsion fatigue or shock loading.

Dynamic Loading Studies . . . The research of this report is concerned with the testing of seven commercial steel castings to failure by fatigue. The studies are very meaningful in that they support and implement the destructive test studies of the commercial castings by tension.

It should be disclosed that research in progress concerning shock loading of cast steel sections and steel castings shows trends similar to the destructive testing of cast steel in tension and fatigue.

The results of these extensive and costly research studies must be brought emphatically to the attention of design and materials engineers. They must realize in a very practical manner that (1) steel castings fail in service because of design deficiencies, (2) discontinuities seldom contribute to the failure of steel castings unless they are located in the important stress concentration area resulting from design deficiencies and even then the casting yields in a normal manner, (3) factors of safety employed by designers for steel castings are greater than required since the loads to failure in tension and fatigue are in most cases many times the service loads, (4) severity of discontinuities cannot be correlated in any way with the ultimate strength or endurance limit of a steel casting or the position of failure, (5) Stresscoat and strain gage tests always predicted where a steel casting would fail if tested to destruction and also the load carrying ability of the casting, and (6) design requirements of the load carrying ability of steel castings in dynamic loading should be based on the R. R. Moore notched fatigue values of the cast steel. If such values are employed no safety factors should be added for cast steel as the material for construction.

The research of this report confirms the above emphatically stated 6 points. For example, the Trip Link Casting containing important surface linear discontinuities located at the high stress concentration area of the designed-in notch (as discussed in point 2 above) produced failure in fatigue and static loading at values below the design requirement. Point 6 is well illustrated by the Fulcrum Bracket casting testing to an endurance limit of 28,000 psi. This value is in between the R. R. Moore unnotched and notched endurance limits of 32,000 and 23,000 psi, respec-

tively, a 29 percent reduction because of the severity of the machined notch. The casting endurance limit is only 12.5 percent below the endurance limit of the unnotched R. R. Moore values. Thus the notched endurance limit values for the cast steel would have been more than ample as the basis of design calculations for the Fulcrum Bracket without additional safety factors being applied.

Materials engineers should take careful note that internal discontinuities in steel castings assessed by radiography, which they never would permit under any nondestructive testing specification, are of little importance in the service application of steel casting and are of no significance when steel castings are designed with safety factors. Surface discontinuities in steel castings in stress concentration areas are important detriments in dynamic loading designs but the most severe discontinuities as listed by ASTM E-125 have less effect on the endurance properties than those of the notched fatigue values, which are the values employed by knowledgeable design engineers in steel casting design for dynamic loaded applications.

The Foundation is most appreciative to the steel casting organizations which contributed commercial castings for these studies and to their customers for permission to study the castings which they designed. The steel casting companies are as follows :

Lebanon Steel Foundry
Malleable Iron Fittings Company
Maynard Electric Steel Casting Co.
National Castings Group,
Midland-Ross Corporation
Texas Foundries, Inc.
Texas Steel Company
Westran Corporation

Also, the Foundation desires to take this opportunity to express its appreciation to Case Institute of Technology for the excellent manner in which the research studies were executed. Special appreciation is accorded to John F. Wallace, Professor of Metallurgy, for directing and coordinating the research and for his two graduate research assistants, Messrs. C. Vishnevsky and M. F. Eertolino, who accomplished a very difficult task of designing test fixtures and carrying out the many phases of the research studies.

Charles W. Briggs
Director of Research
Steel Foundry Research Foundation

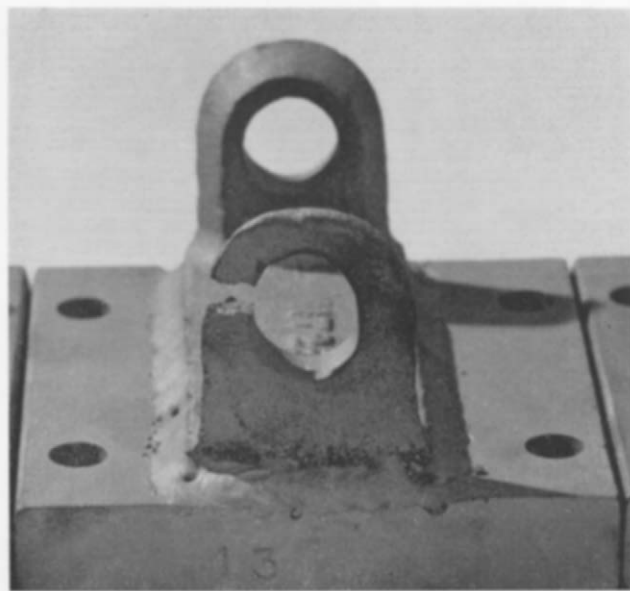
**THE EVALUATION OF DISCONTINUITIES
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LOADING TO FAILURE IN FATIGUE**

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**Steel Foundry Research Foundation
in contract with
Case Institute of Technology**

SHEAVE HOLDER



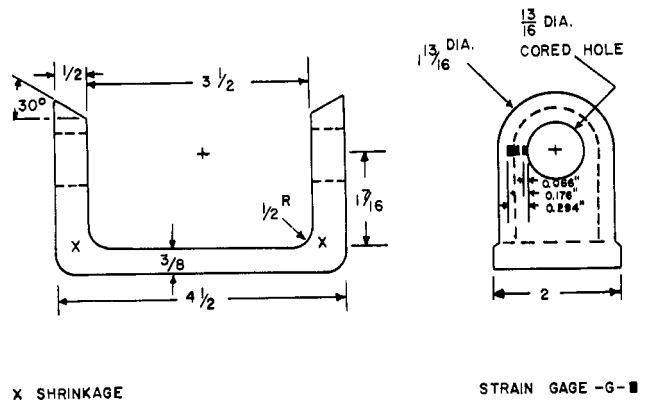
LOCATION OF THE FATIGUE FAILURES FOR THE SHEAVE HOLDER CASTING AND ALSO SHOWING SURFACE SHRINKAGE AT THE FILLET AREA

MECHANICAL PROPERTIES

Tensile Strength	69,300 psi
Yield Strength	42,000 psi
Elongation	31.5 percent
Reduction in Area	51.4 percent

Sheave Holder for Digging Machine

The sheave holder was produced from carbon steel of ASTM A-27, Grade 70-36 for service as a pivoting anchor for a sheave on a hole digging machine. All the castings were radiographed and visually inspected to locate and classify the discontinuities. Radiography and visual examination indicated some gas and shrinkage porosity were located at the surface in the fillet area as well as internally in all the sheave holder castings. In three of the castings, slag inclusions were also observed in the cored hole region. The stresscoat test was conducted to determine the area of stress concentration and directions of principal stress. Stress analysis was performed using strain gages located in the maximum stress areas. The experimental stress analysis and subsequent fatigue



DIMENSIONS OF SHEAVE HOLDER WITH LOCATION OF STRAIN GAGES AND DISCONTINUITIES

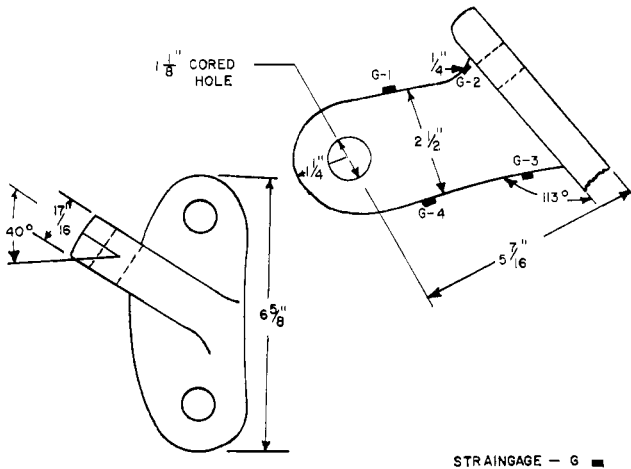
SERVICE DATA

Service Load	10,000 cycles/yr.	7,400 pounds
Load to Failure		
Fatigue		10,400 pounds
Static		18,300 pounds
Endurance Limit of Casting		36,000 psi
Safety Factor		
Fatigue		1.4
Static		2.5

and static tests were conducted which simulated service loading.

The stress analysis indicated that the maximum stress area is located in the cored hole region and not in the fillet area where most of the discontinuities were present. Since all the sheave holder castings failed through the cored hole region surface, surface discontinuities at the fillet area, usually a critical location, exerted no influence on the fatigue properties of the casting. However, surface discontinuities present in the cored holed region were detrimental to the fatigue properties of the casting. Therefore, surface discontinuities are detrimental to the fatigue properties only if located in the areas of maximum stress.

FULCRUM BRACKET



STRAIN GAGE - G

DIMENSIONS OF FULCRUM BRACKET WITH LOCATIONS OF STRAIN GAGES

MECHANICAL PROPERTIES

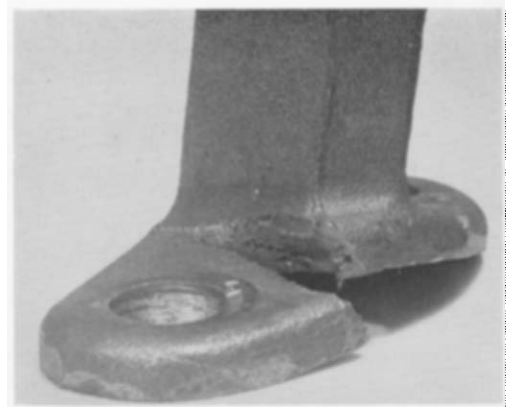
Tensile Strength	71,750 psi
Yield Strength	42,800 psi
Elongation	32.8 percent
Reduction in Area	42.4 percent

SERVICE DATA

Service Load	
6000 cycles/yr.	3,333 pounds
Load to Failure	
Fatigue	10,000 pounds
Static	25,000 pounds
Endurance Limit of Casting	28,000 pounds
Safety Factor	
Fatigue	3.0
Static	6.5

Fulcrum Bracket for Freight Train Braking Systems

The Fulcrum Bracket was produced from a grade 0.22 percent carbon normalized cast steel for service as a component, of a freight train braking system. Radiography and visual examination indicated that the casting contained sand and slag inclusions and some shrinkage cavities and surface roughness in rear fillets. The Stresscoat tests determined areas of stress concentration to be located at the front fillet. Strain gages located in the maximum stress areas showed stresses to be essentially uniaxial with the maxi-



LOCATION OF FATIGUE FAILURE IN FULCRUM BRACKET

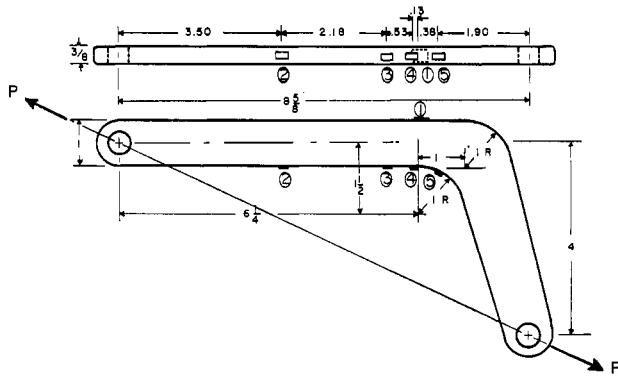


SEVERE GAS POROSITY IN BASE OF FULCRUM BRACKET

imum measured stresses in the front fillet. The yield strength of the casting was exceeded at an applied load of 15,000 pounds.

All the Fulcrum Bracket castings failed in fatigue and tension through the front fillet region, surface discontinuities located in the rear fillet exerted no influence on the fatigue properties of the casting. Thus, the results of the tests on the Fulcrum Bracket casting indicate that prominent surface discontinuities as located by visual and magnetic particle inspection were not detrimental to the fatigue properties of the casting since they were not located in the areas of maximum stress.

HANGER



DIMENSIONS OF HANGER CASTING AND LOCATIONS OF STRAIN GAGES AND DIRECTION OF LOADING

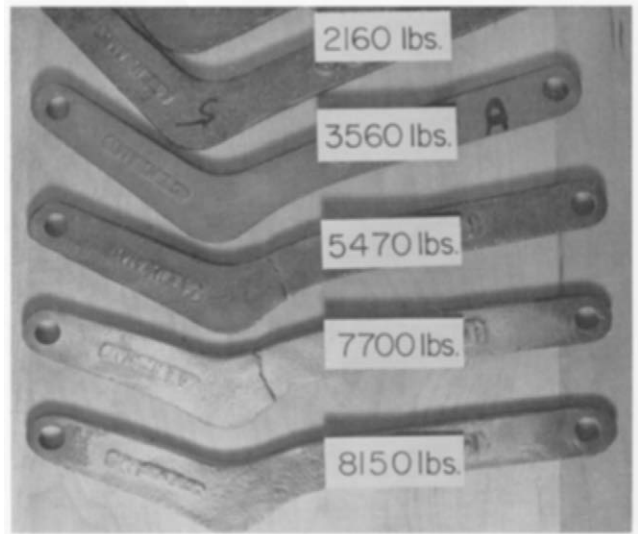
SERVICE DATA

Service Load	500 to 600 cycles/yr.	400 pounds
Load to Failure		
Fatigue		1,000 pounds
Static		5,470 pounds
Endurance Limit of Casting		41,400 psi
Safety Factor		
Fatigue	2.5	
Static	1.9 (initial yield basis)	
	13.7 (ultimate failure)	

Hanger Casting for Tank Roof

Hanger steel castings are used in supporting a floating roof in a liquid storage tank. These are produced from a 0.27 percent carbon steel to ASTM specification A27. All castings employed in the test program were examined using radiography and magnetic particle inspection to determine discontinuities though the castings were not purchased to nondestructive test specifications. These nondestructive tests revealed dispersed shrinkage and porosity was revealed by the nondestructive tests. The position of stress concentration was located by employing Stresscoat techniques. Strain gages placed at these areas provided, under simulated service loading conditions, a quantitative measure of actual stresses. These same loading conditions were also utilized in performing fatigue tests to failure of the Hanger casting and a plot of load versus cycles to failure was obtained. Static load to failure tests were also performed to determine the ultimate load carrying capacity.

The location of highest tensile stress was in the fillet section of the Hanger casting. Eleven cast-



APPEARANCE OF HANGER CASTINGS AFTER THE APPLICATION OF VARIOUS STATIC LOADS

MECHANICAL PROPERTIES

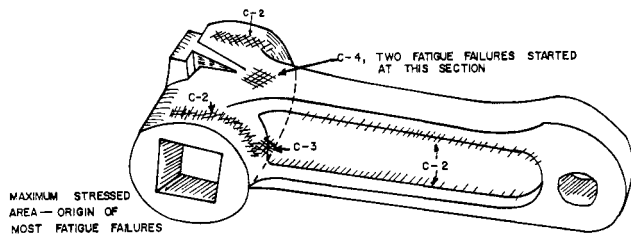
Tensile Strength	71,000 psi
Yield Strength	41,400 psi
Elongation	25.4 percent
Reduction in Area	43.6 percent

ings failed in fatigue and two in static loading at this maximum stressed area; no discontinuities existed near the tension surface in these castings. Internal shrinkage and porosity were effective in changing the failure location when the discontinuities occurred at the tension surface and four fatigue failures were experienced outside the area of highest stress concentration. However, the surface discontinuities had no apparent effect on fatigue or static properties.

The endurance limit load of 1000 pounds constitutes a safety factor of 2.5 in fatigue as related to the design service load of 400 pounds. The endurance limit of the Hanger Casting tested in fatigue when compared to unnotched R. R. Moore test results on a Goodman diagram shows that the presence of the numerous discontinuities within the casting had no effect on the dynamic loading properties of the cast steel Hanger.

The static tensile loading tests to failure showed first failure at a load of 5470 pounds providing a safety factor of 13.7 based on the design service load of 400 pounds.

LEVER



LOCATION AND SEVERITY CLASS OF DISCONTINUITIES IN THE LEVER CASTING

SERVICE DATA

Service Load	
250 cycles/yr	1800 in-pounds torque
Load to Failure	
Fatigue	3000 in-pounds
Static	>9200 pounds
Safety Factor	
Fatigue	1.7
Static	4.2 (initial yield basis)
	>5.1 (ultimate failure)

Cast Steel Lever Casting on Railroad Car Door

Lever casting was produced from a normalized 0.27 percent carbon cast steel as a part of a mechanism that operated a hopper door on a railroad car. Radiographic and magnetic particle examination revealed the presence of pronounced (Class 4) shrinkage at similar locations in each casting and porosity in some castings.

Stresscoat techniques determined that the areas of highest stress were the small designed-in and cast notches at the corners of the cored square hole in the barrel about which the castings were torqued. Strain gages located in the maximum stress areas showed that the yield strength of the casting was exceeded at an applied load of 1000 pounds.

All Lever castings on test to failure in fatigue developed fatigue cracks at the location of stress concentration and all but two failed as a result of propagation of these fatigue cracks. The two Lever castings which did not fail by growth of these cracks were tested at very high loads with the fatigue failure occurring at the junction of the lever arm and the barrel at a position of a pronounced shrinkage area which was near the casting surface. Otherwise, the presence of



TYPES OF FATIGUE FAILURE FOUND IN THE LEVER CASTINGS

MECHANICAL PROPERTIES

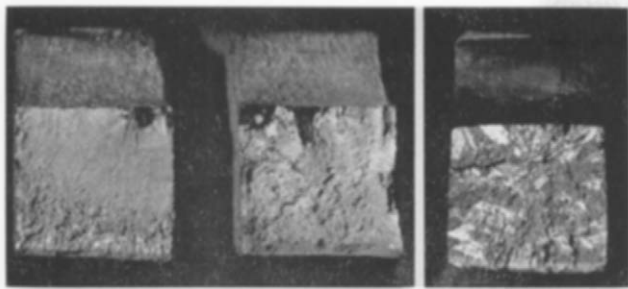
Tensile Strength	74,600 psi
Yield Strength	47,500 psi
Elongation	27.1 percent
Reduction in Area	44.4 percent

shrinkage and other internal discontinuities exerted no influence on the fatigue failures or fatigue properties.

Calculations comparing the fatigue results at the endurance limit with loads encountered in service yield a safety factor of 1.67. When failure is defined by initial yielding without considering fatigue life, a safety factor of 4.17 resulted.

The Lever was also loaded statically in a failure test. However, testing was terminated at a maximum applied load of 9200 pounds because the Lever arm deformed and contacted the bottom of the testing fixture. Although considerable distortion was observed, there was no evidence of cracks in any area including the high stressed area of the cored square opening.

TRIP LINK



FRACTURE SURFACES OF TRIP LINK CASTINGS BROKEN IN FATIGUE AND STATIC LOADING

MECHANICAL PROPERTIES (min. specified)

Tensile Strength	100,000 psi
Yield Strength	70,000
Elongation	15 percent
Reduction in Area	30 percent
Actual Hardness BHN	241
Equivalent to a tensile strength of 118,000 psi	

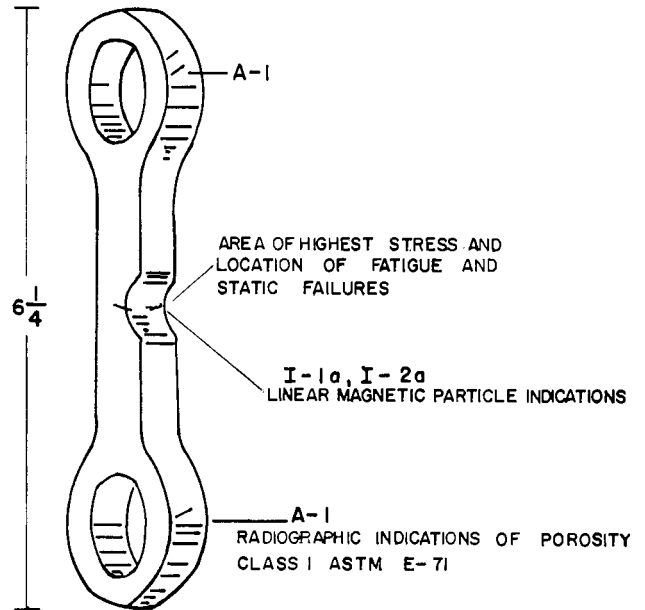
Trip Link Casting for Pile Driver

The Trip Link is used as a safety device in a pile driver and is designed to break at the central notch in case of an overload. Radiography and magnetic particle inspection indicated porosity of Class 1, ASTM E-71 in the area of the loading holes and linear discontinuities of I-2a, ASTM E-125 at the base of the center notch. Stresscoat and strain gage measurements showed that the base of the notch was the region of maximum stress.

Fatigue tests conducted on the Trip Link castings using a unidirectional zero to maximum loading cycle resulted in casting failures at the position of the linear discontinuities in the center notch. The stress at the endurance limit load of 1250 pounds was 20,000 psi indicating that an appreciable reduction in fatigue strength resulted from the linear discontinuities.

These results indicate that stress concentrations arising from design and the location of discontinuities relative to these regions are far more significant than the mere presence of discontinuities in the casting.

A load of 15,200 pounds was required to produce fracture in a static load-to-failure test. This



POSITION AND SEVERITY OF DISCONTINUITIES IN TRIP LINK

CASTINGS SERVICE DATA

Service Load

100 cycles/min continuous for loads to 4000 pounds with sudden failure on overloads in excess of 17,000 pounds

Load to Failure

Fatigue	1,250 pounds
Static	15,200 pounds

Endurance Limit

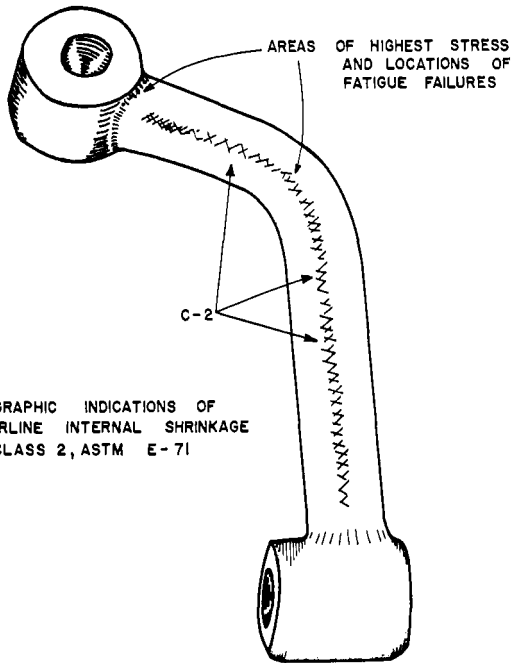
of Castings	20,000 psi
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failure also occurred at the designed notch with the linear discontinuity contributing to the reduced load carrying ability.

It was unfortunate that test coupons were not available of this cast to permit R. R. Moore unnotched and notched test specimens to be machined and tested. Also, Trip Link castings without linear discontinuities in the notch area were not available for testing. Therefore comparisons between sound and defective castings could not be made as to both fatigue and static loading.

The marked loss in the fatigue strength because of the location of the linear discontinuities being exactly at the position of maximum stress in the notch of the link is significant and illustrates the reason why the service requirements for the part were not met.

HINGE



C-2: RADIOGRAPHIC INDICATIONS OF CENTERLINE INTERNAL SHRINKAGE TO CLASS 2, ASTM E-71

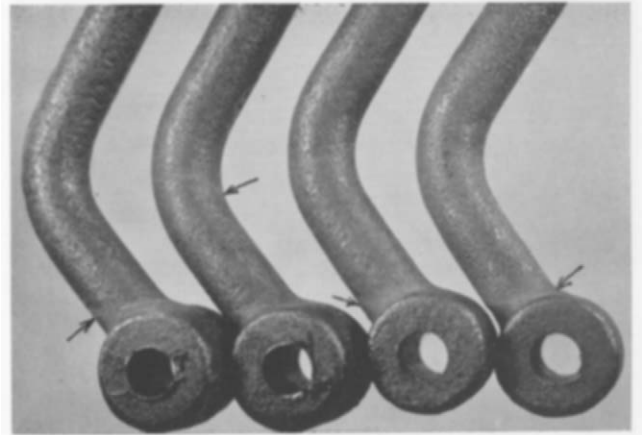
POSITION AND SEVERITY OF DISCONTINUITIES IN THE CAST STEEL HINGE

MECHANICAL PROPERTIES

Tensile Strength	72,000 psi
Yield Strength	40,000 psi
Elongation	27 percent
Reduction in Area	46 percent
BHN	145

Hinge Casting for Trap Door

The cast steel Hinge was produced from 0.21 percent carbon steel to ASTM specification A216, Class WCB, for service as a trap door hinge in the petroleum industry. The castings were radiographed and magnetic particle inspected though not required by the purchase order and found to be free of magnetic particle indications. Radiography showed internal centerline shrinkage of Class 2 ASTM E-71 in all castings. A Stresscoat brittle lacquer test showed the areas of stress concentration to be at the fillet joining the bar and hinge and at the bend in the bar. Strain measurements at the positions of high stress showed yielding at a load of 600 pounds.



MAGNETIC PARTICLE INDICATIONS OF FATIGUE FAILURES IN HINGE CASTINGS TESTED IN FATIGUE

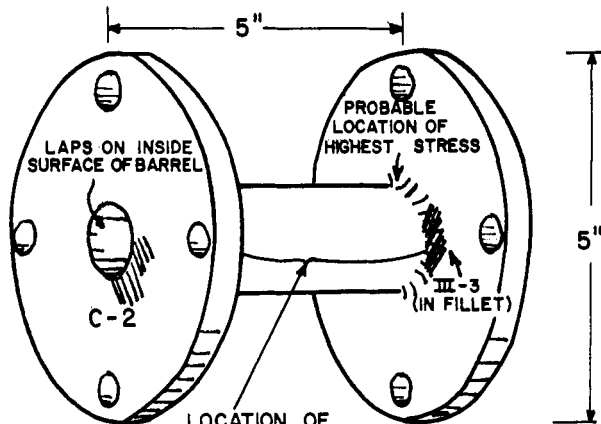
SERVICE DATA

Service Load	1000 cycles/yr	350 pounds
Load to Failure	Fatigue	850 pounds
	Static	>1100 pounds
Endurance Limit	of Casting	40,000 psi or 850 pound load
Safety Factor	Fatigue	2.4
	Static	1.7 (initial yield basis)
		>3.1 (ultimate failure)

The endurance limit of 850 pounds for the Hinge was reached at a loading cycle of 0 to 850 pounds which, when compared to the service load of 350 pounds, gave a safety factor of 2.43. However, the load at the endurance limit was accompanied by considerable permanent deflection. Since in service such deflection may hinder proper closure of the trap door, incipient yielding rather than fatigue may be a more important consideration, resulting in a safety factor of 1.71. Tensile loading to failure resulted in no casting failure at a load of 1100 pounds but with a deflection of 1.5 inches resulting in a safety factor greater than 3.1.

The centerline shrinkage exerted no influence on either the fatigue or static loading properties of the part.

FLANGE



- LOCATION OF FATIGUE FAILURES; DISCONTINUITIES OF TYPE III-3, V-1
- C-2 : RADIOGRAPHIC INDICATIONS OF INTERNAL SHRINKAGE TO CLASS 2, ASTM E-71
- III-3 : MAGNETIC PARTICLE INDICATIONS OF INCLUSIONS TO DEGREE 3, ASTM E-125
- V-1 : MAGNETIC PARTICLE INDICATIONS OF POROSITY TO DEGREE 1, ASTM E-125

POSITION AND SEVERITY OF DISCONTINUITIES IN THE CAST STEEL FLANGE

MECHANICAL PROPERTIES

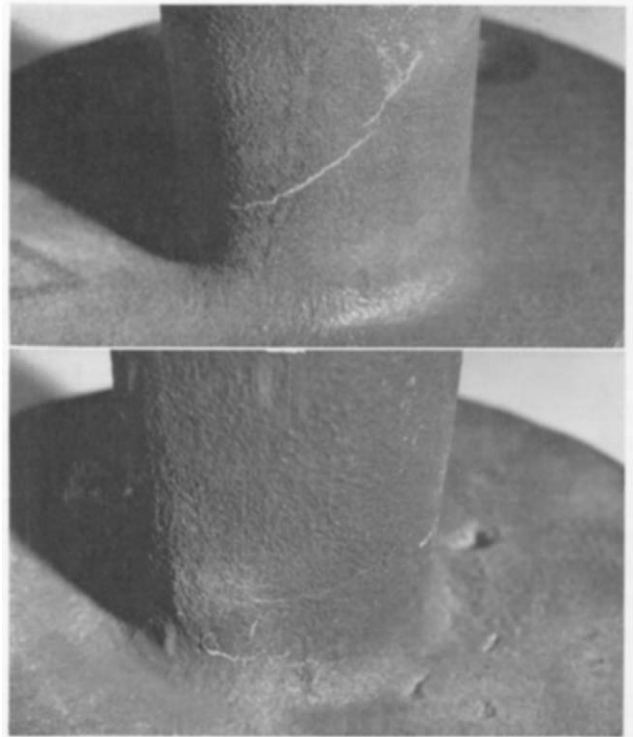
Tensile Strength	75,800 psi
Yield Point	39,900 psi
Elongation	25.7 percent
Reduction of Area	39.7 percent
Hardness, BHN	151

Cast Steel Flange

The Flange Casting was produced from a 0.27 percent carbon cast steel to ASTM A-27 Grade 70-36. The part is not used commercially but was cast specifically by a commercial steel foundry for pure torsional loading studies and to assess the effect of discontinuities on the casting properties.

Discontinuities were deliberately produced in the casting during its manufacture and recorded by radiographic and magnetic particle testing. Radiography revealed internal shrinkage Class 2, ASTM E-71 and magnetic particle examination showed surface porosity to degree 1 and inclusions to degree 3, ASTM E-125.

Stresscoat analysis determined that the first cracks in the brittle lacquer appeared at random locations on the barrel and in the fillet area at



MAGNETIC PARTICLE INDICATIONS OF TYPICAL FATIGUE FAILURES IN FLANGE CASTINGS

FAILURE DATA

Load to Failure	
Fatigue	10,200 inch-pounds
Static (Torsion)	>18,900 inch-pounds
Endurance Limit of Casting	31,000 psi
(equivalent tensile stress)	

10,350 inch-pounds torque. Strain gages showed that the yield point was reached at 11,800 inch-pounds torque.

Fatigue tests of the casting showed an endurance limit of 10,200 inch-pounds torque at 10 million cycles. This corresponds to an endurance limit of 31,000 psi, equivalent tensile stress. The endurance limit for R. R. Moore unnotched test bar at 10 million cycles was also 31,000 psi.

The notch bar endurance limit of 20,500 psi is a 34 percent reduction in fatigue value because of the notch and constitutes a good value for design for dynamically loaded cast steel parts.

The high stress conditions of the barrel and fillets of the Flange Casting rather than the severity or location of discontinuities determined the fatigue behavior of this cast steel part.

SECTION I SHEAVE HOLDER

Steel Casting Application

The Sheave Holder casting (Figure 1) is employed as a pivoting anchor for a cast steel sheave on a truck-mounted hole digging machine. The sheave is bolted to the holder by a 3/4 inch mild steel bolt through the 13/16 inch diameter cored holes. The casting is welded to the machine frame by a fillet weld on all four sides of the base.

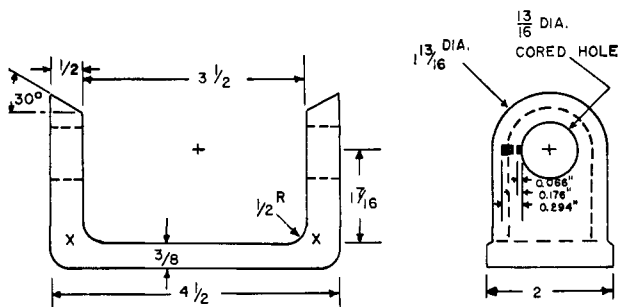
Loading of the holder casting is steady during the drilling operation. The greatest shock loading is exerted when the drilling auger is lifted after drilling its full depth into various rock and clay soils. The number of shock loading applications the casting receives in service is estimated to be less than 10,000 cycles per year. The casting was designed on the basis of a service load of 7400 pounds, the breaking load 1/2 inch 7-strand standard grade cable (ASTM A22) which turned over the sheave.

The castings were produced to ASTM A-27 grade 70-36 carbon cast steel. The composition and properties of the steel in the normalized and tempered condition are as follows:

C	0.33 percent	Tensile Strength, psi	69,300
Mn	0.66 percent	Yield Strength, psi	42,000
Si	0.78 percent	Elon. (1.4 gage) percent	31.5
		Red. of Area percent	51.4

Test Method

The castings were examined by radiographic and magnetic particle inspection for internal and surface discontinuities. Shrinkage cavities were located at the juncton of the base and flanges with some of the shrinkage coming to the surface in the fillet area as shown in Figure 2. The severity of the shrinkage was Class C-5 ASTM E71-64.



X SHRINKAGE

STRAIN GAGE -G- ■

Figure 1—Dimensions of Sheave Holder with location of strain gages and discontinuities. Shrinkage class C-5.

Magnetic particle examination showed porosity present in the fillet area at the junction of the base and flanges and in areas near the cored openings. This was of a severity of Grade ASTM E-125. Also in some of the castings tested in fatigue, slag and/or sand inclusions of Grade ASTM E-125 were lodged near the cored opening. Figure 3 shows these discontinuities. They resulted in premature failure of the Sheave Holder casting because of the reduction in cross-sectional area and the increased stress concentration around the cored opening.

The castings were purchased by the customer on the basis of no nondestructive testing require-

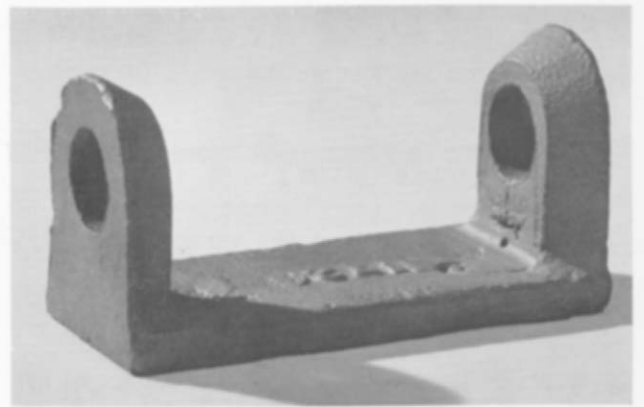


Figure 2—Photograph of Sheave Holder.



Figure 3—Slag inclusions in cored hole area.

ments. The Sheave Holder casting was selected for this study because it contained discontinuities. The castings were coated with a Stresscoat brittle lacquer and loaded in a test fixture simulating the service conditions to determine the areas of greatest stress concentration. Strain gages were positioned at locations indicated by the brittle lacquer test. The strain readings were used to compute equivalent stresses and stress analysis was employed to determine and compare calculated and experimental stresses. Fatigue studies of the actual casting and small scale R. R. Moore notched and unnotched specimens, machined from keel blocks that were cast from the same steel as the holder castings, were made to determine the fatigue properties of both the cast steel and the castings. The method of loading the casting in tension and fatigue is shown in Figure 4.

The service load on the Sheave Holder varied from zero to a maximum that depends on the particular service conditions. The castings were tested with a preload of 660 pounds because of the limitations of the Amsler Pulsator used in the fatigue testing. The pulsator operated at a frequency of 500 cycles per minute. The small scale fatigue specimens were tested on a R. R. Moore fatigue machine at a frequency of 10,000 cycles per minute.

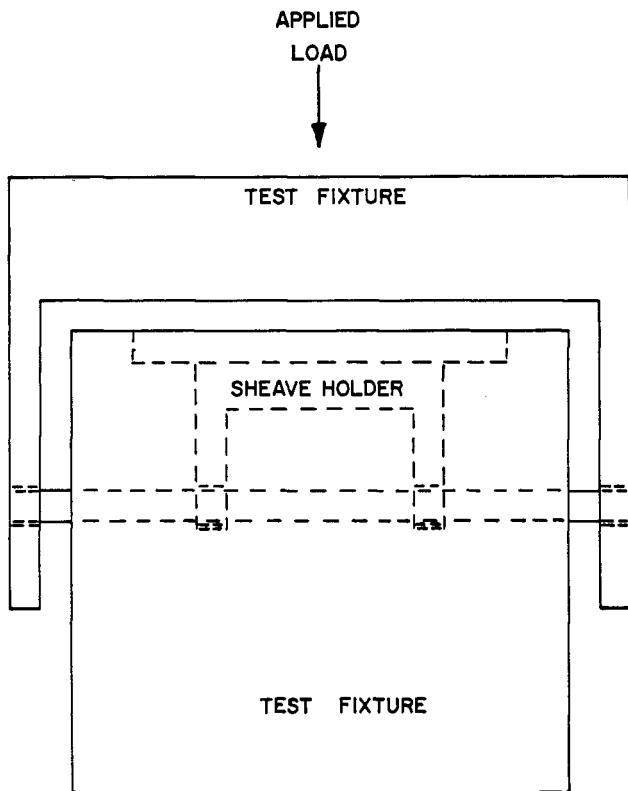


Figure 4—Fatigue test arrangement indicating test fixture, position of applied load and Sheave Holder casting.

Test Results

The first cracks in the Stresscoat appeared at a load of 12,050 pounds or a stress of 21,300 psi. The sketch, Figure 5, indicates the crack pattern as a function of applied load. The highest stress area is located at the edge of the cored opening.

Strain gages were located as shown in Figure 1 on the basis of the brittle lacquer test. The stresses being uniaxial were calculated by multiplying the experimental strain readings by Young's modulus. Stresses obtained experimentally and the calculated stresses are shown in Figure 6. A good correlation between experimental and calculated stresses (finite plate theory) was obtained at all gage locations except after yielding at the location of Gage 1.

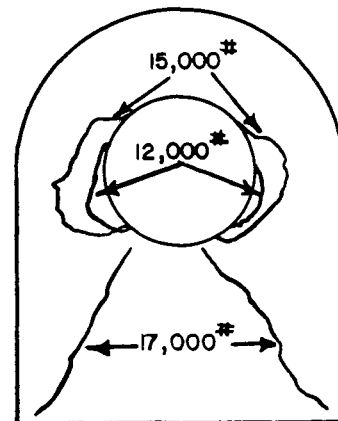
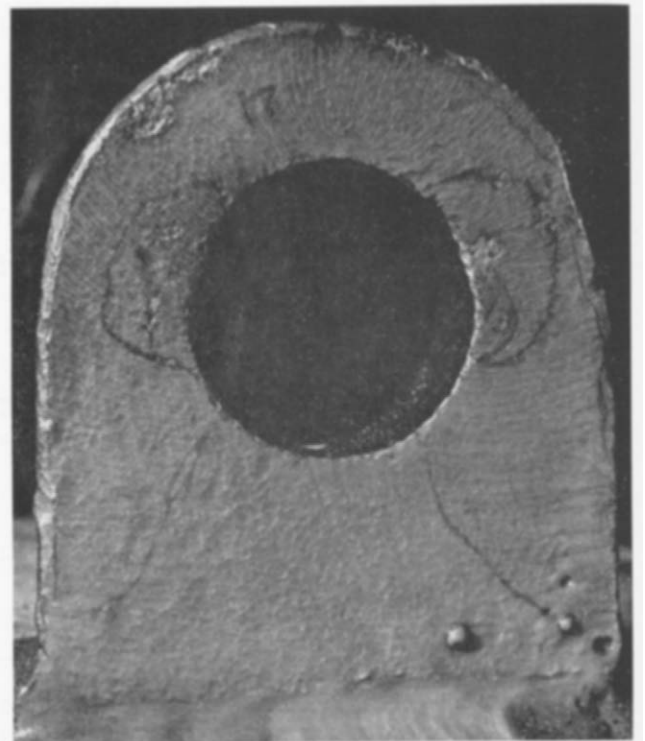


Figure 5—Stresscoat crack pattern for Sheave Holder.

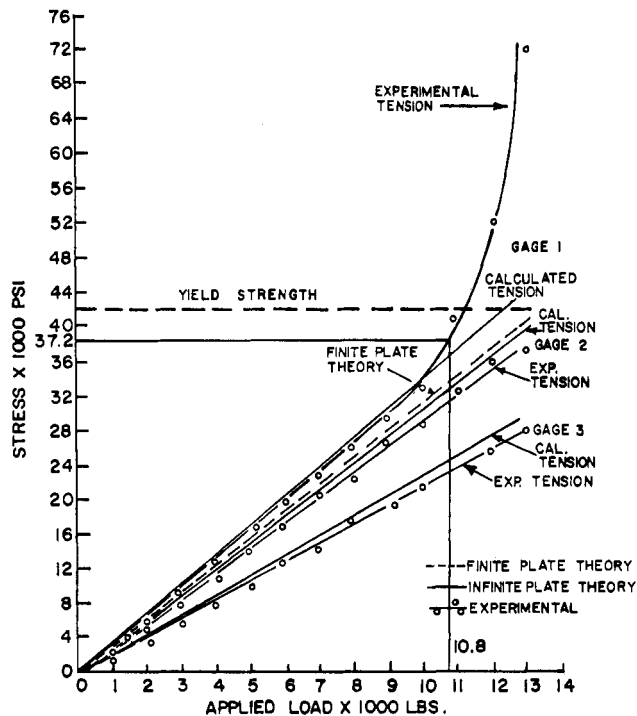


Figure 6—Calculated and measured stresses versus applied load at strain gage locations for Sheave Holder.

Stress concentration factors K_t in the area of the cored openings are shown in Table 1.

TABLE 1
Stress Concentration Factors for Cored Opening

Gage No.	Distance from Cored Opening (inch)	Calculated (K_t)	Experimental (K_t)	Error (%)
1	0.666	2.52	2.43	3.5
2	0.176	2.18	2.08	4.5
3	0.294	1.71	1.55	9.3

Fatigue Tests . . . The load versus cycles to failure curves obtained from the fatigue tests conducted on the Sheave Holder casting are plotted in Figure 7. The endurance limit was selected at five rather than ten million cycles in order to expedite testing with the slow operating Amsler Pulsator. The lower number of cycles for the endurance limit does not introduce significant error since these curves for this type of steel attain a constant stress level after two or three million cycles. Fatigue failure occurred by fracturing completely through one side of the cored hole area of the casting as indicated in Figure 8. None of the castings failed through the fillet area where the major surface discontinuities and internal discontinuities were located. Failure, therefore, resulted because of the maximum stress con-

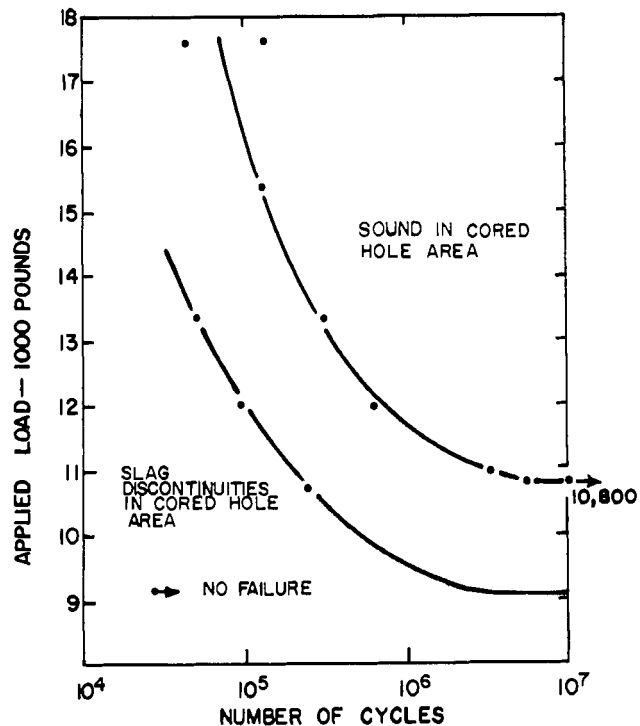


Figure 7—Load versus cycles to failure plot for Sheave Holder casting.

centration in the cored opening region as foretold by the brittle lacquer tests rather than the presence of discontinuities. However, sand or slag inclusion discontinuities which were located in the maximum stress area caused three of the Sheave Holders to fail at a reduced stress level.

The results of the R. R. Moore notched and unnotched fatigue specimens have been summarized in Table 2 and the S-N curves shown in Figure 9.

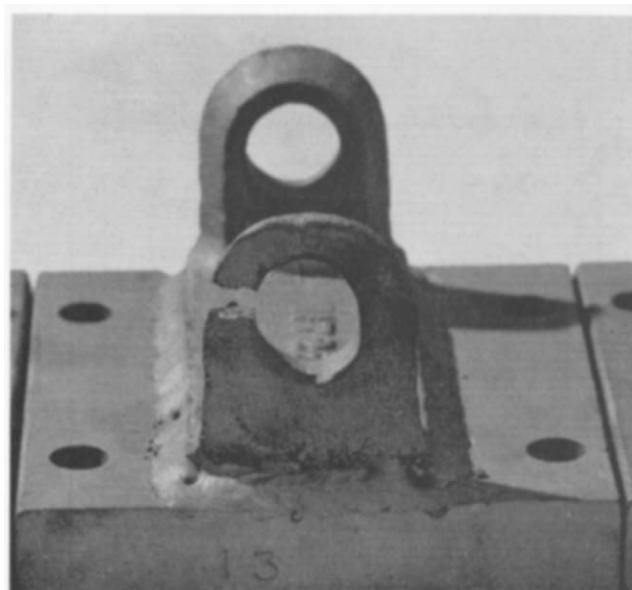


Figure 8—Location of the fatigue failures for the Sheave Holder casting.

TABLE 2

Fatigue Tests, R.R. Moore Specimen, for Normalized and Tempered 0.33 Percent Carbon Cast Steel

	Unnotched	Notched
Endurance Limit	40,000 psi	22,000 psi
Endurance Ratio	0.575	0.317
Fatigue Strength Reduction Factor, K_t^*		1.82
Notch Sensitivity Factor, q^{**}		0.68
$*K_t = \frac{\text{Unnotched endurance limit}}{\text{Notched endurance limit}}$		
$**q = \frac{K_t - 1}{K_t - 1}$, where K_t is the theoretical stress concentration factor (2.2) for the notch design used for the R. R. Moore specimens.		

The behavior of this steel is typical for normalized and tempered steel of a 70,000 psi tensile strength level.

An endurance limit of 10,800 pounds was obtained by fatigue testing the Sheave Holder castings that did not contain sand inclusions in the cored openings. (See Figure 7 for this value.) The load values can be converted over to stress values by studying Figure 6. The applied load of 10,800 pounds projected to the experimental tension curve gives a stress value of 37,200 psi as the endurance limit for the Sheave Holder castings.

In the same way the minimum preload of 660 pounds employed in testing is equivalent to 1800 psi. A mean stress of 19,500 psi $[(37,200 + 1800)/2]$ results.

The fatigue test results can be converted to actual service loading conditions by constructing and employing a modified Goodman Diagram as shown in Figure 10. The position of the maximum and minimum stress lines at zero mean stress are constructed using the R. R. Moore unnotched endurance limit for the carbon cast steel of 40,000 psi. The maximum and minimum stress lines also at zero mean stress for the R. R. Moore notched specimen are shown at the 22,000 psi value.

The endurance limit of the Sheave Holder casting under service conditions can be obtained from Figure 10 by plotting the 19,500 psi casting mean stress on the mean stress line and vertically extending a line upward to the casting endurance limit of 37,200 psi and downward to the minimum preload stress of 1800 psi. These points establish the maximum and minimum stress lines for the casting. At the point where the minimum stress line for the casting intersects the mean stress (horizontal axis) line, 18,000 psi, construct a vertical line to intersect the maximum stress line determined from the casting. This point on the

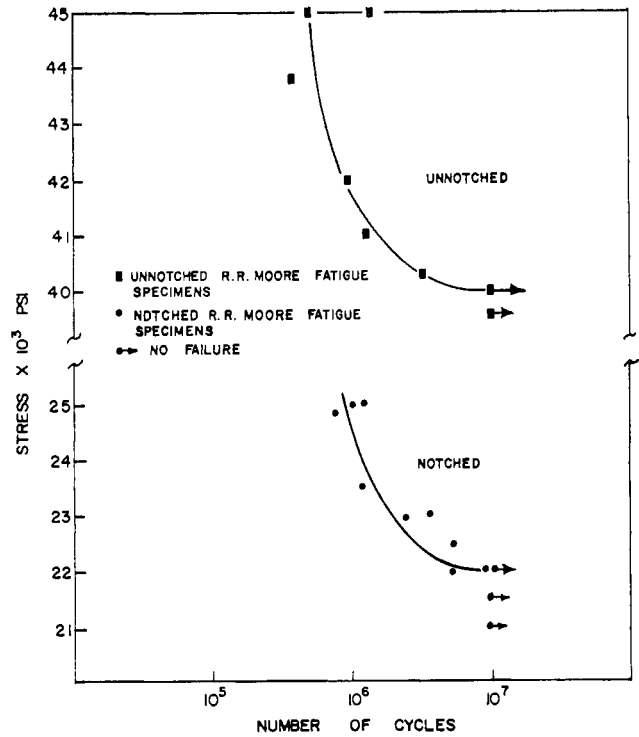


Figure 9—S-N curves for R. R. Moore fatigue specimens for a normalized and tempered 0.33 percent carbon cast steel.

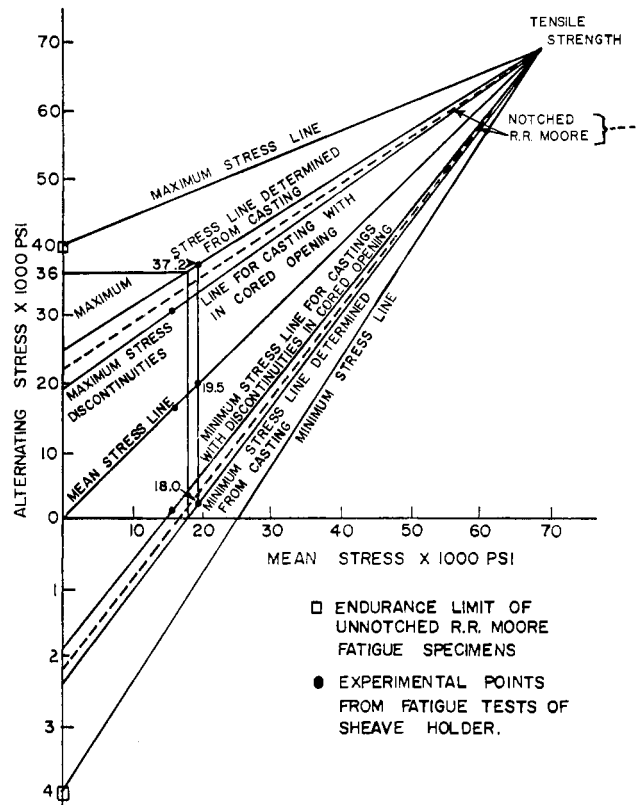


Figure 10—Modified Goodman diagram from fatigue tests of Sheave Holder.

vertical axis is 36,000 psi stress. Returning to Figure 6 and drawing a horizontal line from 36,000 psi stress to the experimental tension curve and extending the point to the horizontal axis, will determine that the endurance limit for the casting is a 10,400-pound load.

The endurance limit load for the castings with discontinuities in cored opening area can be determined by using a 9100-pound load from the S-N curve of Figure 7 to determine the stress of 30,000 psi from Figure 6 which would determine 15,900 psi on the mean stress line of Figure 10. The three points can then be drawn to establish the maximum and minimum stress line for the castings with discontinuities in the cored opening region. A line vertical from the horizontal axis mean stress line would be equivalent to a stress of 29,000 psi which from Figure 6 would give an endurance limit of 8800 pounds. This indicates that a 13 percent decrease in the endurance limit results from the surface discontinuities in the position of maximum stress which is in the cored opening region. Any notch effect, whether it be a cast-in one, a machined one or a designed-in one, would be detrimental to the fatigue properties.

The notch in the R. R. Moore specimen is responsible for a reduction of 45 percent in the endurance limit of the steel.

Static Tensile. . . Sheave Holder castings were tested to failure with failure occurring at a maximum load of 18,300 pounds. The position of failure as shown in Figure 11 was in the same area as the fatigue failure. Local yielding has occurred around the tensile fracture in the area of maximum stress. It also will be observed from the photograph of Figure 11 that the discontinuity at the fillet position has opened up and even though this was a Class 5 shrinkage discontinuity of considerable severity the casting did not fail through this location but failed at the position of maximum stress concentration.

Conclusions

Stress analysis of the Sheave Holder steel casting showed that the maximum stress area of the casting as employed in service is located in the cored opening area of the flanged sections and not in the fillet area which is the position of the

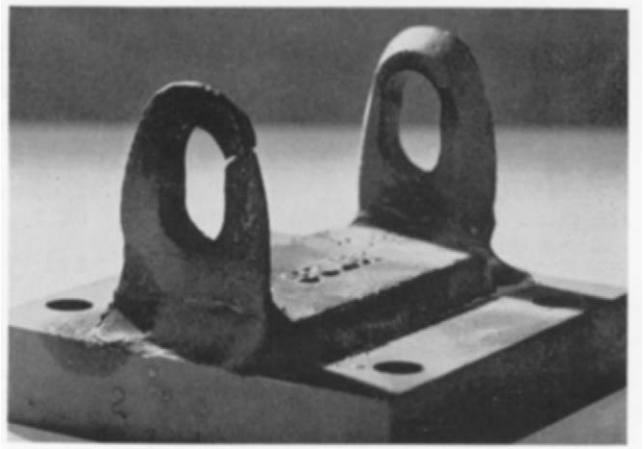


Figure 11—Location of fracture on Sheave Holder from 18,300-pound load. Also showing shrinkage at fillet area.

serious discontinuities. All of the Sheave Holder castings failed through the cored opening area when tested in both fatigue and tension. The discontinuities located in the fillet area exerted no influence on the fatigue or tension properties of the casting. However, surface discontinuities located in the highly stressed cored opening region of the flanges were detrimental to the fatigue properties of the casting as indicated by a 13 percent reduction of these properties.

The test results on the Sheave Holder casting show that surface discontinuities are detrimental to the fatigue properties only if they are located in the areas of maximum stress and that they are of a severe nature.

The casting was designed to sustain a load of 7400 pounds without failure. The load to failure in fatigue at 10,400 pounds is 1.4 times the service load in fatigue and the load to failure in tension at 18,300 pounds is 2.5 times the service load.

The corrected endurance limit of the casting of 36,000 psi is between the R. R. Moore unnotched and notched endurance limits of 40,000 and 22,000 psi. The carbon steel endurance limit is reduced 45 percent because of the serious character of the machined notch. The casting endurance limit is reduced 15 percent resulting from the surface slag discontinuity at the high stressed area. The notch fatigue (R. R. Moore) specimen endurance limit value for the carbon steel would have been more than ample as the basis of design calculations regardless of the presence of a gross discontinuity.

SECTION II FULCRUM BRACKET

Steel Casting Application

The Fulcrum Bracket (Figure 12) is used in conjunction with the braking system on freight trains. This bracket is mounted to the under-carriage chassis by two bolts through the holes in its base. The maximum combined bending and tensile service load, applied through the hole in the bracket, is 3333 pounds for every service application. The number of service applications is estimated to be under 6000 cycles per year.

The castings were produced from A.A.R. Grade B, 70-38, cast steel. The composition and properties of the steel in the normalized condition are as follows:

C	0.22 percent	Tensile Strength, psi	71,750
Mn	0.69 percent	Yield Strength, psi	42,800
Si	0.78 percent	Elon. (1.4" gage), percent	32.8
		Red. of area, percent	42.4

Test Method

The castings were examined by radiographic and magnetic particle methods to indicate both internal and external discontinuities. Gas porosity existed in the base of the casting. The severity of this gas porosity, shown in Figure 13, was Class A-4 and A-5 ASTM E-71-64. The castings were not produced to meet radiographic or magnetic inspection standards.

Magnetic particle examination showed surface discontinuities present in the fillet area at the junction of the base. Also the fillet on one side of the flange consistently showed a greater amount

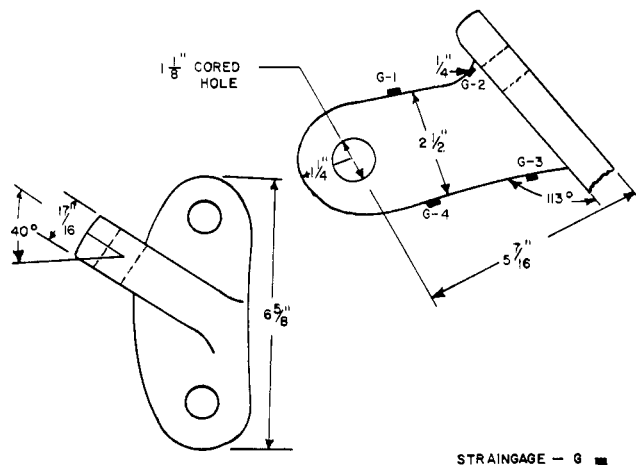


Figure 12—Dimensions of Fulcrum Bracket with locations of strain gages.

of discontinuities than the other fillet. Some shrinkage came to the surface in the fillets. Figures 14 and 15 show the sand, slag and shrinkage discontinuities.

The castings were coated with a Stresscoat brittle lacquer and loaded in a test fixture simulating the service conditions to determine the areas of greatest stress concentration. Strain gages



Figure 13—Severe gas porosity in base of Fulcrum Bracket.

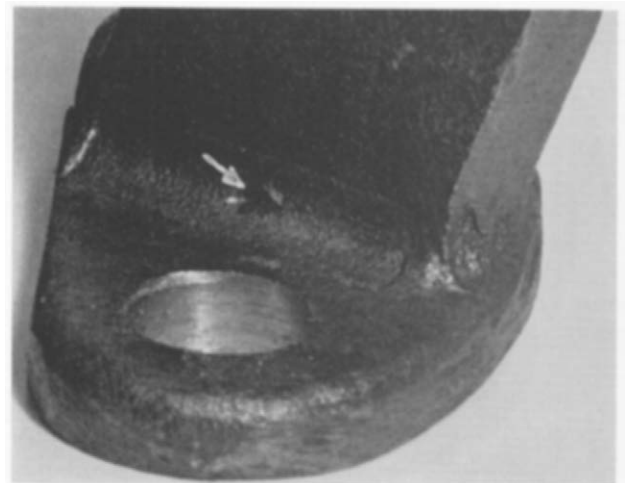


Figure 14—Slag and eroded particles at surface in fillet area.

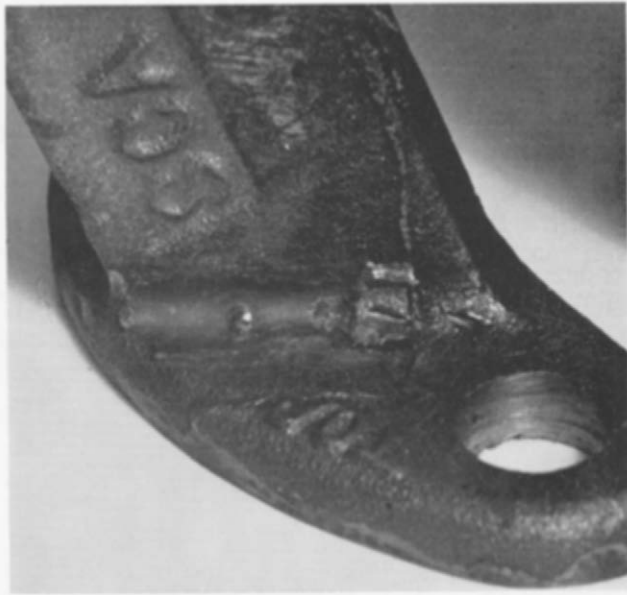


Figure 15—Shrinkage and slag in fillet area.

were positioned at locations indicated by the brittle lacquer test. The strain readings were used to compute equivalent stresses and stress analysis was employed to determine and compare calculated and experimental stresses. Fatigue studies of the actual casting and small scale R. R. Moore notched and unnotched specimens, machined from keel blocks which were cast from the same steel as the Bracket Casting, were made to determine the fatigue properties of both the cast steel and the castings. The method of loading the casting in tension and fatigue is shown in Figure 16.

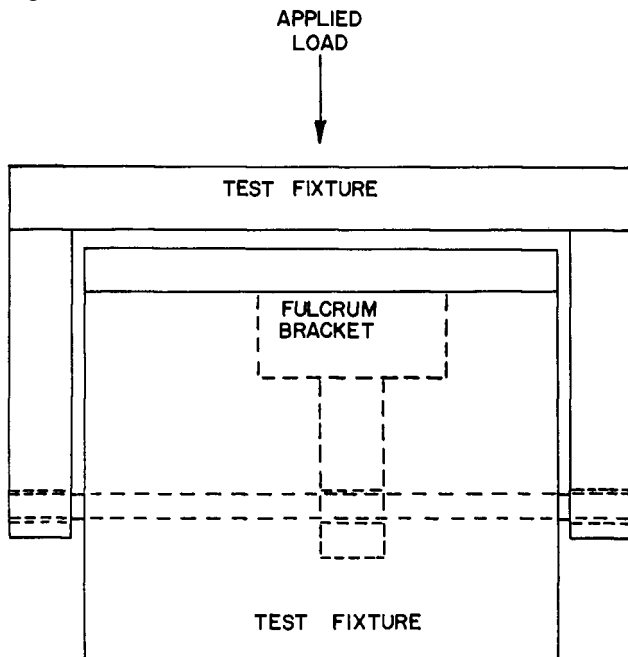


Figure 16—Fatigue test arrangement indicating test fixture and position of applied load on the Fulcrum Bracket casting.

The service load on the Fulcrum Bracket varied from zero to a maximum of approximately 3400 pounds. The castings were tested with a preload of 3850. The pulsator of the Amsler fatigue unit operated at a frequency of 500 cycles per minute. Small scale specimens were tested on a R. R. Moore fatigue machine at a frequency of 10,000 cycles per minute.

Test Results

The first cracks in the Stresscoat appeared at a load of 5000 pounds or a stress of 18,000 psi. The sketch, Figure 17, indicates the crack pattern as a function of applied load. The highest stress area is located in the front fillet area. The rear fillet area was the one containing most of the surface discontinuities.

Strain gages were located as shown previously in Figure 12 on the basis of the brittle lacquer test. Since the stresses were essentially uniaxial, they were calculated by multiplying the experimental strain reading by Young's modulus. Stresses obtained experimentally and the calculated stresses are shown in Figure 18. A good correlation between experimental and calculated stresses was obtained at all gage locations except

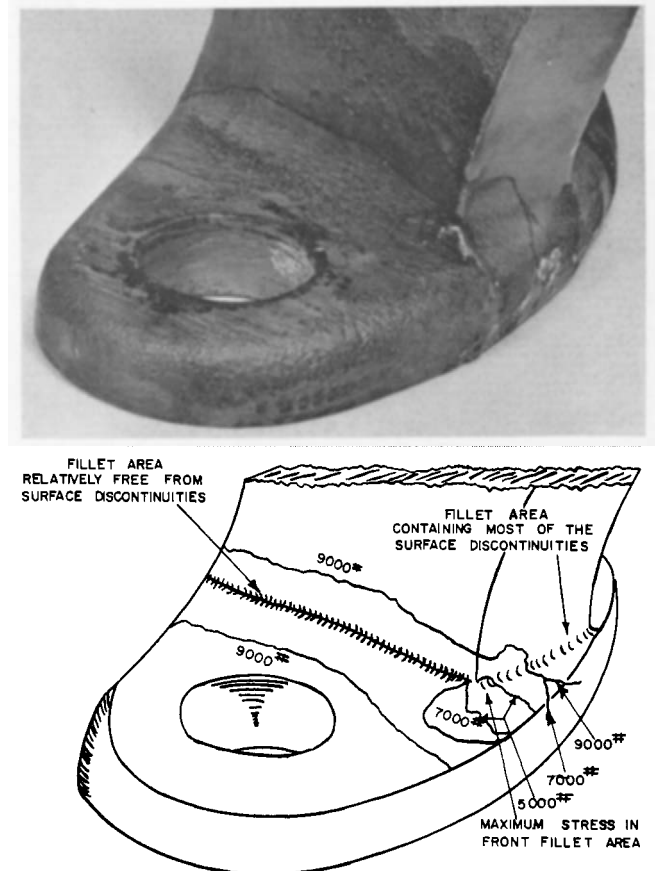


Figure 17—Stresscoat crack pattern for Fulcrum Bracket.

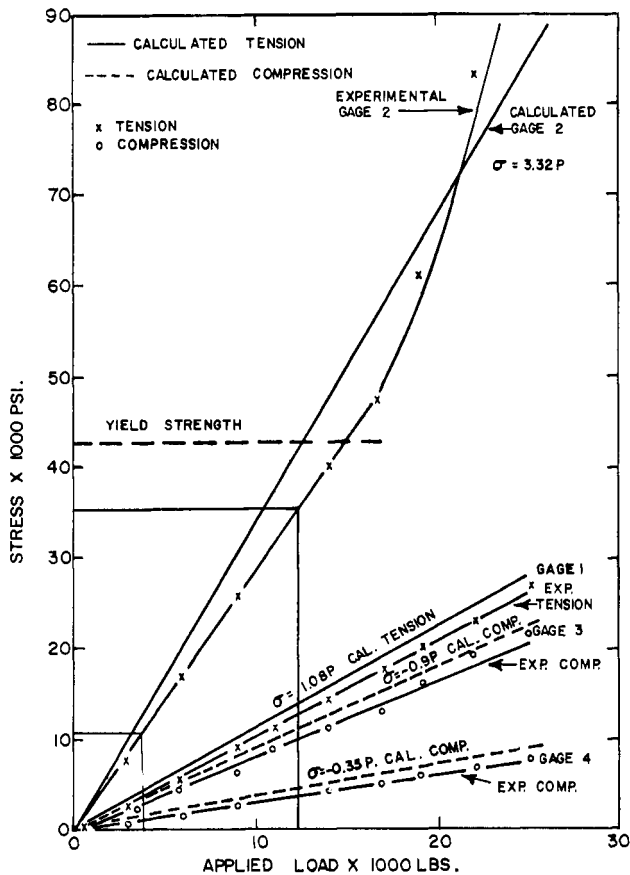


Figure 18—Calculated and measured stresses versus applied load at strain gage locations for Fulcrum Bracket.

gage 2. Since no stress concentration factor was available for combined bending and tension for the 1/4 inch fillet (gage 2), the weighted average of the theoretical stress concentration factor in tension and bending was employed and computed to be 3.32 for this fillet. The experimental and computed stresses correlated within 12 percent for this gage which was considered as very good correlation in view of the circumstances.

The yield strength of the Fulcrum Bracket was exceeded (gage 2) at an applied load of 15,000 pounds.

Fatigue Tests

The load versus cycles to failure curves obtained from the fatigue tests conducted on the Fulcrum Bracket casting are plotted in Figure 19. The load at endurance limit was 12,100 pounds. The endurance limit was selected at five rather than ten million cycles in order to expedite testing with the slowly operating Amsler Pulsator. The lower number of cycles for the endurance limit does not introduce significant error since these curves for this type of steel attain a constant stress level after two or three million cycles.

The fillet on one side of the flange blends into the base of the bracket, while the fillet on the front side shows the full contour and yields a maximum stress concentration factor of 3.32. Fatigue failures of all the Fulcrum Bracket castings, shown in Figure 20, occurred in the area of the fillet which does not blend into the base and

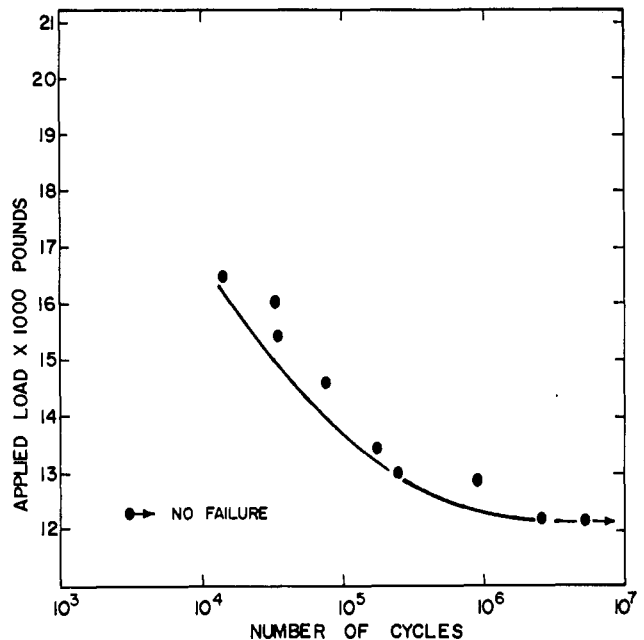


Figure 19—Load versus cycles to failure for Fulcrum Bracket casting.



Figure 20—Location of fatigue failures in Fulcrum Bracket.

has the high concentration factor of 3.32. This was the fillet which consistently showed very few discontinuities compared to the one on the other side of the flange. Failure, therefore, resulted because of the maximum stress concentration in this area as foretold by the brittle lacquer tests rather than the presence of surface discontinuities which were pronounced in the other fillet.

The results of the R. R. Moore notched and unnotched fatigue specimens are summarized in Table 3.

TABLE 3
Fatigue Tests, R. R. Moore Specimen,
for Normalized 0.22 Percent Carbon Cast Steel

	Unnotched	Notched
Endurance Limit	32,000 psi	23,000 psi
Endurance Ratio	0.45	0.32
Fatigue Strength Reduction Factor, K_f *		1.39
Notch Sensitivity Factor q **		0.33
* $K_f = \frac{\text{Unnotched endurance limit}}{\text{Notched Endurance limit}}$		
** $q = \frac{K_f - 1}{K_t - 1}$, where K_t is the theoretical stress concentration factor.		

The behavior of this cast steel is typical for normalized cast steel of a 70,000 psi tensile strength level. An endurance limit of 12,100 pounds was obtained for the Fulcrum Bracket casting. The load values can be converted over to stress values by using Figure 18. The applied load of 12,100 pounds projected to the experimental tension curve gives a stress value of 35,000 psi as the endurance limit for the Fulcrum Bracket casting.

In the same way, the minimum applied load of 3850 pounds employed in testing is equivalent to 11,000 psi. A mean stress of 23,000 psi $\left(\frac{35,000 + 11,000}{2}\right)$ results.

The fatigue results can be converted to actual service loading conditions by constructing and employing a modified Goodman Diagram as shown in Figure 21. The position of the maximum and minimum stress lines at zero mean stress are constructed using the R. R. Moore unnotched endurance limit for the carbon cast steel of 32,000 psi. The maximum and minimum stress lines, also at zero mean stress, for the R. R. Moore notched specimen are shown at the 23,000 psi value.

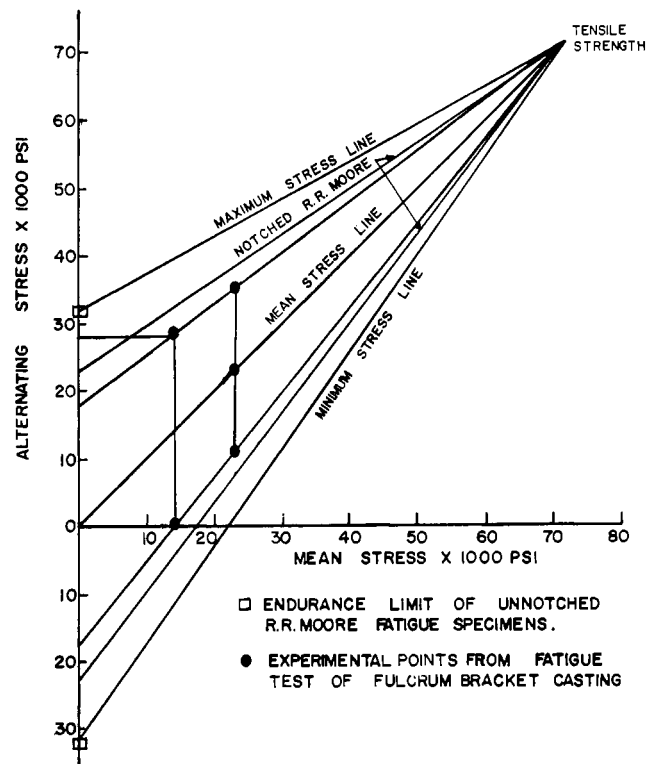


Figure 21—Modified Goodman diagram from fatigue tests of Fulcrum Bracket.

The endurance limit of the Fulcrum Bracket casting under service conditions can be obtained from Figure 21 by plotting the 23,000 psi casting mean stress on the mean stress line and vertically extending a line upward to the casting endurance limit of 35,000 psi and downward to the minimum preload tensile stress of 11,000 psi. These points establish the maximum and minimum stress lines for the casting. At the point where the minimum stress line for the casting intersects the mean stress line (horizontal axis), 12,500 psi, construct a vertical line to intersect the maximum stress line determined for the casting. This point of intersection is at 28,000 psi stress. Returning to Figure 18 and drawing a horizontal line from 28,000 psi stress to the experimental tension curve and extending this point to the horizontal axis will determine that the endurance limit in fatigue for the Fulcrum Bracket casting is a load of 10,000 pounds.

The notch in the R. R. Moore specimen is responsible for a reduction of 29 percent in the endurance limit of the steel. The discontinuities (both surface and radiographic internal) present in the casting, which many engineers would consider serious, only lower the endurance limit 12.5 percent, based on the unnotched R. R. Moore endurance limit of 32,000 psi.

Static Tests . . . Fulcrum Bracket castings were tested to failure, with failure occurring at a maximum load of 25,000 pounds. The position of failure as shown in Figure 22 was the same area as the fatigue failure and in the area of high stress as indicated by the brittle lacquer technique and strain gage analysis. Local yielding has occurred around the tensile fracture in the area of maximum stress.

Conclusions

Stress analysis of the Fulcrum Bracket steel casting showed that the maximum stress area of the casting as employed in service is located in the front fillet area and not in the base or side fillet area which are the positions of the serious discontinuities. All of the Fulcrum Bracket castings failed through the high stress concentration fillets in the front and side away from the discontinuities when tested in both fatigue and tension. The discontinuities located in the base and the area of the fillet which blends with the base exerted no influence on the fatigue or tension properties or the test results to failure of the casting.

The test results on the Fulcrum Bracket casting show that surface discontinuities are detrimental



Figure 22—Result of 25,000-pound load on Fulcrum Bracket.

to the fatigue properties only if they are located in the areas of maximum stress.

The casting was designed to sustain a load of 3833 pounds. This figure is the 3333-pound maximum service load plus a fifteen percent increase for emergency service. The load to failure in fatigue at 10,000 pounds is a safety factor 3.0 on the designed loading and 2.6 on emergency fatigue loading. The load to failure in the static test at 25,000 pounds is 6.5 times the design load. Both are rather high safety factor design values for steel castings.

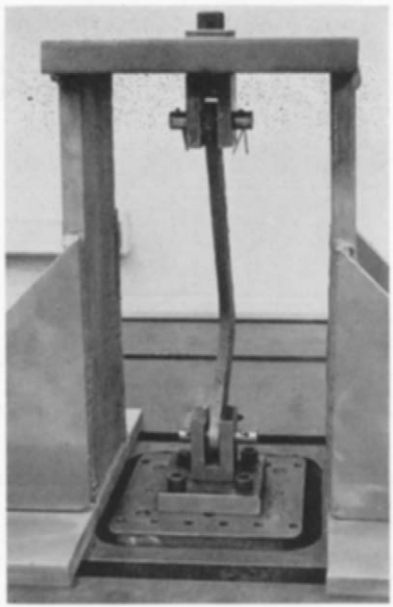


Figure 25—Test fixture in experimental stress analysis and fatigue tests of Hanger casting.

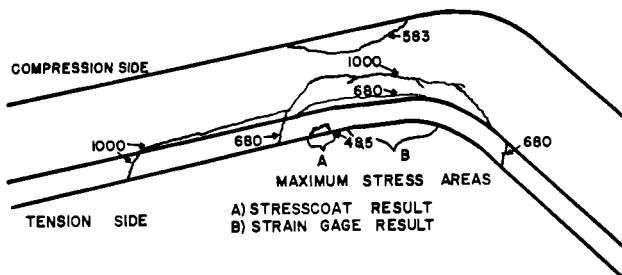
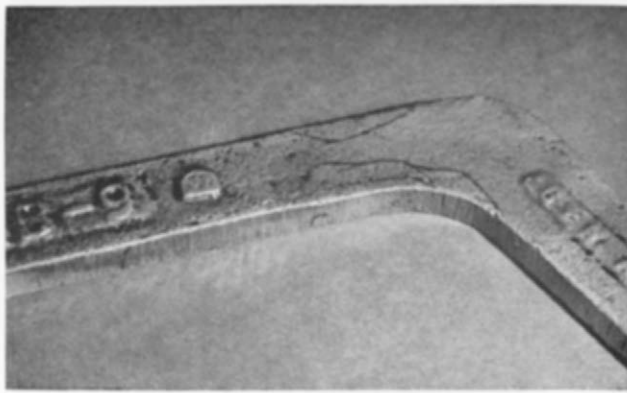


Figure 26—Stresscoat patterns produced in loading the Hanger casting.

tern as a function of applied load. The stress concentration area is located where the first cracks appear.

Strain gages were located as shown in Figure 23 on the basis of the findings of the Stresscoat test. The results of the strain gage tests are plotted in Figure 27 as stress versus applied load. The maximum applied load was 16,000 pounds; the maximum stress was equal to the yield

strength of 41,400 psi. The yield point in tension was first reached at the location of gage 5 at a load of 750 pounds. Yielding in compression occurred at gage 1 at a load of 960 pounds.

Theoretical stress calculations were performed for all strain gage locations and are compared with experimental results in Table 4.

TABLE 4
Comparison of Calculated and Experimental Stresses at Strain Gage Locations on Hanger Casting

Gage No.	Calculated Stress psi	Experimental Stress psi	Percentage Deviations from Experimental Results
1	-44.2P	-42.0P	-5.2
2	28.5P	30.5P	6.6
3	44.6P	47.0P	5.1
4	48.6P	49.5P	1.8
5	37.8P	54.0P	30.0
5	49.6P*	54.0P	8.1

* Calculated using Curved Beam Method—all other values calculated using Straight Beam Method.

P = Applied load in pounds.

Fatigue Tests

The maximum load versus cycles to failure curve obtained from fatigue tests conducted on the Hanger casting is plotted in Figure 28. An endurance limit of 1000 pounds was obtained for the Hanger casting. Of the 15 castings tested, 11 failed in the section between gages 4 and 5. (See Figure 23.) This behavior was consistent with the fact that this position was the area of highest stress. The remaining four castings (represented by solid data points in Figure 28) failed in the vicinity of gage 2.

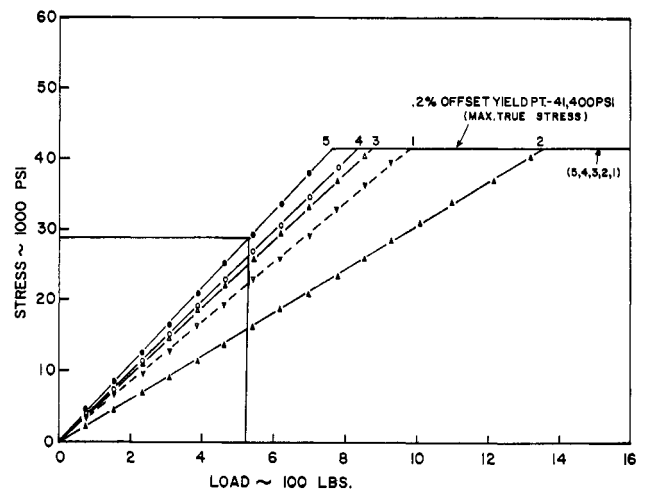


Figure 27—Stress versus applied load at various strain gage locations on Hanger casting.

The occurrence of fatigue failures outside the region of highest stress is related to the distribution of discontinuities. When the shrinkage and porosity were located near the center line of the casting, away from the tension surface, failure originated in the region of gages 4 to 5 which was the position of stress concentration. When discontinuities extended to the surface, then the resulting localized stress increase was sufficient to change the locus of failure for four specimens because of the notch effect. This observation is illustrated in Figure 29 which shows the fracture surface and the fracture locations on the radiographs of two of the four specimens. A gas hole at the surface and shrinkage extending to the surface were the origins of the failures. Seventy-five percent of the castings tested, however, failed in the highly stressed area indicated by the Stress-coat and strain gage tests regardless of the quantity, location or type of internal discontinuities as long as they did not act as surface notches.

The results of the R. R. Moore notched and unnotched fatigue specimens machined from keel blocks cast with the Hanger castings are summarized in Table 5. These fatigue properties are consistent with the usual behavior of normalized cast steel of medium (0.27 percent) carbon content.

TABLE 5
Fatigue Tests, R. R. Moore Specimens
for Normalized 0.27 percent Carbon Cast Steel

	Unnotched	Notched
Endurance Limit, psi	28,500	20,000
Endurance Ratio	0.401	0.282
Fatigue Strength Reduction Factor, K_f^*		1.42
Notch Sensitivity Factor, q^{**}		0.350
*Endurance Limit—Unnotched/Endurance Limit—Notched		
** $q = (K_f - 1) / (K_t - 1)$ where $K_t =$ Theoretical Stress Concentration Factor = 2.2.		

The endurance limit of 1000 pounds load can be converted over to stress values by using Figure 27. The applied load of 1000 pounds is projected to the experimental curve for gage 5, located at the area of maximum stress. This curve, however, cuts off at the yield point resulting in a maximum true stress of 41,400 psi at the endurance limit.

The minimum load is zero pounds corresponding to a zero stress. The mean stress, therefore, is 20,700 psi, $\frac{(41,400 + 0)}{2}$.

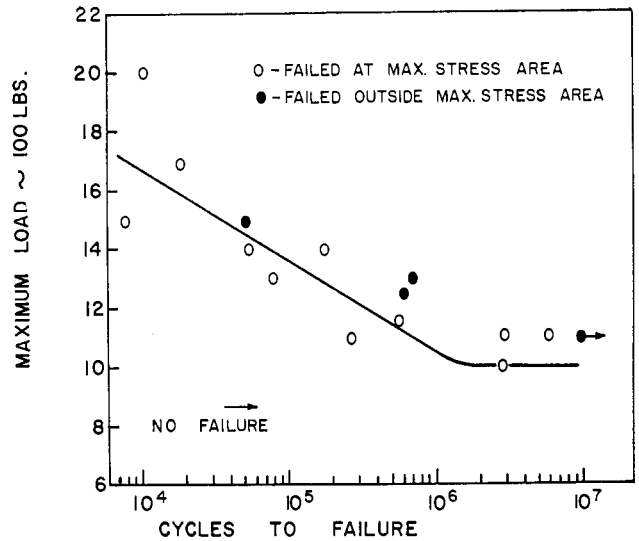


Figure 28—Maximum load versus cycles to failure for fatigue testing of Hanger casting.

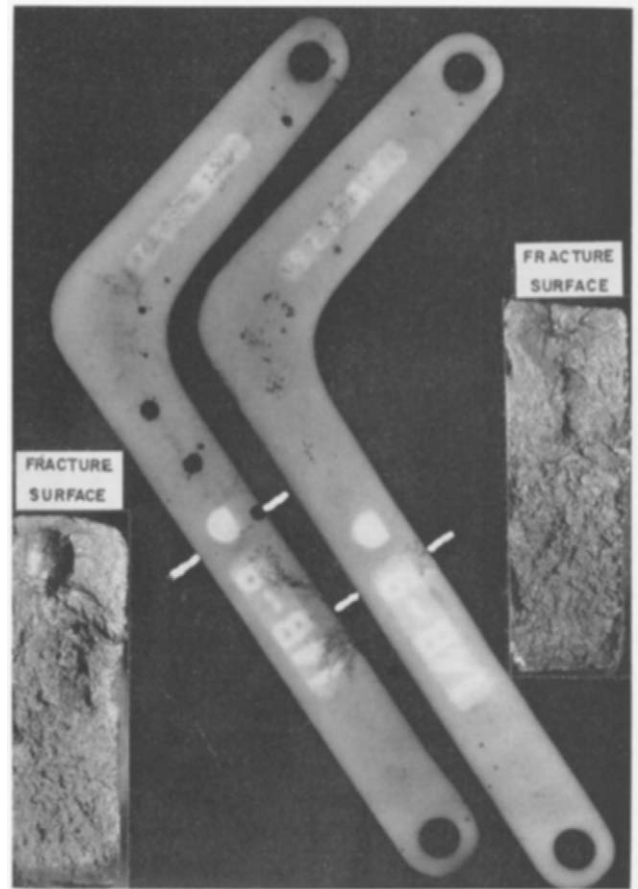


Figure 29—Comparison of radiographs and fracture surfaces of two Hanger castings tested in fatigue.

- A. Load cycle, 0-1500 pounds; 53,000 cycles
- B. Load cycle, 0-1250 pounds; 654,000 cycles

The fatigue test results can be converted to actual service loading conditions by constructing and employing a modified Goodman Diagram as shown in Figure 30. The position of the max-

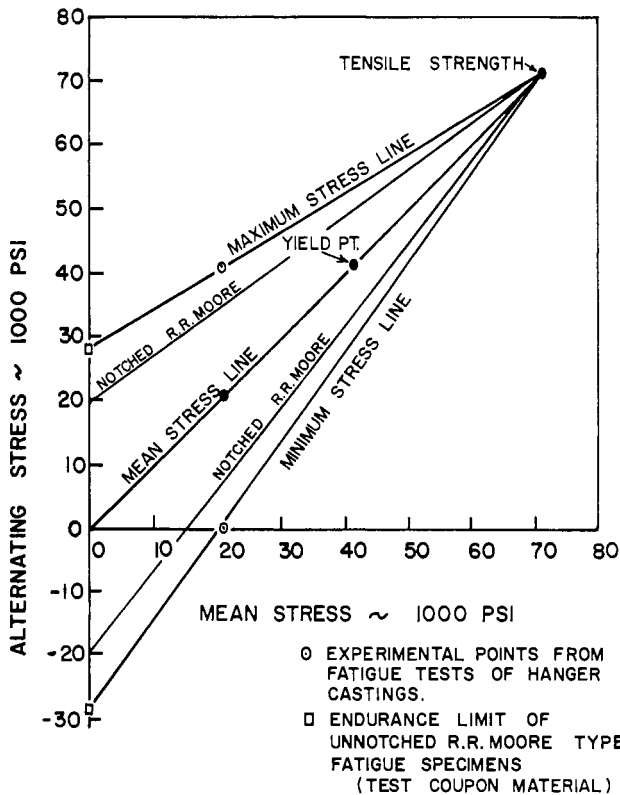


Figure 30—Modified Goodman diagram for fatigue testing of the cast steel Hanger castings.

imum and minimum stress lines at zero mean stress are constructed using the R. R. Moore unnotched endurance limit for the carbon cast steel of 28,500 psi. The maximum and minimum stress lines for the R. R. Moore notched specimens are shown at the 20,000 psi value.

The curve representing the Hanger casting is obtained by plotting the 20,700 psi casting mean stress on the mean stress line with the maximum and minimum stresses of 41,400 and zero psi, respectively, as coordinate points. Since the fatigue testing in this project was performed at zero mean stress, the endurance limits under these conditions are the intersections of lines drawn from the tensile strength point through the maximum and minimum stress points for the casting with the vertical axis (alternating stress). In this case, two lines correspond to the maximum and minimum stress lines for the steel obtained from the unnotched R. R. Moore specimen; thus these intersect the vertical axis at $\pm 28,500$ psi stress. These would constitute the endurance limit of the casting when the stress conditions have a zero mean stress. The actual casting service load varied from 0 to 400 pounds, however, with a mean load of 200 pounds.

The notch in the R. R. Moore specimen is, therefore, responsible for reduction of 30 percent in the

endurance limit of the steel. The discontinuities present in the casting, however, hardly lower the endurance limit at all, based on the unnotched R. R. Moore endurance limit of 28,500 psi.

Static Failure, . . Hanger castings were tested to failure, with the first failure occurring at a load of 5470 pounds. The position of failure, as shown in Figure 31, was in the same area as the majority of the fatigue failures. Local yielding has occurred around the tensile fracture in the area of maximum stress.

Conclusions

Stress analysis of the Hanger casting showed that the maximum stress area of the casting as employed in service is located at the large central fillet. All but four of the Hanger castings failed in fatigue and static testing in the area of the highest stress. The internal discontinuities present in the Hanger casting even though of Class 2 and 5 severity exerted little damaging influence on the fatigue or static properties of the casting. Discontinuities located at or adjacent to the surface (four castings) were responsible for a change in the location of failure but did not influence the properties of the casting to any extent.

The maximum design load for the Hanger casting is 400 pounds. The load to failure in fatigue as shown in Figure 28 is 1000 pounds giving a

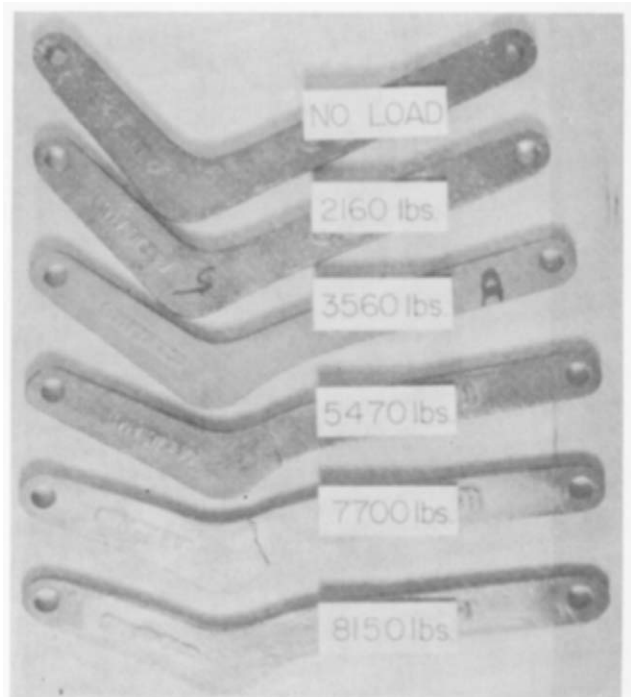


Figure 31—Appearance of cast steel Hanger castings after the application of various static loads.

safety factor of 2.5. However, the 1000-pound applied load represents deformation past the yield point, Figure 27. If the load at which first yielding occurs is the limiting design criterion, the safety factor is $750/400$ or 1.87. The smallest load which broke the Hanger casting in the static test was 5470 pounds or 13.7 times the design load.

The lines representing the fatigue behavior of both the unnotched and notched R. R. Moore specimens and the Hanger casting, Figure 30, show that the carbon steel endurance limit is

reduced 30 percent because of the serious character of the machined notch. The discontinuities in the casting and at the casting surface exerted little influence on the casting fatigue properties. In fact, the lines for the Hanger casting and the lines for the unnotched R. R. Moore fatigue specimens were so close that only one line could be drawn to represent the two test conditions. The notch fatigue (R. R. Moore) specimen endurance limit value for the carbon steel would have adequate basis of design calculations without additional safety factors.

SECTION IV LEVER CASTING

Cast Steel Application

The Lever casting (Figure 32) is part of an assembly which operates a hopper door in a railroad car. A torque is applied to a 1 1/4-inch square shaft which fits through the cored hole in one end of the casting. The other end of the lever is attached to links which transmit the load to the hopper door. As the hopper door is opened and closed, the load is reversed in magnitude and direction. The maximum torque is 1800 inch-pounds applied at a frequency not likely to exceed 250 cycles per year.

The material used for this part is a plain carbon cast steel of about 1030 specification. The composition and properties of this cast steel as normalized are as follows:

C	0.27 percent	Tensile strength, psi	74,600
Mn	0.72 percent	Yield strength, psi	47,500
Si	0.48 percent	Elon. (1.4 gage) percent	27.1
		Red. of Area, percent	44.4

Test Method

Radiography and magnetic particle examination were used to determine the discontinuities in the Lever casting though the castings were not ordered to nondestructive test requirements. Entrapped slag and gas porosity of Class 1, ASTM E-71 were found widely dispersed in a few castings. Internal shrinkage of Classes 2,3 and 4 was found at locations indicated on Figure 33.

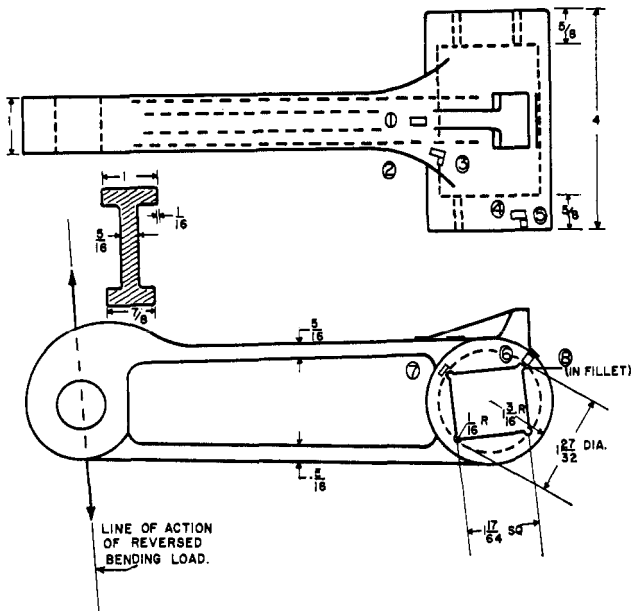


Figure 32—Dimensions of Lever casting and locations of strain gages.

The castings were coated with Stresscoat brittle lacquer and loaded in a test fixture simulating the service conditions to determine the areas of greatest stress concentration. Strain gages were positioned at the locations indicated by the brittle lacquer test. The strain readings were multiplied by the modulus of elasticity to obtain the equivalent stresses for uniaxial stress states and by a slightly more complicated means for biaxial stress. The principal stresses resulting from these calculations were in turn combined into equivalent stresses by using the distortion energy theory.

Fatigue studies of the actual castings and small scale R. R. Moore notched and unnotched specimens, machined from keel blocks which were cast from the same steel as the Lever casting, were made to determine the fatigue properties of both the cast steel and the castings. The direction of loading the casting in tension and fatigue is shown by the arrows in Figure 32. The Lever test fixture is shown in Figure 34.

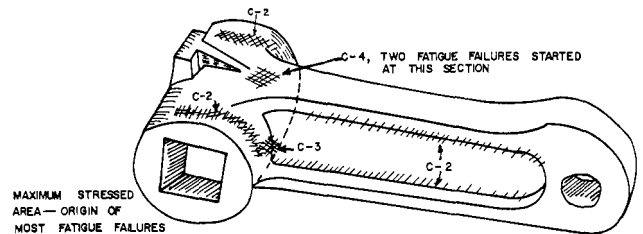


Figure 33—Location and severity class of continuities in the Lever castings.
C-2 to C-4 internal shrinkage of classes 2 to 4 ASTM Reference Radiographs E-71
Porosity to Class 1 observed in a few castings in dispersed areas.

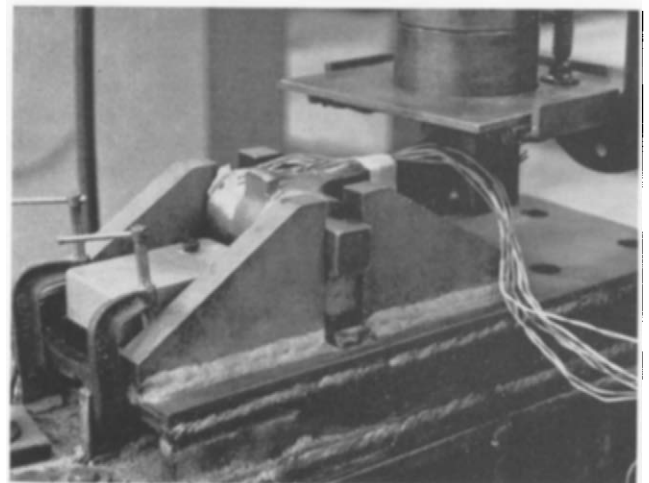


Figure 34—Fixtures for static and fatigue testing of the Lever casting.

Limitations in the apparatus prevented the application of a reversed load (tension-compression) in the fatigue tests. The actual loading cycle used for the fatigue tests was from a minimum of 660 pounds applied load up to a maximum load that was varied to provide a curve of load versus cycles to failure. The Amsler Pulsator used in the fatigue testing operated at a frequency of 250 cycles per minute. The small scale R. R. Moore fatigue machine operated at a frequency of 10,000 cycles per minute.

Test Results

The first cracks in the Stresscoat appeared in the corners of the square hole at an applied load of 440 pounds as shown in Figure 35. The sketches indicate the crack pattern as a function of applied load. The highest stress areas are concentrated in the cast in notches in the four corners of the square cored barrel. All other areas showed low stress conditions.

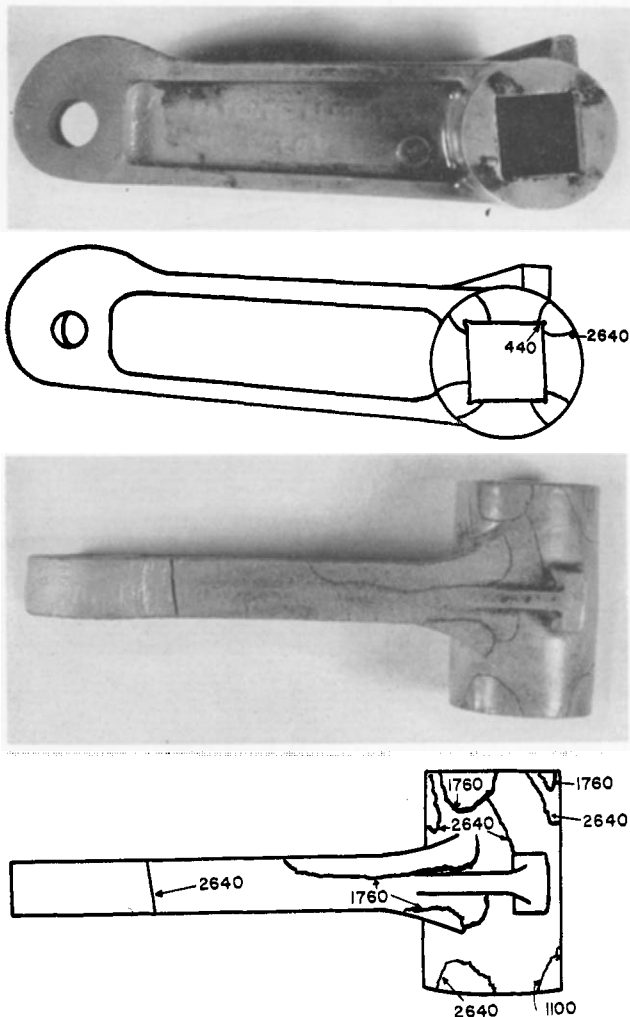


Figure 35—Crack patterns produced in the Stresscoat applied to the Lever casting.

Strain gages were located as shown previously in Figure 32 on the basis of the Stresscoat analysis. The results of the strain gage studies are plotted in Figures 36 and 37 as stress, or equivalent stress in the case of the rosette gages, versus applied load. The yield point of 47,500 psi was first reached at gage 8 at an applied load of 1000 pounds.

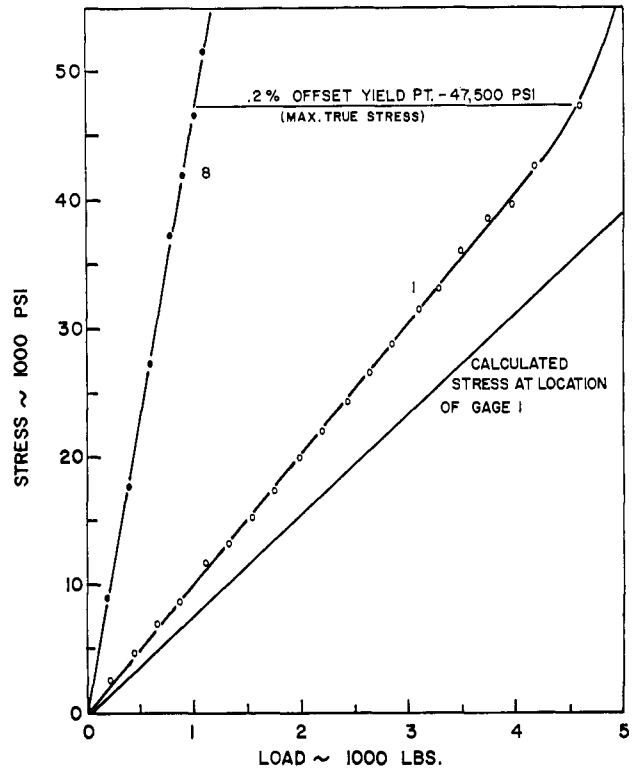


Figure 36—Stress versus applied load at locations of gages 1 and 8 on Lever casting.

Fatigue Tests

The maximum load versus cycles to failure curve obtained from fatigue tests conducted on the Lever casting is plotted in Figure 38. Only two of the castings tested failed in a manner shown in Figure 39a. Both of these castings contained fatigue cracks at the corners of the square hole, but the major failure started at the location of gage 1. The fracture then proceeded into the shrinkage cavity directly below the surface. One of the castings was sectioned longitudinally through the shrinkage cavity. The severity of this shrinkage can be seen in a photograph of this section shown as Figure 40. The remainder of all the castings tested consistently failed through the area of highest stress as shown in Figure 39b. This area was foretold by the brittle lacquer tests and did not contain discontinuities.

The results of the R. R. Moore notched and unnotched fatigue specimens are summarized in Table 6.

TABLE 6

**Fatigue Tests, R. R. Moore Specimens
for Normalized 0.27 Percent Carbon Cast Steel**

	Unnotched	Notched
Endurance Limit, psi	32,500	21,000
Endurance Ratio	0.436	0.281
Fatigue Strength Reduction Factor, K_t^*		1.55
Notch Sensitivity Factor, q^{**}		0.458
*Endurance Limit—Unnotched/Endurance Limit—Notched		
** $q = (K_t - 1) / (K_t - 1)$ where $K_t =$ Theoretical Stress Concentration Factor = 2.2.		

These fatigue properties are consistent with the usual behavior of normalized cast steel of this composition.

An endurance limit of 2000 pounds (Figure 38) was obtained for the Lever castings. The load values can be converted to stress values by using Figure 36. The applied load of 2000 pounds is projected toward the experimental curve for gage 8 located at the area of maximum stress. This

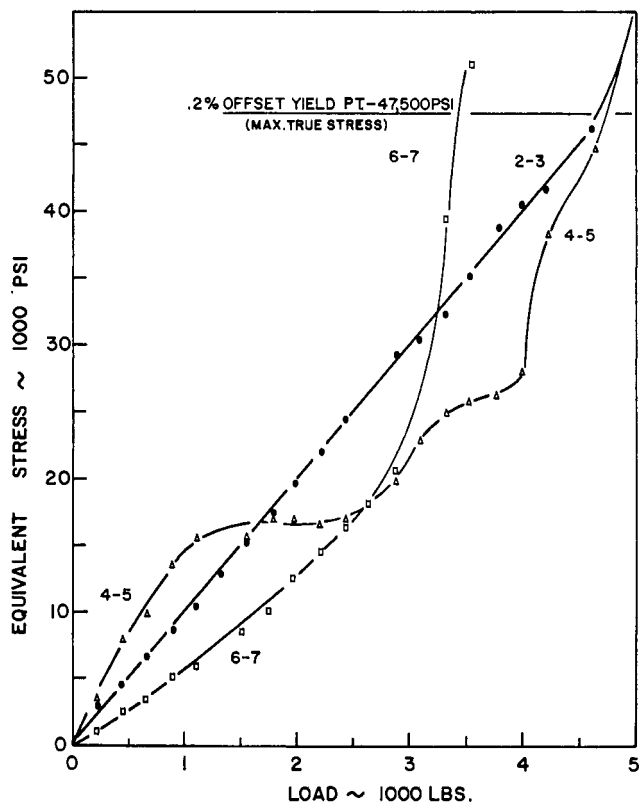


Figure 37—Equivalent stress versus applied load at Lever casting strain gage rosette locations.

curve, however, cuts off at the yield point resulting in a maximum true stress of 47,500 psi as the endurance limit for the maximum load. The 660-pound minimum load projected to the curve of gage 8 corresponds to a 30,200 psi stress value. The mean stress, therefore, is 38,850 psi,

$$\left(\frac{47,500 + 30,200}{2} \right).$$

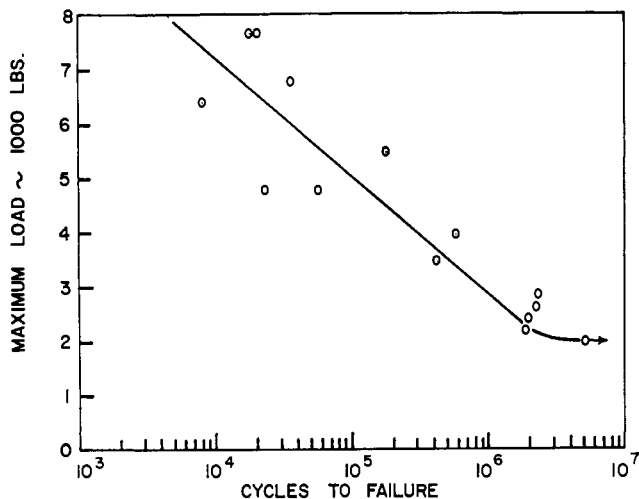


Figure 38—Maximum load versus cycles to failure for the Lever castings tested at a minimum load of 660 pounds.



a. b.
Figure 39—Types of fatigue failure found in the Lever castings
(a) One of two castings loaded at 7700-pound maximum load after 17,300 cycles.
(b) Typical failure exhibited by all other Lever castings at lower maximum loads and larger number of cycles.

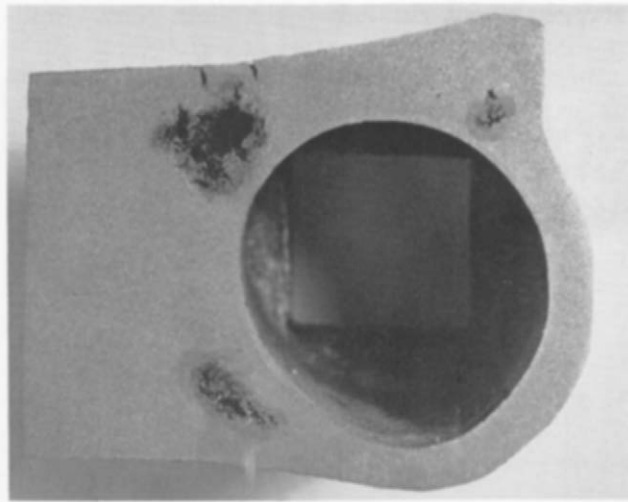


Figure 40—Macroetched cross section of the Lever casting through the center of the rib section on the barrel. This casting failed in fatigue at a high load of 7,700 pounds maximum load after 19,900 cycles.

The fatigue test results can be converted to actual service loading conditions by constructing and employing a modified Goodman Diagram as shown in Figure 41. This diagram is constructed as explained in previous casting studies. The alternating stress obtained is $\pm 18,000$ psi. Returning to Figure 36 shows that the 18,000 psi is equivalent to an applied load of 400 pounds or a torque (the lever arm from the center of the round hole to the center of the square hole is 7.5 inches) of 3000 inch-pounds.

Static Fatigue . . . A static load to failure test was conducted on one casting. At the maximum applied load of 9200 pounds, the casting bottomed on the test fixture. Although a large distortion of the square hole and considerable bending of the lever arm occurred, no evidence of any cracks was noted.

Conclusions

Stress analysis of the Lever casting showed that the maximum stress area of the casting as employed in service is located in the fillet area of the cored hole in the barrel. This position is not the location of discontinuities but is the location of stress concentration because of the designed in cast notch. All but two of the Lever castings

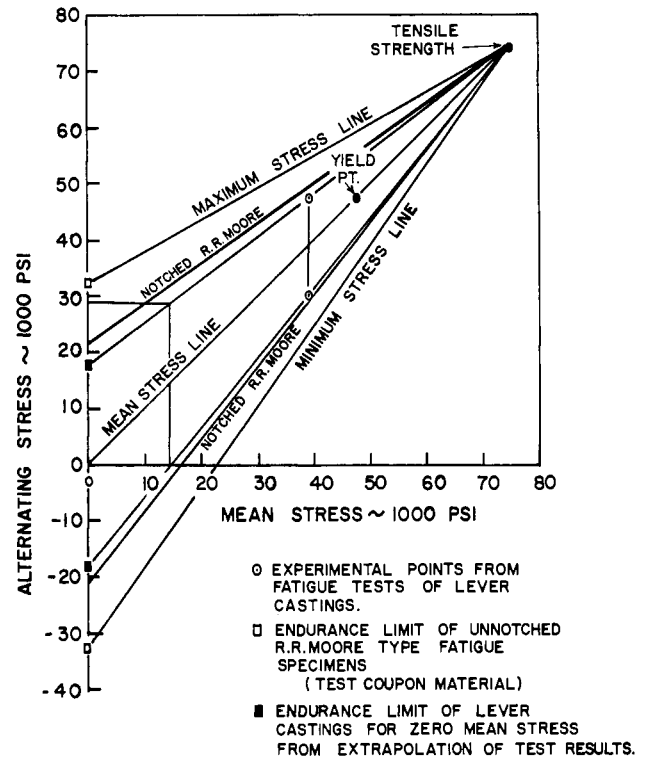


Figure 41—Modified Goodman diagram for the fatigue testing of Lever castings.

when tested to failure in fatigue failed in the area of maximum stress. Two castings tested at very high loads, approaching tensile strength values, failed at low cycles of stress at an area on the barrel over a prominent shrinkage area (Class 4) near the casting surface. Loads below about 6000 pounds resulted in fatigue failures at the position of stress concentration regardless of the presence of a pronounced shrinkage area within the castings.

The maximum torque for the Lever casting is 1800 inch-pounds. The torque at failure in fatigue is 3000 inch-pounds. Thus, the Lever casting has a safety factor of 1.67 figured on this basis.

Gage 8 was the first to reach the yield point at 1000 pounds applied load which corresponds to 7500 inch-pounds of torque. If the design were based entirely on incipient yielding, then the safety factor becomes 7500/1800 or 4.17.

SECTION V TRIP LINK CASTING

Steel Casting Application

The Trip Link casting (Figure 42) is a safety link device in a pile driver mechanism which is designed to break at the center notch if the pile driver becomes jammed or overloaded for any reason. The castings are employed without machining. In service, a tensile load is applied along a line joining the centers of the two eyes, as shown in Figure 43. Under normal conditions this part is designed to withstand a load cycle of 0 to 4000 pounds at approximately 100 cycles per minute.

The castings were produced from a Cr-Mo cast steel. The composition and minimum specified properties of the steel in the normalized and tempered condition are as follows:

C	0.41 percent	Tensile Strength, psi	100,000
Mn	0.63 percent	Yield Strength, psi	70,000
Si	0.46 percent	Elong. (2 gage) percent	15
Cr	0.98 percent	Red. of Area, percent	30
Mo	0.31 percent		
Ni	0.10 percent		

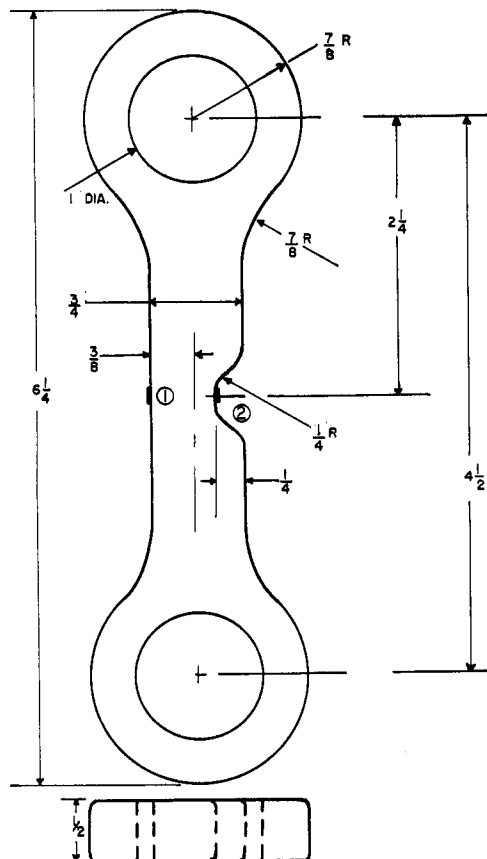


Figure 42—Dimensions of Trip Link casting and locations of strain gages.

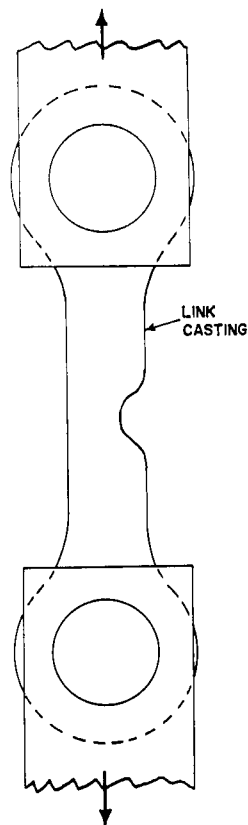


Figure 43—Schematic representation of Trip Link casting service loading.

Hardness measurements on the castings provided for test averaged a Brinell hardness of 241 which is equivalent to a tensile strength of approximately 118,000 psi.

Test Method

The castings were examined by radiographic and magnetic particle inspection for internal and surface discontinuities though they were not ordered to nondestructive tests standards. Porosity of Class 1, ASTM E-71,⁽¹⁾ was found in the area of the eyes. Linear discontinuities of I-2a, ASTM E-125,⁽²⁾ were located at the base of the central notch. These discontinuities are shown in Figures 44 and 45.

The castings were coated with a Stresscoat brittle lacquer and loaded in a test fixture (Figure 46) simulating the service conditions to determine

- (1) E-71 Industrial Radiographic Standards for Steel Castings.
- (2) E-125 Reference Photographs for Magnetic Particle Indications on Ferrous Castings.

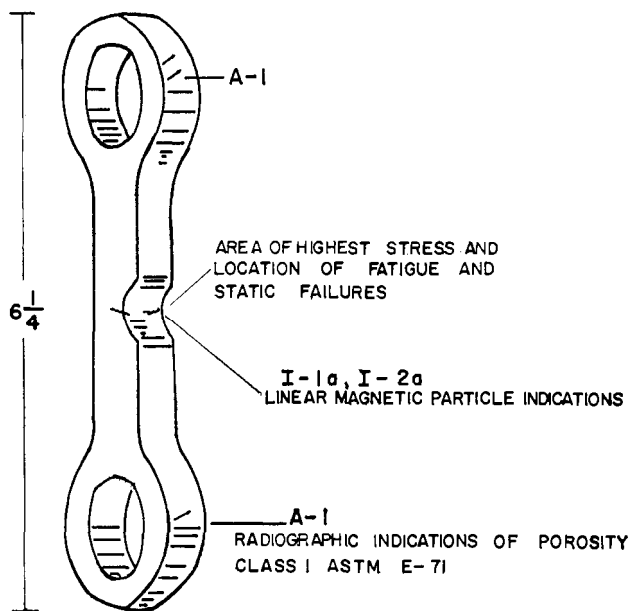


Figure 44—Position and severity of discontinuities in Trip Link casting.

the areas of greatest stress concentration. Strain gages were positioned at locations indicated by the brittle lacquer test. The strain readings were used to compute stresses and theoretical stress analysis was employed to determine and compare calculated and experimental stresses.

The actual service loading varied from zero to a maximum load in tension. The fatigue testing of the castings to failure was determined by employing a Sonntag SF-1-U machine operating at 1800 cycles per minute.

Test Results

The first cracks in the Stresscoat appeared at a load of 1450 pounds. The sketch, Figure 47, indicates the crack pattern as a function of applied load. The highest stress is located at the base of the central notch as shown previously in Figure 44.

The stresses were essentially uniaxial and they were computed by multiplying the strain gage readings by Young's modulus. The experimental and calculated stresses are compared in Figure 48.

Fatigue Tests . . . The load versus cycles to failure curve obtained from the fatigue tests conducted on the Link casting is plotted in Figure 49. This curve shows the endurance limit to be 1250 pounds. This load corresponds (Figure 48, gage 2, measured data) to a stress of 20,000 psi. In all cases, the fatigue failures occurred at the designed notch, the area of highest stress concentration as indicated by the brittle lacquer test.

The fatigue failures at the notch started at the linear discontinuities. Figures 50a and 50b show the fracture surface of two Trip Link castings tested in fatigue. The black oxidized regions at the surface are the areas of the linear discontinuities.

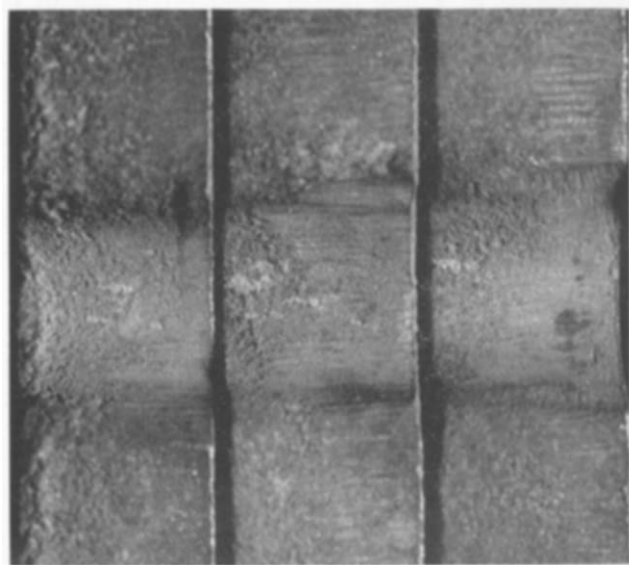


Figure 45—Magnetic particle indications of hot tears in Trip Link casting.

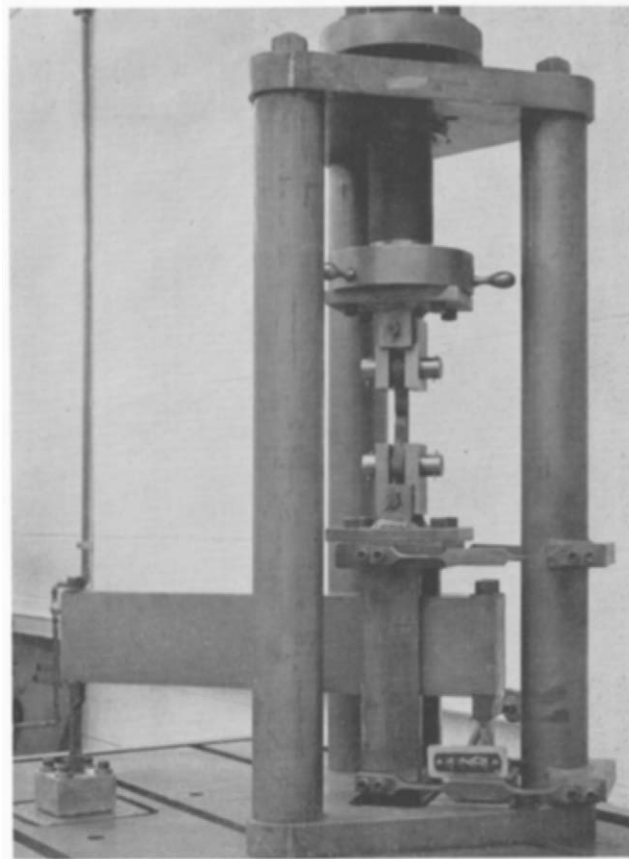


Figure 46—Test setup used for experimental stress analysis and fatigue tests of Trip Link castings.

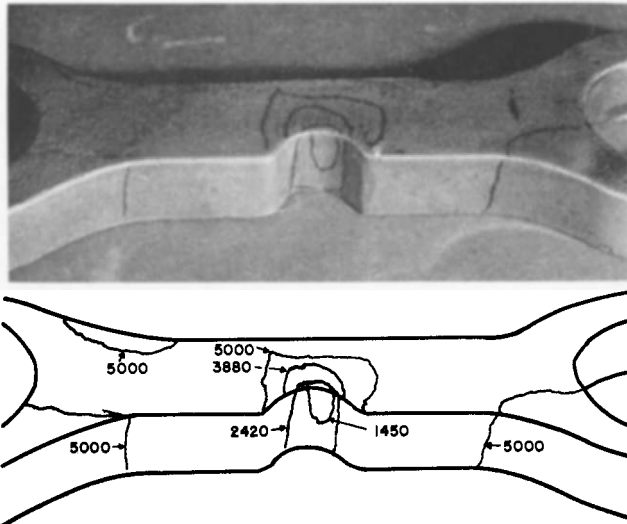


Figure 47—Crack patterns produced in brittle lacquer test of Trip Link casting.

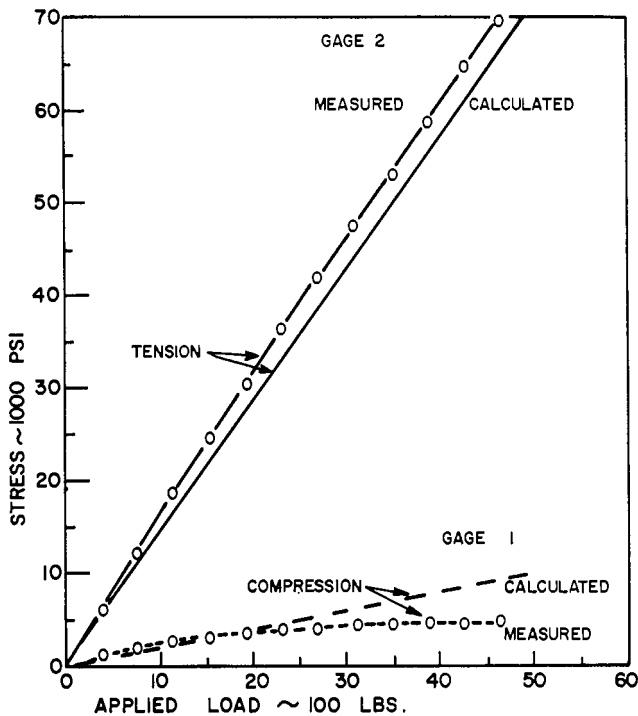


Figure 48—Calculated and measured stresses versus applied load at strain gage locations on Trip Link casting.

Static Test . . . A static load to failure test produced a brittle failure of the castings at a load of 15,200 pounds. The fracture surface of this casting is shown in Figure 50c. This failure also occurred at the designed notch with the linear discontinuity contributing to a reduced load carrying ability. It is estimated that loads in excess of 17,000 pounds would produce failure if the linear discontinuities were not present.

Conclusions

Stress analysis of the Link casting showed that the maximum stress area of the casting as em-

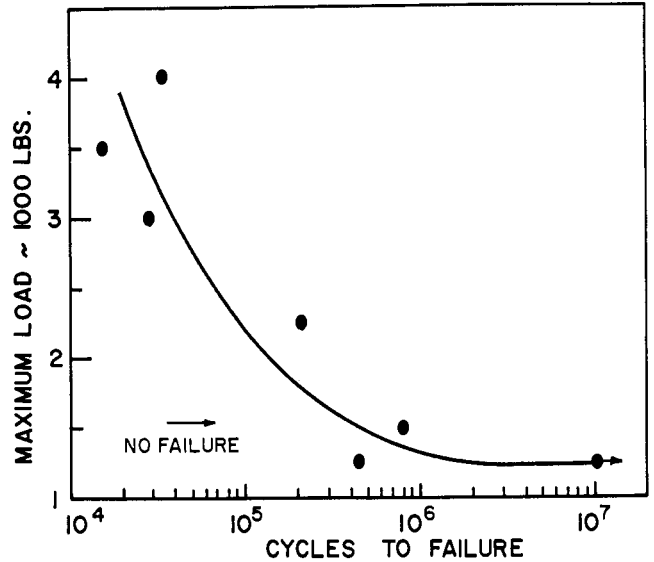


Figure 49—Maximum load versus cycles to failure for fatigue tests of Trip Link castings.

ployed in service is located in the central designed notch. All of the Trip Link castings failed in the notch when tested in both fatigue and tension.

All failures in fatigue and testing began at the linear discontinuities present at the base of the central notch. The stress at the endurance limit load of 1250 pounds was 20,000 psi indicating that an appreciable reduction in fatigue strength resulted from the linear discontinuities in the notch. The discontinuities located in other portions of the casting exerted no influence on the behavior of the part.

These results indicate that stress concentrations arising from design and the location of discontinuities relative to these regions are far more significant than the mere presence of discontinuities in the casting.

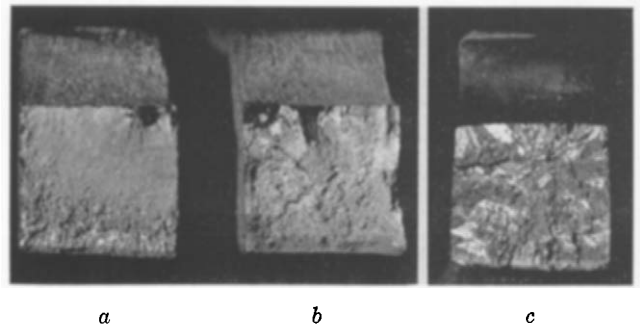


Figure 50—Fracture surfaces of Trip Link casting broken in fatigue and static loading.

- (a) Fatigue failure, load range 0 to 1500 pounds (24,000 psi), 796,000 cycles.
- (b) Fatigue failure, load range 0 to 3000 pounds (46,500 psi), 28,000 cycles.
- (c) Static failure at load of 15,200 pounds.

SECTION VI HINGE CASTING

Cast Steel Application

The Hinge casting (Figure 51) is employed in the petroleum industry to support a 350-pound door on a trap assembly. Figure 52 shows the Hinge in service. The sliding pin supports the weight of the door and applies the load to the Hinge. This load varies from 0 to 350 pounds with upward of 1000 cycles per year.

The castings were produced to ASTM A-216, Class WCB cast steel. The composition and properties of the carbon cast steel are as follows:

C	0.21 percent	Tensile strength, psi	72,000
Mn	0.65 percent	Yield strength, psi	40,000
Si	0.53 percent	Elongation, percent	27
		Reduction in Area, percent	46
		Hardness BHN	145

Test Method

The castings were examined by radiographic and magnetic particle inspection for internal and surface discontinuities though the castings were not ordered to nondestructive testing requirements. Center line shrinkage of Class 2, ASTM E-71, was found dispersed along the center line of the casting as shown in Figure 53. A typical cross section indicating the location of this center line shrinkage is illustrated in the macroetched

section of Figure 54. The Hinge was free of magnetic particle indications.

The castings were coated with a Stresscoat brittle lacquer and loaded in the test fixture of Figure 55, simulating the service loading conditions to determine the areas of greatest stress concentration. Strain gages were positioned at locations indicated by the brittle lacquer test. The strain readings obtained were employed to compute principal stresses and these stresses were combined into equivalent stresses by the distortion energy theory.

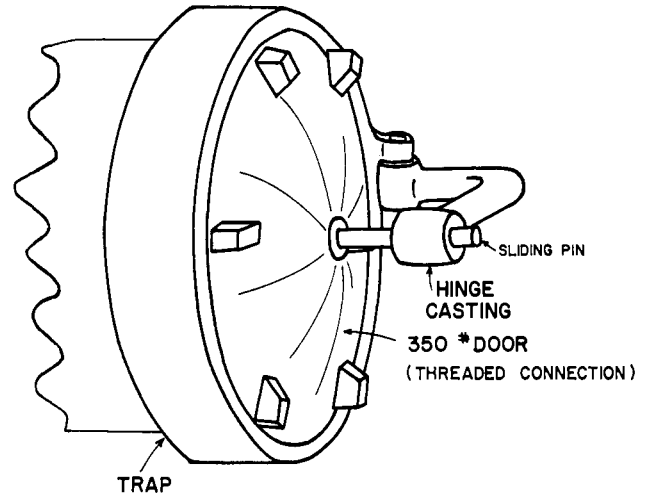


Figure 52—Service application of the cast steel Hinge.

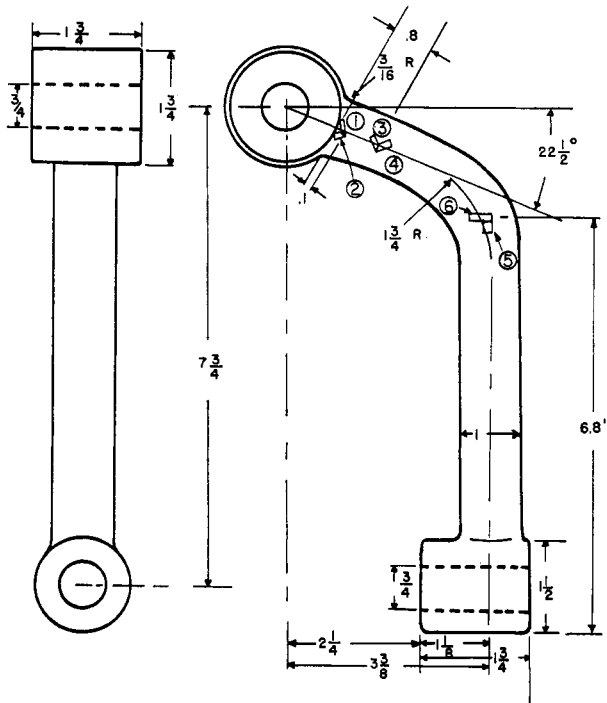


Figure 51—Dimensions of the Hinge casting and locations of strain gages.

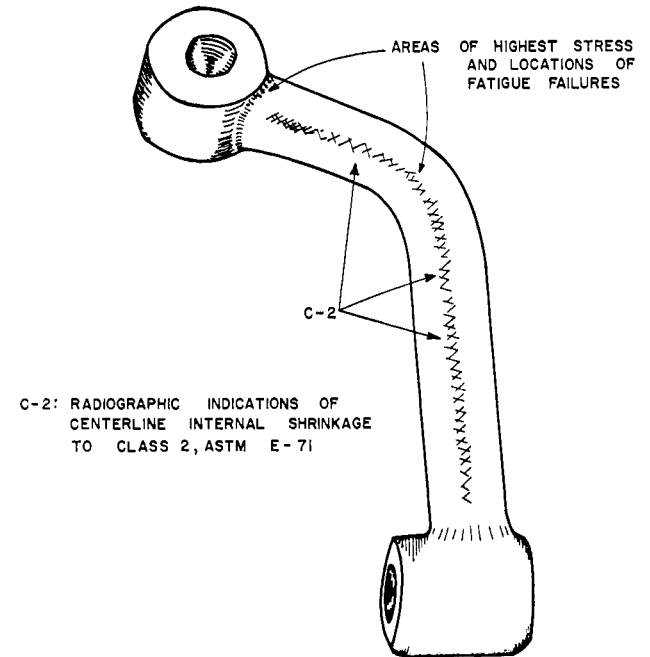


Figure 53—Positions and severity of discontinuities in the Hinge casting and areas of fatigue test failures.

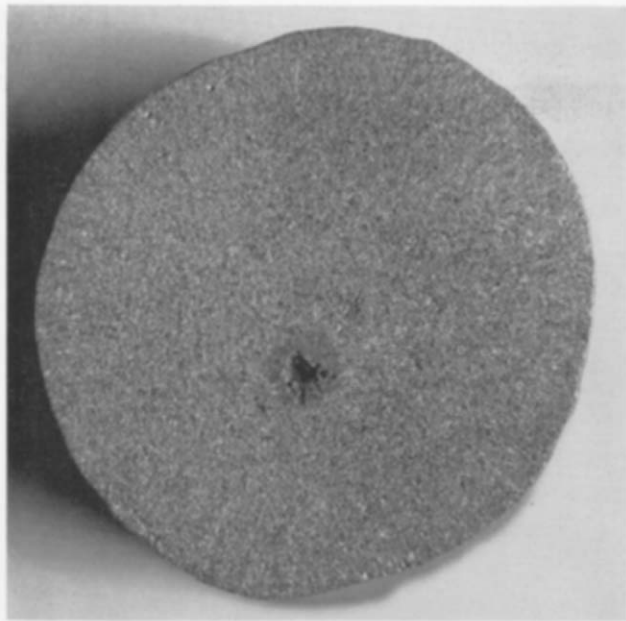


Figure 54—Macroetched cross section of the Hinge casting (Location of gage 5-6).

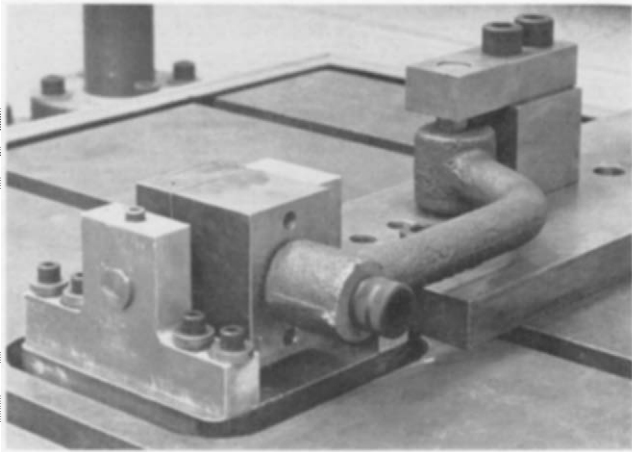


Figure 55—Test setup used in experimental stress analysis and fatigue tests of the cast steel Hinge.

The service load on the Hinge casting varied from zero to a maximum of 350 pounds. Fatigue tests were conducted on a number of castings in an attempt to obtain a load versus cycles to failure curve, but as it turned out, all castings were tested to failure at one applied load. This load, 850 pounds, was the endurance limit and provided significant information on the mechanical behavior of the casting. Higher loads produced excessive yielding in the casting and smaller loads failed to produce failure in fatigue. The fatigue machine was run at a speed of 1800 cycles per minute.

Test Results

The first cracks in the Stresscoat appeared at a load of 485 pounds. The sketch, Figure 56, in-

dicates the crack pattern as a function of applied load. The highest stress areas are those where the lacquer first cracked. They are located at the fillet between the end containing the fixed pin and the bar and at the bend in the bar.

Strain gages were located as shown previously in Figure 51 on the basis of the brittle lacquer test. The equivalent stresses for the strain gage combinations employed are shown in Figure 57 plotted against the applied load. Yielding first occurred at an applied load of 600 pounds at the location of gage 1-2. The stress state at all positions along the one-inch diameter body of the Hinge was combined torsion and bending. The initial slope of the equivalent stress versus load curve for the experimental observed values at gage 1-2 is 64.8P (66.3P calculated) and for gages 3-4, 5-6 was 58.7P (64.6P and 62.6P calculated, respectively) where P is the applied load in pounds.

Fatigue Tests . . . Fatigue test results, shown in Table 7, indicate that considerable scatter occurred in the data.

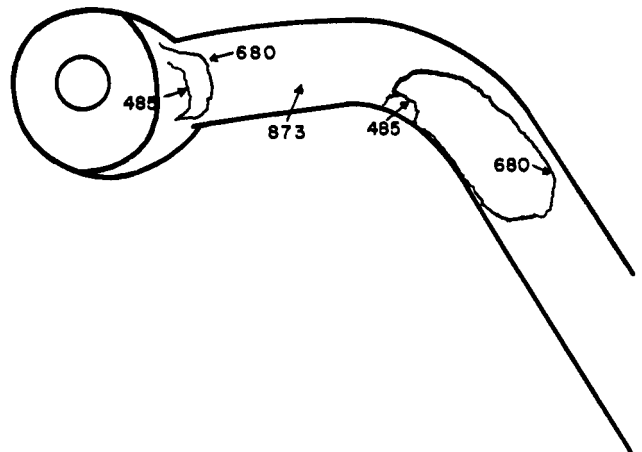


Figure 56—Stresscoat crack patterns produced in the brittle lacquer testing of the Hinge casting.

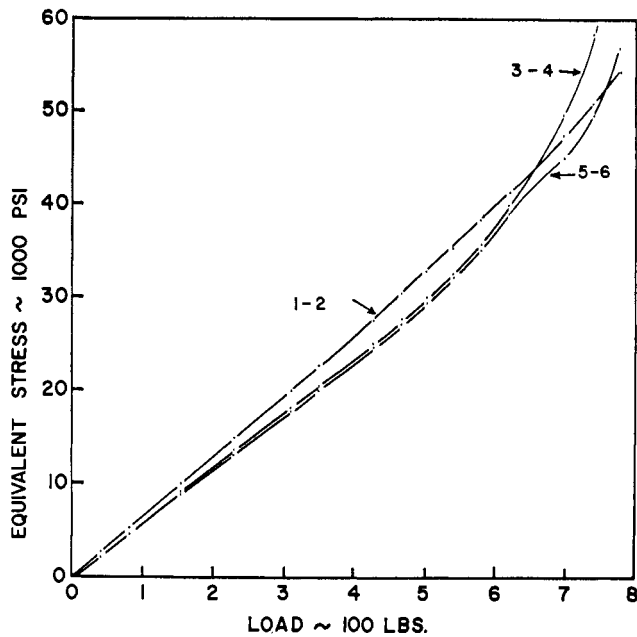


Figure 57—Equivalent stress versus applied load at strain gage locations on the Hinge casting.

TABLE 7

Data from Fatigue Tests of Hinge Castings

Casting No.	Load Cycle, lbs.	Cycles to Failure	Location of Failure
1	0 to 850	13,600,000	Gage 1-2
2	0 to 850	3,450,000	Gage 1-2
3	0 to 850	1,467,000	Gage 1-2
4	0 to 850	10,483,000	Gage 5-6

This scatter reflects geometrical and structural differences among the castings tested. The 850-pound load limit appears to be very close to the endurance limit based on ten million cycles to failure. This load provides a safety factor of 850/350 or 2.43 based on fatigue loading.

Three of the Hinges failed in fatigue at the location of gage 1-2 and the fourth failed at the location of gage 5-6. These are the locations of maximum stress as foretold by the brittle lacquer test. Failure, therefore, resulted because of this stress and not because of the center line shrinkage which was dispersed throughout the casting. The four Hinge castings are shown in Figure 58 after testing.

Static Test . . . Static load to failure tests were conducted on two castings. Neither casting fractured, but both bottomed on the fixture at a deflection of one and one-half inches. The maximum applied loads were 1050 and 1100 pounds as compared to a maximum service load of 350 pounds.

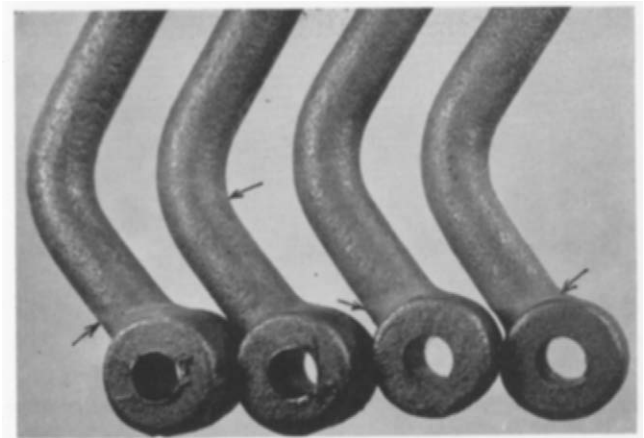


Figure 58—Magnetic particle testing indications of fatigue failures in the cast steel Hinge.

Conclusions

Stress analysis of the Hinge casting showed that the maximum stress areas of the casting as employed in service are located in the fillet at the end containing the fixed stationary pin and at the center of the bend in the bar. All of the Hinge castings failed through these areas even though shrinkage discontinuities were present throughout the center section of the casting thereby showing that centerline shrinkage exerted no influence on either the fatigue or static loading behavior of the part.

The yield strength of the Hinge casting, 40,000 psi, corresponds, Figure 57, to an applied load of 600 pounds. If yielding was the primary failure criterion, the safety factor would be 600/350 or 1.71. The safety factor based upon fatigue loading is the endurance limit of 850 pounds divided by the maximum service load, 350 pounds, or 2.43. Based on static load to failure, the safety factor for the Hinge casting is greater than 3.1 (1100/350) since the casting deformed and did not fail at a load of 1100 pounds.

SECTION VII FLANGE CASTING

Steel Casting Application

The Flange casting (Figure 59) is not employed in service but is a test casting designed specifically for pure torsional loading. However, numerous cast steel Flanges of similar design are used commercially. The Flange castings were manufactured by a commercial steel foundry with the discontinuities produced deliberately.

The castings were made to ASTM A-27, Grade 70-36 carbon cast steel. The composition and properties of the steel in the normalized condition are as follows:

C	0.27 percent	Tensile Strength, psi	75,800
Mn	0.64 percent	Yield Strength, psi	39,900
Si	0.43 percent	Elong. (1.4 gage) percent	25.7
		Red. of Area, percent	39.7
		Hardness BHN	151

Test Method

The castings were examined by radiographic and magnetic particle inspection for internal and surface discontinuities. Dispersed surface porosity to degree 1, inclusions to degree 3, ASTM E-125, and internal shrinkage to Class 2, ASTM E-71, were found in the fillets and flange sections at the locations indicated in Figure 60. Some of the castings showed cold shuts or laps on the inside surface of the bore.

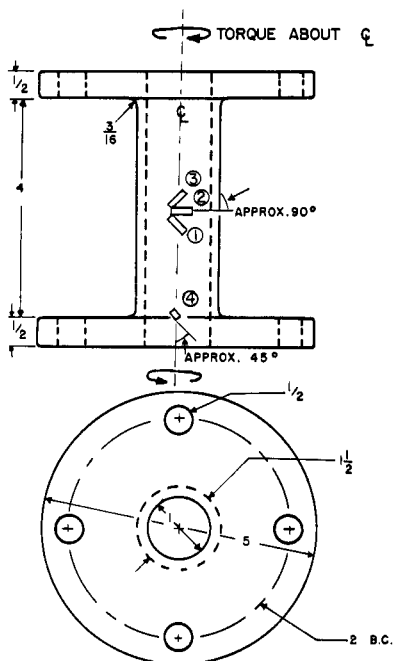


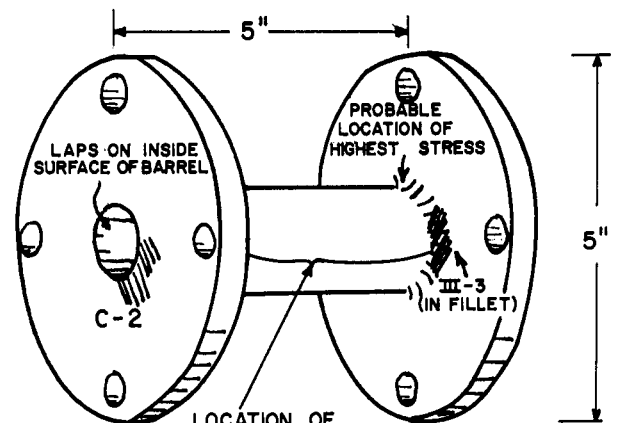
Figure 59—Dimensions of Flange casting showing location of strain gages and type of loading used.

The castings were coated with a Stresscoat brittle lacquer and loaded in a test fixture to determine the areas of greatest stress concentration. Strain gages were positioned at locations indicated by the brittle lacquer test. The strain readings were used to compute equivalent stresses and stress analysis was employed to determine and compare calculated and experimental stresses. Fatigue studies of the actual casting and small scale R. R. Moore notched and unnotched specimens, machined from keel blocks that were cast from the same steel as the Flange castings, were made to determine the fatigue properties of both the cast steel and the castings.

Both the strain gage measurements and subsequent completely reversed torsion fatigue tests were performed in the test arrangement shown in Figure 61 at a speed of 1800 cycles per minute. For a static load to failure test, a different testing arrangement in a standard testing machine was employed because of the load and deflection limitations of the Sonntag machine.

Test Results

The first cracks in the Stresscoat appeared at random locations on the barrel of the casting at 10,350 inch-pound applied torque. The probable location of highest stress is located in the fillet



- LOCATION OF
FATIGUE FAILURES;
DISCONTINUITIES OF TYPE III-3, V-1
- C-2 : RADIOGRAPHIC INDICATIONS OF
INTERNAL SHRINKAGE TO CLASS 2, ASTM E-71
- III-3 : MAGNETIC PARTICLE INDICATIONS OF INCLUSIONS
TO DEGREE 3, ASTM E-125
- V-1 : MAGNETIC PARTICLE INDICATIONS OF POROSITY
TO DEGREE 1, ASTM E-125

Figure 60—Position and severity of discontinuities in the cast steel Flange.

area as shown in Figure 60. Since the sensitivity of the casting was 21,000 psi, this indicates that the barrel was subject fairly uniformly to a principal stress of approximately this magnitude.

Strain gages were located as shown in Figure 59 on the basis of the brittle lacquer test. Stresses obtained experimentally and calculated stresses are shown in Figure 62. Although the stresses in Figure 62 are plotted above the yield point, the

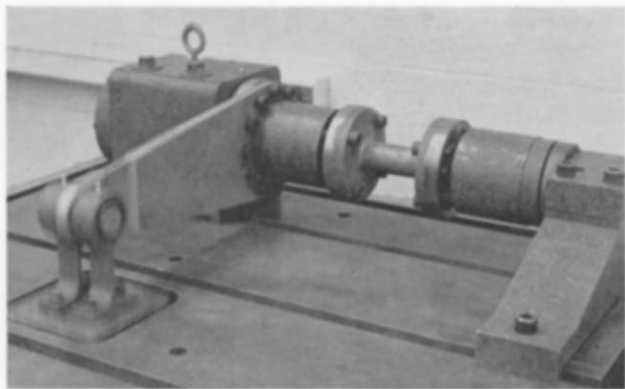


Figure 61—Test setup used for experimental stress analysis and fatigue tests of the Flange casting.

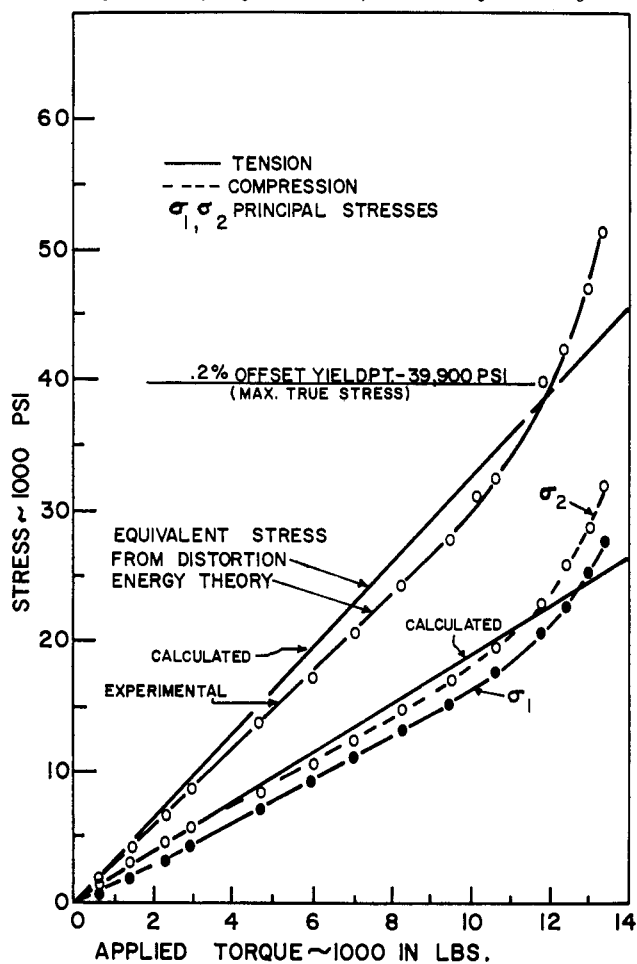


Figure 62—Principal and equivalent stresses versus applied torque at strain gage rosette locations on the Flange casting.

actual equivalent stresses did not exceed this value since low carbon steel undergoes considerable strain above the yield point without any increase in stress.

Fatigue Tests . . . The applied torque versus cycles to failure curve obtained from the fatigue tests conducted on the Flange casting is plotted in Figure 63. The endurance limit was reached at 10,200 inch-pounds of applied torque. The equivalent stress on the experimental curve for this value of torque in Figure 62 is 31,000 psi and in exact agreement with the endurance limit for unnotched R. R. Moore specimens. Typical fatigue failures of the Flange castings are illustrated in Figure 64. Both shear and tensile type fractures were observed.

Fatigue failures were not confined to any specific locations on the castings. In some cases failures initiated on the barrel, in other instances at the fillets. Fatigue cracks at both locations were also noted in a few test castings.

The exact agreement between the endurance limit for unnotched R. R. Moore specimens and the equivalent stress at the endurance limit of the Flange castings shows that the discontinuities present were not damaging.

The internal shrinkage at the flange-barrel junction and the occasional small laps on the inside surface of the bore were sufficiently far removed from the outer, higher stressed surfaces to have any influence. The inclusions and porosity were in general subsurface. Small pits resulting from inclusions or porosity extending to

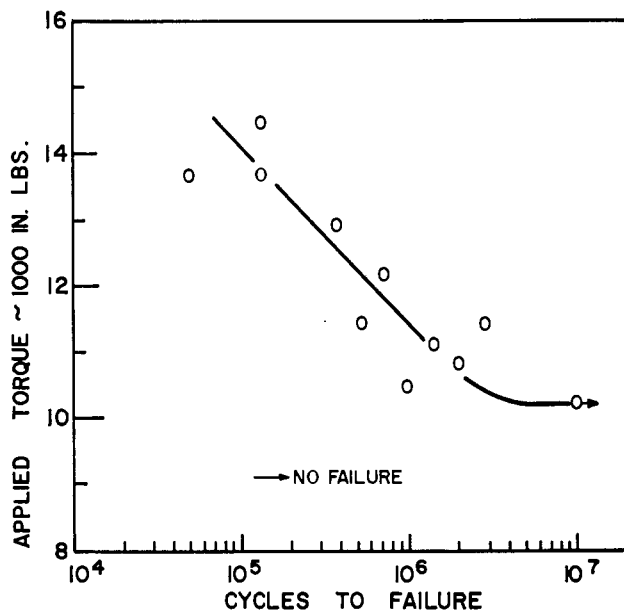
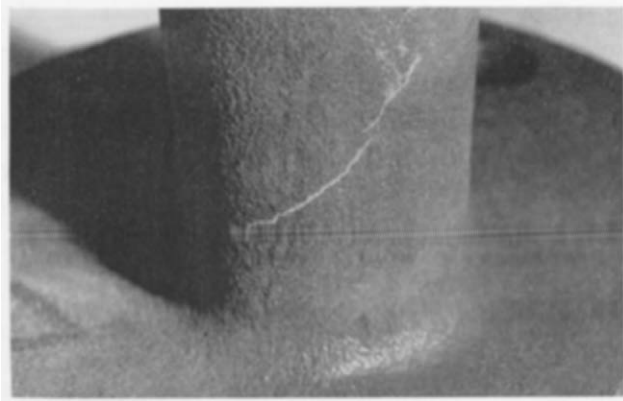
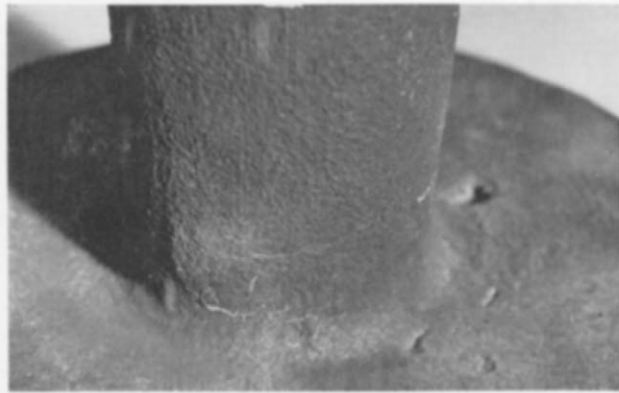


Figure 63—Applied Torque versus cycles to failure for reversed torsion fatigue tests in the Flange Casting.



Tensile failure.



Transverse shear failure.

Figure 64—Magnetic particle indications of typical fatigue failures in the Flange casting.

the surface could not be correlated with specific locations of fatigue cracks.

Consequently the high stress conditions of the barrel end fillets rather than severity or location of discontinuities determined the fatigue behavior of this cast steel part.

The results of the R. R. Moore notched and unnotched fatigue specimens have been summarized in Table 8 and the S-N curves shown in Figure 65.

TABLE 8

Fatigue Tests, R. R. Moore Specimens for Normalized 0.27 Percent Carbon Cast Steel

	Unnotched	Notched
Endurance Limit	34,400 psi	20,500 psi
Endurance Ratio	0.409	0.270
Fatigue Strength Reduction Factor, K_t^*		1.52
Notch Sensitivity Factor, q^{**}		0.433
*Endurance Limit—Unnotched/Endurance Limit—Notched		
** $q = (K_t - 1) / (K_t - 1)$ where $K_t =$ Theoretical Stress Concentration Factor = 2.2.		

These results indicate that the fatigue properties are normal for normalized 0.27 percent carbon cast steel.

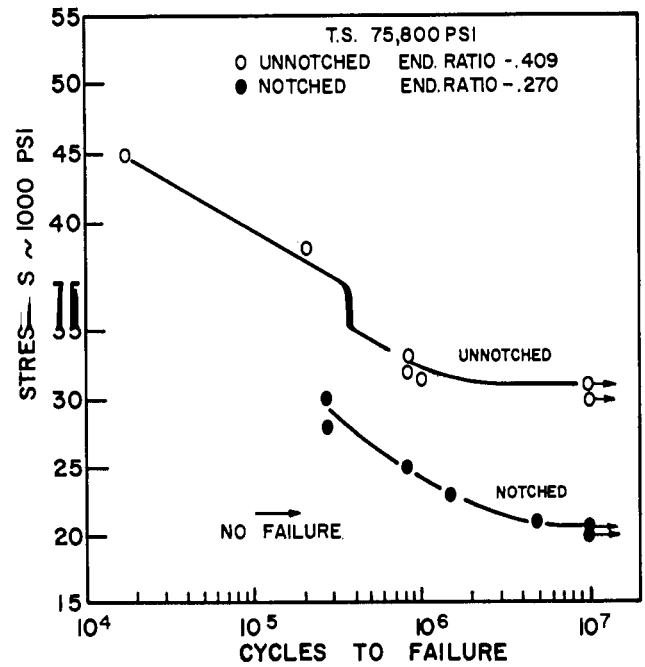


Figure 65—S-N curves for R. R. Moore fatigue specimens machined from cast steel coupons cast with the Flange castings.

Static Test. . . A static load to failure test was performed on one casting. The angle of twist versus torque curve is shown in Figure 66. The test was terminated at a torque of 18,900 inch-pounds when the lever arm bottomed on the test fixture. No sign of incipient cracks was observed in the casting after removal from the fixture.

Conclusions

Stress analysis of the cast steel Flange showed that the maximum stress areas of the casting

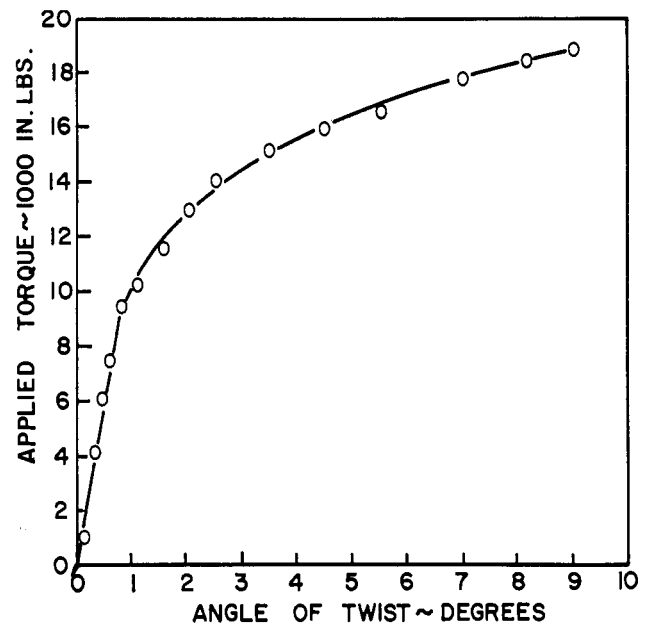


Figure 66—Torque-twist curve obtained in static test of the Flange casting.

were along the barrel and in the fillet area. The fatigue failures of the Flange castings were not confined to any specific location. In some cases failure initiated on the barrel and in other castings failure took place at the fillet. Fatigue cracks in both locations were observed.

The endurance limit for the Flange castings tested in reversed torsion was reached at a torque of 10,200 inch-pounds. This identical behavior under equivalent stresses for tests of unnotched R. R. Moore fatigue specimens. The equivalent stress at the endurance limit for the Flange cast-

ings was 31,000 psi and was also the same endurance limit for the R. R. Moore specimens tested in reversed bending.

Although the Flange casting studied is not used in service and therefore was not designed to a particular service load or cyclic conditions of stress, the various test results do permit an understanding of the influence of the various discontinuities on the fatigue and static behavior of the casting. The results of this study show that the discontinuities present did not exert any effect on the fatigue and static properties or behavior of the cast steel part.

CONCLUSIONS TO THE RESEARCH REPORT

Stress analysis studies, fatigue and static testing of seven steel castings of different commercial applications provided significant information on failure loads and the safety factors employed in steel casting design. The influence of casting properties and discontinuities on the simulated service behavior of steel castings was also determined. The conclusions from the research investigation are as follows:

1. A comparison of the results of the simulated service fatigue tests and static load-to-failure tests with the stress analysis data on the 7 cast steel parts indicated that failure occurred (primarily) in the areas of maximum stress that resulted from the design. The fatigue and static failures usually occurred at the location of maximum stress regardless of the presence of discontinuities in other sections.

2. Failure of the 7 cast steel parts under static testing occurred either as yielding or as fracture at loads well in excess of the maximum designed service loads. The failure in these static tests was influenced (primarily) by the design rather than by the presence of discontinuities. Extensive deformation occurred in the high stress areas of the castings during static testing to failure.

3. Although nearly all of the cast steel parts tested in fatigue under simulated service loading

failed in areas of maximum stress, a few exceptions were noted. In these cases, the discontinuities were severe and were located at the surface of a fairly high stressed area; failure occurred at these locations away from the area of maximum design stress.

4. The endurance limit for all of the steel castings under simulated service fatigue stresses was greater than the cyclic service loads. The safety factors for the steel castings in fatigue varied from 1.4 to 3.0. These factors provide a sufficient allowance for service behavior, and fatigue failures in these steel castings in service would be very unlikely.

5. Tensile and R. R. Moore fatigue specimens were machined from separately cast steel coupons which accompanied 5 of the commercial castings ; coupons were not available for the other two parts and the tensile properties were estimated from hardness measurements. The tensile and fatigue properties determined for these cast steels were typical for the types of steel utilized.

6. The test results illustrate conclusively that steel castings with discontinuities of considerable magnitude will perform satisfactorily in fatigue loading. Accordingly, the presence of discontinuities may not require casting rejection.

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