# CORRELATION OF DESTRUCTIVE TESTING OF STEEL CASTINGS WITH STRESS ANALYSIS AND MECHANICAL PROPERTIES

## PART I-A Summary Report

A Research Project at Case Institute of Technology

Sponsored by

Steel Foundry Research Foundation

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# TABLE OF CONTENTS

# SCOPE OF THE RESEARCH REPORT

Research concerning steel castings as engineering structures has been needed in order to develop certain relations in stress analysis, nondestructive testing, destructive testing, and mechanical properties of steel castings. It is believed that such a study has been awaited by many design engineers in order that they can evaluate the entire casting as a reliable engineering structure. It is necessary, in a complete evaluation, that the engineer be apprised of the importance which minor manufacturing inconsistencies or natural phenomena have on casting serviceability.

The research, therefore, was planned with the purpose of determining the influence of the following factors on commercial steel casting performance under simulated service loads carried to destruction : ( 1) discontinuities in the steel casting; (2) relation between casting properties and test bar properties; (3) stress distributions and concentrations in the casting; and (4) safety factors of design.

# SUMMARY OF THE RESEARCH REPORT CONCLUSIONS

Stress analysis and destructive testing of 12 steel castings of different commercial applications provided significant information as to safety factors being employed in steel casting design, and the relation of casting properties and discontinuities on simulated service failure. Conclusions that can be readily drawn from the research investigation are as follows:

1-The testing of nine of the twelve steel castings was carried to failure by applying loads that were from four to over twenty times the maximum service load. In the testing of the other three steel castings, the accompanying service components failed before casting failure or the strength of the casting exceeded the capacity of the testing facilities. In these three cases the applied loads were many times the designed service load. Since the design load included allowances for design factors, the test data clearly indicate that unreasonably large safety factors are being applied in the preparation of steel casting designs.

2-Brittle lacquer technique and stress analysis applied to the commercial castings showed that the positions of stress concentration were also the positions of casting failure upon destructive testing.

3-Nine of the twelve steel castings selected for testing contained discontinuities of various types and severity. However, all twelve castings withstood loads that simulated service conditions and were in considerable excess of service requirements before yielding. The results illustrated conclusively that castings with discontinuities of even considerable magnitude will perform satisfactorily in many highly stressed applications.

4-The position of failure of castings, under the high loads of destructive testing, is dictated by stress concentration resulting from casting design and not from the presence or location of discontinuities.

5-The excessive strength of the individual castings provided through very large safety factors built into the designs are of such magnitude that they make insignificant the variations in strength properties between the test bar and the casting.

6-The strength properties of the casting, as defined by test specimens machined from it, were not more than 10 percent less than the strength properties of the steel as determined by test bars from coupons. The small variation is the result of their location, position, and casting thickness. The notched bar impact properties of test bar and casting are similar in magnitude. Ductility values in the casting are usually lower than the test bar but casting fracture under destructive testing of the 12 steel castings was always preceded by extensive deformation.

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# PREFACE TO THE RESEARCH REPORT

The importance of hidden flaws, or non-homogeneous sections in castings is a subject of some disagreement. Minor discontinuities, as revealed by radiography, are often classed as serious imperfections and subject to casting rejection or extensive welding repairs, very frequently out of proportion to their intrinsic real effect.

Materials engineers may point with alarm to differences found in ductility values from specimens taken from separately cast test coupons and from various sections of castings, even though they know that ductility does not enter into design calculations. Its only consideration is its incorporation in safety factors. If ductility exceeds 5 percent, the material is considered ductile instead of brittle.

A decrease in casting yield strength or ductility or the presence of small discontinuities often has been blamed for service failures when the true culprit was inadequate design, resulting in stress concentration. It is a difficult task indeed to persuade a customer that his design is at fault, but factual information has shown that over 95 percent of all service failures are directly attributable to stress concentration resulting from improper design.

The need for information concerning destructive testing of commercial steel castings with comparative information on stress analysis studies, the need for an evaluation of the importance of discontinuities on the service life of the casting, and the need for test bar properties vs. casting properties, led the Steel Foundry Research Foundation to carry on the extensive research investigations of this report and to publish the information so that it will be available to all design and materials engineers.

The summary report, Part I, of which this is a copy, presents the 4-year research studies in consolidated and summary form for a fast reading review of the findings of the research. This summary may be sufficient for most engineers who are inundated with reading requirements.

The detailed report, Part II, on this same subject, also has been published and is available for a small fee on request. This report takes up, in detail, stress analysis information, and a full report of the destructive testing, mechanical property testing, and nondestructive test examination for those design engineers who would like to go more fully into the study so that they can apply this information to the designing of parts for industry.

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

Alloy Steel and Metals Company
Canadian Steel Foundries, Limited
Crane Company
Duncan Foundry & Machine Works
Empire Steel Castings, Incorporated
Evinrude Motors Division, Outboard Marine Corporation
Minneapolis Electric Steel Castings Company
Missouri Steel Castings Company
Oklahoma Steel Castings Company, Division of American Steel and Pump Corporation
The Pacific Steel Casting Company

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, and Daniel K. Wright, Professor of Machine Design, for directing and coordinating the research.

Additional research is presently in progress to incorporate the findings listed in this report into a more useful tool for the design engineer. Some of the test castings are being redesigned to obtain more uniform stress distributions. Destructive testing of these components will permit evaluation of the importance of proper design.

Another part of this investigation has been published by the Foundation under the title of "Effect of Shrinkage Porosity on Mechanical Properties of Steel Casting Sections," January 1962, and is available from the Foundation. This report presents information on steel casting specimens containing controlled quantities and distribution of discontinuities which were subjected to standard testing techniques. The results of this prior study provide quantitative information on the influence of centerline porosity on the strength of steel castings.

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March, 1962

# CORRELATION OF DESTRUCTIVE TESTING OF STEEL CASTINGS WITH STRESS ANALYSIS AND MECHANICAL PROPERTIES

by

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## PART I - A SUMMARY REPORT

### Introduction

Prior to the development of stress analysis techniques, it was necessary to design a part rather arbitrarily, produce it, and test it in service to determine whether it would perform as desired. With the information gained through stress analysis techniques, however, it is now possible to design a casting for a specific application and predict its service performance. Large safety factors imposed during early stages of the development of design technique have been retained to allow for the nonideal behavior of materials. Since casting discontinuities did not lend themselves to the generalization necessary for designing purposes, castings exhibiting these irregularities frequently are classified as unacceptable. It is the purpose of this research to show that more complete utilization of the information obtained from stress analysis permits a more realistic consideration of the acceptability of steel castings, especially those containing certain discontinuities.

The primary reason designers are reluctant to consider casting irregularities is the lack of quantitative data on their effect on service behavior. One cannot place a strain gage on the inside of a shrinkage discontinuity and study the complex stress distribution around it. Analog methods which could be employed are often brushed over because these are considered as oversimplifications. Simultaneous application of the many stress analysis methods, however, led to a quite conclusive method of investigating the significance of discontinuities in casting performance under stress.

In order to determine the importance of these discontinuities, twelve different commercial castings were subjected to a simulated service testing. Casting flaw detection methods such as magnetic particle examination, radiography, and macrometallography were utilized to locate and classify any discontinuities located in the castings. The mechanical properties of the steel were determined for specimens prepared from SFSA-ASTM keel blocks and from critical positions within the castings. Brittle lacquer and strain gage methods of stress analysis were employed during destructive and nondestructive testing.

Analysis of the data proved that the presence of discontinuities of various types and severity were not cogent reasons for scrapping steel castings. Centerline shrinkage, which was one of the most common discontinuities encountered, was the least damaging. With a general knowledge of the stress requirements for a given casting, a design engineer can readily ascertain the significance of the discontinuity on casting behavior under stress.

Requirements for sound castings without regard for the relative importance of irregularities increase the cost of casting production to unnecessarily high values. When a casting is subjected only to low or negligible stress, few requirements other than dimensional are specified. However, a casting which is to be subjected to a nonuniform stress state is often called upon to maintain the same quality requirements in the region of low stress that are necessary in the highly stressed areas. The cost savings experienced by design engineers in the utilization of I-beams in place of solid beams has been accepted. Why then cannot a square bar with centerline shrinkage receive the same type of acceptance?

## Procedure

Commercial castings were inspected to determine their acceptability for engineering applications and subsequently tested to destruction. Industrial nondestructive testing techniques were employed to detect and classify discontinuities. Brittle lacquer and strain gage tests, used in conjunction with breakdown tests, determined the performance of the casting under simulated service conditions.

A total of forty steel castings was made available for study, and twelve that were most appropriate for this investigation were selected for examination and testing. The only size limitation was that of a maximum load of 600,000 pounds, the capacity of the universal testing machine available. This high load enabled steel castings with wide variations in shape, loading conditions, and weight to be considered. The final selection was also based on the existence of discontinuities in the various castings, so that their effect on casting performance under test could be determined.

Detection and classification of defects included radiographic and magnetic particle techniques. These methods were extended beyond normal industrial procedures by permitting destruction of the castings. Whenever it was necessary, the castings were sectioned to investigate internal or overlapping portions which resulted in low radiographic sensitivity. The major reasons for casting rejection were included in the castings tested. These discontinuities were, according to ASTM Radiographic Standards for Steel Castings E 71-52:

| | |
|---|---|
| A | Gas and blowholes |
| B | Sand spots and inclusions |
| C | Internal shrinkage |
| D | Hot tears |
| E | Cracks |

All defects were classified according to type, severity, and location. Based upon these results, twelve industrial steel castings were selected and subjected to detailed radiographic inspection prior to testing.

Mechanical properties were measured for each casting type from specimens machined from keel blocks and at selected positions within the castings. The keel blocks represented the properties of the steel employed in a particular casting. Test specimens machined out of the casting were removed from critical locations, when possible, so that the discontinuities were often included in the material to be tested.

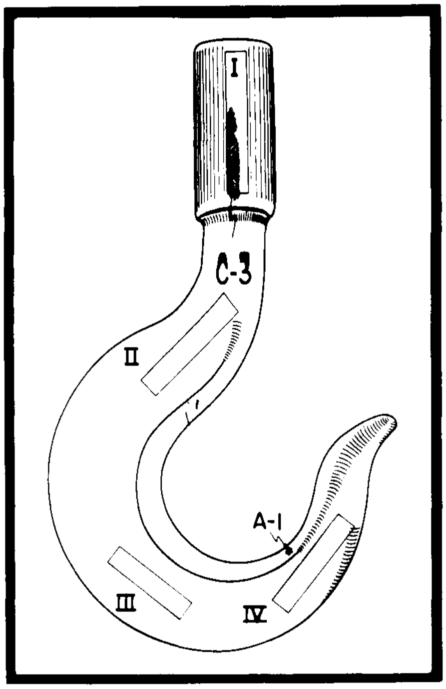
Details of the brittle lacquer analysis, strain gage technique and loading tests to complete failure are fully explained in the Detailed Report - Part II, a companion to this report, which is available upon request.

Loading tests to complete failure were conducted to determine the location and load at which ultimate failure occurred in each casting. In some cases, this was evidenced by an actual fracture of the specimen. In many others a bending or buckling was detected that indicated substantial plastic deformation. Three of the twelve castings, however, could not be tested to failure since the components with which they would normally operate failed before sufficient load could be applied. The methods of load application in these breakdown tests were also intended to duplicate service conditions.

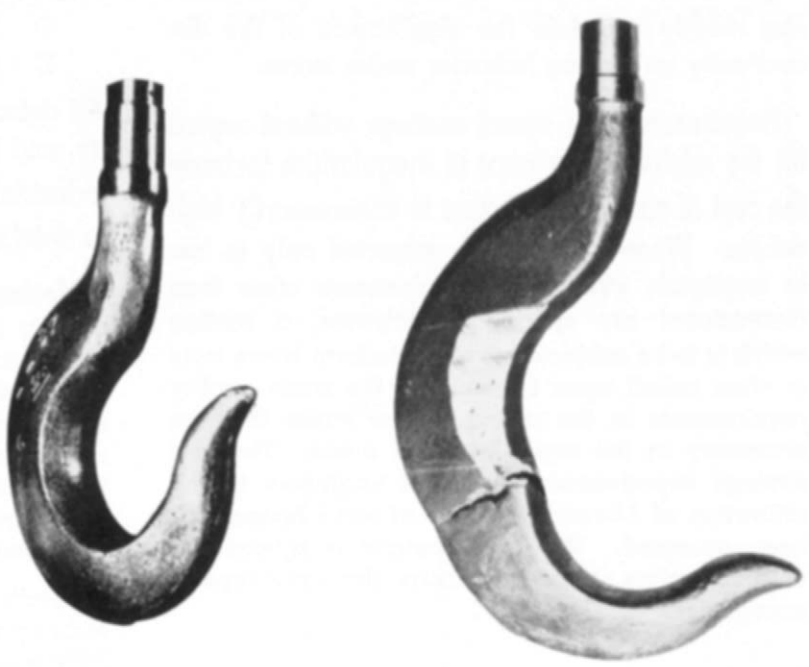
## Discussion of Results

An extensive performance record under simulated service conditions has been developed for each casting application. The length of such analyses has required that the bulk of the information be included in a separate extensive report of much detail, including 12 sections, one separate section for each type of steel casting. The summary presented in this report describes the behavior of the casting under load compared to its stated service conditions. The influence of wide variations in the type, location, and severity of discontinuities in the finished castings on their simulated service behavior has been evaluated. The results of the tensile and impact tests from the casting and keel block are also for each type in this report. The data for each casting have been presented individually in this summary report.

# HOOK



TEST SPECIMEN LOCATIONS AND TYPES AND LOCATIONS OF DEFECTS



TESTED CASTING SHOWING STRESS COAT PATTERN AND FAILURE

TENSILE AND IMPACT DATA

| | Control | I | II | III | IV |
|---|---|---|---|---|---|
| Tensile (1000 psi) | 128 | 85 | 117 | — | 117 |
| Yield (1000 psi) | 103 | 71 | 96 | — | 96 |
| Elongation (%) | 15.4 | 2.9 | 9.7 | — | 10.4 |
| 70°F Charpy | | | | | |
| V-notch (ft-lb) | 43 | — | — | 42 | — |
| Trans. Temp. (°F) | 30 | — | — | 50 | — |
| Trans. Energy (ft-lb) | 41 | — | — | 40 | — |

BREAKDOWN DATA

| | |
|---|---|
| Service Load (x1000 lb) | 10 |
| Yield Stress Load (x1000 lb) | 35 |
| Deformation Load (x1000 lb) | 40* |
| Fracture Load (x1000 lb) | 101** |

*Five castings tested varied from 40,000 to 48,000 pounds.

**Five castings tested varied from 101,000 to 111,000 pounds.

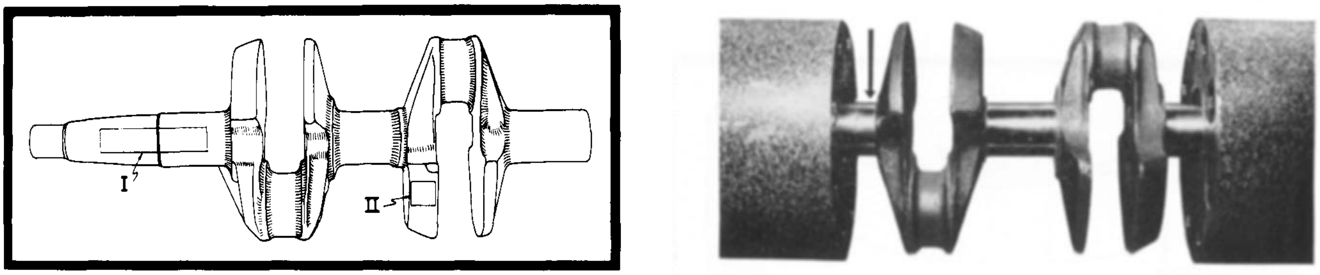
*Figure 1—Summary of mechanical properties, discontinuities and simulated service performance of 5-ton swivel crane hook steel casting.*

### 5-Ton Swivel Crane Hook

The crane hook steel casting was designed with a safety factor of four for a capacity of 5 tons. A summary of the condition and performance of the production casting is presented in Figure 1. A Class 3 shrinkage defect (C-3) was located in the neck of the casting while a Class 1 porosity (A-1) was apparent near the point of the hook. Test bars were removed from these and other critical areas in the casting to determine tensile and impact properties. Comparison of these results with those obtained from separately cast coupons showed that in sound areas of the hook casting the tensile strength was 90 percent of the control (coupon) specimens while the elongation in the casting was reduced from 15.4 to 10.4 percent. Specimens which included the shrinkage discontinuity in the casting neck were only 66 percent as strong as the keel block specimens and exhibited 2.9 percent elongation as compared to 15.4 percent for the latter specimens. Charpy V-notch impact results indicated very little difference between the cast section and the separately cast coupons. Energy levels were similar but the transition temperature was slightly higher in the production casting.

The hook was given brittle lacquer and strain gage tests before the casting was tested to destruction. Failure took place where the stress analysis indicated was the position of maximum stress concentration. Furthermore, failure did not occur in the area of the low mechanical properties as indicated by tests taken from the casting. Also, in no instance did failure occur through one of the discontinuities detected by radiography.

# CRANKSHAFT



TEST SPECIMEN LOCATIONS AND TYPES

TESTED CASTING SHOWING FAILURE

TENSILE AND IMPACT DATA

| | Control | I | II |
|---|---|---|---|
| Tensile (1000 psi) | 84 | 88 | 88 |
| Yield (1000 psi) | 63 | 64 | 64 |
| Elongation (%) | 28.6 | 20.7 | 27.5 |
| 70°F Charpy V-notch (ft-lb) | 46 | 34 | 50 |
| Trans. Temp. (°F) | 170 | — | — |
| Trans. Energy (ft-lb) | 62 | — | — |

BREAKDOWN DATA

| | |
|---|---|
| Service Torque (x1000 lb-in) | 0.5 |
| Deformation Torque (x1000 lb-in) | 11.0* |
| Fracture Torque (x1000 lb-in) | 23.6** |
| Fatigue Limit Torque (x1000 lb-in) | 2.8* |

*Torque applied at spline shaft

**Torque applied at crankpin

*Figure 2—Summary of mechanical properties, discontinuities and simulated service performance of crankshaft steel casting.*

Breakdown tests conducted on these castings demonstrated that the discontinuities did not exert a discernable influence on the ultimate performance of the hook. The yield strength was first reached on the tension side of the hook throat during simulated testing. In five separate tests, the lowest applied load at which this yielding occurred was 35,000 pounds. Subsequent deformation first became visually apparent at values of applied load varying from 40,000 to 48,000 pounds. This deformation continued in the throat of the casting until failure resulted at this location at applied loads of 101,000 to 111,000 pounds. The load to failure is 10 times the service load of 10,000 pounds.

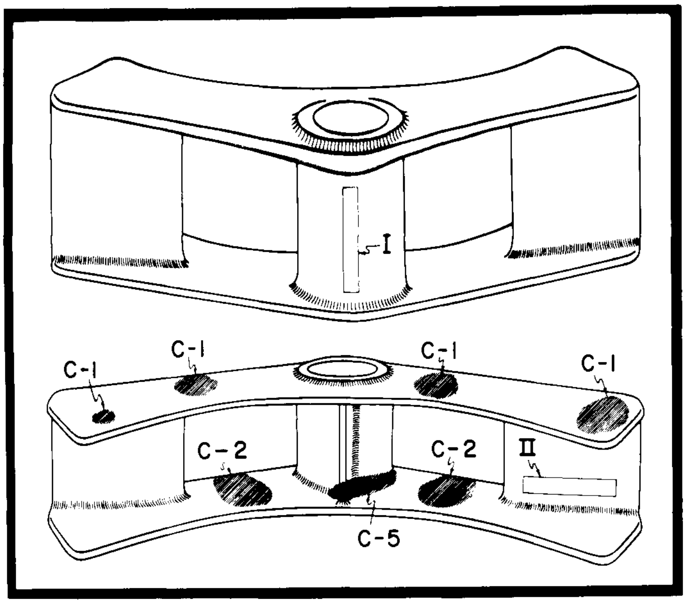
The studies show that test specimens taken from the center of sections may give poor value but it is the entire section that must be tested in order to determine the true properties of a steel casting. It is not the properties along the centerline of a section that are important, but the character of the stresses and their concentration that are of major importance.

### Crankshaft for Outboard Motor

The steel casting crankshaft of Figure 2 was designed with a safety factor of two for operation in a motor rated at 35 horsepower at a speed of 4500 revolutions per minute. These power requirements correspond to a mean torque of 490 pound-inches. Specimens were removed from the crankshaft at positions I and II in Figure 2 and compared with tests on keel block specimens. The similarity in section sizes resulted in only slight variations in properties. Specimens from the crankshaft exhibited slightly higher tensile and yield strengths and slightly lower ductility than specimens machined from separately cast coupons. Limited Charpy V-notch impact data did not reveal significant differences in toughness between the crankshaft and the coupons.

Breakdown tests were conducted to determine both the static performance and fatigue limit of this casting. Torque application through the spline shaft resulted in sufficient deformation at this area to require the testing to stop at 11,000 pound-inches torque. Static load applied through the crankpin to simulate service torque resulted in fracture near the main bearing fillet at 23,600 pound-inches torque. During these tests the casting was supported at all three bearing locations. Fatigue tests indicated an endurance limit of 2800 pound-inches of completely reversed maximum torque. For these tests it was not necessary to support the casting at the center bearing location since pure torque was applied through the spline shaft. Although completely reversed torque was applied during the test, the casting performance indicated a safety factor many times greater than design considerations dictated- or a factor of 5 on the basis of fatigue limit torque, or a factor of 22 on deformation torque.

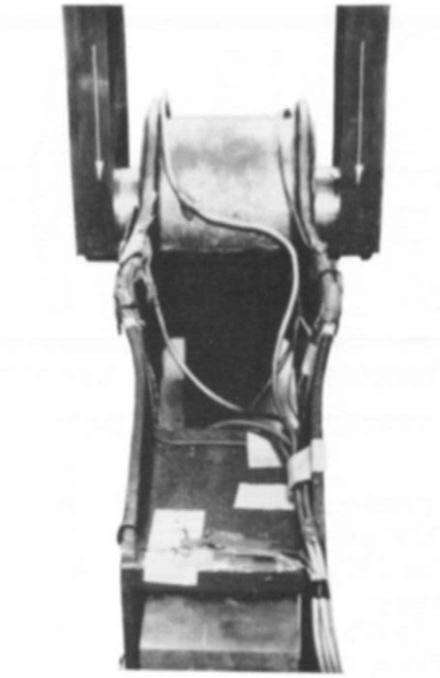
# LOAD EQUALIZER



TEST SPECIMEN LOCATIONS AND TYPES AND LOCATIONS OF DEFECTS

TENSILE AND IMPACT DATA

| | Control | I | II |
|---|---|---|---|
| Tensile (1000 psi) | 101 | 88 | 94 |
| Yield (1000 psi) | 73 | 61 | 64 |
| Elongation (%) | 23.6 | 9.7 | 21.5 |
| 70°F Charpy | | | |
| V-notch (ft-lb) | 30 | 18 | 24 |
| Trans. Temp. (°F) | 190 | — | — |
| Trans. Energy (ft-lb) | 45 | — | — |



TESTED CASTING SHOWING FAILURE BY BUCKLING

BREAKDOWN DATA

| | |
|---|---|
| Service Load (x1000 lb) | 18* |
| Yield Stress Load (x1000 lb) | 16** |
| Deformation Load (x1000 lb) | 65 |

*And infrequent impact loads

**Highly localized. More general yielding apparent at 35,000 pounds.

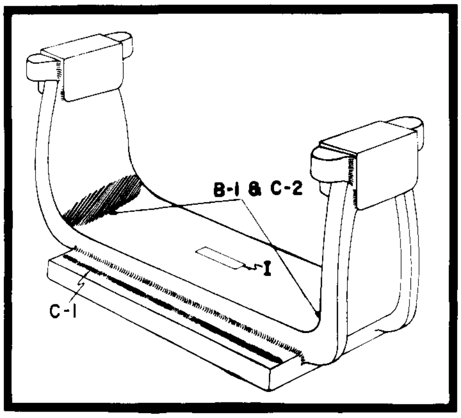
*Figure 3—Summary of mechanical properties, discontinuities and simulated service performance of load equalizer steel casting.*

**Load Equalizer for Truck Suspension System**

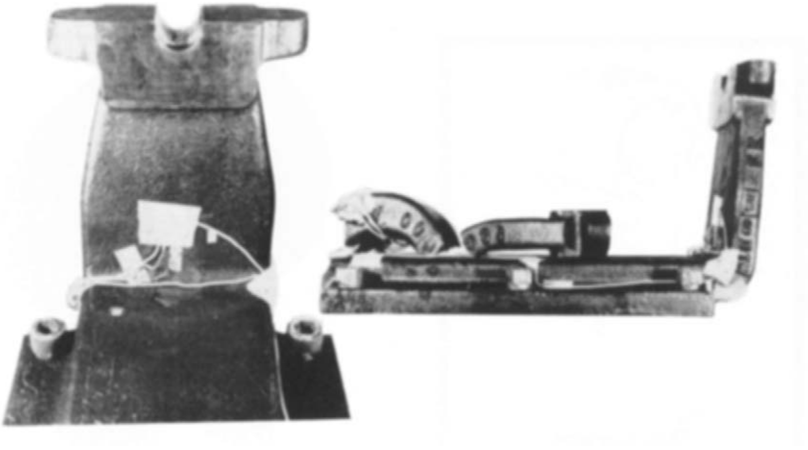
The casting of Figure 3 was used as a load equalizer in the suspension system of a truck. Service conditions imposed a static load of 18,000 pounds and infrequent impact loads. The casting contained extensive areas of shrinkage porosity. Classes 1 and 2 shrinkage (C-1 and C-2) were located at the center of every web of uniform section size. In addition a Class 5 shrinkage (C-5) was located at a fillet of the midspan hole. Tensile tests revealed that the mechanical properties for specimens removed from the castings were somewhat lower than for separately cast coupons. Strength reductions were approximately 10 percent in magnitude, while the elongation decreased from 23.6 percent for keel blocks, to 21.5 percent in a sound web, to 9.7 percent near the midspan hole. Limited impact data indicated that the toughness of the steel was slightly lower in the casting than in the separately cast coupons.

Breakdown tests were conducted to determine the simulated service performance of the load equalizer. With the casting supported at either end, a static load was applied to a pin through the midspan hole in the manner of a simple beam. A highly localized, compressive yielding was initiated at the top edge of the web near the midspan hole at a load of 16,000 pounds. A more generalized yielding of the casting, however, was not experienced until 35,000 pounds applied load. This also occurred in compression and at a position adjacent to the initial yielding. The ultimate failure of the casting took place at this same location at an applied load of 65,000 pounds by buckling of the side webs. The load to failure of 65,000 pounds is 3.6 times the service load of 18,000 pounds.

# SHAFT SUPPORT



TEST SPECIMEN LOCATIONS AND TYPES AND LOCATIONS OF DEFECTS



TESTED CASTING SHOWING FAILURE

TENSILE AND IMPACT DATA

| | Control | I |
|---|---|---|
| Tensile (1000 psi) | 134 | 135 |
| Yield (1000 psi) | 117 | 120 |
| Elongation (%) | 16.2 | 13.8 |
| 70°F Charpy V-notch (ft-lb) | 33 | 34 |
| Trans. Temp. (°F) | 120 | 100 |
| Trans. Energy (ft-lb) | 37 | 37 |

BREAKDOWN DATA

| | |
|---|---|
| Service Load (x1000 lb) | low* |
| Yield Stress Load (x1000 lb) | 153 |
| Fracture Load (x1000 lb) | 320 |

*Design criterion was low deflection at subcritical loads

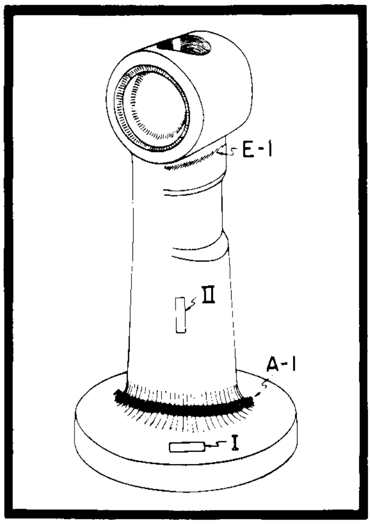
*Figure 4—Summary of mechanical properties, discontinuities and simulated service performance of shaft support steel casting.*

### Shaft Support

The shaft support steel casting of Figure 4 was designed with a large safety factor to sustain cyclic tensile and compressive loads. Low deflection specifications resulted in a heavier casting than normal design considerations dictated. Application of the load was through a rotating shaft with a diameter of one inch. Casting discontinuities such as Class 1 inclusions (B-1) and Class 2 shrinkage (C-2) were critically located at the two inside corners of the casting. Some Class 1 shrinkage (C-1) was detected at the base plate fillet. Test specimens machined from the center of the base plate exhibited mechanical properties comparable to those obtained with separately cast coupons. The tensile and yield strengths were slightly higher for specimens from the shaft support, but the ductility dropped from 16.2 percent for the keel block specimens to 13.8 percent in the casting. Impact transition curves indictated that the toughness at various temperatures was similar, with a slightly lower transition temperature in the casting than in the separately cast coupons.

Static tests were conducted with a vertical load applied at the shaft journals. The first location to reach the yield strength of the casting was the lower inside corner with the larger fillet radius. This stress level was first attained at an applied load of 153,000 pounds. Subsequent failure of the casting occurred simultaneously at this lower inside corner, the opposite lower corner and at mid-elevation of a support at a load of 320,000 pounds. Although these failures were experienced at positions of the casting where discontinuities were located, the casting withstood very high loads before failure. Since the defects were located at the center of the cross section, and the applied stress was bending, the importance of the defects was substantially reduced. The load to failure is more than 20 times the service load.

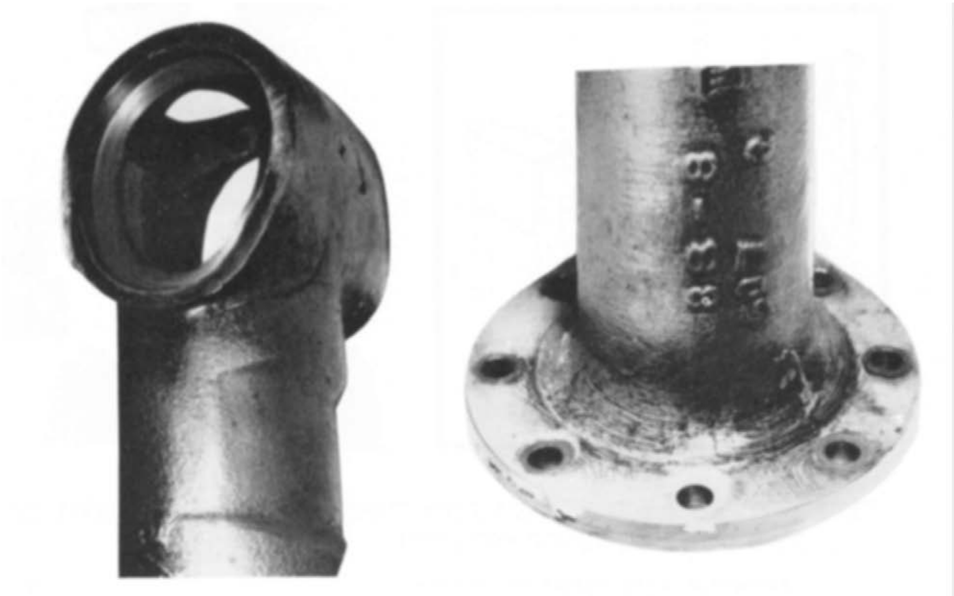
# TRUCK AXLE



TEST SPECIMEN LOCATIONS AND TYPES AND LOCATIONS OF DEFECTS

TENSILE AND IMPACT DATA

| | Control | I | II |
|---|---|---|---|
| Tensile (1000 psi) | 105 | 93 | 88 |
| Yield (1000 psi) | 65 | 59 | 59 |
| Elongation (%) | 20.5 | 18.3 | 9.5 |
| 70°F Charpy | | | |
| V-notch (ft-lb) | 23 | 23 | — |
| Trans. Temp. (°F) | 130 | 130 | — |
| Trans. Energy (ft-lb) | 27 | 33 | — |



TESTED CASTING SHOWING STRESS COAT PATTERN

BREAKDOWN DATA

| | |
|---|---|
| Service Load (x1000 lb) | 4.5* |
| Yield Stress Load (x1000 lb) | 8.0 |
| Fracture Load (x1000 lb) | >50.0** |

*And undetermined dynamic loads

**Bolts of testing fixture failed at this load

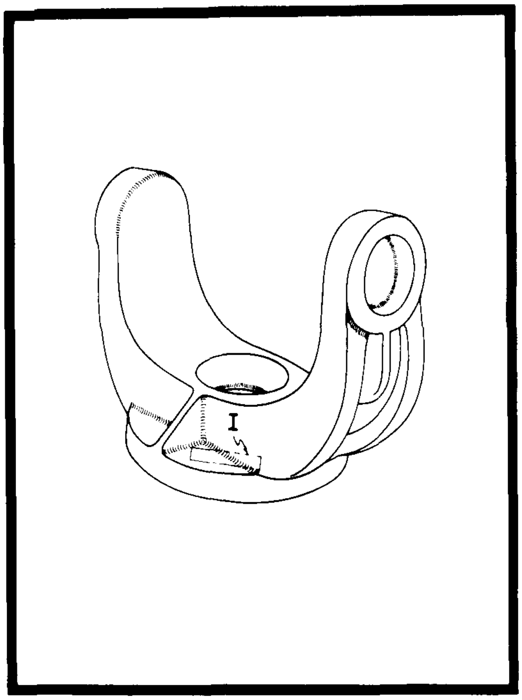
*Figure 5—Summary of mechanical properties, discontinuities and simulated service performance of truck front axle steel casting.*

**Front Axle of Truck**

The steel casting truck axle shown in Figure 5 was designed for use on a 1 1/2-ton truck. This type of service application included a static load of 4500 pounds on each axle and undetermined dynamic loads. Radiographic examination of the casting revealed Class 1 blowholes (A-1) near the fillet of the flange and Class 1 cracks (E-1) in the shaft near the opening for the king pins. Specimens were machined from a position near the mid length of the shaft and from the flange. Mechanical properties at both of these locations were somewhat lower than those obtained with separately cast coupons. However, the toughness was nearly identical for both types of specimens, with the energy level of ductile fracture slightly higher in the casting than in the keel blocks.

Breakdown tests were conducted to simulate the normal static load on the axle. The flange fillet attained the yield strength of the material on the tension side of the casting at an applied load of 8,000 pounds. However, substantial deformation was not observed in the axle even at an applied load of 50,000 pounds. The test was stopped at this load because the bolts which normally supported the casting failed. This occurred in spite of the fact that special heat-treated bolts were used for this test. Casting discontinuities did not appear to affect the performance of the axle at the applied load of 50,000 pounds which was considerably in excess (11 times) of normal service loads of 4500 pounds.

# SUSPENSION YOKE



TEST SPECIMEN LOCATIONS AND TYPES AND LOCATIONS OF DEFECTS

TESTED CASTING SHOWING FAILURE

TENSILE AND IMPACT DATA

| | Control | I |
|---|---|---|
| Tensile (1000 psi) | 111 | 107 |
| Yield (1000 psi) | 88 | 86 |
| Elongation (%) | 19.7 | 14.3 |
| 70°F Charpy V-notch (ft-lb) | 42 | 30 |

BREAKDOWN DATA

| | |
|---|---|
| Service Load (x1000 lb) | 4.5* |
| Yield Stress Load (x1000 lb) | 24** |
| Failure Load (x1000 lb) | 60 |

*And undetermined dynamic loads

**This value is somewhat low due to casting modification to accommodate test fixture

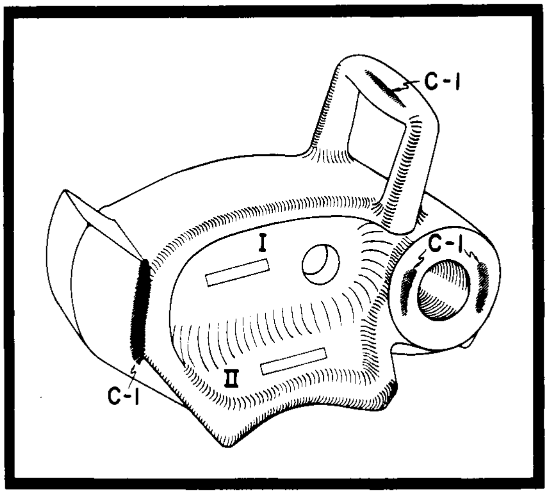
*Figure 6—Summary of mechanical properties, discontinuities and simulated service performance of suspension yoke steel casting.*

### Suspension Yoke for Truck Front Axle

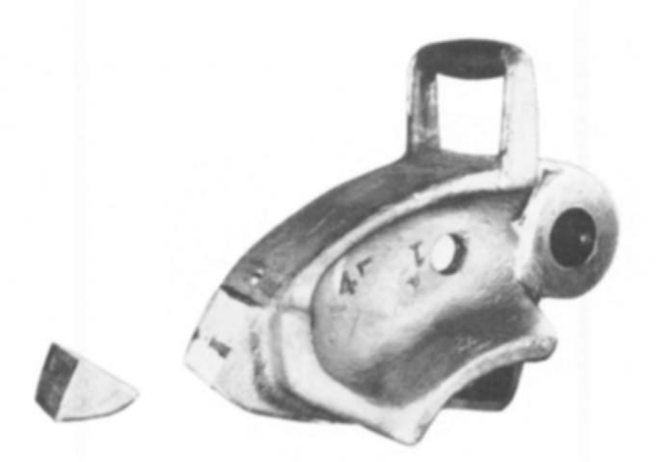
The suspension yoke steel casting of Figure 6 was designed for a static load of 4500 pounds and undetermined dynamic loads due to cornering, braking, etc. Specifications required that the yoke be made of cast steel with a tensile strength of 120,000 psi. No other design considerations were submitted by the designer with the casting. Specimens removed from the yoke at location I in Figure 6 compared favorably with those obtained from separately cast coupons. The tensile strength was 96 percent and the yield strength was 98 percent of the keel block tests. The tensile elongation decreased from 19.7 in the coupon to 14.3 percent in the casting. Limited data from impact tests indicated a somewhat lower room temperature impact energy of tests from the casting but were insufficient in number to permit the development of complete transition curves.

Breakdown tests were conducted to simulate the vertical static loading conditions on the casting. Two suspension yokes were tested simultaneously by applying the load to the ring supporting the lower bearing race. Both castings failed by shearing the ring at a total load of 120,000 pounds (approximately 60,000 pounds per casting). The yield strength of the material was reached at a load of 24,000 pounds per casting by gages directly below the ring. Modifications of the casting to accommodate the test fixture were believed to have resulted in somewhat premature yielding at this location. The second area to experience yielding was on the compression side of the yoke at an applied load (per casting) of 32,000 pounds. The load to failure of 60,000 pounds is 13 times the service load of 4,500 pounds.

# LUG JAW



TEST SPECIMEN LOCATIONS AND TYPES AND LOCATIONS OF DEFECTS



TESTED CASTING SHOWING FRACTURE SURFACE AND FAILURE

### TENSILE AND IMPACT DATA

| | Control | I | II |
|---|---|---|---|
| Tensile (1000 psi) | 144 | 122 | — |
| Yield (1000 psi) | 123 | 85 | — |
| Elongation (%) | 14.5 | 10.5 | — |
| 70°F Charpy | | | |
| V-notch (ft-lb) | 32 | — | 32 |
| Trans. Temp. (°F) | 30 | — | 50 |
| Trans. Energy (ft-lb) | 31 | — | 31 |

### BREAKDOWN DATA

| | |
|---|---|
| Yield Stress Load (x1000 lb) | 140 |
| Fracture Load (x1000 lb) | 470* |
| Fracture Load (x1000 lb) | 436** |

*With cleat fully engaged loading pin failed

**Cleat sheared with load application 3/16" from fillet

*Figure 7—Summary of mechanical properties, discontinuities and simulated service performance of lug jaw steel casting.*

**Lug Jaw**

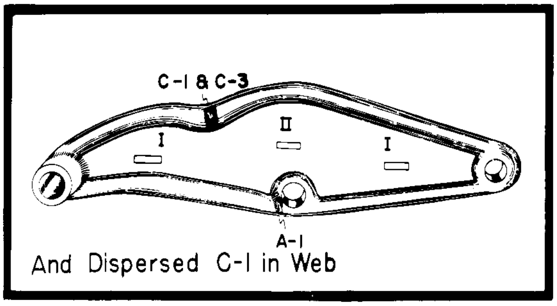
The lug jaw steel casting of Figure 7 is part of a tong used to couple oil well casings. Service load information was not submitted with the casting. The reason for this, apparently, is that the cleat portion of the casting fractured in service several times and the design and steel strength specification were changed so as to prevent failure. The present specification requires steel of a yield strength of 120,000 psi and an elongation of 12.0 percent.

These requirements were fulfilled with a tensile strength of 144,000 psi, a yield strength of 123,000 psi and 14.5 percent elongation for the separately cast coupons, but not with specimens cut from the lug jaw at location I in Figure 7. At this position, the tensile strength was 122,000 psi, the yield strength 85,000 psi and the elongation 10.5 percent. The room temperature and super transition temperature impact values were similar in the keel block and casting, but the transition temperature was slightly higher for specimens removed from the lug jaw at location II in Figure 7. Class 1 shrinkage porosity (C-1 ) was detected radiographically at three locations in the casting: the latch nose, the handle, and near the pin.

Tests conducted under simulated service conditions did not result in failure of the casting when the latch nose was fully engaged. Instead, the tong pin failed at a load of 470,000 pounds. By shifting the position of load application away from the latch nose fillet by 3/16 inch it was possible to shear the latch nose at a load of 436,000 pounds. However, this failure occurred through the sound material rather than the C-1 shrinkage porosity near this location. The yield strength of the material was exceeded in the lower flange of the casting at an applied load of 140,000 pounds but this did not substantially affect the performance of the casting at loads up to 436,000 pounds.

A service load in shear of 60,000 psi can be estimated on the basis of the 120,000 psi yield strength or a load of 240,000 pounds at the position of fracture of the cleat (4 sq. inches) if no safety factors are employed. Normally a safety factor of 3 would

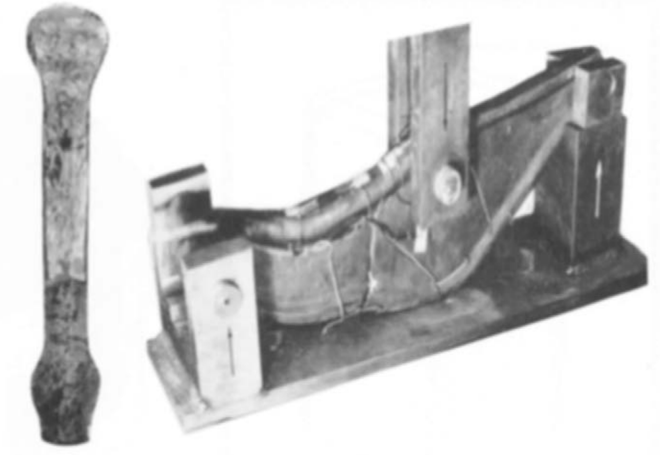
# LIFTING ARM



TEST SPECIMEN LOCATIONS AND TYPES AND LOCATIONS OF DEFECTS

TENSILE AND IMPACT DATA

| | Control | I | II |
|---|---|---|---|
| Tensile (1000 psi) | 90 | 80 | — |
| Yield (1000 psi) | 71 | 59 | — |
| Elongation (%) | 31.4 | 8.0 | — |
| 70°F Charpy V-notch (ft-lb) | 47 | — | 26 |
| Trans. Temp. (°F) | 120 | — | 200 |
| Trans. Energy (ft-lb) | 53 | — | 49 |



TESTED CASTING SHOWING FRACTURE SURFACE AND FAILURE

BREAKDOWN DATA

| | |
|---|---|
| Service Load (x1000 lb) | 29 |
| Yield Stress Load (x1000 lb) | 53 |
| Fracture Load (x1000 lb) | 202 |

*Figure 8—Summary of mechanical properties, discontinuities and simulated service performance of lifting arm steel casting.*

be used as a minimum, and therefore the fracture load of 436,000 pounds would constitute a value of 2 to 5.5 times the service load.

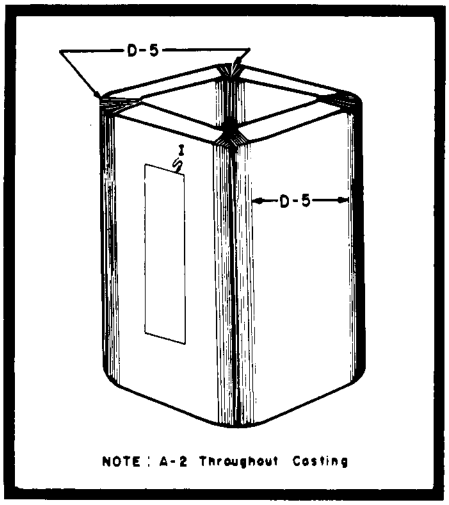
Neither the location of the discontinuities nor the 30 percent fall-off in yield strength in the casting was significant in the position of fracture or the fracture load when compared to that required by specifications.

### Lifting Arm for Truck Hoist

The lifting arm steel casting of Figure 8 was used as part of the hoisting mechanism in dump trucks. In service a maximum load of 29,000 pounds is applied to the central hole with the casting supported at the end holes similar to a beam in simple bending. The casting contained Class 1 porosity (A-1) near the central hole and Class 1 and Class 3 shrinkage (C-1 and C-3) in the heavy section of the saddle. Class 1 shrinkage (C-1) was dispersed throughout the web. Mechanical properties from the web of the casting were somewhat lower than those obtained with keel block specimens. The tensile and yield strengths were 80,000 and 59,000 psi in the casting compared to 90,000 psi and 71,000 psi, respectively, in the keel block. The corresponding values of elongation were 8.0 percent for specimens machined from the web, and 31.4 percent in the separately cast coupons. Charpy V-notch impact properties were generally lower in the casting than in the keel blocks.

Breakdown tests conducted on the lifting arm casting resulted in failure at an applied load of 202,000 pounds. Fracture occurred through an area containing shrinkage defects which were close to the maximum tensile bending stress surface. In spite of the critical location of these defects, the casting performance was acceptable. Although service conditions specified an applied load of 29,000 pounds, the most highly stressed area did not reach the yield strength until an applied load of 53,000 pounds. Subsequent failure occurred at the same location at 202,000 pounds load. This load is 7 times the service load of 29,000 pounds.

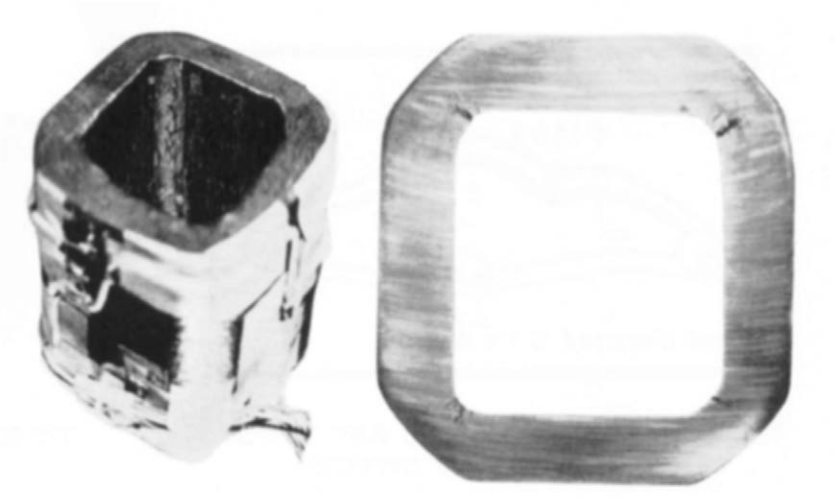
# COUPLING



TEST SPECIMEN LOCATIONS AND TYPES AND LOCATIONS OF DEFECTS

TENSILE AND IMPACT DATA

| | Control | I |
|---|---|---|
| Tensile (1000 psi) | 71 | 74 |
| Yield (1000 psi) | 47 | 46 |
| Elongation (%) | 31.2 | 19.8 |
| 70°F Charpy | | |
| V-notch (ft-lb) | 21 | 24 |
| Trans. Temp. (°F) | 160 | 80 |
| Trans. Energy (ft-lb) | 32 | 25 |



TESTED CASTING SHOWING FAILURE AND CASTING SECTION BEFORE TESTING SHOWING HOT TEARS

BREAKDOWN DATA

| | |
|---|---|
| Service Torque (x1000 lb-in) | 13 |
| Yield Stress Torque (x1000 lb-in) | 17 |
| Fracture Torque (x1000 lb-in) | >77* |
| Fatigue Limit (x1000 lb-in) | >12** |

*Test fixture failed

**Shaft operating with coupling failed with 12,500 lb-in torque at 3.6x$10^6$ cycles

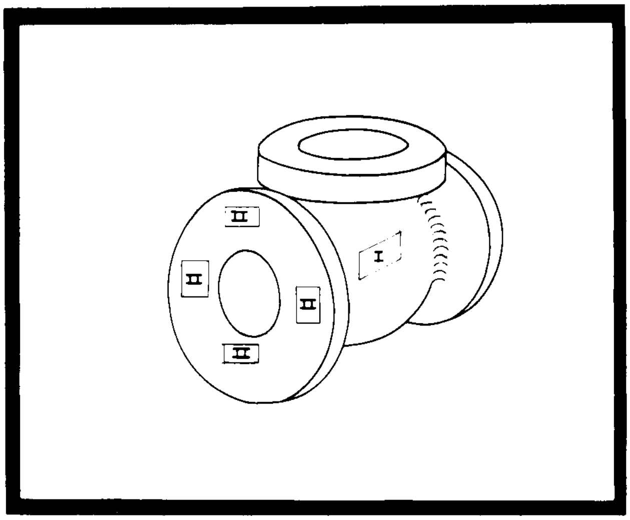
*Figure 9—Summary of mechanical properties, discontinuities and simulated service performance of the drive shaft coupling steel casting.*

**Drive Shaft Coupling**

The steel casting coupling shown in Figure 9 was designed to perform as a connecting member between a drive shaft and a sprocket shaft. Service conditions imposed a normal operating torque of 5,000 pound-inches and a maximum torque of 13,000 pound-inches at speeds below one revolution per minute. Hot tear defects (D-5) were located at all four internal corners. Tensile specimens removed from a radiographically sound position (I in Figure 9) in the casting exhibited a tensile strength of 74,000 psi, which was 4 percent higher than attained on separately cast coupons. The higher tensile strength was accompanied, however, by a slight reduction in yield strength and a decrease in elongation from 31.2 to 19.8 percent. Charpy V-notch transition curves indicated that the transition temperature was reduced from 160 degrees F for separately cast coupons to 80 degrees F for specimens removed from the casting at location I. However, the level of impact energy with a fibrous or ductile fracture is somewhat higher for test bars from the coupon.

Torsion tests conducted on the coupling were unable to produce failure of the casting. In both static and fatigue tests, the drive shafts submitted by the manufacturer failed before sufficient torque could be applied to the coupling. The shaft fracture occurred at a torque of 77,000 pound-inches during static loading and at 12,500 pound-inches after 3.6 x $10^6$ cycles in the fatigue test. At the conclusion of these tests, the hot tears at the corners of the coupling had opened slightly and some distortion was noted where the driving corner of the shaft contacted the coupling. The yield stress of the coupling was attained at the outside surface opposite the contact point of the shaft at a torque of 17,000 pound-inches. The fracture torque of the drive shaft of 77,000 pound-inches is 6 times the service torque of 13,000 pound-inches.

# GLOBE VALVE



TEST SPECIMEN LOCATIONS AND TYPES

TESTED CASTING SHOWING STRESS COAT PATTERN

TENSILE AND IMPACT DATA

| | I | II |
|---|---|---|
| Tensile (1000 psi) | 73 | — |
| Yield (1000 psi) | 43 | — |
| Elongation (%) | 26.4 | — |
| 70°F Charpy V-notch (ft-lb) | — | 46 |
| Trans. Temp. (°F) | — | 125 |
| Trans. Energy (ft-lb) | — | 50 |

BREAKDOWN DATA

| | |
|---|---|
| Service Pressure (x1000 psi) | 0.6 |
| Yield Stress Pressure (x1000 psi) | 6.1 |
| Deformation Pressure (x1000 psi) | >9.0* |

*Substantial deformation was not yet apparent when equipment limitations halted the test at 9000 psi

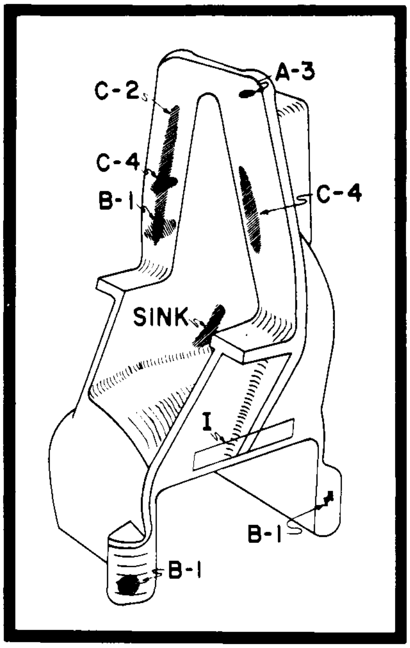
*Figure 10—Summary of mechanical properties, discontinuities and simulated service performance of globe valve body steel casting.*

**4-inch Globe Valve Body**

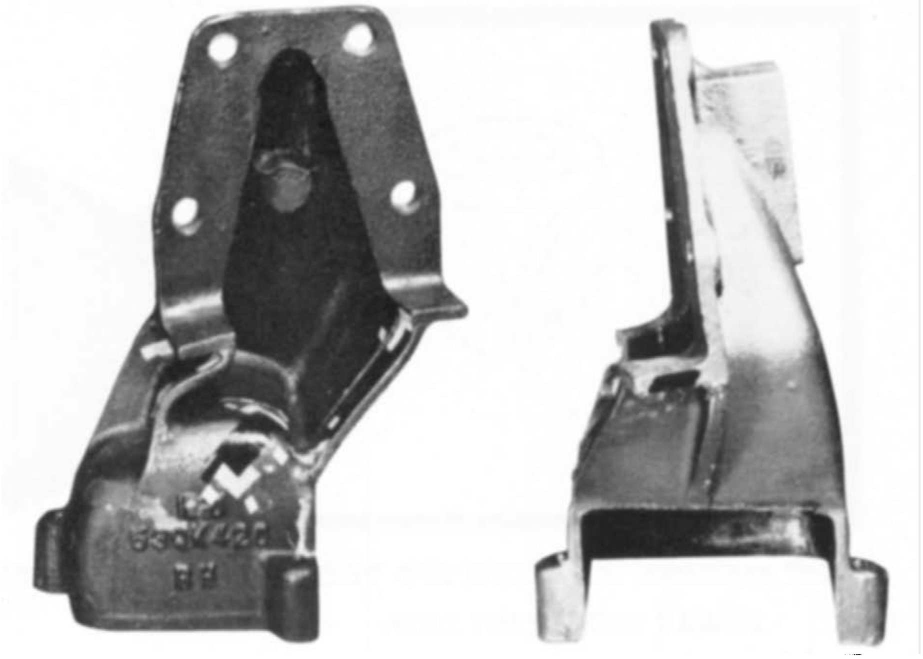
The steel casting globe valve shown in Figure 10 was designed for four-inch pipe lines operating at pressures up to 600 psi. No discontinuities were revealed by magnetic particle or radiographic examination of the casting. At the positions indicated at Figure 10, coupons were removed and subsequently machined to tensile and Charpy V-notch impact specimens. At the center of the "globe" portion of the valve at location I the tensile strength, yield strength, and elongation were 73,000 psi, 43,000 psi, and 26.4 percent, respectively. Limited data were available from impact tests to develop a transition curve for material removed from the flange at II. These indicated a room temperature impact energy of 46 ft-lbs., a transition temperature of 125 degrees F, and a ductile fracture energy of about 50 ft-lbs.

Hydrostatic tests conducted on fully machined valves did not result in failure of the casting. At a pressure of 8000 psi, one of the Cranite gaskets used under plates to seal the three ends of the casting blew out. When this was replaced with a hard O-ring, a pressure of 9000 psi was sustained by the valve. Testing was not continued above this level because additional testing equipment would have been required, and a safety factor of 15 had already been attained. At a pressure of 6100 psi, tensile stresses in excess of the yield strength were detected by strain gages near the neck of the center opening. Stresses at all other locations were shown to be below the yield at loads up to 9000 psi.

# SPRING BRACKET



TEST SPECIMEN LOCATIONS AND TYPES AND LOCATIONS OF DEFECTS



TESTED CASTING SHOWING FAILURE

TENSILE AND IMPACT DATA

| | Control | I |
|---|---|---|
| Tensile (1000 psi) | 79 | 75 |
| Yield (1000 psi) | 50 | 43 |
| Elongation (%) | 25.5 | 31.5 |
| 70°F Charpy V-notch (ft-lb) | 18 | — |

BREAKDOWN DATA

| | |
|---|---|
| Service Load (x1000 lb) | 3.4* |
| Yield Stress Load (x1000 lb) | 12 |
| Deformation Load (x1000 lb) | 85 |

*And 6000 to 8000 lbs. dynamic

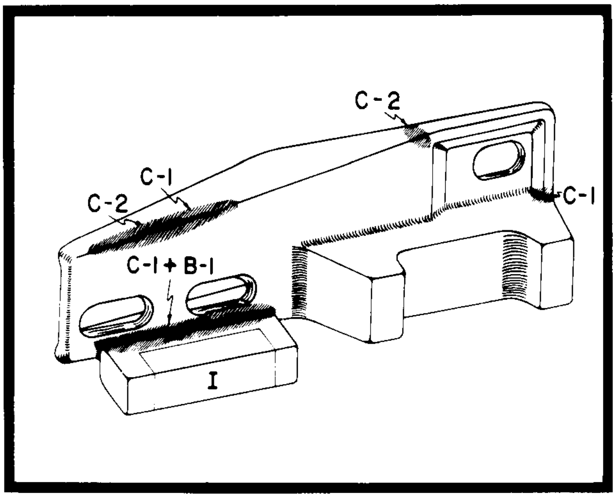
*Figure 11—Summary of mechanical properties, discontinuities and simulated service performance of truck front spring bracket steel casting.*

**Front Spring Bracket for Truck**

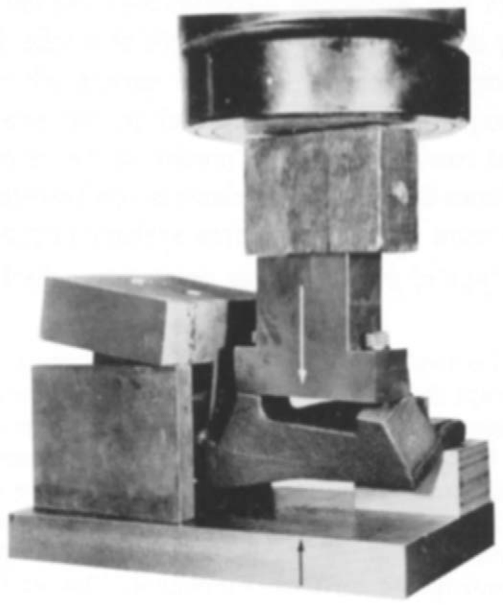
The spring bracket steel casting was designed to support the front spring of a truck with static load of 3400 pounds and dynamic loads of 6000 to 8000 pounds. Figure 11 provides a summary of the analysis of this casting. Extensive defects were detected radiographically in the thin webs, including Class 3 blowholes (A-3), Class 1 inclusions (B-1), and Class 2 and 4 shrinkage (C-2 and (C-4). The large lugs at the bottom of the casting contained Class 1 inclusions (B-1). At an internal junction of three thin webs, an external sink developed in the center of the fillet. The thin section size of the casting permitted specimen removal for mechanical properties only at the single location designated by I in Figure 11. Since this represented a sound area of approximately the same section size as the separately cast coupons, the mechanical properties were nearly identical. The tensile strength of the casting was reduced slightly from 79,000 to 75,000 psi compared to the coupons, but this was accompanied by an increase in elongation from 25.5 to 31.5 percent.

Testing of this casting under simulated service conditions resulted in failure by buckling of the lower stiffening ribs. The first location to reach the yield strength was the casting body adjacent to the rib. This occurred in a highly localized area at a load of 12,000 pounds and did not appreciably affect the performance of the casting at loads up to 85,000 pounds. Deformation became apparent at this load and had progressed to the extent illustrated in Figure 11 when testing was stopped at 100,000 pounds. In spite of this extensive deformation, no cracks appeared in the casting. Buckling occurred through the lower half of the casting in an area that was devoid of casting defects. The load to deformation failure of 85,000 pounds is 25 times the service load of 3,400 pounds.

# BUMPER BRACKET



TEST SPECIMEN LOCATIONS AND TYPES AND LOCATIONS OF DEFECTS



TESTED CASTING SHOWING FAILURE

TENSILE AND IMPACT DATA

| | Control | I |
|---|---|---|
| Tensile (1000 psi) | 79 | 68 |
| Yield (1000 psi) | 50 | 46 |
| Elongation (%) | 25.5 | 17.1 |
| 70°F Charpy V-notch (ft-lb) | 18 | 18 |

BREAKDOWN DATA

| | |
|---|---|
| Service Load (x1000 lb) | Nil* |
| Yield Stress Load (x1000 lb) | 9 |
| Deformation Load (x1000 lb) | 60 |
| Fracture Load (x1000 lb) | 93** |

*Dynamic loads up to 26,000 lbs. in collision

**Bolt in test fixture failed

*Figure 12—Summary of mechanical properties, discontinuities and simulated service performance of bumper bracket steel casting.*

### Bumper Bracket for Bus

The bumper bracket steel casting was designed for negligible static stresses, but dynamic loads up to 26,000 pounds during a collision. Data for evaluating this casting by nondestructive and breakdown tests are presented in Figure 12. Class 1 inclusions (B-1), Class 1 shrinkage (C-1), and Class 2 shrinkage (C-2) were revealed by radiographic examination of the casting. These were located primurily at areas with sharp changes in section size. Sufficient material for test specimens was available only at position I indicated in Figure 12. Tensile and impact properties from these specimens were compared with those obtained from separately cast coupons. The tensile strength within the casting was 86 percent of the control value from the separate coupons, while the elongation decreased from 25.5 to 17.1 percent. Limited Charpy impact transition curves did not reveal any difference between the toughness of the production casting and the separately cast coupons.

Breakdown tests conducted on this casting produced substantial distortion, but did not result in fracture of the casting at loads up to 93,000 pounds. Although a rib of the casting attained the yield strength of the material at a load of 9000 pounds, appreciable plastic deformation was not apparent until loads in excess of 60,000 pounds were applied. This was well in excess of the peak service load of 26,000 pounds. At a load of 93,000 pounds the test fixture failed as shown in Figure 12. Although distortion of the casting was severe, no external cracks had developed. The large number of defects detected radiographically did not substantially affect the performance of this casting.

## Conclusions

A previous section of this general investigation(l) showed that shrinkage discontinuities exerted only a very slight effect on the strength of tensile, bend, and joined T-section test bars except when the shrinkage defect was positioned in the areas of highest tensile stress. This portion of the investigation shows that similar conclusions can be extended to the more complicated stress systems or more diverse type of discontinuities present in actual castings.

Of the twelve steel castings selected for testing, all except three had discontinuities of various types and severity. However, all twelve castings withstood loads that simulated service conditions and were in excess of service requirements before yielding. In most cases, the applied load to produce yielding was many times the maximum applied load anticipated for that component. The testing of the castings was carried to failure by applying loads that were from four to over twenty times the maximum service load. In fact, in three cases the accompanying service components failed before casting failure, or the strength of the casting exceeded the capacity of the testing facilities.

These results illustrate conclusively that castings with discontinuities of considerable magnitude will perform satisfactorily in many highly stressed applications. Accordingly, the presence of discontinuities need not require rejection of the casting. The influence of a discontinuity on the load-carrying ability of a casting was primarily determined by the type of defect and the stress state at the discontinuity location that resulted from service loads. In a few instances, the presence of discontinuities did modify existing stress distributions in the casting and decrease the over-all casting strength. Even in these cases, the maximum service load was borne without difficulty. In most instances, the discontinuities were located at regions of low stress and exerted no significant effect on casting performance. It is believed that the results of this research provide the engineer with data for evaluating the influence of discontinuities and on steel casting performance in a realistic manner.

The examples of steel castings tested to failure show that all the castings failed at loads far in excess of the service loads and that failure was related to design and not to sub-standard properties as indicated from test specimens machined from the castings or from possible discontinuities within the casting. Many of the examples showed that the safety factors used in the design were abnormally high and could have been reduced at significant cost advantage to the purchaser. These points have been brought out more fully and emphatically in the conclusion of the report given on page 3.

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(1) Effect of Shrinkage Porosity on Mechanical Properties of Steel Casting Sections, Steel Foundry Research Foundation, January 1962.