FATIGUE STRENGTH OF TWO HEAT TREATED CARBON STRUCTURAL STEELS FOR LOW TEMPERATURE SERVICE

A Thesis

Presented to

The Faculty of the Department of Civil Engineering

The University of Houston

In Partial Fulfillment

of the Requirements for the Degree

Master of Science in Civil Engineering

---

by

Chao Pinyopusarerk

Dec., 1972

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Thanks are due to Miss Pisamai Anomaiprasert who carried out the neat and accurate work of typing this thesis.

Lastly, sincere appreciation is expressed to Miss Fely G. Corrales for providing general encouragement throughout the entire project.

DEDICATION

To

My Parents

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ABSTRACT

Quenched and tempered carbon steels are used in the construction of offshore platforms, refrigerated gas cargo tanks, storage tanks, pipelines, pressure vessels, and other structures which require a high degree of notch toughness at low temperatures or where the increased strength with minimized weight is the standpoint in design. These steels not only provide high static strength, good weldability and excellent notch toughness at low temperatures, but also high fatigue strength as reported in this thesis.

The main objective of this thesis was to determine the fatigue strength of two different kinds of quenched and tempered structural steel; A-537B (Armco Super Lo-Temp) and CG-A-537M (Armco LTM-QT). The A-537B specimens were tested under bending and the CG-A-537M specimens were tested under both bending and axial loading.

Both bending and axial-loading fatigue tests were performed at stress ratios of 0, 1/2, and -1 representing zero-to-tension, half-tension-to-tension, and tension-to-compression loading respectively. The experimental results are presented in conventional S-N curves. The highest stress for which no failure occurred in 2,000,000 cycles was chosen as the fatigue limit. The data from the tests for both steels at stress ratios of 0, 1/2, and -1 together with the static tensile strength (R = 1) were used to construct modified Goodman diagrams

on which other stress ratios can be interpolated.

The results from the A-537B bending tests are compatible with previous axial-loading tests as reported in the literature for any positive stress ratio and for all fatigue lives. The results reveal that the fatigue strength of Armco LTM-QT is higher than that of A-537B when comparing ratios of their fatigue strength to tensile strength. The results of both sets of tests are in agreement that the fatigue strength in bending is greater than that in axial loading.

Results of axial-loading tests on notched specimens are also reported because the effect of stress concentration for different size notches was determined. From the data of plain and notched specimens, the effective stress concentration factor was computed and was found to be smaller than the theoretical one.

Observations were made on the progression of the fatigue cracks until final failure occurred. Fatigue fracture is discussed with reference to photographs of fatigue-fracture appearances. The photographs are used to explain how the crack originated and propagated for both types of loading.

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LIST OF SYMBOLS

K_t = Theoretical stress concentration factor

K_f = Effective stress concentration factor or fatigue notch factor (determined by fatigue tests)

N = Number of cycles to failure

q = Notch sensitivity factor

R = Stress ratio

S_a = Stress amplitude

S_m = Mean or steady stress

S_{min} = Minimum stress during a cycle

S_{max} = Maximum stress during a cycle

S_r = Stress range

S_e = Fatigue limit of unnotched specimen

S_{ne} = Fatigue limit of notched specimen

S_u = Ultimate tensile strength

σ_{nom} = Nominal normal stress

σ_{max} = Maximum normal stress or peak stress

CHAPTER I

INTRODUCTION

1.1 Historical Review and Importance of Fatigue

Fatigue damage in metals due to repeated applications of stress within the apparent elastic range of the material has been emphasized over the past 100 years. This discovery came in the mid-nineteenth century when fatigue failure of railway axles in Europe became widespread, probably because only then were parts subjected to the tens or hundreds of thousands of cycles required for fatigue failure without general yielding. As is usually the case with unexplained service failure, the first step was to reproduce it in the laboratory. Wöhler in Germany and Fairbairn in England made extensive fatigue studies as early as 1860.[23]* The technical literature on fatigue is now well in excess of three thousand references, and is accumulating at a rate of more than three hundred additional references per year.[25] A great aid to the survey of recent literature is provided by the American Society for Testing Materials, which has published a collection of "References on Fatigue" for each year since 1950.[26] In recent years there has been an interest in microscopic observation of the mechanism of fatigue failure by the use of X-ray and electron-microscopic techniques. Through these methods one can learn how a fatigue crack initiates and how it propagates.

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* Numbers in parentheses refer to references in the bibliography. References are listed alphabetically.

Today, more than ever, fatigue is of paramount importance and is receiving increased attention in design. Larger airplanes, ships and other engineering structures are being designed to meet arduous service. Fatigue failures involve loss of considerable capital and sometimes many human lives. Consequently, fatigue is not a negligible problem. Furthermore, it is one of the most difficult and challenging fields for engineering research.

1.2 Quenched and Tempered Carbon Steels for Offshore Structures

In recent years hurricanes have caused great damage to offshore operations in the Gulf of Mexico. In other parts of the world platforms have been extended into deep water and into severe cold regions, such as Alaska and the North Sea. It has become necessary to study the problems of brittle fracture at low temperatures. The failures of offshore drilling platforms under severe weather conditions emphasize the need for increased reliability in these structures to protect the large capital investments and human lives.

The design criteria for marine structures are primarily based on the characteristics of the steels used. The development of steels with improved properties has enabled engineers to design offshore platforms with better performance. Conversely, the continual demand for offshore platforms with better performance leads to the development of steels with improved characteristics.

Low carbon steels are widely used for marine structures and high strength steels have also been used increasingly. Many of the early platforms were built of ordinary structural carbon steels satisfying ASTM specifications. These steels have low strength and poor brittle fracture resistance. Therefore, platforms constructed of such materials can only be built stronger by increasing the plate thicknesses of the various members. New offshore structural requirements have created a demand for steels strong enough to withstand particularly severe conditions such as hurricanes and subzero temperature. At the same time these steels must remain ductile at low temperature. High strength with minimum structural weight is an important standpoint in design for any offshore structure.

To solve the problems of brittle fracture at low temperature and to meet the need for stronger offshore platforms with minimum structural weight, designers have chosen heat-treated carbon steels of extremely high strength which are now available through new heat treatment techniques. Quenching is made to prevent the transformation of the high-temperature austenite phase into undesirable microstructure constituents which are a normal result of slow cooling. These quenched and tempered steels not only have increased static strength, but also have higher fatigue strength and a high degree of notch toughness to remain ductile and resist brittle fracture. They can be used alone, and also in combination with common structural steels. However, increasing the strength of a steel tends to make it more difficult to weld without producing cracks. Some steel compositions are essentially designed to provide good weldability.

The purpose of this thesis is to determine the fatigue strength of two kinds of quenched and tempered structural steel; A-537B and CG-A-537M*. A-537B has been used in offshore platforms, ships, pressure vessels, refrigerated gas cargo tanks, storage tanks, pipelines and other structures which require low-temperature notch toughness and where increased strength is a design factor. CG-A-537M, which is not yet covered by ASTM designations, has been used in refrigerated gas cargo tanks, storage tanks, ships and pipelines where low-temperature notch toughness is required.

In setting up the research project it was decided to test the A-537B steel only in bending as axial-loading fatigue results for this material were already reported in the literature. Stress ratios of 0, 1/2, and -1 were selected. For statistical accuracy several specimens should be tested under the same stress conditions to obtain the expected spread in fatigue lives. As time and available material would not permit the repetitive testing required for statistical sampling, this aspect of fatigue study had to be ignored. Only one specimen was tested at each stress condition.

The planning for CG-A-537M included both bending and axial tests. Again stress ratios of 0,1/2 and 1 were chosen for study. Only one specimen was tested at each stress condition.

All together, 40 individual fatigue tests are reported herein.

*U.S. Coast Guard Designation

CHAPTER II

PREVIOUS FATIGUE WORK OF A-537B STEEL

Fatigue tests of A-537B steel were conducted by Havens and Bruner [11]. The tests were made at stress ratios of 0 and 1/2 under axial loading. Their results are presented as S-N curves in Figure 1. Data from the S-N curves were used to construct the modified Goodman diagram shown in Figure 2.

The results show that the fatigue strength at any positive stress ratio exceeds the yield strength of the steel for lives up to 250,000 cycles. The S-N curves indicate the fatigue limit of 53.0 ksi at a stress ratio of 0. At a stress ratio of 1/2, the fatigue strength exceeds the yield strength of the steel at lives greater than 2,000,000 cycles. It was concluded that, at a stress ratio of 0, the fatigue strength of A-537B steel is 40% to 60% higher than that of hot rolled A-7 steel. The fatigue strength advantage increases as the stress ratio becomes more positive or as lives become shorter at higher stress values where the yield strength becomes limiting.[11]

Havens and Bruner also made tests on transversely butt-welded A-537B steel in the welded condition. The fatigue strength of butt-welded specimens is considerably lower than the fatigue strength for the unwelded condition. However, the fatigue strength of butt-welded A-537B steel is significantly higher than that of butt-welded A-7 steel.

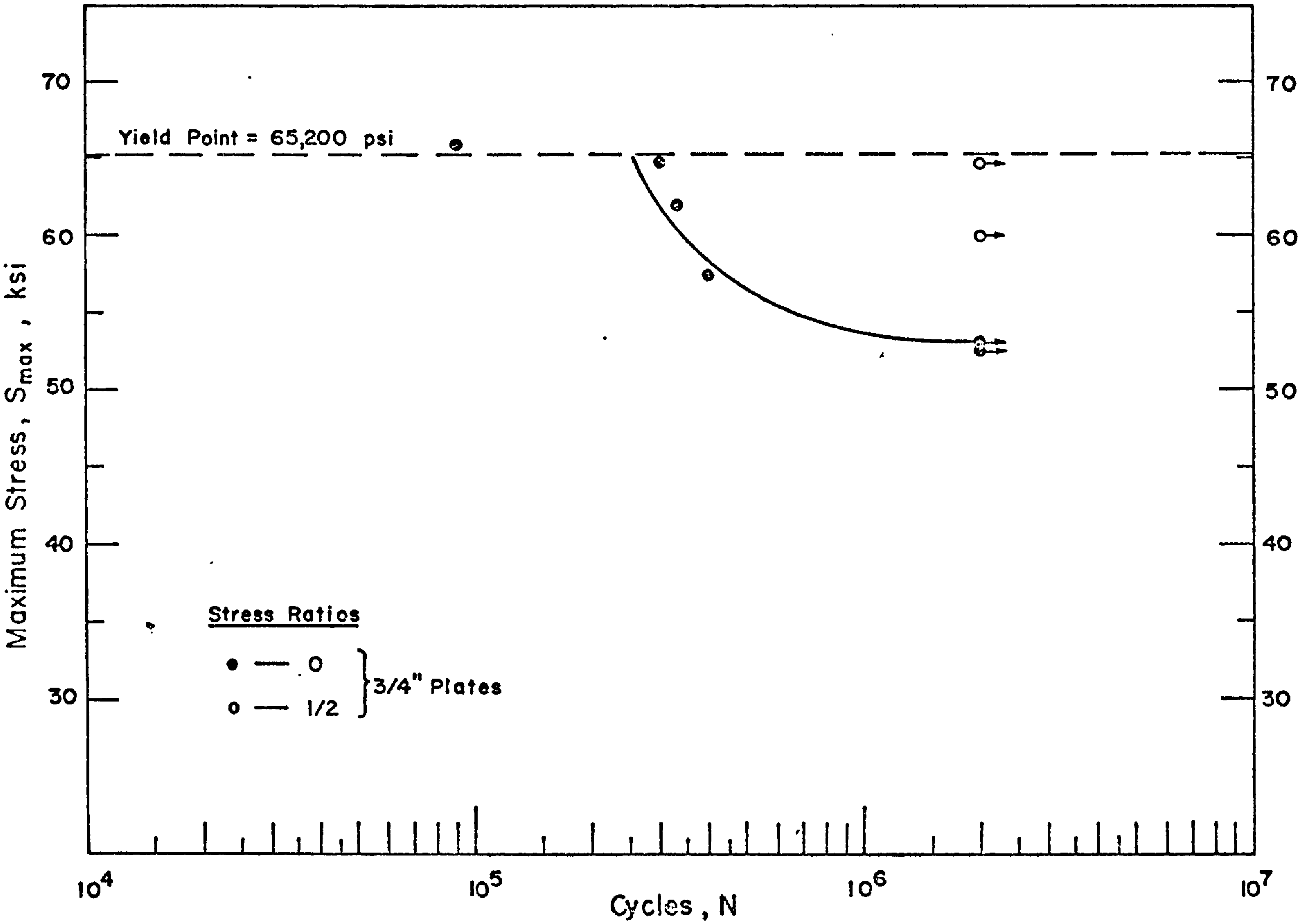


Figure 1. S-N Curves of Armco Super Lo-Temp (A 537B) Steel in Axial-Loading Test. [11]

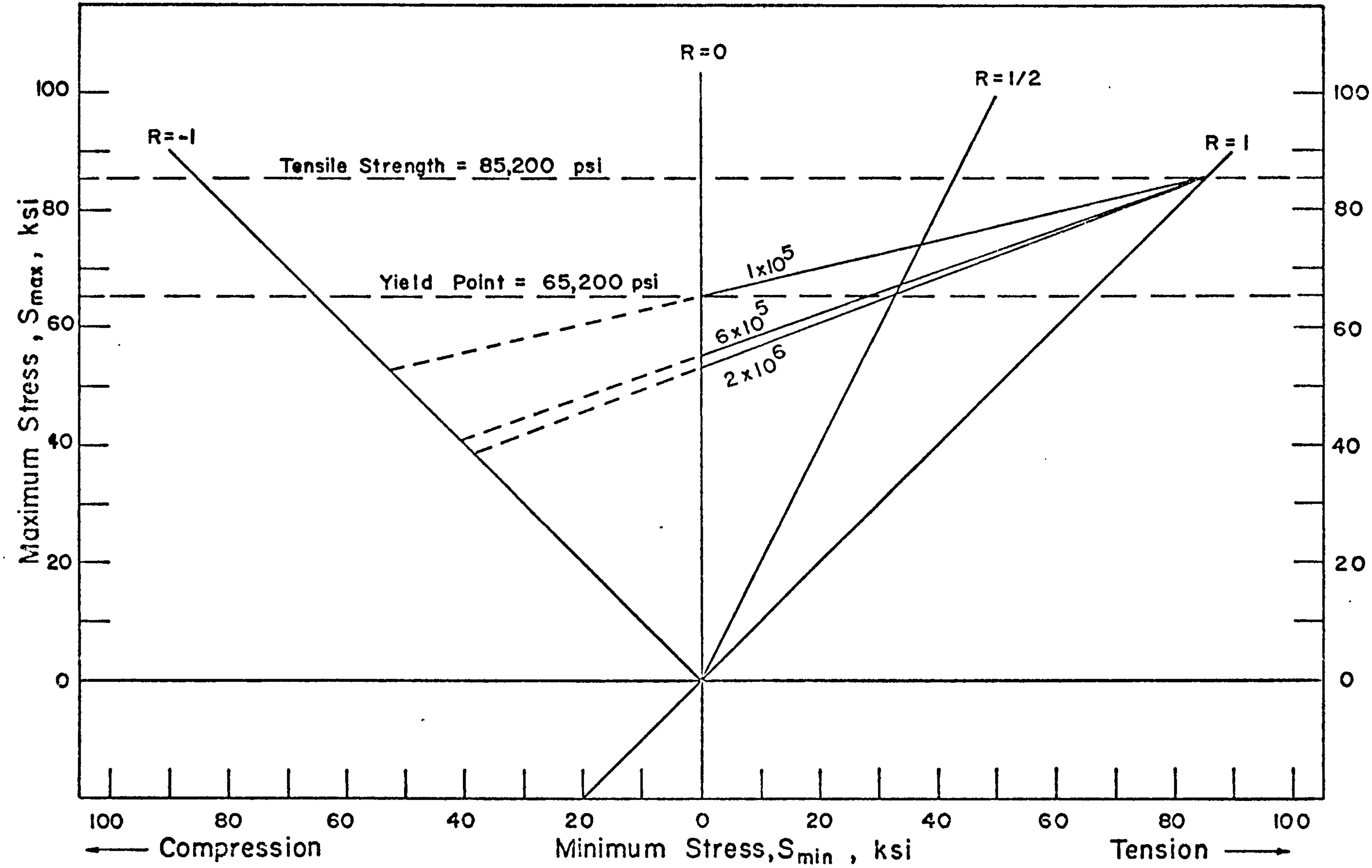


Figure 2. Goodman Diagram of the Fatigue Strength of Armco Super Lo-Temp (A 537B) Steel in Axial-Loading Test. [11]

CHAPTER III

MATERIALS, EQUIPMENT AND PROCEDURE

3.1 Materials

All of the materials used in this investigation were produced at Armco's Houston Works. They were received in the form of steel plates; two 1/2" thick plates of Armco Super Lo-Temp (A 537B) steel and two 5/8" thick plates of Armco LTM-QT (CG-A 537M) steel. The plate surface was in the as-rolled condition. The chemical analyses are listed in Table 1. The mechanical properties of each steel are given in Table 2.

Table 1. Chemical Analysis*

Element	Composition %		
	Armco Super Lo-Temp (A 537B)	Armco LTM-QT (CG-A 537M)	
		Plate Number 1	Plate Number 2
Carbon	0.17	0.15	0.10
Managanese	1.24	1.24	1.15
Phosphorus	0.016	0.010	0.010
Sulfur	0.016	0.022	0.022
Silicon	0.24	0.25	0.21
Copper	0.10	0.21	0.19
Chromium	0.21	0.10	0.14
Nickle	0.18	0.13	0.14
Molybdenum	0.07	0.03	0.03

*From Armco Steel Corporation

Table 2. Mechanical Properties*

Properties	Steel		
	Armco Super Lo-Temp (A 537B)	Armco LTM-QT (CG-A 537M)	
		Plate Number 1	Plate Number 2
Yield Point, ksi	65.35	60.20	57.40
Tensile Strength, ksi	83.80	75.15	72.15
Elongation, %	44 in 2"	40 in 8"	43 in 8"
Charpy V-notch (transverse) energy at-60° F, ft-lbs	22	43	54

All the steel was heat treated by quenching and tempering. The heat treatment of each steel consisted of the following: The Armco Super Lo-Temp steel plates were austenitized at 1,650° F, water-spray quenched and then tempered for 30 minutes at 1,240° F; the two Armco LTM-QT steel plates were austenitized for 38 minutes at 1,650° F, water-spray quenched and then tempered for 30 minutes at 1,200° F and 1,140° F respectively.

3.2 Specimens and Preparation

All of the fatigue test specimens used in the experiment were cut from Armco LTM-QT and Armco Super Lo-Temp steel plates, provided by Armco Steel Corporation. The LTM-QT steel was used for both transverse bending and axial-loading tests; the other

*From Armco Steel Corporation

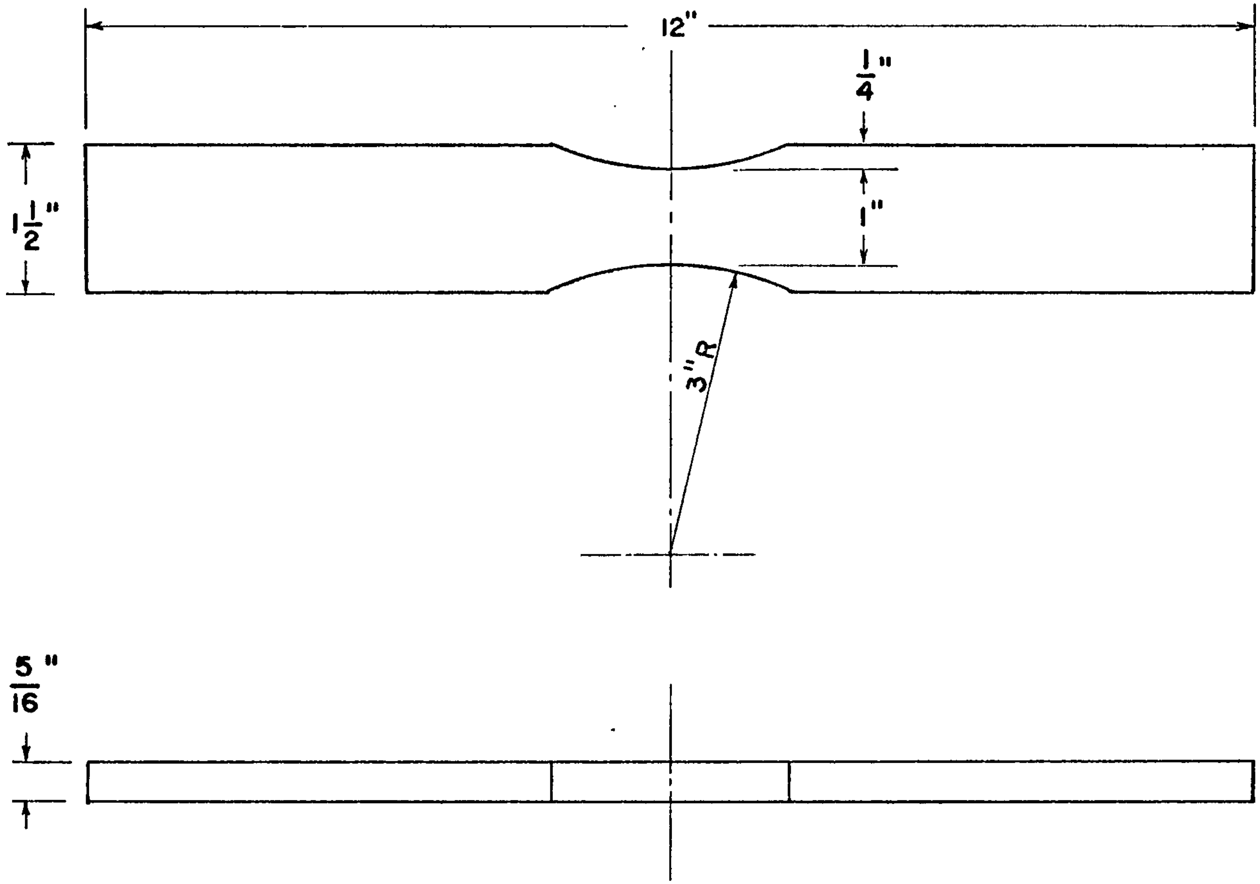


Figure 3. Fatigue Specimen in Axial-Loading Test.

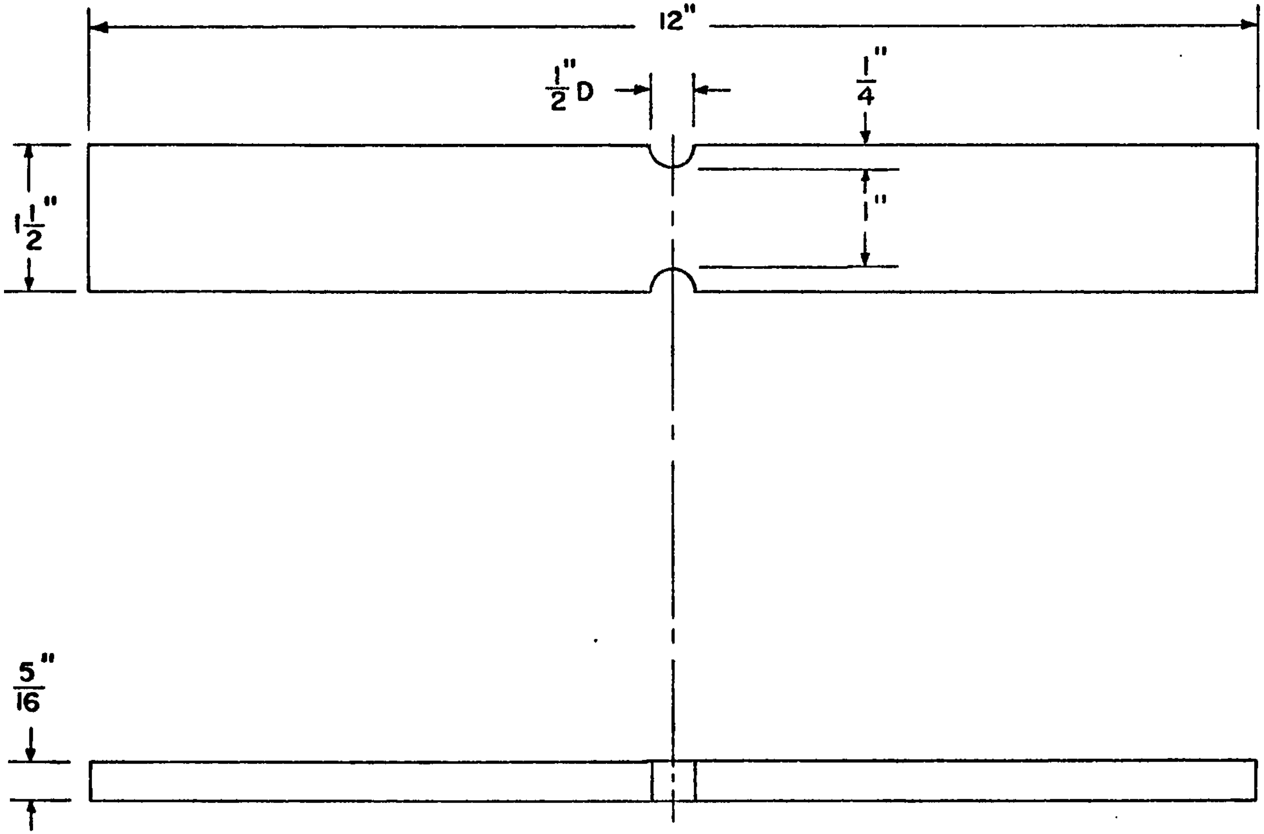


Figure 4. Small Notched Specimen in Axial-Loading Test.

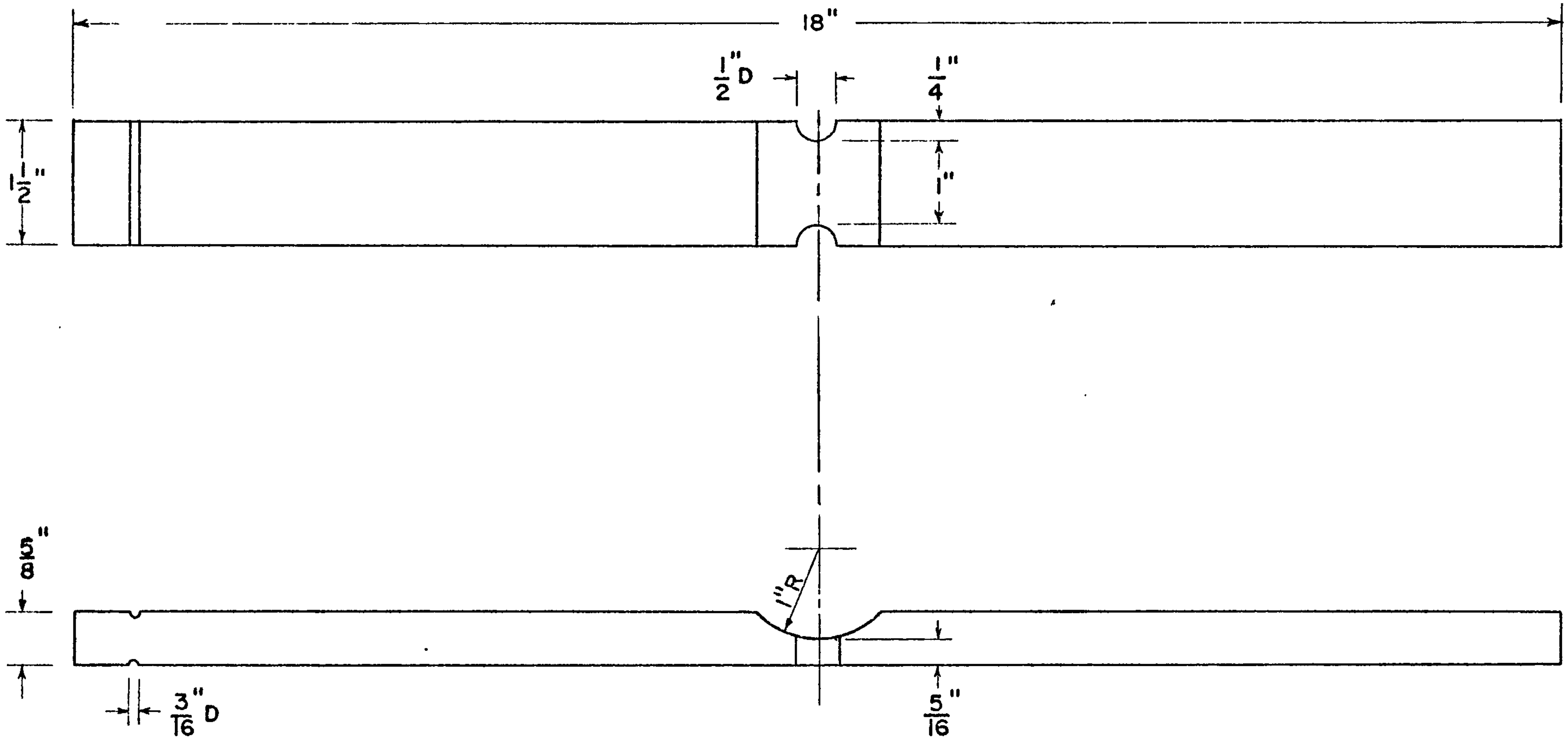


Figure 5. Fatigue Specimen in Bending Test.

steel was used for bending tests only. The specimens were carefully designed so that they were of appropriate size to fit in the testing machines. All the specimens were cut and prepared at the Engineering Services Machine Shop, College of Engineering, of the University of Houston.

The specimens tested under axial loading in the M.T.S. machine were cut from 5/8" thick Armco LTM-QT plate number 1 in such a manner that their longitudinal direction coincided with the direction of primary rolling. Specimens were 1½" wide and 12" long. The thickness was reduced to 5/16" by machining one surface of the plate. The center sections of the specimens were reduced to 1" wide by machining a 3" radius from each side of the specimens as shown in Figure 3. Thus, the narrowest cross-sectional area of each specimen was approximately 0.310 square inches. In order to compare the fatigue strength of the specimens with that of the small notched specimens, the center sections of some specimens were also reduced by a 1/4"-radius notch at each side.

In the bending fatigue tests the specimens were cut from both 1/2" thick Armco Super Lo-Temp plate and 5/8" thick Armco LTM-QT plate number 2. Specimens were 1½" wide and 18" long. The center sections were reduced to 1" wide by machining a 1/4" radius from each side and to 5/16" thick by a 1" radius from one flat side. The purpose of this design is to initiate the fatigue fracture at the narrowest reduced section. The dimensions and shape of the test specimens employed are shown in Figure 5. Only the specimens of Armco LTM-QT steel were taken so that the 18" direction was transverse to the primary rolling direction.

Each specimen was lettered to designate the type of steel and this designation was followed by a letter A for axial-loading test or B for bending test.

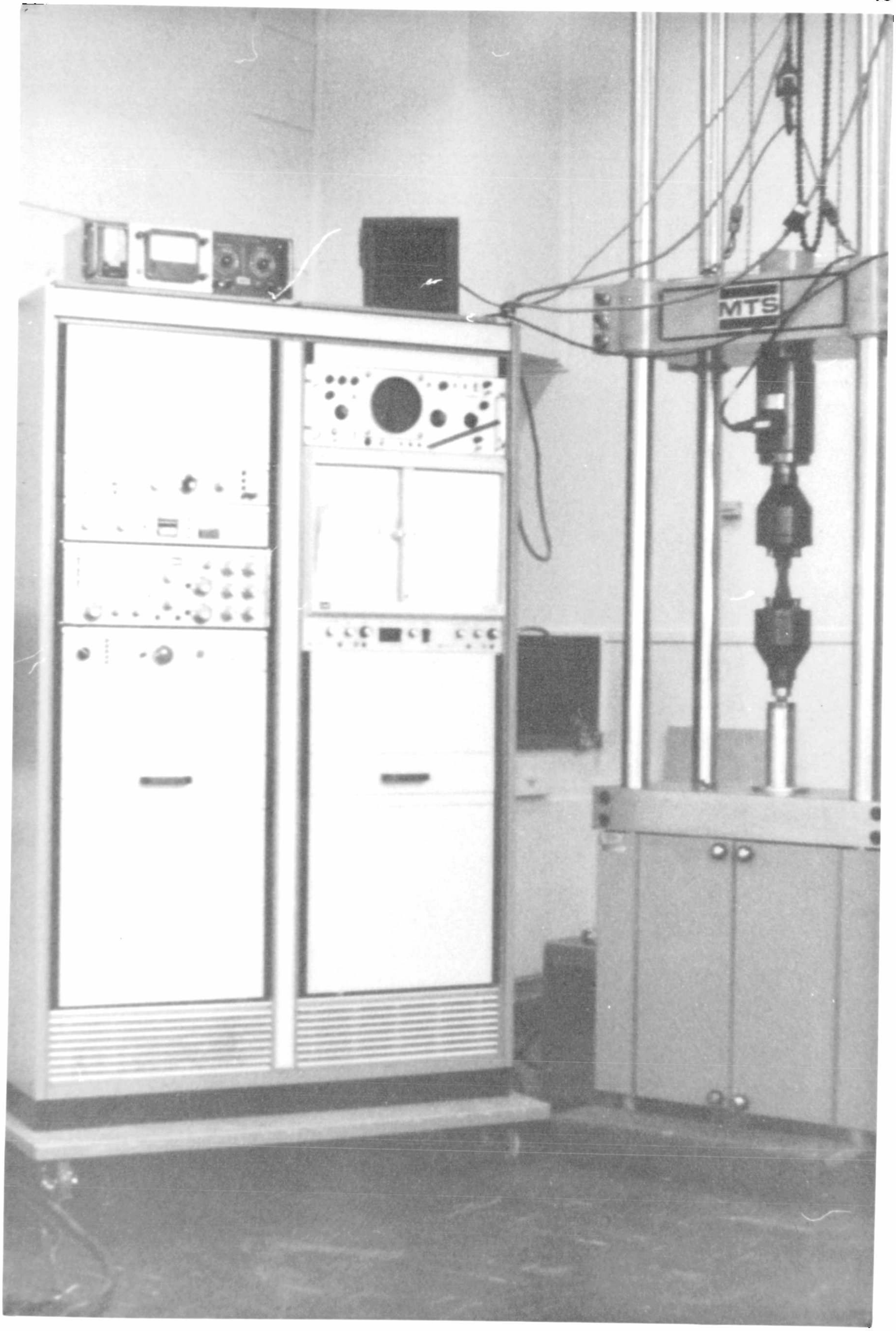
3.3 Equipment

Fatigue tests were performed in the M.T.S. machine and bending machine in the Materials Laboratory of the Civil Engineering Department of the University of Houston. The machines operate at a speed of 600 cycles per minute. One SR-4 type strain gage was mounted on the face at the reduced section of each specimen to determine strains. Both testing machines are described in detail under their headings in this thesis.

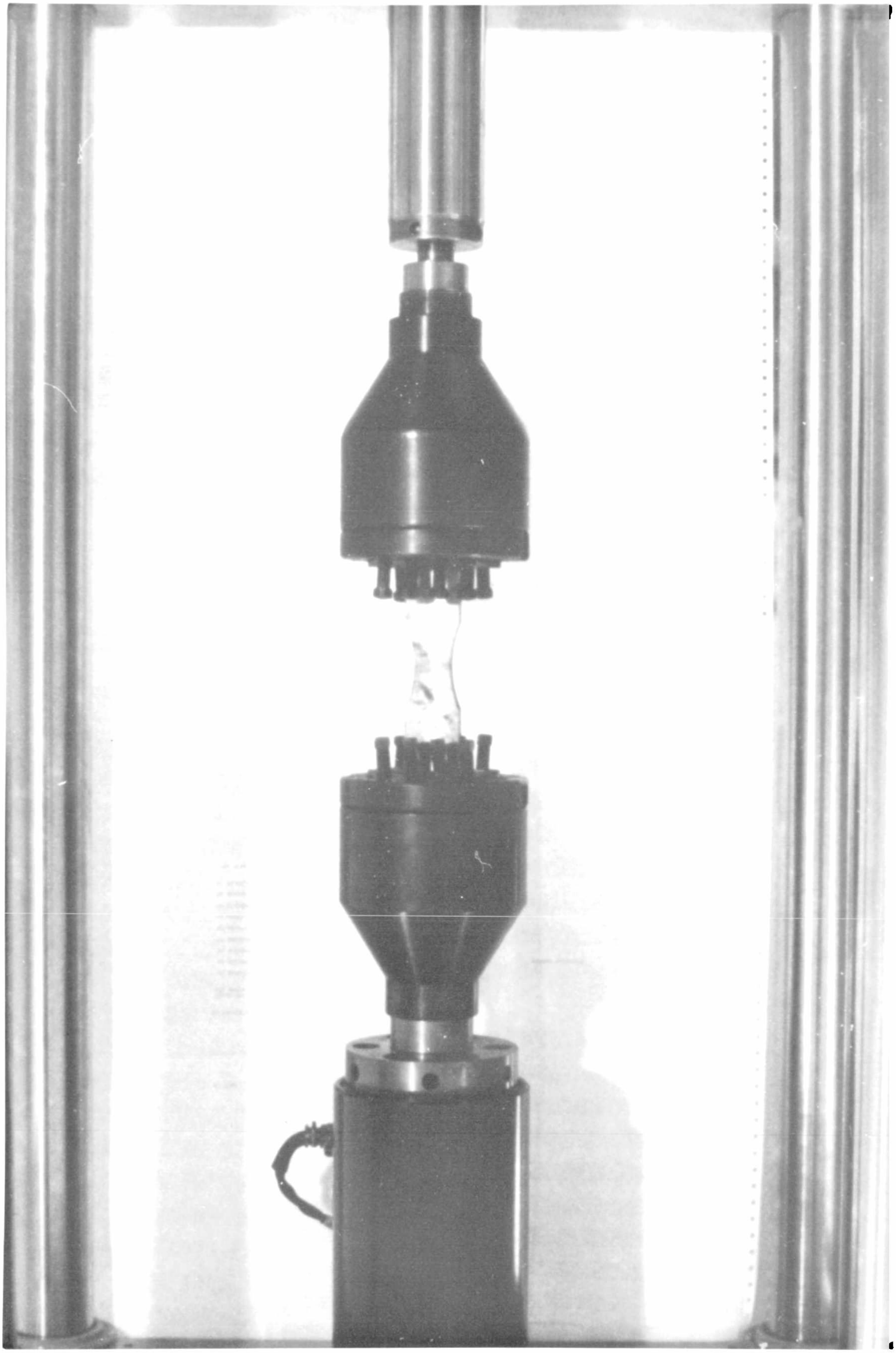
3.4 M.T.S. Machine

All of the specimens in the axial-loading tests were tested in the M.T.S. (Material Testing System) machine. This machine is of a closed-loop electrohydraulic materials testing system. It was made by the M.T.S. Corporation. The machine consists of three major systems: Hydraulic power supply, load frame and control system.

The hydraulic power supply provides a source of hydraulic



Photographic Plate I. M.T.S. Machine



Photographic Plate 2. Specimen in M.T.S. Machine power (fluid and pressure) for the system. The hydraulic fluid flows 10 gallons per minute (gpm) at a constant pressure within safe limits of temperature. The output pressure is adjusted to 3,000 pounds per square inch (psi).

In a closed-loop control system, a load frame is required principally for reacting forces imposed upon the specimen by the hydraulic actuator. It is also for convenience in mounting the various types of instrumentation associated with the testing of the specimen. The load frame consists of four columns, a fixed lower base and an upper crosshead which is adjustable in height to accommodate specimens of different lengths. Since the frame is entirely controlled by electronic signals from the console, there are no operating controls on the frame.

The control system controls the operation of the machine. The system has different parts as follows:

1. Control Panel
2. Counter Panel
3. Function Generators
4. Servo Controllers
5. Controller
6. Transducer Conditioner
7. Feedback Selector

The function generator provides various types of cyclic wave shapes. The output of the Function Generator is usually applied to one of the span controls. It is noted that all

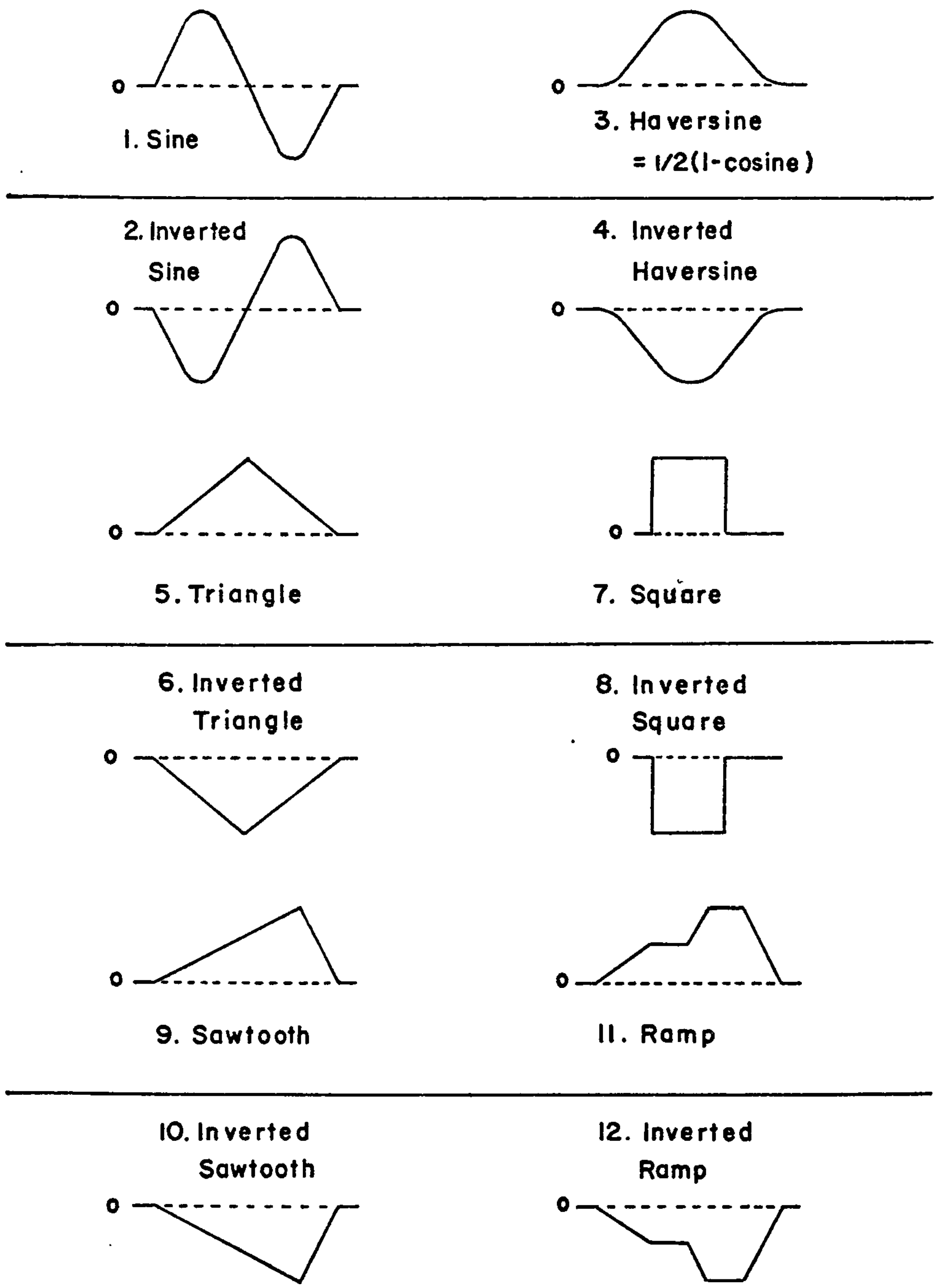


Figure 6. Function Generator Output Waveforms

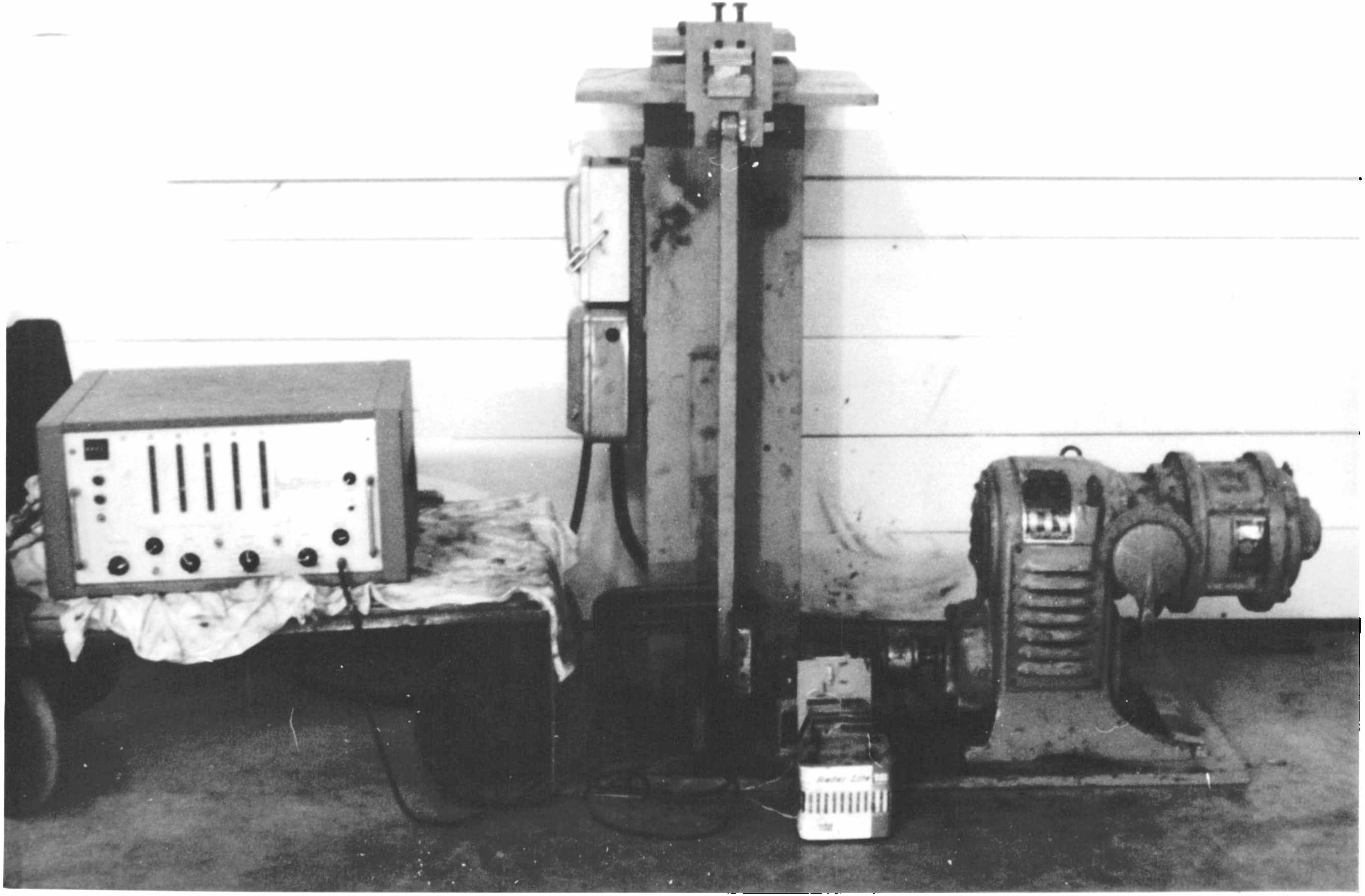
output signals have an amplitude of 100%, positive or negative, except the sine function which has an amplitude of ± 100%. In fatigue testing the generator operates in a continuous mode. Figure 6 shows the selectable Function Generator outputs.

Since the characteristics of the test specimen will directly affect the behavior of the system, it is a part of the closed-servo loop. The machine can be run in either stroke or load control. There are four different limits for stroke control; they are: 0.05, 0.1, 0.25, and 0.5 inches. There are three different load limits: 5, 10, and 25 kips. The maximum capacity of the machine is limited by the size of the hydraulic actuator. The speeds are of 1, 10, and 100 cycles per second. In the present work a load limit of 25 kips and a speed of 10 cycles per second were set.

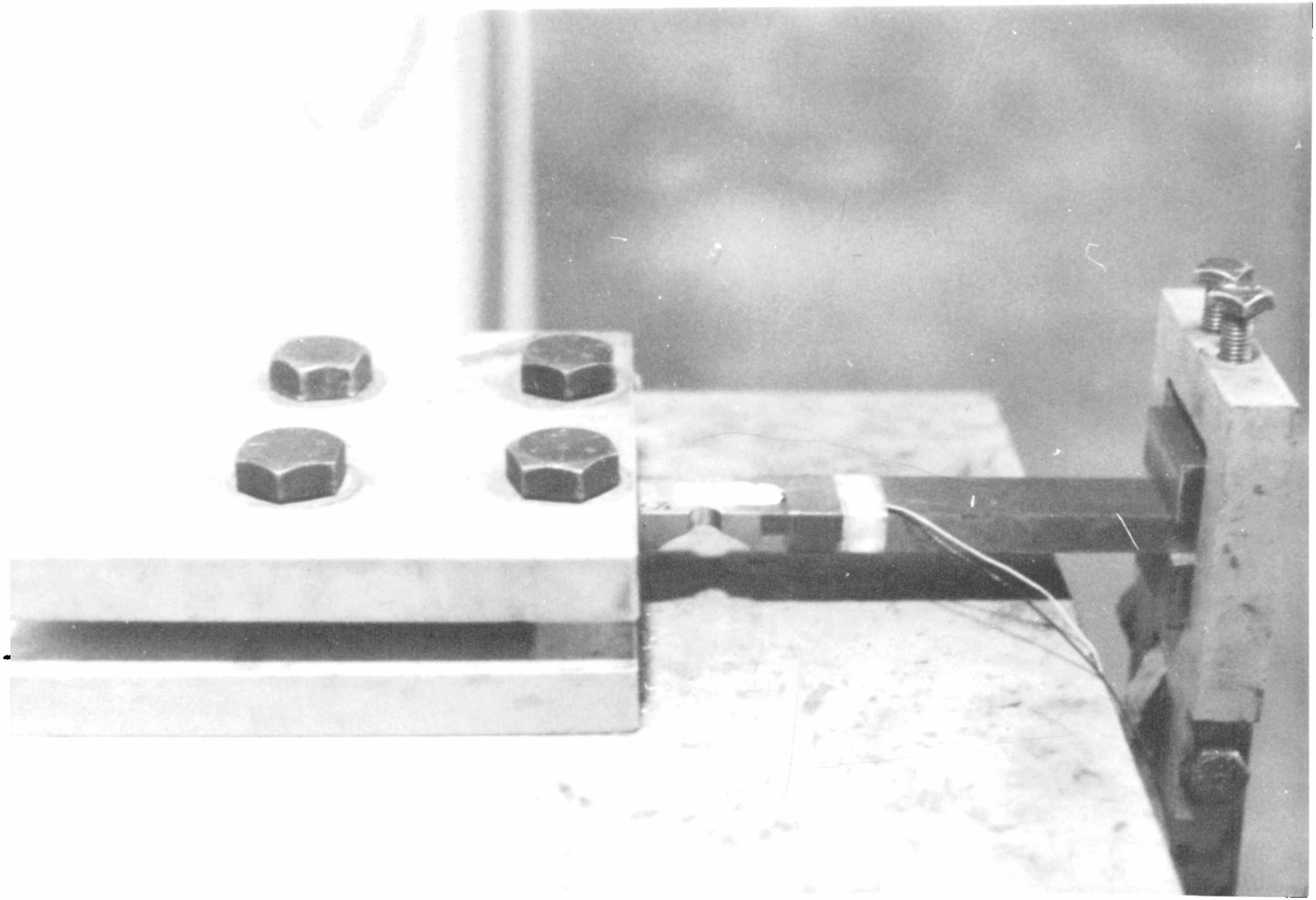
3.5 Bending Fatigue Machine

The major parts of this machine are: Base plate, driving motor, powerstat, specimen clamping plates, shaft the end of which is fitted with an eccentric crank, and connecting arm with a clamping block at the end of the specimen.

The specimen is mounted as a stationary beam. The motor drives a shaft which has the eccentric head which produces a fixed alternating deflection. The motor can be regulated by the powerstat to run at the desired speed. A speed of 600 rpm was used in the tests. The specimen is in the form of a cantilever beam deflected up and down. Flat and square bars of



Photographic Plate 3. Bending Fatigue Machine and Electronic Counter



Photographic Plate 4. Specimen in Bending Fatigue Machine sheet metal can be tested in this repeated-bending machine. It should be noted that an important characteristic of the machine is that it produces constant displacement, unlike the M.T.S. machine which produces constant load.

For the different stress levels and/or different stress ratios, changes in the amount of deflection were necessary. This was achieved by adding the shim plates at the fixed support or by changing the eccentricity at the crank.

Because of the difficulty in measuring the deflection accurately, SR-4 type strain gages connected to an oscilloscope were used to measure strains at the required stress levels. By such means, the stresses were also checked during the tests. The number of cycles to failure was obtained by an electronic counter which received the trigger voltage signal from a photocell light pulse detector.

3.6 Experimental Procedure

The specimens for this present work were carefully measured, placed into the machine and then tested. A structure that is subjected to stress variations will be, in the same process, subjected to a steady stress which is the mean of the maximum stress and minimum stress. Variations in the stress ratio significantly influence the fatigue strengths. Therefore, fatigue tests were performed at stress ratios of 0, 1/2, and -1, representing zero-to-tension, tension-to-tension, and tension-to-compression loading respectively. Hence, the tests simulated actual service conditions.

A stress ratio of 0 might simulate the loading condition of a structural member that is not significantly stressed due to the weight of the structure but has stress in tension when dynamically loaded; the stress fluctuates from zero to some value of tension as a maximum. A stress ratio of 1/2 might simulate the condition of a structural member that has some tension due to the weight of the structure and is dynamically stressed by an additional equal tension. Therefore, the maximum tension in such a cyclic loading is equal to twice the minimum. A structural member may be subjected to both tension and compression forces of the same magnitude just as some machinery parts move in a reverse manner. This condition can be simulated by a stress ratio of -1. A stress ratio of 1 can be established by using the static tensile strength.

For each stress ratio, specimens were tested at various maximum stress levels up to the yield strengths of the steels. The number of cycles was obtained when the specimen failed. Since 2,000,000 cycles of stress was considered to be equivalent to infinite life, the approximate endurance limit was indicated when a specimen reached 2,000,000 cycles.

CHAPTER IV

RESULTS AND DISCUSSION OF A-537B STEEL

In the present work, fatigue tests of A-537B steel were carried out under bending at stress ratios of 0, 1/2, and -1. The ratio of -1 was not included in the earlier work. The mechanical properties of the A-537B steel employed in this test are similar to those reported in the literature, which are tensile strength and yield point. The results of the bending fatigue tests are presented as S-N curves in Figure 7. The modified Goodman diagram shown in Figure 8 is also constructed for lives of 100,000, 600,000, and 2,000,000 cycles.

In these bending tests, A-537B steel exhibited a fatigue limit of 52.5 ksi at a stress ratio of 0, which is 63% of the tensile strength (83.8 ksi). At a stress ratio of 1/2, the fatigue limit equals the yield strength of the steel (65.35 ksi). The fatigue limit at a stress ratio of -1 is 34.0 ksi and is 40% of tensile strength. The results also indicate that, at any positive stress ratios, the fatigue strength exceeds the yield strength for lives up to 250,000 cycles, which is exactly the same as that of axial loading from the literature. For comparison, it can be seen that, at positive stress ratios, the Goodman diagram (Figure 8) looks the same as that (Figure 2) for the axial-loading tests. The results from the present work on A-537B steel are therefore consistent with those from the literature.

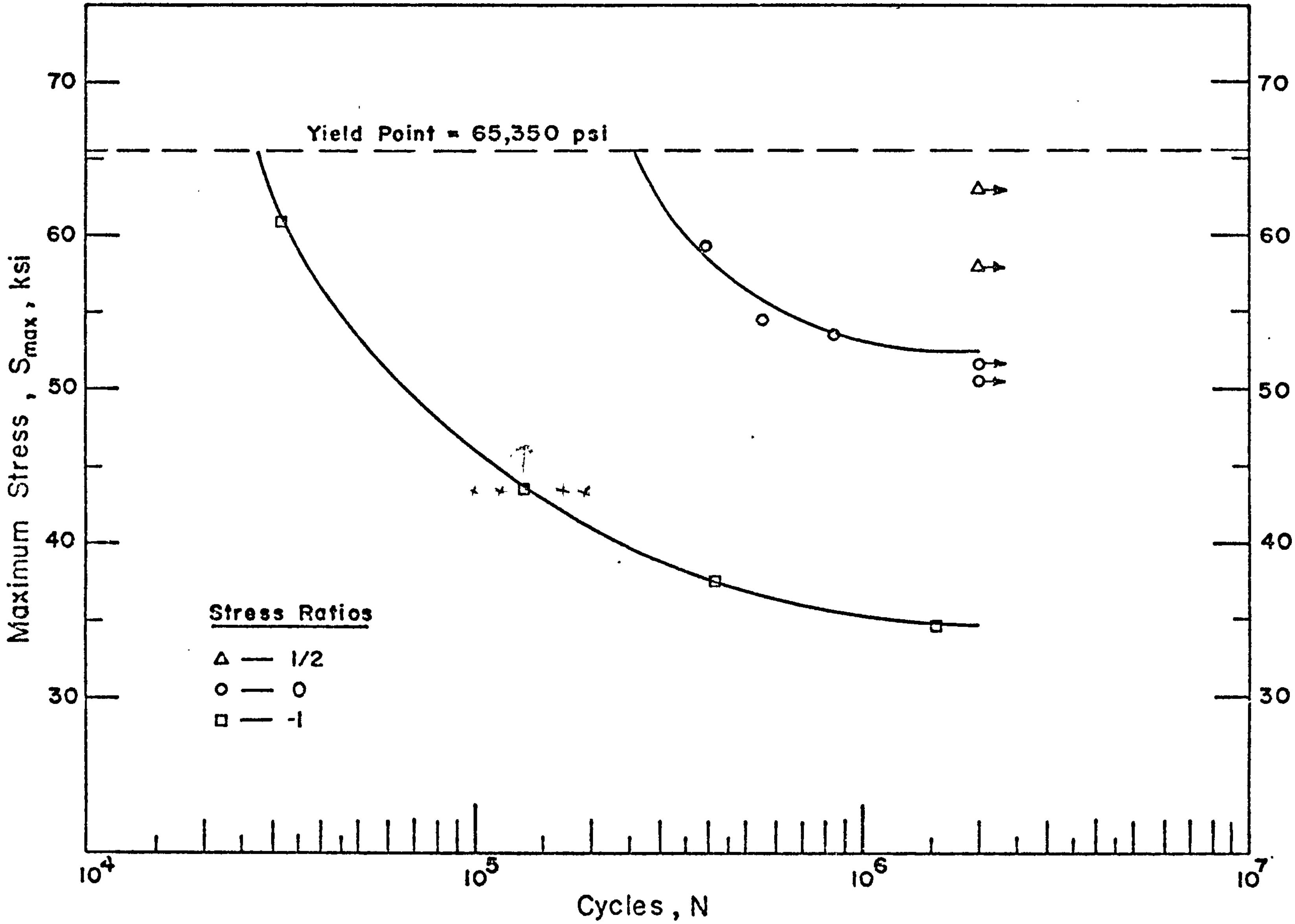


Figure 7. S-N Curves of Armco Super Lo-Temp (A 537B) Steel in Bending Test.

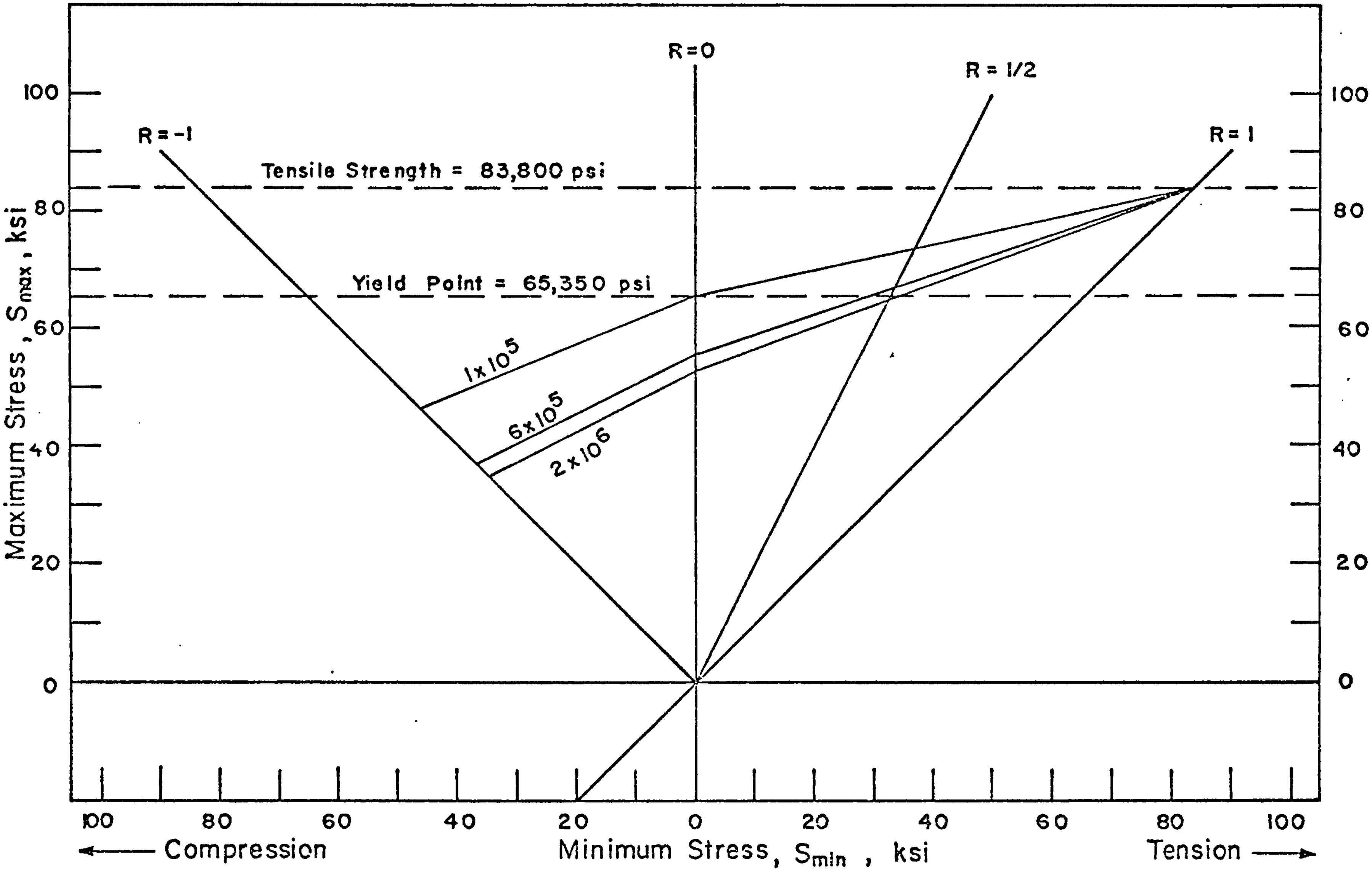


Figure 8. Goodman Diagram of the Fatigue Strength of Armco Super Lo-Temp (A 537B) Steel in Bending Test.

CHAPTER V

RESULTS AND DISCUSSION OF CG-A-537M STEEL

5.1 Fatigue Strength in Axial-Loading Test

Twelve specimens of CG-A-537M steel, tested under axial loading, were from Armco LTM-QT plate number 1 for which the yield strength and tensile strength were 60.20 and 75.15 ksi respectively. The S-N curves in Figure 9 represent the results of the tests. Figure 10 is the modified Goodman diagram plotted from the S-N curves.

The results indicate a fatigue limit of 51.0 ksi at a stress ratio of 0, and is 68% of the tensile strength. At a stress ratio of -1, the fatigue limit is 32.0 ksi, 42% of the tensile strength. The modified Goodman diagram shows that the fatigue limit at a stress ratio of 1/2 is equal to the yield strength. At any positive stress ratio, the fatigue strength exceeds the yield strength for lives up to 300,000 cycles.

5.2 Fatigue Strength in Bending Test

Twelve specimens under bending were cut from Armco LTM-QT plate number 2 which was tempered at a different temperature from plate number 1. Because of this change in the final process plate 2 had a lower yield strength and tensile strength; they were 57.40 and 72.15 ksi respectively. The results of the bending fatigue tests are presented as S-N curves in Figure 11. Data from the S-N curves were used to construct the modified Goodman diagram shown in Figure 12.

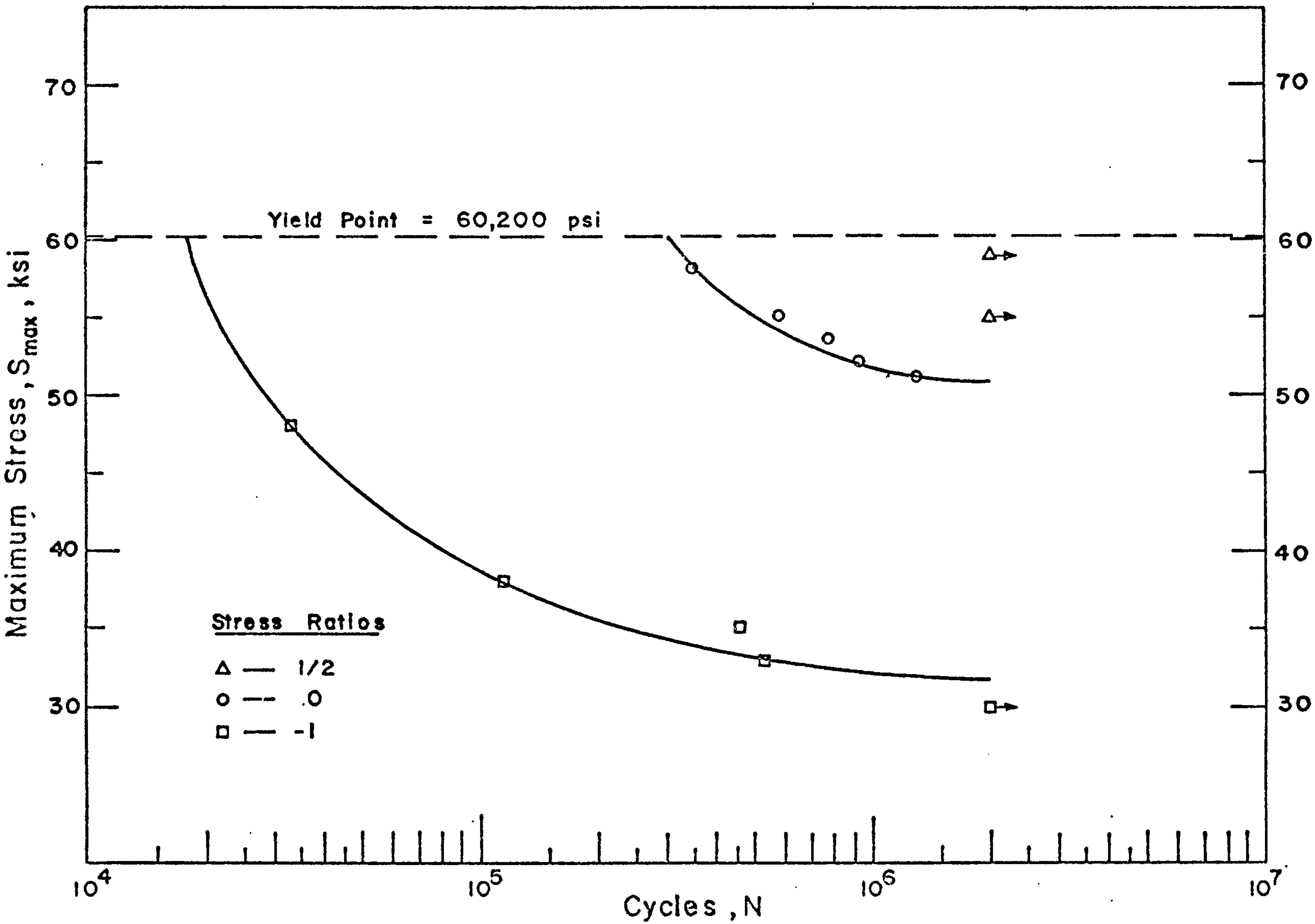


Figure 9. S-N Curves of Armco LTM-QT(CG-A537M) Steel in Axial-Loading Test.

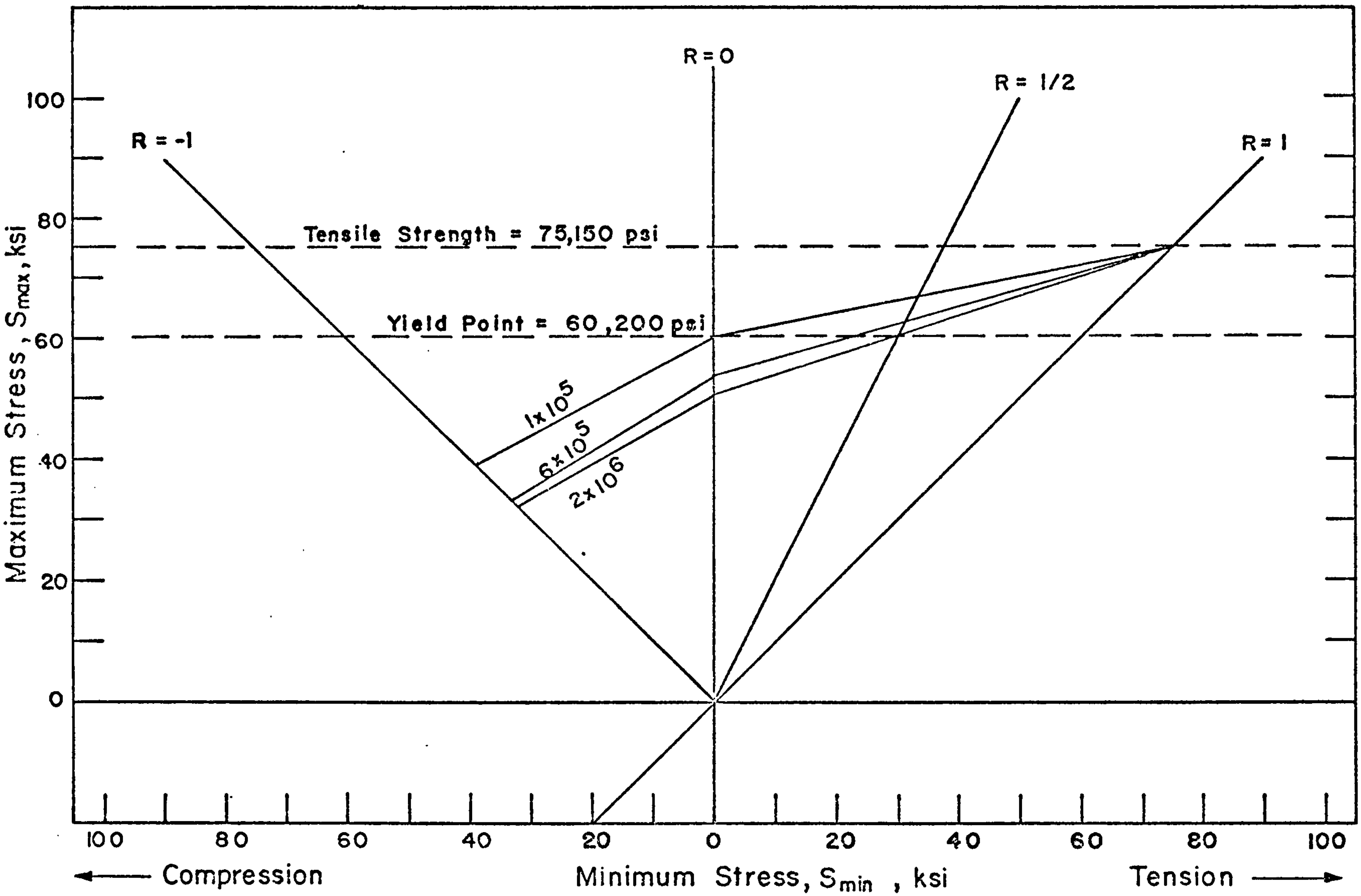


Figure 10. Goodman Diagram of the Fatigue Strength of Armco LTM-QT (CG-A537M)

Steel in Axial-Loading Test.

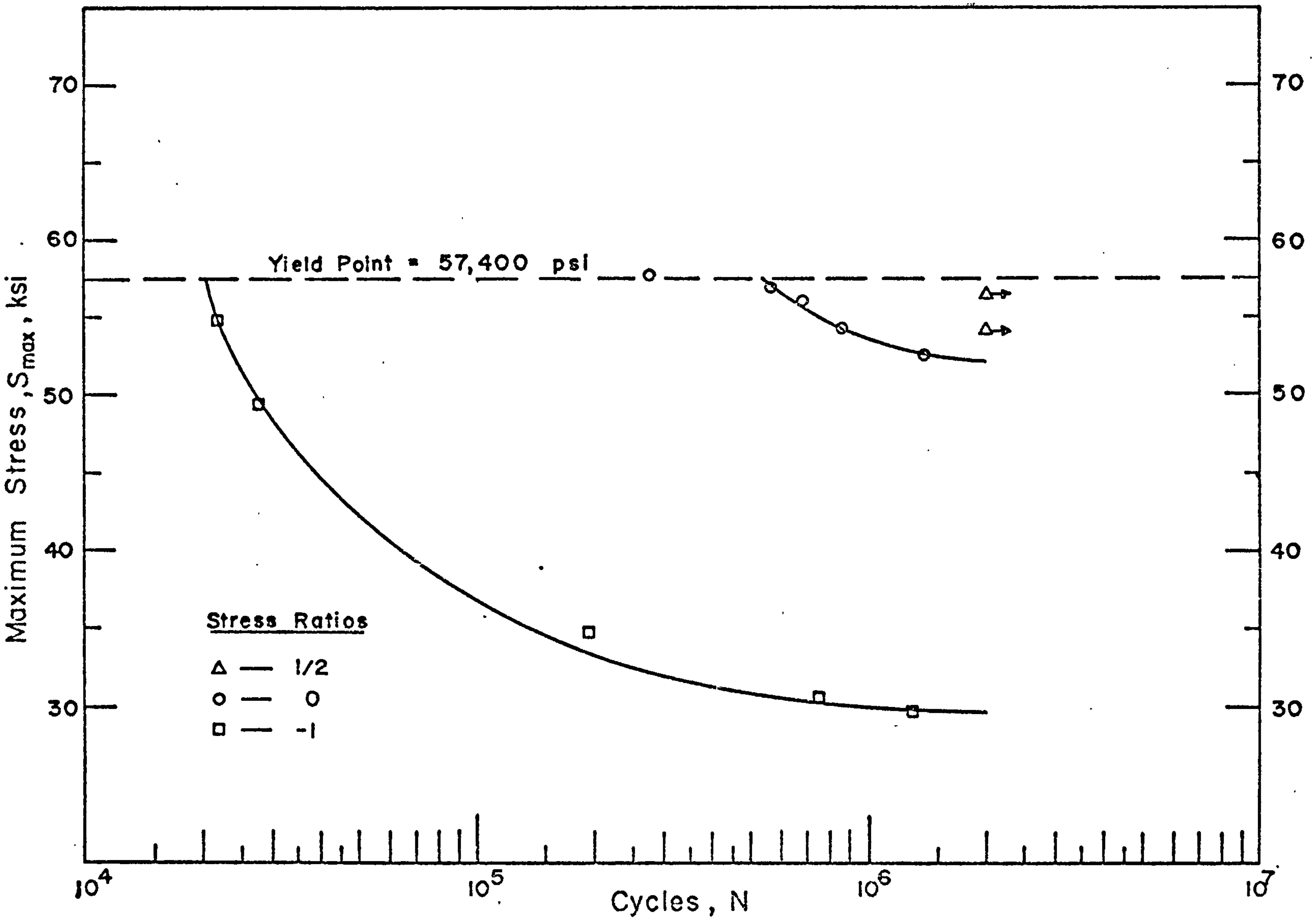


Figure 11. S-N Curves of Armco LTM-QT (CG-A537M) Steel in Bending Test.

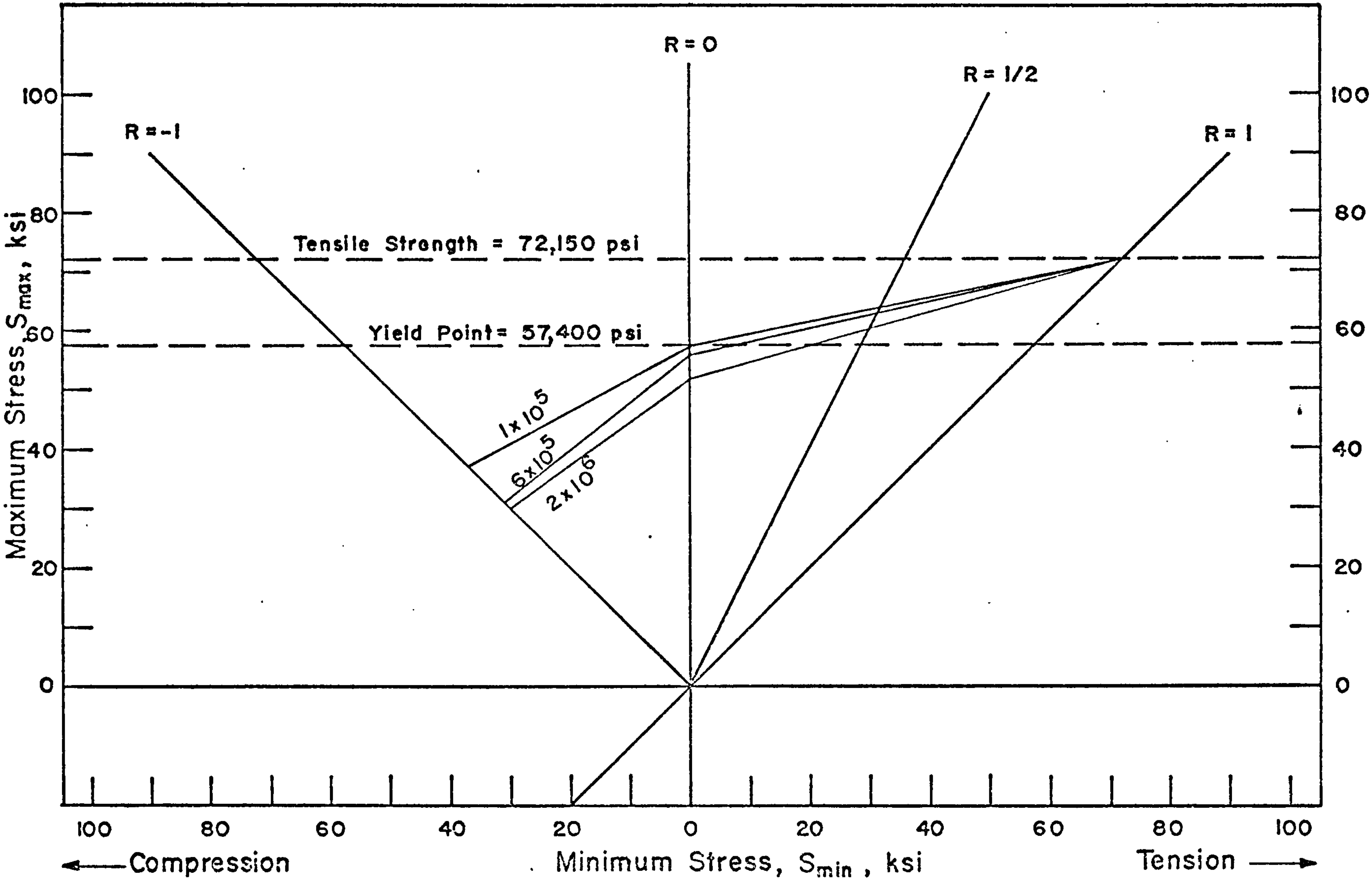


Figure 12. Goodman Diagram of the Fatigue Strength of Armco LTM-QT (CG-A 537M) Steel in Bending Test.

In the bending tests, at a stress ratio of 0 CG-A-537M steel exhibited a fatigue limit of 52.0 ksi, 72% of tensile strength. The fatigue limit at a stress ratio of -1 was found to be 29.0 ksi; this is 40% of the tensile strength. From the modified Goodman diagram the fatigue limit at a stress ratio of 1/2 is seen to be above the yield strength.

5.3 Comparison of Fatigue Limits

At a stress ratio of 0, the fatigue limit of CG-A-537M steel in bending is slightly higher at the 72.15 ksi level of tensile strength than at the 75.15 ksi level in axial loading, it is 72% of the tensile strength, which is also higher than that of axial-loading test, which is 68%. These results are conclusive with the experiments that Forrest and Tapsell [8] conducted showing that the bending test gives a definitely higher fatigue limit value than that obtained from axial loading. One explanation is that plastic flow or inelastic strain may cause a redistribution of stress during each cycle, so that the maximum stress becomes less than the calculated elastic value. This gives one reason why the fatigue strength in bending is greater than that in axial loading.

However, because the fatigue limit of steel is subject to considerable variation because of the statistical nature of fatigue behavior, it must be realized that deviations from an exact relationship between fatigue limit and tensile strength can be expected.

Including the similar behavior explained above, it is reasonable that, at a stress ratio of -1, the fatigue limit in axial loading is higher than that in bending due to the higher value of tensile strength. Nevertheless, the effect of a notch on the bending fatigue specimens was encountered when the specimen was under completely reversed bending. The specimen was placed into the bending machine in the manner that the notched side was subjected to compression when the specimen was deflected downward (See Photographic Plate 4). At a stress ratio of -1, the notched surface was expected to be subjected to tensile stress of the same value as the upper surface. The theoretical stress concentration factor for the notch was about 1.4 from Leven and Frocht [16]; the stress on the notched surface was higher than that on the upper surface. However, the effective stress concentration factor is smaller than the theoretical one for notched specimens in bending [12]; it may be quite close to unity. The fatigue strengths from these tests were less influenced than theoretically expected.

For stress ratios of 0 and 1/2, the influence of stress concentration was disregarded, since the effect of compression on fatigue is much less than that for tension.

5.4 Fatigue Strength of Notched Specimens in Axial-Loading Test and Effective Stress Concentration Factor

A stress concentration is formed wherever there is a discontinuity in the geometry of a structural member. The

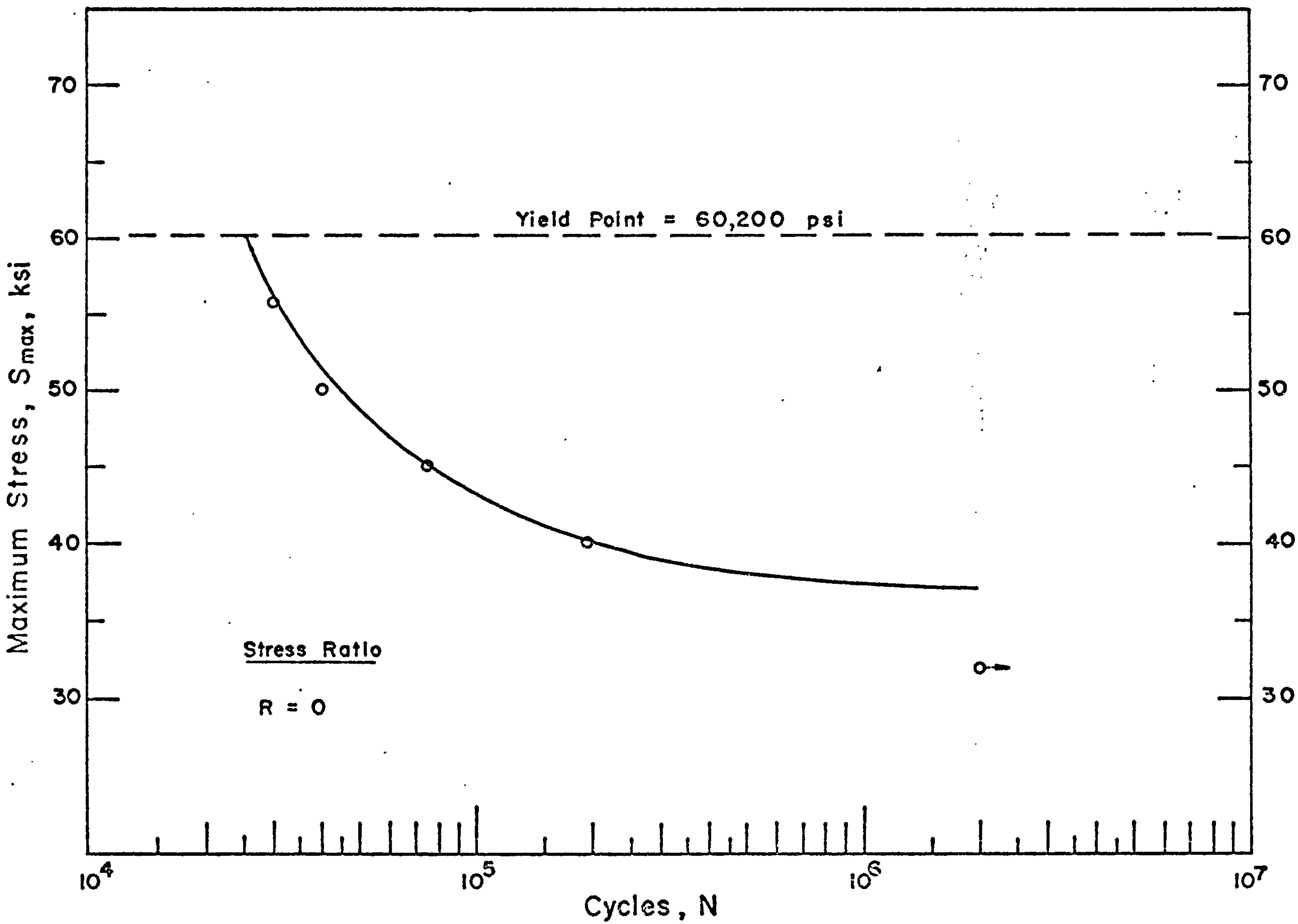


Figure 13. S-N Curves of Small Notched Specimens of Armco LTM-QT(CG-A537M) Steel in Axial-Loading Test.

term stress concentration generally refers to the stress increase resulting from a notch in a member. Based on the theory of elasticity, a theoretical stress concentration factor K_t, previously defined as the ratio of the maximum stress to the norminal stress in the member, can be computed for most types of notches. Another stress factor which is used in fatigue studies is the "effective stress concentration factor" or fatigue notch factor K_f, defined as the ratio of fatigue strength of an unnotched specimen to that of a notched specimen at a certain life. At the present time, the effective stress concentration factor can only be obtained by experimental means.

Five notched specimens of CG-A-537M steel were tested under axial loading at a stress ratio of 0. The semi-circular notch geometry which was employed is shown in Figure 4. The theoretical stress concentration factor K_t for the notch was about 1.9 as determined by Peterson [21], based on the Neuber Theory. Figure 3 is said to be a plain specimen ($K_t = 1$). The results shown in Figure 13 were obtained on the notched specimens. In this condition, CG-A-537M steel exhibited a zero-to-tension fatigue limit of 37.0 ksi. From the data of both plain or unnotched specimens and notched specimens, the effective stress concentration factor for this particular type of member can be obtained as

$$K_f = \frac{S_e}{S_{ne}}$$

$$= \frac{51.0}{37.0}$$

$$= 1.37$$

This number shows that the effective stress concentration factor is smaller than the theoretical one. This is because the idealized homogeneous and elastic behavior of the material which was assumed in arriving at the theoretical stress concentration factor does not exactly occur in practice. The fatigue strength of notched specimens is greater than that which is indicated by a direct application of theoretical stress concentration factors. Thus a conservative and uneconomic design would be produced if full allowance for the stress concentration were made.

In view of the practical importance of the matter, it would be desirable to determine the notch sensitivity as

$$q = \frac{K_f - 1}{K_t - 1}$$

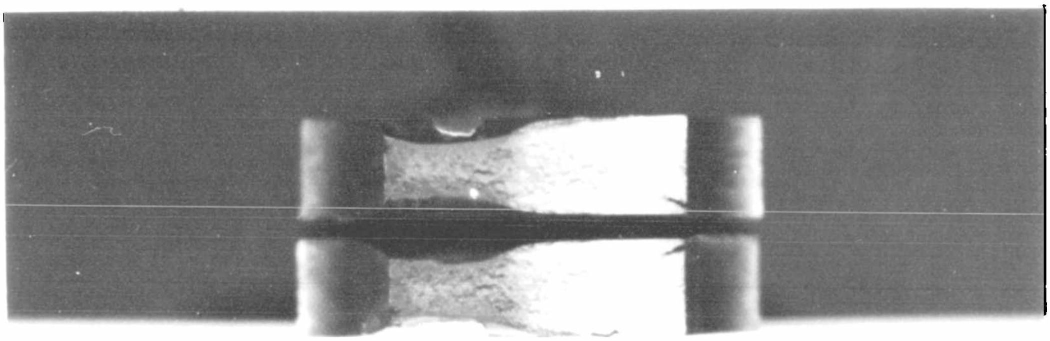
$$= \frac{1.37 - 1}{1.90 - 1}$$

$$= 0.41$$

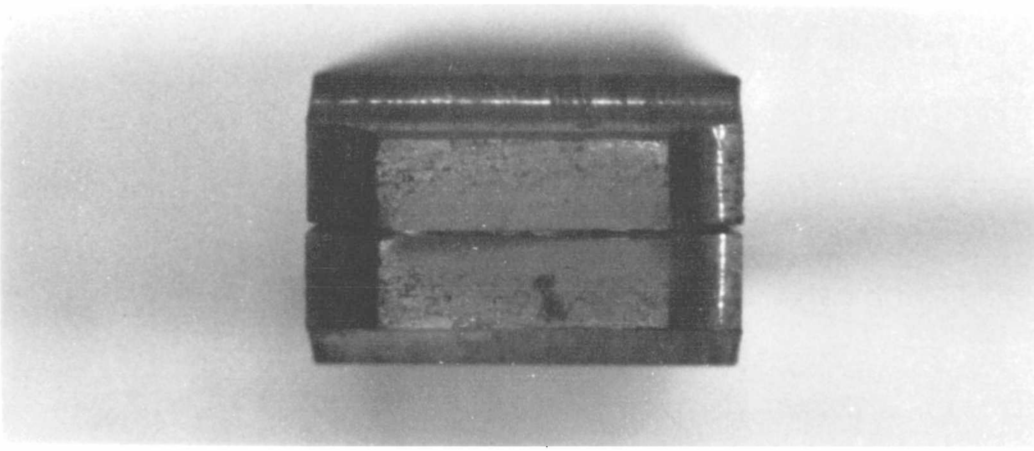
This number shows that CG-A-537M steel for the proposed geometry of the notch is not significantly notch-sensitive.

5.5 Observations of Mode of Fatigue Failure

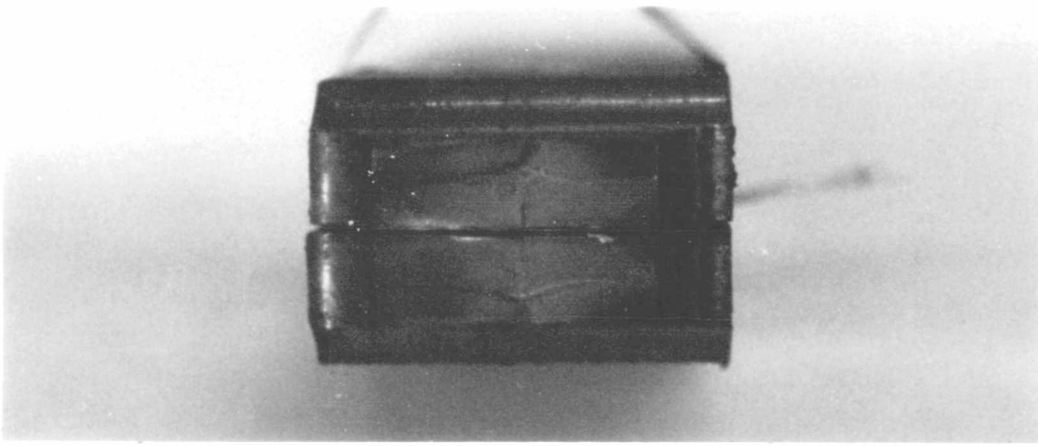
To aid in the detection of the cracks the specimens were sprayed with a thin covering of white paint over the surface at the narrowest section. Employing this technique permits visual observation of the progression of the cracks without the use of a microscope. As a crack developed in the specimen, a dark streak appeared in the white paint. This made possible



(a) Axially Loaded Specimen , R = 0



(b) Bending Specimen , R = 0



(c) Bending Specimen , R = -1

Photographic Plate 5. Appearances of Fatigue Fracture Cross Sections detection of the initial crack and facilitated the outlining of crack growth. Photographic plate 5 illustrates the appearances of the fatigue failures. In spite of outward appearances, fatigue failures are neither sudden nor hidden. They are progressive and visible.

In the axial loading case the specimen was under a constant-load test. Careful inspection revealed that the fatigue fracture originated in a crack or a series of cracks which formed on the surface of the specimen in the course of cyclic loading. The crack, once formed, spread inward across the cross-sectional area. After progressive growth the unaffected portion of the section was reduced to such an extent that it was no longer capable of sustaining the applied load and the specimen suddenly fractured. The regions corresponding to the progressive and sudden fracture can be easily indentified in freshly broken specimens as shown in Photographic Plate 5a. One region is smooth (the progressive fatigue growth) at the light area; the other is rough. While the fracture is progressing, the severed portions of the section rub and hammer against each other every time the repetition of loading closed the crack. This treatment ends up by smoothing out any roughness produced by the crack propagation. However, the roughness appeared as a dark area when the break occurred under a single load application in the last cycle. The rough portion of failure occurred in the same manner as in the case of static tests.

The surface cracking of a specimen tested in bending is very significant since the stress is a maximum on the surface and constant deflection was controlled in the test. From observation the progressive failure in bending may be described in two stages as

1. Cracks on the surface: Fatigue cracks initiated from the roots of the side notches at the maximum stress, and propagated on the surface of the specimen. The cracks may join together as they grow and thus two cracks suddenly develop into one which is as long as the width of the reduced test section.

2. Penetration of a crack: A crack as it propagated into the specimen penetrated into regions of lower nominal stress as it approached the neutral axis; this propagation led to the eventual or ultimate fatigue fracture. The smooth areas shown in Photographic Plates 5b and c represent the penetration of a fatigue crack from the surface down to the lamination in the specimen where the rough appearance represents the final fracture.

By observing the series of specimens taken to final fracture, it was found that fatigue cracks were initiated during early stages in the fatigue test and these cracks were aligned perpendicular to the direction of the maximum stress for all types of specimens.

CHAPTER VI

CONCLUSIONS

The values of the fatigue limits obtained with both steels, depending on the type of stressing, are summerized in Table 3.

Table 3. Fatigue Limits of A-537B and CG-A-537M Steels

Steel	Type of Stressing	Tensile Stressing psi	Stress ratio (R)	Fatigue limit	
				Stress psi	% of tensile strength
A-537B	Axial Loading†	85,200	1/2	65,200*	-
			0	53,000	62
			-1	-	-
	Bending	83,800	1/2	65,350*	-
			0	52,500	63
			-1	34,000	40
CG-A-537M	Axial Loading	75,150	1/2	60,200*	-
			0	51,000	68
			-1	32,000	42
	Bending	72,150	1/2	57,400*	-
			0	52,000	72
			-1	29,000	40

*Yield Strength

†From Havens and Bruner

From the experimental results and observations, the following conclusions can be drawn:

1. For quenched and tempered steels the empirical relationship between fatigue limit and tensile strength which can be found from fatigue tests, is not satisfactorily explained by theory at the present time. Unfortunately, it is not possible to reach any conclusion on an exact relationship between fatigue limit and tensile strength because of the considerable variation in material properties and the statistical nature of fatigue.

2. The results of the tests are sufficient to support the conclusion that the fatigue strength in bending is somewhat greater than that in axial loading. As explained by Forrest and Tapsell [8], this is probably because inelastic strain may cause a redistribution of stress during cyclic loading.

3. For quenched and tempered steels, the fatigue limit at a stress ratio of 1/2 is either above or close to the yield strength of the steel. At a stress ratio of -1, the fatigue limit is approximately 40% of the tensile strength for both types of loading. These results are consistent with the general observations that the fully-reversed bending fatigue limits of steel are approximately 30 to 50% of their tensile strength.

4. These results are in agreement that the fatigue strength of steel increases as the stress ratio becomes more positive.

5. The results of A-537B bending tests are consistent with those of the axial-loading tests conducted by Havens and

Bruner [11]. At a stress ratio of 0 the fatigue limit is about 52.5 ksi, 63% of the tensile strength.

6. At a stress ratio of 1/2 the fatigue limit of CG-A-537M steel in bending is above the yield strength and in axial loading it is equal to the yield strength.

7. The results also indicate that the fatigue limit of CG-A-537M steel at a stress ratio of 0 is 68% of the tensile strength in axial loading and 72% when in bending.

8. Comparison of results for A-537B steel and CG-A-537M steel showed that the value of CG-A-537M fatigue strength is almost as high as A-537B steel, although its tensile strength is less. When a comparison is made on the fatigue limit-tensile strength ratios of both steels, it can be seen that CG-A-537M steel (Armco LTM-QT) has a higher value of the ratio than A-537B steel. With the significantly high fatigue strength and excellent notch toughness at low temperatures, CG-A-537M steel can be proposed for use in offshore applications as well as A-537B steel.

9. The fatigue strength reduction caused by a semi-circular notch machined in the specimen was significant. The effective stress concentration factor of 1.37 calculated from the fatigue data was smaller than that predicted by the theoretical stress concentration factor of 1.9 for the notch. In notched specimens for axial loading stress redistribution can occur and give an effective factor lower in value than

the theoretical stress concentration factor. Considering the notch sensitivity factor (q of 0.41), CG-A-537M steel is said to be not significantly notch sensitive in fatigue. It was also found that the notch sensitivity factor q is slightly greater for higher maximum stresses.

10. On the basis of observations of fatigue fractures and their appearances, fatigue failure is definitely progressive and visible. The main fatigue crack originated from high localized stress with a plastic movement in the material, especially from the root of the notch in the specimen. Propagation of this crack led to the eventual or ultimate fatigue failure. The crack, which usually initiates during rather early stages in the service life, is either formed at a stress raiser on the surface of the specimen or at some weak point inside the cross section due to inhomogeneity and imperfections of the material. The progressive part of the failure cross section appears bright and smooth, whereas the part failing by a single load application in the last cycle appears rough and silky in the same manner as in the case of static tests and shows that the material has ductility.

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APPENDIX A

FATIGUE TEST DATA

Bending Tests of Armco Super Lo-Temp (A-537B) Steel

Specimen	Strain μ in./in.	Max. Bending Stress psi	Number of Cycles
	Stress Ratio, R = 1/2		
SLT B-1	1,960	58,000	2,000,000→
SLT B-2	2,140	63,000	2,000,000→
	Stress Ratio, R = 0		
SLT B-3	2,010	59,300	397,220
SLT B-4	1,840	54,300	556,180
SLT B-5	1,812	53,500	845,270
SLT B-6	1,745	51,500	2,000,000→
SLT B-7	1,715	50,600	2,000,000→
	Stress Ratio, R = -1		
SLT B-8	2,060	60,800	31,852
SLT B-9	1,470	43,400	135,360
SLT B-10	1,273	37,600	424,930
SLT B-11	1,175	34,700	1,524,600

→ Specimen did not fail at this number of cycles.

Bending Tests of Armco LTM-QT (CG-A537M) Steel

Specimen	Strain μ in./in.	Max. Bending Stress psi	Number of Cycles
	Stress Ratio, R = 1/2		
LTM B-1	1,915	56,500	2,000,000→
LTM B-2	1,830	54,000	2,000,000→
	Stress Ratio, R = 0		
LTM B-3	1,960	57,800	276,000
LTM B-4	1,930	57,000	572,600
LTM B-5	1,900	56,000	685,400
LTM B-6	1,835	54,200	860,430
LTM B-7	1,785	52,700	1,405,560
	Stress Ratio, R = -1		
LTM B-8	1,860	54,860	22,292
LTM B-9	1,665	49,200	28,154
LTM B-10	1,175	34,700	195,246
LTM B-11	1,037	30,600	752,657
LTM B-12	1,002	29,600	1,307,560

→ Specimen did not fail at this number of cycles.

Axial-Loading Tests of Armco LTM-QT (CG-A-537M) Steel

UNNOTCHED SPECIMEN

Specimen	Maximum Stress psi	Number of Cycles
	Stress Ratio, R = 1/2	
LTM A-1	55,000	2,000,000→
LTM A-2	59,000	2,000,000→
	Stress Ratio, R = 0	
LTM A-3	58,000	350,380
LTM A-4	55,000	587,200
LTM A-5	53,500	781,740
LTM A-6	52,000	829.170
LTM A-7	51,000	1,308,780
	Stress Ratio, R = -1	
LTM A-8	48,000	33,000
LTM A-9	38,000	114.140
LTM A-10	35,000	457,000
LTM A-11	33,000	529,110
LTM A-12	30,000	2,000,000→

→Specimen did not fail at this number of cycles.

Axial-Loading Tests of Armco LTM-QT (CG-A-537M)

Notched Specimens, R = 0

Specimen	Maximum Stress psi	Number of Cycles
LTM A-13	55,700	30,000
LTM A-14	50,000	40,290
LTM A-15	45,000	76,060
LTM A-16	40,000	194,460
LTM A-17	31,900	2,000,000 →

→ Specimen did not fail at this number of cycles.

APPENDIX B

PHENOMENON OF FATIGUE

PHENOMENON OF FATIGUE

Fatigue Fracture and Mechanism of Fatigue

Failure of metals under repeated applications of load, commonly called "fatigue" is well described as failure by progressive fracture. The fatigue failure can be baiscally stated of three stages:

1. The start of a crack: Over a period of time it starts a plastic movement within a localized region. Although the average unit stress across the entire cross section may be below the yield point, a nonuniform distribution of these stresses may cause them to exceed the yield point within a small area and cause plastic movement. This eventually produces a minute crack. The nucleation of the microscopic crack may be initiated at an early stage of the fatigue life.

2. The propagation of the crack: Under repeated stress the localized plastic movement further aggravates the nonuniform stress distribution, and further plastic movement causes the crack to progress.

3. Final rupture of the weakened section: Finally, after the crack has reached sufficient size and the material has no ability to carry the stress, a sudden, complete rupture occurs.

A large number of researchers have conduted investigations on the micromechanism of fatigue. Extensive use of metallurgical and electron microscopes has produced much information as to what occurs when a metal crystal is loaded repeatedly. It is not possible in this paper to list in detail the results and conclusions of individual contributors. However, observations on that which appears to be helpful and in good general agreement will be summerized.

Observations on the Mechanism of Fatigue [25]

I Visual means: Optical and electron microscope

A. Fatigue crack formation is preceded by formation of slip bands.

1. Slip occurs on the same crystallographic plane and in the same crystallographic directions as under static loading.
2. Slip follows the same maximum resolved shear stress law as under static conditions.
3. Most slip bands are formed during the first few cycles of stress.
4. Slip bands grow in width during tests.
5. The plastic deformation due to slip is highly localized.

B. Crack formation

1. Cracks form within slip bands.
2. Cracks appear very early during the finite fatigue life (they have been observed at as little as 0.1% of the total life)
3. Many cracks form at high stress. Few cracks form at low stress.

C. Crack growth

1. Cracks grow within slip bands.
2. Small cracks join up to form large cracks.
3. Cracks grow at an increasing rate with number of cycles, N.
4. Small holes or fracture origins may form in advance of the tip of a crack, and the large crack may grow by "jumping" into the damaged area.

II <u>X-ray evidence</u>

A. Metal subjected to repeated loading.

1. Deformation is highly localized.
2. Crystal disassociates into a few large elements (disoriented).
3. Disorientation increases with N.
4. Reversal of strain partially removes disorientation (this is not true of the same strain applied unidirectionally).

From these observations a general conclusion is that the formation of fatigue cracks occurs within highly localized regions of plastic deformation inside the metal crystal. Since plastic deformation is a result of the stress-induced motion of imperfections or dislocations in the crystal lattice, the nucleation of a fatigue crack is likely to result from the dynamic behavior of dislocations.

Fatigue Loadings

To define the stress level more precisely the actual service conditions must be considered. In practice, no two pieces of machinery, no two elements of structure, undergo exactly the same type of fatigue loading during their lifetime.

Repeated or fatigue loading may be of two major types: One in which the direction of stresses is not reversed during the cycle, and the other in which the direction is reversed. To achieve some degree of understanding, various types of fatigue loadings are illustrated in Figure 14 by considering the stress ratio (R) which is the algebraic ratio of the minimum to maximum stress in a stress cycle. The curve represents the applied stress at any given moment of time. A cyclic or fluctuating stress having a maximum value S_{max} and minimum value S_{min} can be considered as having an alternating component of amplitude

$$S_a = \frac{S_{max} - S_{min}}{2}$$

and a mean or steady stress

$$S_m = \frac{S_{max} + S_{min}}{2}$$

where S_a = stress amplitude

S_m = mean or steady stress

S_{max} = maximum stress during a cycle

S_{min} = minimum stress during a cycle

When the maximum and minimum stresses of a reversed loading are equal in magnitude but opposite in direction, R = -1, the condition is called "complete reversal" as in Figure 14a.

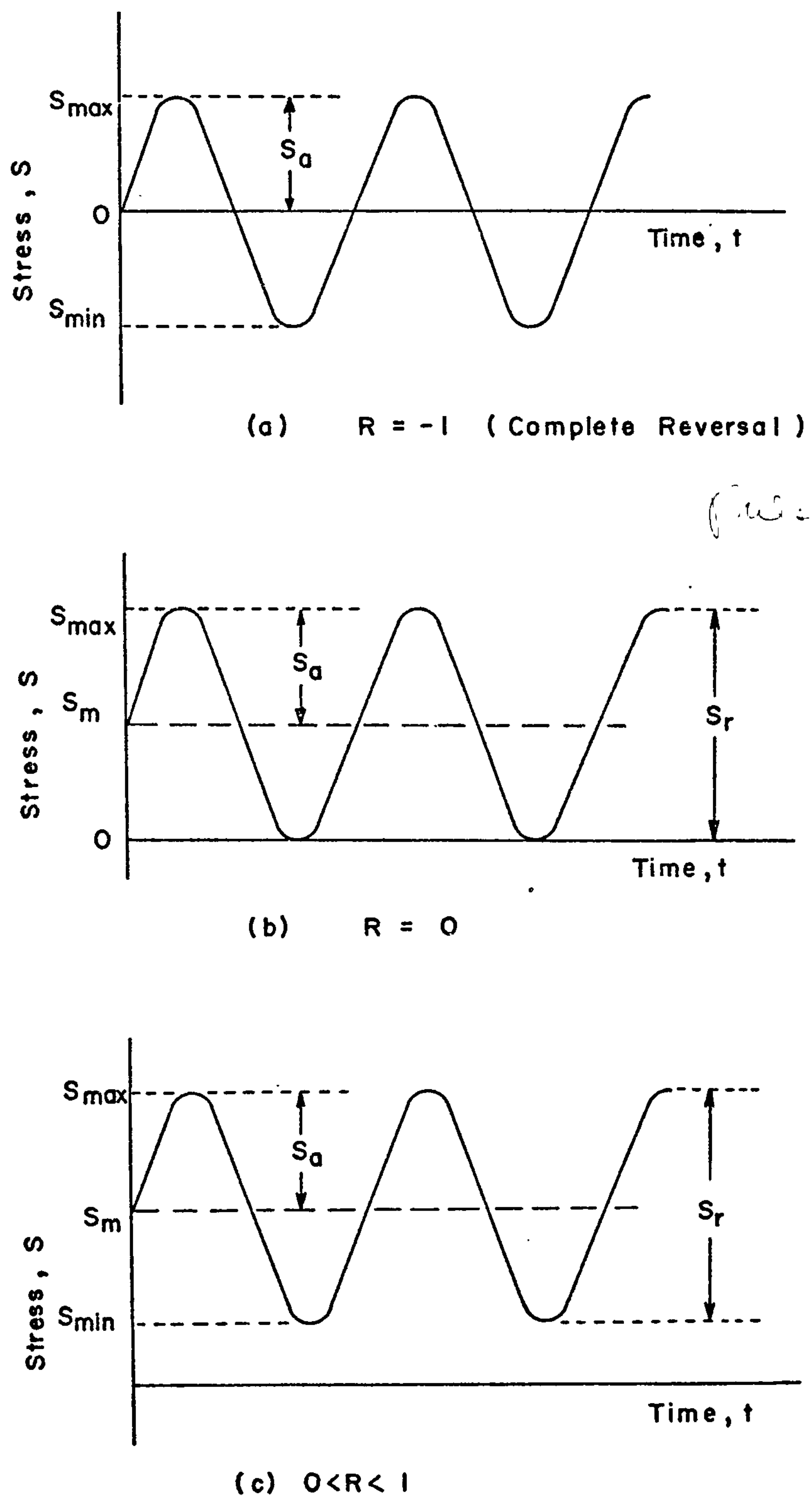

Figure 14. Types of Fatigue Loadings.

A stress ratio of 0 (Figure 14b) denotes a range of stress from zero to a maximum. Figure 14c represents tension-to-tension loading in the condition that the structural member is subjected to the dead weight before being repeatedly loaded in one direction.

S-N Curves

In laboratory tests the main problem is to determine the stress level at which a given material can withstand a predetermined number of cycles N. The smaller the amplitude S_a, the longer it will take to break the specimen. The specimen will break sooner or later, depending upon the type of fatigue.

The results of fatigue investigations are most commonly presented in the form of S-N (fatigue strength-number of cycles) curves. They are often called "Wöhler's curves", with stress plotted as the ordinate and number of cycles to failure as the abscissa. Ordinally the stress is plotted to a uniform scale and the number of cycles to a logarithmic scale, providing a semi-logarithmic plot. Each S-N curve represents only one type of cyclic loading or stress ratio R.

It will be noticed that there is a steady increase of N as S decreases up to about 10^6 cycles. Thereafter a small decrease of S causes an appreciable increase of N, and the curve trends to be almost horizontal. Thus, there seems to be a stress below which the fracture is unlikely to occur, no matter how large the number of cycles becomes. This stress is called the "fatigue limit" or "endurance limit". Therefore, the endurance limit for a given material is defined as the stress which can endure an infinite number of cycles without failure by progressive fracture. In addition, the term fatigue strength is defined as the maximum stress which a material can withstand without fracture for a stated number of cycles (also called fatigue life).

Fatigue data show considerable scatter owing to minor variations in specimen preparation, testing machine, and testing techniques, in addition to the inhomogeniety of the material and surface condition. In such cases the plotted points will not lie along a smooth curve, but will fall within an area known as the "scatter band". Some investigators prefer to show average curves, some prefer minimum curves, and some prefer the drawing of bands bounding all the points. The upper boundary will be the curve for extremely well made specimens whereas the lower boundary will be the curve for the poorest specimens. If sufficient data are avaliable, a statistical analysis of the tests can be made, resulting in more meaningful results, but this should be attempted only where a sufficient number of tests has been done. The studies made of the scatter of fatigue-test results have created considerable interest and the use of statistical methods in analyzing fatigue data is growing in popularity.

Goodman Diagram

An S-N curve can only represent one type of stress cycle. Thus there will be many S-N curves for a complete pattern. The Goodman diagram is a graphical representation of the fatigue limits of any value of the minimum stress in the cycle. This is a more convenient method for summerizing the data from several S-N curves in one diagram. It was first devised by J. Goodman and the diagram bears his name. Goodman diagrams are usually plotted for fatigue limit data unless a definite lifetime is stated.

A typical Goodman diagram is illustrated in Figure 15. Each diagram represents the fatigue behavior for a given fatigue life or number of repetitions of stress for failure.

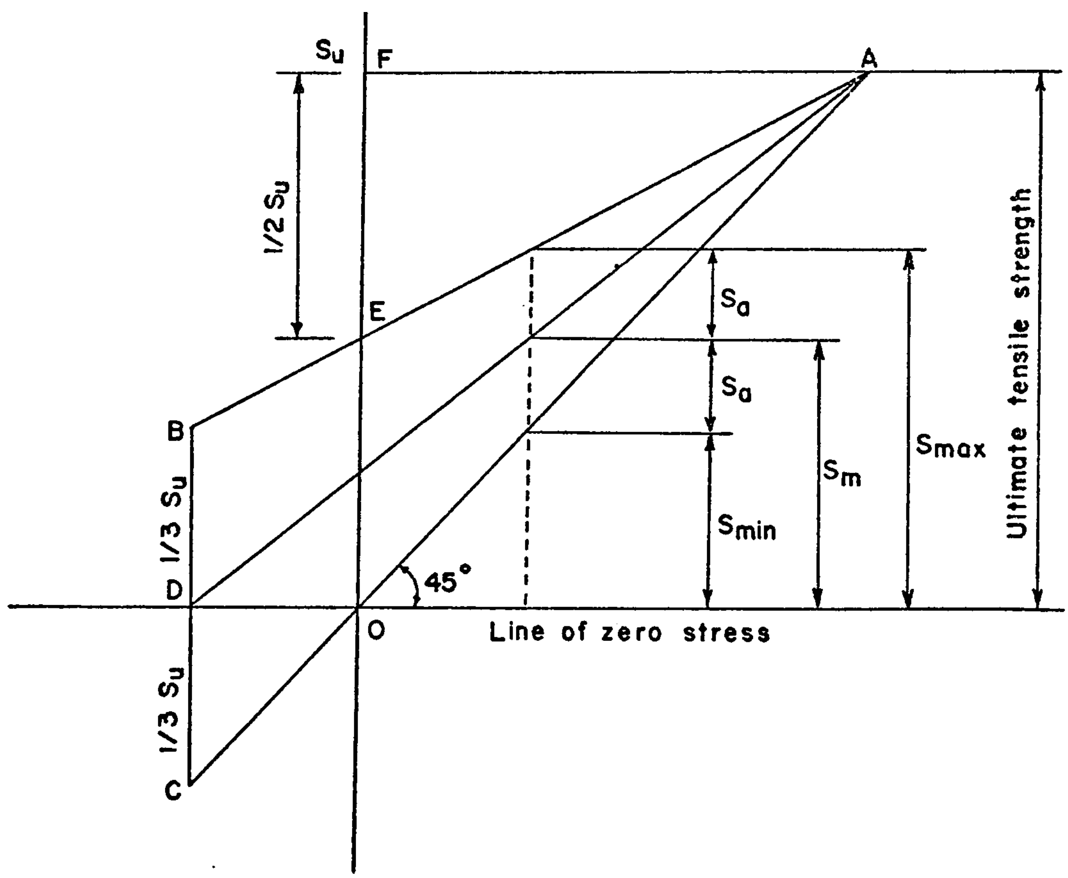

Figure 15. Goodman Diagram

The minimum stress is plotted as an ordinate to the line of zero stress with an equal abscissa so that one lies on a line OA making a 45 angle with the line of zero stress. Point A is a point having an ordinate equal to the ultimate tensile strength S_u of the material; line OA is extended to a point C having an ordinate equal to one-third of S_u; point B is plotted an equal distance above the zero line. DA is drawn from A through the intersection of BC and the zero line. The intercept of an ordinate between AC and AB represents the anticipated applied stress in the cycle which could be applied an indefinite number of cycles. Line AD cuts the applied stress into two equal parts (S_a), and hence represents the mean stress or steady stress (S_m).

Goodman found that, if S_{max} is plotted as an ordinate at the same abscissa as the minimum stress, the upper ends of the ordinates (S_{max}) lie approximately on the line AB where DB is 1/3 S_u and OE = EF = 1/2 S_u.

Modified Goodman Diagram

The modified-Goodman diagram was adopted by the American Welding Society - Welding Research Council as a convenient method of interpreting fatigue data. This modified diagram is developed by extending the line AC to the point established by complete reversal of stress, rather than to a value of one-third of the ultimate tensile strength. The N-cycle curve may not be of a straight line, depending on the fatigue strength of the S-N curves from the tests.

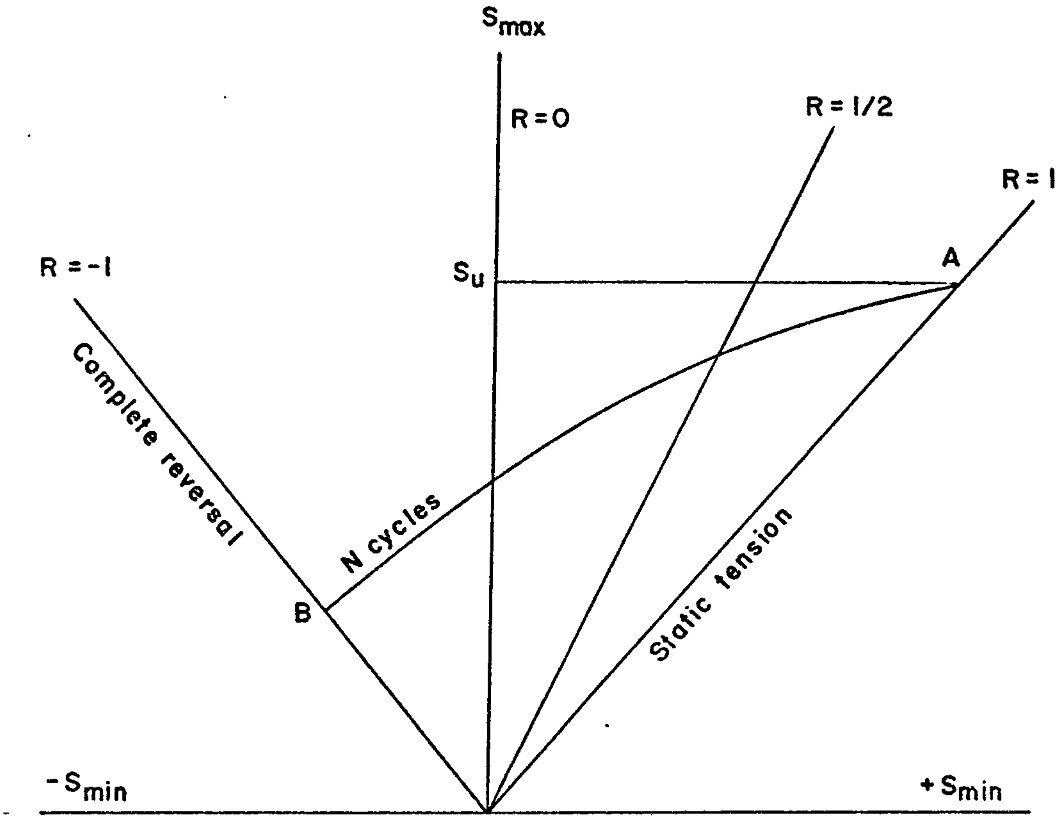

Figure 16. Modified Goodman Diagram

Figure 16 is a typical diagram which relates maximum and minimum stresses to the number of cycles for fatigue failure. The curve of N cycles shown could be 2,000,000 cycles, or 6,000,000, etc. There must be a curve for each number of cycles investigated. Many recent investigations indicate that a modified-Goodman diagram represents the anticipated fatigue limits somewhat closer than the original Goodman diagram [27].

Factors Affecting Fatigue Strength

The fatigue failure starts in some small region which probably consists of only tens of thousands of individual atoms. It is not sufficient to simply refer to the S-N curves or other fatigue data published on the specific material since such information is usually based on laboratory tests of small, carefully made specimens. A designer must realize the fact that the fatigue strength observed from small laboratory specimens can not be entirely used for full-scale components subjected to the service environments, since there are numerous factors that can reduce the fatigue strength. Those factors should be carefully considered before judging whether the material will withstand the design stress.

Recent investigations have been undertaken to determine the various factors which influence fatigue strength. In the following paragraphs some important factors which affect fatigue strength in service life are described.

1. Stress Concentrations

Sudden changes in cross section of machine parts or structural members, such as those caused by rivet holes, screw threads, mill scale, notches and welds, result in nonstraight-line stress distributions. This localization which causes a high stress is known as a "stress concentration". The "stress concentration factor" is defined as

$$K_t = \frac{\sigma_{max}}{\sigma_{nom}}$$

where K_t = stress concentration factor

σ_{max} = peak stress

σ_{nom} = nominal normal stress

Stress concentration factors can be obtained by experiments in which photoelasticity or strain gage techniques are used. Some stress concentration data are based on mathematics [19] which assume an elastic, homogeneous and isotropic material.

It is well established that stress concentration has no effect on the static strength if the material has sufficient ductility. In static loading of ductile materials the peak stress at a notch or other discontinuity initiates yielding. This local yielding does not result in failure. With further increase in load, the stress is transfered to other parts of the cross section. The concentration of stress is removed by yielding and the stress distribution gradually becomes uniform across the section in spite of the notch.

Stress concentration becomes applicable when the material is subjected to repeated loads. The loading cycle may produce a stress exceeding the yield point slightly but not sufficient to cause general yielding and redistribution of stress. In fatigue, therefore, stress concentration becomes of great importance.

Design for fatigue employing the stress concentration factor will be safe but conservative. The "Theoretical" stress-concentration factors are based on elasticity, homogeneity and isotropy of the material, hence they have a lack of accuracy in fatigue prediction.

The better measurement of the actual effectiveness of a stress concentration is the "fatigue notch factor", K_f as determined by fatigue tests. It is defined as

$$K_f = \frac{S_e}{S_{ne}}$$

where K_f = fatigue notch factor

S_e = fatigue limit of unnotched specimen

S_{ne} = fatigue limit of notched specimen

It is often called the fatigue-strength reduction factor. K_f is merely a factor that is applied to a particular type of member, material, stress raiser and loading cycle. The static-stress concentration K_t is generally found to be greater than K_f. A considerable amount of work on the effect of stress concentrations on fatigue behavior has been done by Peterson.

A convenient factor for studying the effect of stress concentrations is the "notch sensitivity factor" defined as

$$q = \frac{K_f - 1}{K_t - 1}$$

where q = notch sensitivity factor

The numerator represents the effectiveness of the notch in fatigue. If $q = 1$ ($K_f = K_t$), the notch is fully effective to the material. If $q = 0$ ($K_f = 1$), the notch is completely ineffective.

2. Mean stress

The effect of mean stress S_m on fatigue strength can be described in the relation between mean stress and stress amplitude S_a of a stress cycle. In fatigue loadings there might be cyclic patterns which have the same amplitude but differ in mean stress.

In the completely reversed type of loading, the stress oscillates about a mean stress which is equal to zero. However, it often happens in practice that the mean stress is not zero. Generally S_m is not equal to S_a. It may be larger or smaller.

For a given life or number of cycles to failure, it is easily seen in Goodman diagram that the stress amplitude decreases when the mean stress is tension and increases when the mean stress is compression. Conversely, for a given amplitude, the cycle with the higher mean stress will produce failure in the shorter time.

3. Residual Stress

The final stage during the process of rolling steel is cooling from the required high temperature for rolling to room temperature. Because cooling rate depends on thickness, the thinner sections cool first and as a result of the thin portions of a structural shape of nonuniform thickness develop internal tension stresses, whereas the thicker parts which cool last develop internal compressive stresses.

Residual stresses have a more important effect than is generally realized, since they may be an important factor in fatigue strength by changing the mean stress. If the residual stresses are compressive, they will improve the fatigue life by lowering the mean stress toward the compression side. In some cases residual tensile stresses are introduced due to cold forming cause a loss of fatigue strength.

4. <u>Fatigue in Compression</u>

For any stress system the fatigue damage occurs by shear and the mean normal stress has a strong influence. A mean tensile stress greatly accelerates failure. The fatigue tests on specimens loaded in compression which were obtained by Christensen 5 show that the fatigue limit in compression will be very much higher than that in tension and that the number of cycles to failure will be very much higher for compression than for tension. However, for practical purposes, service fatigue failures in compression are rare.

5. <u>Surface Condition</u>

Rough surfaces are important as much as notches. Surface roughness causes a stress concentration that should not be overlooked. The fatigue strength, therefore, decreases as surface roughness increases. The effect is more significant in the harder materials.

Studies of the effect of surface roughness on fatigue generally show large scratterings of results such as those of some tests 13 on the effect of roughness of a milling cut on the fatigue strength of 7075-T6 aluminium alloy. There are at least two reasons for the scatter. One is that most finishing operations produce residual stresses in the surface layers, and these stresses may be of uncontrolled magnitude. Another difficulty in predicting the effect of irregular roughness is making a reasonable evaluation of the roughest portion.

The importance of stress concentrations caused by surface roughness may be summerized by saying that the effect is much too large to be ignored. They will reduce the fatigue life less than the magnitude of the theoretical stress-concentration factors would indicate.

6. Frequency

In real life loading cycles can occur at a variety of frequencies. In fatigue tests it is desirable to use high frequencies. An increase in frequency will produce two simultaneous changes: The speed of stress application will increase and the time that the specimen is allowed to be at low stresses will decrease. Considerable attention has been paid to the effect of loading speed on fatigue strength. Generally the fatigue strength, especially the endurance limit, increases with increasing frequency.

Experiments have been made to determine the effect of varying the frequency at room temperature on the endurance limit of iron, steel and copper [4,15,18]. The results show that there is no effect when the frequency is varied up to 5,000 cpm, and higher frequencies begin to raise the endurance limit. For the tests carried out at high stresses above the endurance limit, high frequencies caused high temperature of a specimen and premature failure. The data on rest periods and effect of frequency lead to the conclusion that, over a wide range the frequency does not influence fatigue life at room temperature and rest periods also have no influence. However very high or very low speeds will usually cause lower strengths.

7. Size Effect

Most fatigue data on materials are based on small laboratory specimens which do not adequately evaluate the fatigue strength of large members. A fatigue fracture depends on a random distribution of weak points or imperfections in the material. A larger member, having a larger distribution of weak points, will have more localized regions in its distribution. The larger member is therefore more likely to have worst imperfections and fail at a lower stress than the small. Consequently, fatigue strength to some extent depends on the size of the member.

8. Corrosion

The fatigue strength of a steel structure is affected when some parts of the structure are subjected to a corrosion environment like being in sea water. Corrosion is one of the most destrimental factors causing a loss of fatigue strength. Fatigue under corrosion environment is called "corrosion fatigue".

9. Mechanical Properties

Of major interest regarding a particular is the relationship of the material's fatigue characteristics to its mechanical properties. In steel, the fatigue limit is roughly proportional to the static ultimate strength of the material, except in the very high strength range. Fatigue limit-to-tensile strength ratios range from 0.35 to 0.60.

Today, more than ever, fatigue is of paramount importance and is receiving increased attention in design. Larger airplanes, ships and other engineering structures are being designed to meet arduous service. Fatigue failures involve loss of considerable capital and sometimes many human lives. Consequently, fatigue is not a negligible problem. Furthermore, it is one of the most difficult and challenging fields for engineering research.

Methods of Improving Fatigue Property

It has been found that most fatigue cracks are nucleated on the surface of the stressed members. The surface condition is critically important as the fatigue strength is a structure-sensitive property. Obviously, fatigue strength can not be considered as a property of the material alone unless all of the surface defects have been eliminated. Therefore, the surface of all machine parts and structural members which are subjected to fatigue should be carefully and smoothly finished. This can be achieved by slow grinding and polishing operations which remove scratches and damaged surface material without inducing any new residual stresses.

If surface roughness on the final product can not be avoided, the surface treatment can be done by "peening" the surface. Peening is a mechanical treatment and is the most common technique of compressive stressing of surfaces. Peening consists of striking the surface with a rounded hammer or shooting onto it sand or small lead pellets with a predetermined velocity. This produces tiny indentations. In this treatment the deformation is confined to the plane of the surface and the surface area tends to expand. The surface layers become slightly overextended with respect to the untreated underlying layers. These layers react by trying to push the overextended surface layers back. Thus, the surface is held in compression and this increases the fatigue strength of the material.

Another method of improving the fatigue strength is by heat treatment. Steel can be hardened by being heated to a high temperature and then quenched in water. When applied locally to the surface layers, this treatment substantially increases their fatigue strength. In addition, tempering of the material at high temperature will relieve residual stresses. Further increase of strength can be achieved by combining heat treatment with chemical action of elements like carbon and nitrogen, which diffuse into the surface layers of steel at high temperatures.

Carburizing and nitriding are surface changes which produce high compressive stresses in the hardened surface. Nitriding will always build up compressive residual stress, while carburizing and heat treating may produce either compression or tension. Tensile residual stresses in the surface are as bad for fatigue as compressive residual stresses are beneficial. Therefore, nitriding can be expected to improve fatigue resistance.

Considerations in Fatigue Design

The fact that materials may fail under repeated loading while being adequate for static loading becomes an important factor in the design of certain types of structures. The mathemathical representation of fatigue behavior is not well enough developed to make possible the prediction of the number of applications of load that a given structural member might withstand. Progress with methods of fatigue analysis has been slow because of the lack of basic information on material behavior. More important, not even the mechanism of the simplest form of fatigue failure can be described completely by mathematics. Most of the work on fatigue has been done by experiments with particular materials and well defined loading conditions.

An estimate of service life is usually made in terms of the probable number of repetitions the material will withstand before failure. For example, if a member may receive 1,000,000 repetitions of stress in 50 years, the fatigue strength at 1,000,000 cycles from the test data is chosen to design for 50 years of service life. However, in some structural members the maximum stress is not likely to occur so frequently.

One of the important problems in fatigue design is the loading condition. When the designer first encounters a fatigue loading problem, he will often use the material's endurance limit or fatigue strength value given in his engineering handbook without considering what this value represents and how it was obtained. This procedure could lead to serious trouble.

There are many types of fatigue tests, types of loading, and types of specimens. Theoretically the fatigue value used by the designer should be determined in a test that duplicates the actual service conditions. The sample used should preferably be identical to the member, the testing machine should reproduce the actual service load, and the fatigue cycle and frequency should be the same as encountered in actual service.