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THE STRENGTH OF SCREW THREADS UNDER REPEATED TENSION

BY

HERBERT F. MOORE

AND

PROCTOR E. HENWOOD

Price: $.90

BULLETIN No. 264

ENGINEERING EXPERIMENT STATION

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ENGINEERING EXPERIMENT STATION

BULLETIN NO. 264 MARCH, 1934

THE STRENGTH OF SCREW THREADS UNDER REPEATED TENSION

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CONTENTS

LIST OF FIGURES

LIST OF TABLES

THE STRENGTH OF SCREW THREADS UNDER REPEATED TENSION

I. Introduction

1. *Object of Tests.*—Bolts and studs in structural and machine parts are commonly subjected to axial tension in the threaded portion. It is customary to compute the tensile stress in the threaded portion by dividing the axial load by the area of the cross-section at the root of the threads. This result is the *average* stress on the cross-section; but, at the roots of the threads, there exists localized stress much higher than this average. It is a matter of common experience that under repeated loading fractures occur in service in bolts and studs subjected to average stresses at the root of the thread as low as 20 000 lb. per sq. in.* The tests herein reported were undertaken to obtain test data on the behavior under repeated tensile load of ⅜-in. studs with three kinds of screw threads, and of ⅜-in. studs made from ordinary low-carbon steel and ⅜-in studs made from a heat-treated alloy steel. A comparison has also been made of the effective stress concentration at the root of thread as shown by repeated-stress tests to destruction, and the stress concentration as shown by tests of pyralin models examined under polarized light.

2. *Acknowledgments.*—Acknowledgment is made to Mr. N. J. Alleman for assistance both in carrying out tests and in reduction of test data. The tests herein reported have been a part of the work of the Engineering Experiment Station of the University of Illinois, of which Dean A. C. Willard is acting director, and of the Department of Theoretical and Applied Mechanics, of which Prof. M. L. Enger is the head.

II. Materials, Test Specimens, and Apparatus

3. *Materials.*—Three different lots of metal were used for making the test studs which were subjected to repeated stress: (1) a plain carbon steel rod containing about 0.30 per cent carbon designated as "medium-carbon" steel, (2) a plain carbon steel rod containing about 0.30 per cent carbon, and also designated as "medium-carbon" steel, on which threads had been formed by cold rolling along its entire

*Several striking instances of such failure have been furnished by bolts connecting parts of repeated-stress testing machines in the Fatigue of Metals Laboratory at the University of Illinois.

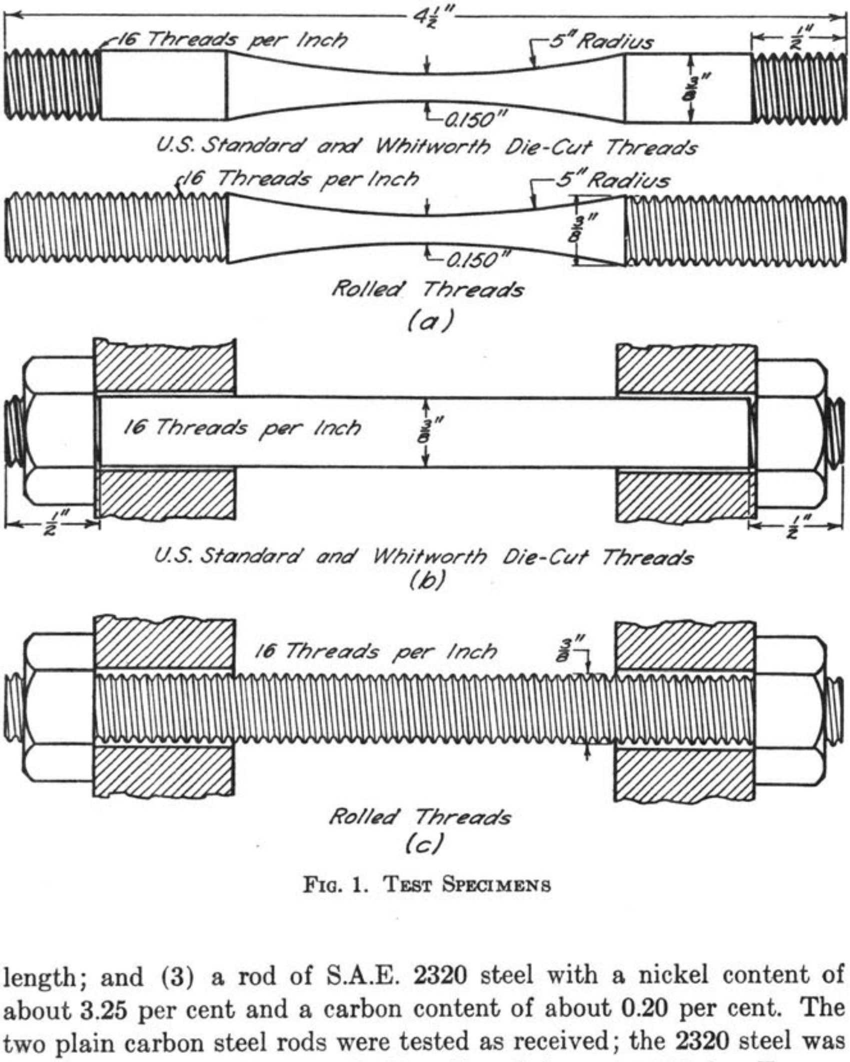

FIG. 1. TEST SPECIMENS

length; and (3) a rod of S.A.E. 2320 steel with a nickel content of about 3.25 per cent and a carbon content of about 0.20 per cent. The two plain carbon steel rods were tested as received; the 2320 steel was heated to 1500 deg. F., quenched in oil, and drawn at 800 deg. F.

4. *Test Specimens.*—Figure 1 shows the specimens used in the tests under repeated tensile load. Figure 1 (a) shows the specimen used for determining the endurance limit* of the material in the test studs.

*Endurance limit (or fatigue limit) is that stress below which fracture will not occur under an indefinitely large number of cycles of stress. In this series of tests the endurance limit determined is for stress ranging from nearly zero to a maximum tension. The endurance limit for this range is probably about 50 per cent greater than the endurance limit for cycles of stress ranging from a maximum tension to a compression of equal magnitude. The range of stress from zero to maximum tension was chosen as the range of stress most representative of the stress bolts and studs receive in service.

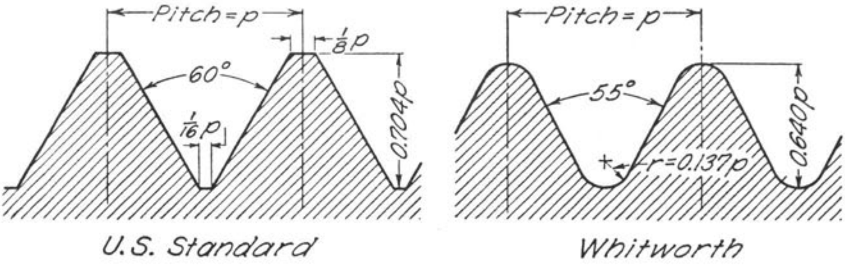

FIG. 2. U. S. STANDARD AND WHITWORTH SCREW THREADS

Figure 1 (b) shows the specimen used to determine the endurance limit of test specimens (3/8-in. studs) made from medium-carbon steel and from heat-treated nickel steel (S.A.E. 2320). Figure 1 (c) shows the specimen used to determine the endurance limit of the studs with rolled threads.

The test specimens made from medium-carbon steel and from heat-treated nickel steel were threaded with a sharp die. For each metal one set of specimens was threaded with a U. S. Standard 3/8-in. die, and a second set of specimens with a Whitworth 3/8-in. die. Figure 2 shows the nominal shape of thread for the two dies. It is to be noted that the absolutely sharp re-entrant corners called for in the U. S. Standard thread cannot be formed, and that there is always some rounding off of corners, although not so much as is found in the Whitworth thread. The stud specimens (Fig. 3(b) and 3(c)) were fitted with nuts as shown. The specimens with die-cut threads (U. S. Standard and Whitworth) then had only one or two threads carrying the maximum tensile stress on the stud, while the rolled-thread studs, which were furnished threaded throughout their whole length, had a long threaded portion carrying the maximum tensile stress. R. R. Moore has shown (and H. F. Moore has checked his results by further tests) that a single groove, shaped like a screw thread, is more effective in reducing fatigue strength than is a long threaded portion of a stud.* A direct comparison of fatigue strength between the studs with rolled threads and the studs with die-cut threads may not, therefore, be quite fair to the die-cut threads.

5. *Testing Machine for Repeated Tension Tests.*—Figure 3 shows the repeated-tension testing machine used in the fatigue tests of test studs. This machine was designed in the Fatigue of Metals Labora-

*See Reference No. 1 in the Selected List of References at the end of this bulletin.

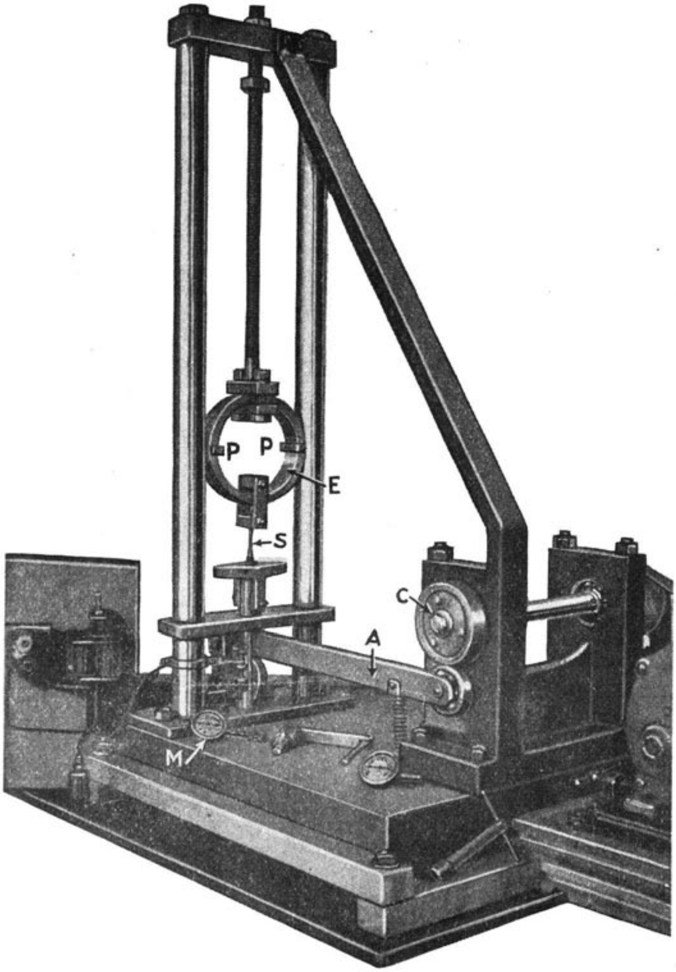

FIG. 3. TESTING MACHINE FOR REPEATED TENSION TESTS
(Courtesy of J. B. Hayes, Inc., Urbana, Ill.)

tory of the University of Illinois.* The variable-throw cam C works the lever A which, in turn, applies tension to the specimen S which is supported on carefully centered balls. The pull on the specimen is transmitted to the elastic ring E, which is fastened to the framework of the machine by means of a long vertical screw. The sidewise contraction of the elastic ring E is a measure of the tensile force applied

*Since the completion of the tests herein described the machine has been materially modified by Mr. G. N. Krouse so that tests under reversal of stress can be made in it as well as tests under repeated tension.

to the specimen, and this sidewise contraction between the points *PP* is measured by means of a micrometer dial gage *M*. The elastic ring is similar to those used for calibrating testing machines. The range of stress to which the specimen *S* is subjected can be regulated by means of the long vertical screw and the nuts at the top cross bar. When a specimen breaks the lower fragment of the specimen and the socket holding it drop, closing an electric circuit, and operating a circuit breaker, stopping the motor which drives the machine. The machine operates at a speed of 1000 r.p.m., has a capacity of 2000 lb. maximum load, and is fitted with a revolution counter to indicate the number of cycles of stress.

The procedure in carrying out a test is as follows: With the specimen properly centered, the load required to produce the (nominal) stress desired is calculated; then, from the calibration curve furnished with each elastic ring, the lateral contraction of the elastic ring corresponding to this load is determined; the variable-throw cam *C* and the nuts at the upper end of the long vertical screw are then adjusted until, during one revolution of the cam, the load on the specimen varies from nearly zero to the desired maximum.

III. Test Data and Results

6. *Test Procedure to Determine Endurance Limit.*—The endurance limit is first estimated for the metal. For repeated stress ranging from nearly zero to a maximum tension this may be estimated at 75 per cent of the tensile strength, as determined by a test of specimens in an ordinary "static" testing machine. A specimen (like that shown in Fig. 1 (a)) is then placed in the repeated-tension machine and the throw of the cam and the position of the upper nuts adjusted until a revolution of the cam causes a range of stress of from nearly zero to a tensile stress (say) 15 per cent above the estimated endurance limit. Then the machine is started, and, for the first hour or two, is stopped at frequent intervals to allow taking up any slack that may be necessary due to adjustments of the specimen to the sockets into which it is screwed. When the specimen shows no further need of adjustment the machine is allowed to run until the specimen breaks. The range of stress and the number of cycles of stress required for fracture are then recorded, and another specimen put in the machine, the throw of the cam being adjusted so that the range of stress is from nearly zero to a slightly lower maximum value than was used for the first speci-

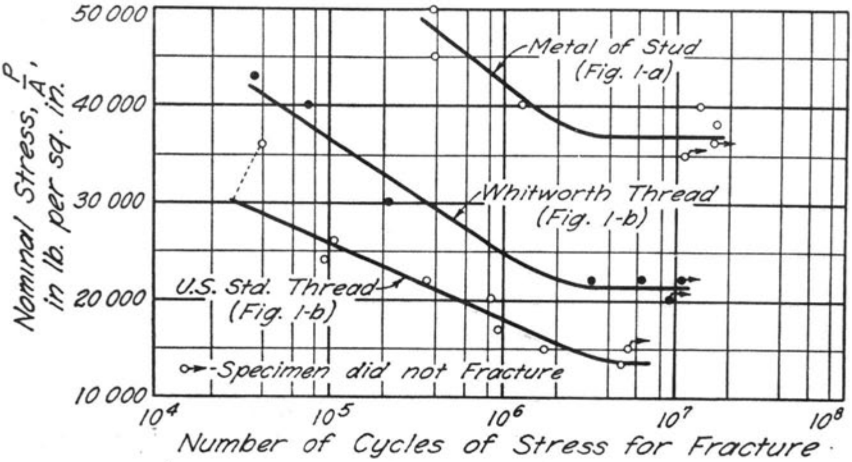

FIG. 4. *S-N* DIAGRAMS FOR TEST STUDS OF MEDIUM-CARBON STEEL—U. S. STANDARD AND WHITWORTH SCREW THREADS

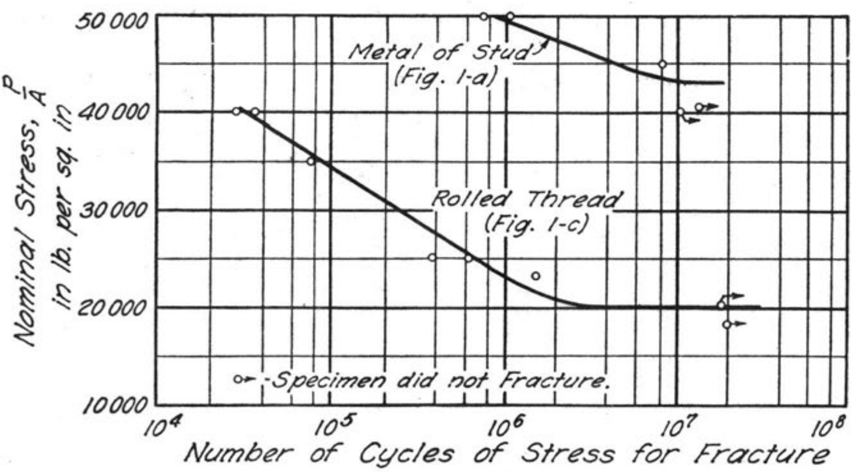

FIG. 5. *S-N* DIAGRAMS FOR TEST STUDS OF MEDIUM-CARBON STEEL—ROLLED THREADS

men. This process is repeated until a specimen withstands a given number of cycles of stress without fracture (if feasible, 10 000 000 cycles for steel).

A diagram is then plotted with stresses as ordinates and number of cycles of stress for fracture as abscissas (abscissas plotted to a log. scale). Such a diagram is known as a *S–N* diagram, and the stress at which this diagram becomes horizontal is taken as the endurance limit.

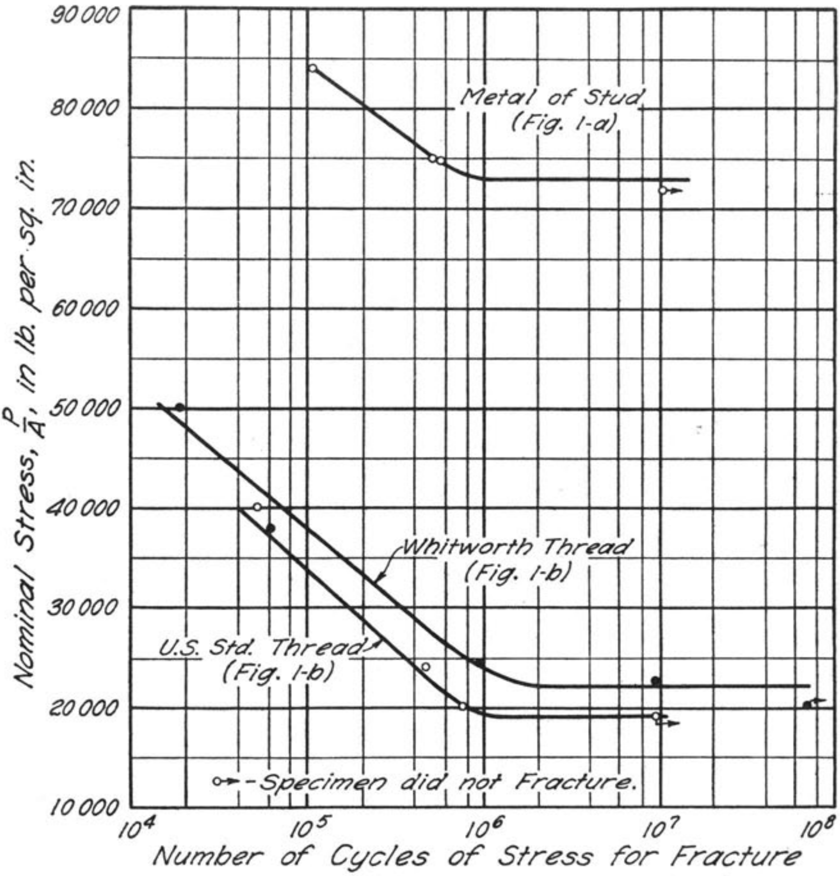

FIG. 6. *S-N* DIAGRAMS FOR TEST STUDS OF HEAT-TREATED NICKEL STEEL—U. S. STANDARD AND WHITWORTH SCREW THREADS

7. *S–N Diagrams of Fatigue Tests and Tabulated Results.*—Figures 4, 5, and 6 show the *S–N* diagrams for the fatigue tests made, and Table 1 gives the endurance limits determined for the different metals and different threads. In Table 1 are also given the results of static tests for tensile strength of the different metals.

IV. DISCUSSION OF RESULTS

8. *"Stress Concentration" in Screw Threads.*—Before taking up the discussion of the quantitative results of the fatigue tests, it seems desirable to consider the general problem of "stress concentration," or perhaps a better term would be "localized stress intensification."

TABLE 1
ENDURANCE LIMITS FOR DIFFERENT SCREW THREADS
Range of stress in a cycle, zero to maximum tension.*

Metal	Tensile Strength (static) lb. per sq. in.	Form of Fatigue Specimen	Thread	Endurance Limit lb. per sq. in.
Medium-carbon Steel............	57 400	Fig. 1 (a)	....	37 000†
		Fig. 1 (b)	U. S. Std.	13 000
		Fig. 1 (b)	Whitworth	21 000
Medium-carbon Steel‡............	74 000	Fig. 1 (a)	....	43 000†
		Fig. 1 (c)	Rolled	20 000
S.A.E. 2320 Nickel Steel Heat-treated......................	109 000	Fig. 1 (a)	....	73 000†
		Fig. 1 (b)	U. S. Std.	19 000
		Fig. 1 (b)	Whitworth	22 000

*The minimum stress in a cycle is actually a slight tension, just sufficient to keep the specimen tight in its shackles as tensile stress is applied and removed during a cycle.
†Endurance limit of the metal under cycles of stress varying from zero to a maximum tension.
‡Steel slightly cold-worked by thread-rolling process.

For a good many years it has been recognized that wherever sudden changes occur in the outline of a structural or a machine member, or where there exist internal discontinuities in a metal (such as a blow hole or crack), stresses of considerable magnitude over very small areas are to be found. These localized stresses are neglected when the ordinary formulas of mechanics of materials are used in designing. A few cases of such localized stress have been considered by students of the elaborate theory of elasticity, and others have been studied by the aid of the examination of transparent specimens under the illumination of polarized light, by the fracture of specimens of plaster of paris or other very brittle material, and by other experimental methods.* Figure 7 shows approximately the stress distribution at the root of a screw thread. Ordinarily the designing engineer would compute the average stress S_{av}, which is equal to load P divided by area of cross-section A. He would neglect the high localized stress S_{max} at the root of the thread. If the machine or structural part is made of reasonably ductile material *and is subjected to steady load,* or to only a few cycles of repeated load, the high localized stress does not cause appreciable structural damage. Localized yielding takes place, and under steady load there is a readjustment of stress with a tendency to equalize the stress over the cross-section. The slight yielding makes the material locally plastic, and hence

*See F. B. Seely, "Advanced Mechanics of Materials," Chapter X; John Wiley & Sons, New York, 1932.

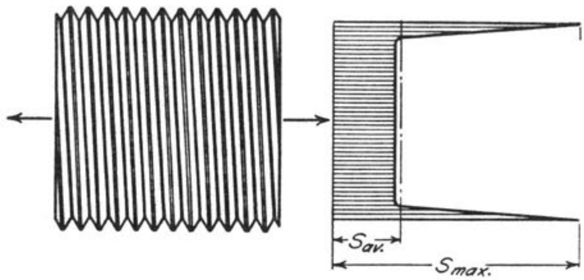

FIG. 7. STRESS DISTRIBUTION AT ROOT OF THREAD

renders the theory of elasticity inapplicable for accurate determination of stress, because that theory assumes perfect elasticity of material. Plastic yielding ("passing the elastic limit" as it is rather loosely termed) causes appreciable structural damage under static load *only after a considerable volume of material is affected.*

Under *many cycles of repeated load* the case is quite different. At the point of localized stress plastic flow occurs over a minute area, and the metal in that minute area is strengthened and *embrittled* by cold work. As cycles of stress are repeated this metal gradually changes its physical properties, not through "crystallization" but by the gradual sliding over each other of layers of metal within crystals. If this sliding is continued for a sufficient number of cycles of stress, extremely minute cracks open up and spread. This spreading fracture constitutes *fatigue failure*, and, while localized stress intensification is not very apt to cause structural damage under a *static* load, it *is* very likely to cause fracture by a spreading crack under a repeated load of sufficient magnitude.

Applying this discussion to the screw thread it can be seen that under a single static load minute rings of metal at the roots of the thread will suffer plastic deformation. This deformation will be very small and will not appreciably affect the serviceability of the bolt. If, however, the bolt is subjected to repeated stress there is danger that at some point of localized overstressing a crack will start and spread to fracture.

9. *Elastic Limit and Endurance Limit.*—From the foregoing discussion it may be thought that the limiting stress under repeated loading would be the "true" elastic limit of a metal. When the structure of metals is studied it is found that the ordinary metals of construction are made up of crystalline grains. X-ray crystallography

indicates that in each one of these crystalline grains the atoms are arranged in a regular geometrical pattern with a definite plane along which slip can take place easily. It would be necessary, then, in determining the "true" elastic limit, to determine the component of stress along the slip planes of the most unfavorably oriented crystal. Inasmuch as thousands of crystals without any clear system of orientation are present in the ring of metal at the root of the thread, this is seen to be impracticable. The elastic limit *as determined in the laboratory* is a stress at which an arbitrarily determined amount of plastic action takes place in a test specimen taken as a whole.

A more practical index of strength under repeated stress is the endurance limit (or fatigue limit). This is the limiting stress below which no fracture of specimen occurs even after an indefinitely large number of cycles of stress have been applied.* Even in a specimen free from grooves, screw threads, or other external causes of stress concentration ("stress raisers" as Dr. H. W. Gillett calls them) the endurance limit is well below the static tensile strength, and shows no well defined relation to the elastic limit as determined in the laboratory. The explanation of this difference between endurance limit and tensile strength is that the structure of the metal itself is non-homogeneous and stress concentration occurs between crystal and crystal, and probably within crystals.

10. *Determination of Stress-concentration Factors.*—The methods of the mathematical theory of elasticity have not, so far as the writers know, been successfully applied to determine stress concentration at the root of screw threads. The determination of stress concentration in screw threads by photo-elastic methods has been given some study by Mr. Stanley G. Hall, and his work is recorded in Bulletin No. 245, Engineering Experiment Station, University of Illinois. The photoelastic method, in which polarized light is passed through specimens of transparent material, is an attempt to use optical and mechanical methods to solve problems of stress concentration. The material tested must be transparent, and bakelite, pyralin, or celluloid are the materials commonly used for specimens. The properties of the materials are not of interest to the user of polarized light except that there must be elastic strength enough to permit the application of loads and deformations which can be measured. The stress concentrations

*See Proceedings, Am. Soc. for Testing Materials, Vol. 30, Part I, pp. 272-284 (1930). This article by Professor J. B. Kommers, a part of the 1930 report of the Research Committee on Fatigue of Metals, discusses variation of endurance limit with range of stress.

TABLE 2
STRESS-CONCENTRATION FACTORS FOR SCREW THREADS AS GIVEN BY FATIGUE TESTS AND BY PHOTO-ELASTIC TESTS

Thread	Metal	Stress-concentration Factor	
		By Fatigue Test*	By Photo-elastic Test†
U. S. Std..........	Medium-carbon Steel..................	2.84	5.62
	S.A.E. 2320 Nickel Steel Heat-treated....	3.85	
Whitworth........	Medium-carbon Steel..................	1.76	3.86
	S.A.E. 2320 Nickel Steel Heat-treated....	3.32	
Rolled............	Medium-carbon Steel..................	2.15‡	

*Stress-concentration factor by fatigue test is determined by dividing endurance limit of metal (tests of specimen shown in Fig. 1 (a)) by endurance limit of specimen with critical section at threaded portion (as shown by Fig. 1 (b) or Fig. 1 (c)).
†Tests on pyralin specimens viewed by polarized light,—see Bulletin 245 of the Engineering Experiment Station, University of Illinois.
‡Metal slightly cold-worked by thread-rolling process.

determined by such tests, may, then, be classed as theoretical stress concentrations.

From the fatigue tests of specimens of the same metal with and without screw threads at the critical section an *effective* stress concentration may be determined by dividing the endurance limit of the metal as determined by fatigue tests of specimens like those shown in Fig. 1 (a) by the endurance limit of specimens like those shown in Fig. 1 (b) or 1 (c).

Table 2 gives the results of Mr. Hall's work with photo-elastic methods and also the effective stress-concentration factors as determined from the data given in this bulletin.

V. CONCLUSIONS

11. *Summary of Conclusions.*—

(1) The stress-concentration factor for a screw thread is defined as the ratio of maximum stress, which is at the root of the thread, to the average stress over the minimum area of cross section of the thread. This factor may be determined directly by photo-elastic tests. The *effective* stress concentration factor may be defined as the ratio of the endurance limit of the metal itself to the endurance limit of specimens which fail in the screw threads. The tests herein reported, taken in connection with photo-elastic tests previously re-

ported, indicate that the stress-concentration factor determined by photo-elastic tests is larger than the effective stress-concentration factor determined by fatigue tests. In other words, determination of stress concentration in screw threads by photo-elastic tests gave results "on the safe side" as compared with those given by fatigue tests.

(2) Both photo-elastic tests and fatigue tests of ⅜-in. studs gave higher stress-concentration factors for die-cut U. S. Standard threads than for die-cut Whitworth threads.

(3) Rolled threads on a medium-carbon steel rod ⅜ in. in diameter gave effective stress-concentration factors intermediate between those for die-cut Whitworth threads and those for die-cut U. S. Standard threads, but this superiority over the U. S. Standard die-cut threads may be explained by the fact that the rolled-thread specimens were threaded for the full length, while the die-cut specimens were threaded at the ends only.

(4) For both U. S. Standard threads and Whitworth threads higher effective stress-concentration factors were found for heat-treated nickel steel studs than for medium-carbon steel studs. This indicates that the heat-treated nickel steel is more sensitive to stress concentration than is the medium-carbon steel, and that a smaller proportion of the tensile strength of the material is available in heat-treated nickel steel bolts and studs subjected to repeated stress than is the case with ordinary structural steel bolts and studs.

(5) For heat-treated nickel steel studs with ⅜-in. U. S. Standard threads an effective stress-concentration factor of 3.85 was observed; for medium-carbon steel this factor was 2.84. These figures suggest that for bolts or studs subjected to repeated tensile stress a safe estimate of the stress at the root of the thread would be *not* the nominal value $\frac{P}{A}$ but $\frac{3P}{A}$ for ordinary structural steel, and $\frac{4P}{A}$ for heat-treated alloy steels commonly carried in stock, where P is the load in pounds and A is the area at the root of the thread in square inches.

APPENDIX

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