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Mathematics
and Computers

MASTER

TORSION TESTING USING A DIGITAL COMPUTER

M. W. Poore
J. H. Smith

UNION CARBIDE CORPORATION
NUCLEAR DIVISION
OAK RIDGE Y-12 PLANT

operated for the **ATOMIC ENERGY COMMISSION** under **U. S. GOVERNMENT** Contract W-7405 eng 26

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Nuclear Division

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ABSTRACT

A digital computer can be used for acquiring and reducing data on torsion tests. The torque and strain signals are fed through an analog-digital converter to a small processor computer where the data are stored, assembled, and reduced. A printout and punched tape are obtained which contain the shear properties and the associated stress-strain data points.

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SUMMARY

A digital computer is being used at the Oak Ridge Y-12 Plant^(a) for the acquisition and reduction of data on torsion tests. Shear strain is obtained by attaching biaxial rosette strain gages to the specimen, and the test is conducted on a standard torsion test machine. The torque and strain signals are fed through an analog-digital converter to a small processor computer where the data are stored, assembled, and reduced. Data that are being calculated are the offset yield strength, shear modulus, and energy of the test. A printout and punched tape are obtained which contain the shear properties and the associated stress-strain data points. In addition, the torque-strain curve that is normally obtained from the test is still available.

(a) Operated for the US Atomic Energy Commission by the Union Carbide Corporation's Nuclear Division.

INTRODUCTION

A torsion test is conducted by applying a force that will cause a body to twist or rotate about some axis which passes through the body. This twisting action causes shear stresses and strains to be set up. The primary purpose for conducting a torsion test is to determine the values of the shearing stresses and strains that are set up and to determine the shear mechanical properties of the material that is being tested. A torsion test may be conducted on a part or on specimens taken from the part.

The tests discussed in this report were conducted on hollow cylindrical specimens using a standard torsion test machine. Electrical signals proportional to the torque applied were available from the tester. Signals proportional to the shear strain were obtained by attaching strain gages to the specimen.

The torque and strain signals are conditioned, changed into a digital form, and fed into a computer. The data are recorded and stored in the computer's memory while the test is in progress. At the completion of the test, the computer will automatically calculate the shear mechanical properties and print the results on a report form which is located on the teletypewriter.

TORSION TESTING

COMPUTER APPLICATION

Shear Stress

The shear stress at any point in a circular shaft at a radius ρ is given by:

$$\tau' = \frac{T\rho}{J}$$

where:

τ' represents the shear stress,

T the total resisting torque about the axis of the shaft, and

J the polar moment of inertia.⁽¹⁾

If r is the radius of the cross section, then the maximum stress, τ , occurs where $\rho = r$, and is:

$$\tau = \frac{Tr}{J}$$

The maximum shear stress at the outer surface of a circular shaft will vary with differently shaped cross sections. Table 1 shows the equations for the polar moments of inertia and the shear stresses for two different cylindrical shapes, where the principal axis is the axis of rotation.

In Table 1, the d_o term represents the outside diameter and d_i the inside diameter.

Table 1
EQUATIONS FOR TWO CYLINDRICAL SHAPES

Shape	Polar Moment of Inertia	Shear Stress on the OD Surface
Solid Cylinder	$J = \frac{\pi}{32} d_o^4$	$\tau = \frac{32T}{\pi d_o^3}$
Hollow Cylinder	$J = \frac{\pi}{32} (d_o^4 - d_i^4)$	$\tau = \frac{32T d_o}{\pi (d_o^4 - d_i^4)}$

Note in Table 1 that the maximum stress varies inversely with the diameter of the specimen. The stress field becomes more uniform as the wall thickness approaches a single radius. For this reason, a more uniform stress field can be obtained in a hollow cylindrical specimen. But, testing difficulties can arise if the walls are made too thin. The walls must have enough strength to prevent such nonlinear disturbances as localized crimping of the specimen.

The tests discussed in this report were conducted on hollow cylindrical specimens (see Figure 1). This specimen design was chosen because the primary properties being determined were the shear modulus and the shear yield strength.

Figure 1. TORSION SPECIMEN FOR SHEAR MODULUS AND YIELD STRENGTH.

The tests were performed on a standard torsion test machine (see Figure 2). One of the specimen supports is fixed; the other rotates. Force is applied through a fixed lever arm to cause rotation and produce torque^(b) in the specimen. A linear variable differential transformer (LVDT) which is attached to the lever arm produces an electrical signal proportional to the applied torque. This signal is fed to a dial indicator and to an x-y recorder.

Shear stress is determined by using the equation given in Table 1 for the hollow cylindrical specimen. The specimen dimensions of the inner and outer diameters are determined prior to the test, and these dimensions are used in all calculations.^(c)

(b) By definition, torque = force x lever arm, where the lever arm is the perpendicular distance between the force vector and the center of rotation.

(c) Engineering stress was determined for all tests in this report.

122328

Figure 2. TORSION TESTER.

Shear Strain

When a cylindrical specimen is placed in a pure shearing mode, the principal axes for linear strain are at ± 45 degrees to the axis of rotation. This relationship is shown in the Mohr's circle analysis in Appendix A. The strain along one of the principal axes is positive (tension); along the other axis it is negative (compression). The sum of the magnitudes of these two strains will equal the magnitude of the shear strain in the specimen (see Appendix A).

Shear strain for the tests discussed in this report was measured by attaching a 90-degree, stacked, rosette-type strain gage to the specimen so that the sensing elements of the gages were at ± 45 degrees to the axis of rotation (see Figure 3). (The gages had a 120-ohm resistance and were mounted using an epoxy cement.)

The gages were then connected in the wheatstone bridge arrangement shown in Figure 4. The output of the wheatstone bridge is the algebraic sum of the two

Figure 3. STRAIN GAGE INSTALLATION.

strains and, ignoring the sign, is equal to the shear strain in the specimen. The output is amplified using a standard strain signal amplifier.

Signal Conditioning

The torque and strain data obtained directly from the test are in the form of analog signals which are continuous. The signals must be fed through an analog-to-digital (A/D) converter, and transformed into a digital form before they can be fed into the computer. A block diagram of the basic hardware needed to get the signals into the computer is presented in Figure 5.⁽²⁾

Before the signals can be fed into the A/D converter, they must be "conditioned" to match the electrical characteristics of the converter. For example, the A/D converter used in this study requires input signals that vary from 0 to -10 volts. Instrumentation to accomplish this "conditioning" was designed and built at the Y-12 Plant (see Figure 6). This instrument is basically a DC amplifier. The levels of the input torque and strain signals are shifted and caused to vary from 0 to -10 volts, and the impedance of the system is matched.

Figure 4. WHEATSTONE BRIDGE ARRANGEMENT FOR THE TORSION TESTS.

Figure 5. SIGNAL CONDITIONING BASIC HARDWARE.

Analog-to-Digital Conversion

Time-division multiplexing is used in this system. The A/D converter and multiplexer are tied directly into the digital computer. The output of the converter is fed into the accumulator register. One hundred and twenty-eight data points each of stress and strain are recorded at designated intervals. The number of data points and the intervals are controlled in the software package. For example, if more data points are desired in the elastic portion of the curve, the intervals can be programmed to be smaller in this region.

Figure 6. SIGNAL CONDITIONER.

The multiplexer allows the computer to monitor more than one signal input at a time. After the data point from one channel is recorded and stored in the computer's memory, the multiplexer will switch to the other channel and a data point will be recorded from it. Because of the interval involved in switching from one channel to the other, the torque and strain data points are not recorded at exactly the same time. This time interval, which is on the order of a few microseconds, is insignificant for tests of this type, which are conducted at a test rate of about 4.5 degrees of rotation per minute. (This value is equivalent to a strain rate of approximately 0.004 inch per inch per minute.) The time interval could become a factor on very fast tests.

Data are recorded and stored in the computer's memory as the test is being conducted. The data points are simultaneously displayed on an oscilloscope in the form of a stress-strain curve. These tests are not conducted to failure, but are stopped at a maximum of four percent strain; therefore, it is necessary to let the computer know when a test is completed, or several false data points can be recorded at the end of the test. This problem was solved by installing a switch which, when operated, grounds out the input signals to the computer (see Figure 6). This loss of signal lets the computer know that the test has been completed, and the computer then disconnects from the A/D converter and begins the calculations.

Software

The programming language used was PAL III (see Figure 7). A floating-point package was used to convert the data from binary to decimal. The mathematical equations and techniques used in the software to determine the shear mechanical properties are discussed in Appendix B.

The general program outline is given in Figure 8.⁽²⁾ Data are converted from binary to the decimal form. The raw data input of torque and strain are converted to shear stress and strain, and the shear mechanical properties are calculated. The properties determined are: offset yield strength, shear modulus, and energy of the test. As the properties are calculated, the results are typed out on a report form (Figure 9) located on the teletypewriter (Figure 10) and are punched on an eight-bit binary paper tape. In addition, the stress-strain data points that were sampled are printed out on the report form (see Figure 11).

Torque is converted to shear stress by using the equation for shear stress for a hollow cylinder given in Table 1. The programming is straightforward, but certain information such as the specimen dimensions must be fed into the computer before it can make these calculations. This information, which is fed into the computer prior to beginning the test, is referred to as "initial data".


```

/ PROGRAM CONTROL ROUTINE
PCF = 6022
*4000

4000 6042 EXEC, TCF / CLEAR TTY PUNCH FLAG
4001 6012 RRB / CLEAR HIGH SPEED READER FLAG
4002 6032 KCC / CLEAR TTY KEYBOARD FLAG
4003 6022 PCF / CLEAR HIGH SPEED PUNCH FLAG
4004 7200 CLA
4005 1377 TAD (200)
4006 6046 TLS
4007 4264 JMS LEADER / GENERATE 64-200 CODE
4010 1376 TAD (215)
4011 4134 JMS 7 WRITE
4012 1375 TAD (204) / EOT START TEST NOTICE
4013 4134 JMS Z WRITE
4014 4716 JMS I INFORM / INITIAL INFORMATION
4015 4730 7000 JMS I INPUT / INTERPRET INPUT CODE & TAKE DATA
4016 4727 JMS I FLOAT / PUT DATA INTO FP
4017 1105 TAD Z HIGH
4020 7650 SNA CLA / IS IT HIGH MAG?
4021 5241 JMP HIMAG / YES
4022 1101 TAD Z COMP / NO
4023 7640 SZA CLA / IS IT 2L?
4024 5230 JMP NOLOCO / NO
4025 1374 TAD (-17) / YES, 15 LF'S
4026 4120 JMS Z SPACE
4027 5235 JMP LOCOM
4030 1373 NOLOCO, TAD (-13)
4031 4120 JMS Z SPACE / 11 LF'S
4032 4726 JMS I ULTSTR / ULTIMATE STRENGTH
4033 1372 TAD (-4)
4034 4120 JMS Z SPACE
4035 4721 LOCOM, JMS I AREA2 / AREA TO END OF TEST
4036 1371 TAD (-3)
4037 4120 JMS Z SPACE
4040 5300 JMP ELONG
4041 1370 HIMAG, TAD (-7)
4042 4120 JMS Z SPACE
4043 4724 JMS I MODULUS / ELASTIC MODULUS
4044 1367 TAD (-2)
4045 4120 JMS Z SPACE
4046 4725 JMS I YIELD / OFFSET YIELD STRENGTH
4047 1367 TAD (-2)
4050 4120 JMS Z SPACE
4051 7040 CMA
4052 1100 TAD Z TENSION
4053 1102 TAD Z BEAR
4054 7650 SNA CLA / IS IT TENSION OR BEARING?
4055 4723 JMS I TENULT / YES, ULTIMATE STRENGTH
4056 1367 TAD (-2)
4057 4120 JMS Z SPACE
4060 4720 JMS I AREA1 / ENERGY TO YLD PT
4061 1366 TAD (-5)
4062 4120 JMS Z SPACE
4063 5300 JMP ELONG
4064 0000 LEADER, 0
4065 7200 CLA
4066 1365 TAD (-100)
4067 3317 DCA NUMBER

```

Figure 7. EXAMPLE OF PROGRAMMING LANGUAGE.

Figure 8. OUTLINE OF THE GENERAL PROGRAM.

There are two types of initial data—necessary and informative. Necessary data for these tests include the specimen dimensions (ID and OD), torque range, strain range, and type of test being conducted. It is necessary to indicate the type of test because this system is capable of performing more than one type.⁽²⁾ The informative data can be any additional information that may be desired to have recorded with the test data. Examples of this type of data are: specimen identity, test temperature, and type material (see Figure 9).

Y-12 PHYSICAL TESTING DEPARTMENT MATERIALS PROPERTIES REPORT

Ø3LG-Ø3ØØ-1	IDENTIFICATION		
1.ØØ	PLATE THICKNESS (IN)		
AL-7Ø79-T651	MATERIAL	ROLLING DIRECTION	
.5	HRS	° F (CONDITIONING)	
RT	TEST TEMPERATURE (° F)		
Ø.248	SPECIMEN DIMENSION (IN)		
2ØØØØ	FULL SCALE STRAIN (μ IN/IN)		
1ØØ	FULL SCALE LOAD (LBS)		
4H	TYPE TEST	1. TENSION	H. HIGH
		2. COMPRESSION	L. LOW
		3. BEARING	
		4. TORSION	
		5. DOUBLE SHEAR	
+ 3.97	ELASTIC MODULUS (PSI X 10^6)		
+37445	OFFSET YIELD STRENGTH (PSI)		
	ULTIMATE STRENGTH (PSI)		
+ 251.37	ENERGY TO YIELD POINT (IN LBS/IN ³)		
	ENERGY TO END OF TEST (IN LBS/IN ³)		
	% ELONGATION		
	% REDUCTION IN AREA		
	UPPER YIELD STRENGTH (PSI)		

COMMENTS:

Figure 9. ACTUAL REPORT FORM. (Initial Data and Properties)

These initial data are typed using the teletypewriter keyboard prior to beginning the test. This task becomes surprisingly easy after the operator gains a little experience. Some of the initial data can be automated. For example, the torque range can be wired into the computer as a part of the interfacing. Then, signals from the test machine will indicate to the computer what torque range is being used.

122325

Figure 10. TELETYPEWRITER AND COMPUTER.

It is a good idea to control as many operations as possible with the software because it gives the system more flexibility and makes it easier and less expensive to make modifications.

CONDUCTING THE TEST

The test system is shown in Figure 12. The following summary describes the steps an operator must go through in order to perform a test.

The test is set up manually, and the initial data are typed in from the keyboard. The torque and strain signals are initialized and the test begun. The test is also controlled manually. By observing the oscilloscope display, the operator can tell if the data are getting into the computer and also observe the shape of the stress-strain curve as the test is being conducted. At the completion of the test, the operator presses the "stop" button on the signal conditioner. This

+	.00	+	.00	+30734.50	+ 7605.08
+	197.01	+	97.75	+31128.54	+ 7741.93
+	541.79	+	215.05	+31571.83	+ 7878.78
+	1083.58	+	351.90	+32064.37	+ 7996.08
+	1576.12	+	469.20	+32507.65	+ 8113.39
+	2117.92	+	586.51	+32704.67	+ 8211.14
+	2511.95	+	684.26	+33000.19	+ 8328.44
+	3004.49	+	801.56	+33344.97	+ 8465.29
+	3447.78	+	918.86	+33689.74	+ 8582.59
+	3841.81	+	1016.61	+33985.26	+ 8699.90
+	4334.35	+	1153.47	+34231.55	+ 8836.75
+	4876.14	+	1251.22	+34477.81	+ 8914.95
+	5171.67	+	1388.07	+34674.84	+ 9032.25
+	5861.22	+	1485.82	+34871.85	+ 9149.55
+	6107.49	+	1583.57	+35265.88	+ 9305.95
+	6452.27	+	1700.87	+35561.40	+ 9423.26
+	6846.31	+	1798.63	+35610.65	+ 9521.01
+	7289.59	+	1915.93	+35807.66	+ 9638.31
+	7929.89	+	2033.23	+35807.66	+ 9755.61
+	8323.92	+	2150.53	+36004.68	+ 9872.92
+	8717.96	+	2267.83	+36152.45	+ 9990.22
+	9407.51	+	2385.14	+36250.96	+10127.07
+	9752.29	+	2482.89	+36497.24	+10244.37
+	10047.82	+	2600.19	+36546.48	+10400.77
+	10491.10	+	2697.94	+36792.76	+10518.08
+	11032.90	+	2834.79	+36891.26	+10654.93
+	11476.18	+	2952.10	+36989.77	+10791.78
+	12017.98	+	3069.40	+37088.28	+10948.18
+	12559.77	+	3186.70	+37186.78	+11045.93
+	13101.56	+	3284.45	+37186.78	+11163.24
+	13446.34	+	3401.75	+37334.54	+11300.09
+	13988.14	+	3519.06	+37433.06	+11456.49
+	14431.43	+	3636.36	+37482.31	+11593.34
+	14825.46	+	3773.21	+37580.82	+11749.75
+	15515.01	+	3890.51	+37728.57	+11906.15
+	16007.55	+	4027.36	+37827.09	+12062.55
+	16450.84	+	4144.67	+37925.60	+12179.85
+	16992.63	+	4281.52	+38024.10	+12316.71
+	17534.43	+	4379.27	+37974.85	+12414.46
+	18026.96	+	4535.67	+38122.61	+12551.31
+	18716.53	+	4672.53	+38122.61	+12668.61
+	19209.06	+	4789.83	+38270.37	+12805.47
+	19701.60	+	4926.68	+38418.13	+12961.87
+	20292.65	+	5043.98	+38467.39	+13079.17
+	20686.68	+	5180.83	+38565.90	+13216.02
+	21228.48	+	5317.69	+38565.90	+13352.87
+	21918.04	+	5434.99	+38713.66	+13470.18
+	22213.56	+	5571.84	+38713.66	+13607.03
+	22853.86	+	5689.14	+38762.91	+13724.33
+	23346.40	+	5806.45	+38861.42	+13880.74
+	23838.94	+	5923.75	+38959.93	+13998.04
+	24380.74	+	6060.60	+38959.93	+14115.34
+	24971.78	+	6177.90	+39009.19	+14232.65
+	25415.07	+	6295.20	+39107.69	+14349.94
+	25858.36	+	6451.61	+39255.45	+14506.35
+	26400.15	+	6549.36	+39206.20	+14682.30
+	26744.92	+	6666.66	+39255.45	+14799.60
+	27385.24	+	6823.06	+39304.70	+14936.45
+	28074.79	+	6940.37		
+	28468.82	+	7057.67		
+	29010.61	+	7174.97		
+	29355.40	+	7272.72		
+	29798.68	+	7390.02		
+	30241.97	+	7507.33		

Figure 11. ACTUAL REPORT FORM. (Stress-Strain Points)

125739

Figure 12. TORSION TEST SYSTEM.

action transmits a signal to the computer, signifying the end of the test. The computer then disconnects from the A/D converter and begins the calculations. All data are printed out on a report form on the teletypewriter. In addition, an x-y plot of the torque versus strain is obtained which is independent of the computer operation (see Figure 5).

Calibration

The torsion tester is calibrated with a system of lever arms and dead weights; the strain system is calibrated with precision-type shunt resistors. The method for determining the size of the shunt resistors is explained in Appendix C.

Error

The specimen should be in pure shear during the test and no bending moments should be introduced; therefore, looseness and backlash should be minimized

Figure 13. STRESS-STRAIN CURVE. (Test 10)

in the holding fixtures and test machine. One method for accomplishing this goal is to mount strain gages on a sample specimen and use it to check for bending moments. Another technique is to mount three strain gages on a specimen and determine if the actual principal strain axes are at ± 45 degrees to the axis of rotation.

Errors can result if the specimens are not uniform and symmetric. This condition can be checked by having each specimen dimensionally inspected prior to testing. An alternative is to check a sufficient number of specimens to establish a statistical confidence level about their quality.

The strain gages, used in the test, should be mounted at exactly ± 45 degrees to the principal axis of the specimen. This error can be reduced by using stacked biaxial gages, mounted perpendicular to each other in the same backing. After the gages are attached to the specimen, the angle error can be checked with an optical microscope. An angle error of 4 degrees can cause approximately a one percent error in the strain measurement (see Appendix A).

The relative accuracy of the data output from the computer was checked by comparing it to hand-calculated data from the torque-strain curve until confidence was established in the computer system. The torque-strain curve is obtained independently of the computer operations (see Figure 5).

ADVANTAGES AND DISADVANTAGES

The biggest advantage gained from using the computer is in the time saved in performing the calculations, and in preparing the test report. The actual testing time is increased slightly, primarily due to typing in the initial data. However, the slight increase is greatly offset by the time saved, and the result is an average time savings of approximately thirty minutes per test. Considerable time savings are best realized when a large number of similar tests are being conducted.

A knowledge of binary and octal numbers is needed, and the operator must become familiar with the controls and operation of the computer. A little experience is required, also, to be able to type in data from the teletypewriter, even if the "one-finger" technique is used. It has been found that these obstacles are fairly easy to surmount once the technician overcomes his initial fear of the system.

Because data are obtained in a digital form, they can be fed into a larger computer and the number of ways in which data can be processed is practically unlimited since they can be stored on magnetic tape. For example, a stress-strain curve can be plotted (see Figure 13), a stress-strain equation can be calculated, the area under the stress-strain curve or energy of the test can be determined, and statistical analyses can be made. These are but a few of the operations that can be performed with the data.

It would be desirable to be able to perform the operations just mentioned in the processor computer, but the limited memory space available makes this virtually impossible. In fact, considerable care must be exercised in programming the small computer to be sure that the available memory space is used as efficiently as possible. This difficulty poses no real threat to obtaining the normal data that are obtained from a test of this type. For example, all of the calculations, displays, and data output (Figures 9 and 11) for the tests performed in this report were accomplished on a small computer that has only 4,096 memory locations using a 12-bit word. The available memory space problem comes from the fact that since there are so many new operations that can be performed on the data, it is difficult to stop adding them to the software.

CONCLUSIONS

A digital computer can be interfaced to a standard torsion test machine and: (1) be used to record and store the data, (2) perform all calculations necessary for determining the shear mechanical properties, (3) provide additional data such as a shear stress-strain curve and the energy of the test that would be difficult to obtain by any other method, (4) print the results out on a data form on the teletypewriter that can be used as a final report form, and (5) provide a time savings in the overall testing program.

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APPENDIX A

AN ANALYSIS OF SHEAR STRAIN MEASUREMENT

Strain gages measure only linear strains; ie, tension or compression. A strain gage is designed to provide a change in resistance that is proportional to its change in length. The change in length in the strain gage, if it is properly connected, will be proportional to the strain in the specimen. By instrumenting the strain gage circuit in accordance with the theory of Ohm's law, an electrical signal can be produced that is proportional to the strain in the specimen.

Linear strain involves primarily a change in dimension and therefore is easily measured using strain gages; shear strain involves an angular change and is not so easily measured.

If a cylindrical specimen is placed in torsion, shear strains will exist in the planes parallel and perpendicular to the axis of the cylinder or axis of rotation. But, along the principal axes, which occur at ± 45 degrees to the axis of the cylinder, only tension and compressive strains will exist.

If strain gages are placed at ± 45 degrees to the specimen's axis, and if the gages are properly connected in a wheatstone bridge circuit (see Figures 3 and 4), then the output of the wheatstone bridge will be proportional to the shear strain in the cylindrical specimen. This theory will be briefly discussed in the section that follows.

Analysis of Mohr's Circle

Mohr's circle is a very helpful tool that can be used in the study of linear and shear strains. The circle is developed as follows:

1. The general equation for linear strain:

$$\epsilon_{\theta} = \frac{\epsilon_x + \epsilon_y}{2} + \frac{\epsilon_x - \epsilon_y}{2} \cos 2\theta + \frac{\gamma_{xy}}{2} \sin 2\theta. \quad (A-1)$$

2. The corresponding general equation for shear strain:

$$\gamma_{\theta} = (\epsilon_x - \epsilon_y) \sin 2\theta + \gamma_{xy} \cos 2\theta, \text{ and}$$

$$\gamma_{\theta/2} = \gamma_{xy/2} \cos 2\theta - \frac{\epsilon_x - \epsilon_y}{2} \sin 2\theta. \quad (A-2)$$

3. Squaring Equations A-1 and A-2 and adding them together gives:

$$\left(\epsilon_\theta - \frac{\epsilon_x - \epsilon_y}{2}\right)^2 + \frac{\gamma_\theta^2}{4} = \left(\frac{\epsilon_x - \epsilon_y}{2}\right)^2 + \frac{\gamma_{xy}^2}{4}. \quad (\text{A-3})$$

Equation A-3 is the equation of a circle of the form: $(x - h)^2 + y^2 = r^2$, see Figure A-1. The axes of the circle are ϵ and $\gamma/2$, the center is at the point $\left(\frac{\epsilon_x + \epsilon_y}{2}, 0\right)$, and the radius is: $\frac{1}{2} \left[(\epsilon_x - \epsilon_y)^2 + \gamma_{xy}^2 \right]^{\frac{1}{2}}$. This circle is known as Mohr's circle of strain.

Every point on the circle gives two values, one for linear strain and the other for shear strain divided by two. The maximum and minimum linear strains, ϵ_1 and ϵ_2 , are the points where the circle cuts the ϵ axis.

The magnitudes of the principal linear strains, ϵ_1 and ϵ_2 , can be determined by examining Figure A-1. The magnitude of ϵ_1 is the distance to the center of the circle plus the radius; the magnitude of ϵ_2 is the distance to the center of the circle minus the radius, or:

Figure A-1. MOHR'S CIRCLE OF STRAIN.

$$\epsilon_1 = \frac{\epsilon_x + \epsilon_y}{2} + \frac{1}{2} \left[(\epsilon_x - \epsilon_y)^2 + \gamma_{xy}^2 \right]^{\frac{1}{2}}, \text{ and} \quad (\text{A-4a})$$

$$\epsilon_2 = \frac{\epsilon_x + \epsilon_y}{2} - \frac{1}{2} \left[(\epsilon_x - \epsilon_y)^2 + \gamma_{xy}^2 \right]^{\frac{1}{2}}. \quad (\text{A-4b})$$

If Equation A-1 is differentiated with respect to θ and the result set equal to zero, the following equation will result:

$$\tan 2\theta = \frac{\gamma_{xy}}{\epsilon_x - \epsilon_y}, \quad (\text{A-5})$$

which can be used to determine the directions of the principal axes of strain. This equation has two solutions which are 90 degrees apart, or 180 degrees apart for 2θ . The directions of the principal strain axes can be determined from Equation A-5, but the solutions do not specify which is algebraically larger. This relationship can be determined from Mohr's circle or from a knowledge of the way the specimen deforms.⁽³⁾

In the case of pure shear, there will be no linear strains along the x and y axes, therefore ϵ_x and ϵ_y will vanish. Using this fact in Equation A-5, the values for θ can be determined as follows:

$$\tan 2\theta = \frac{\gamma_{xy}}{0} = \infty, \text{ then}$$

$$2\theta = 90^\circ \text{ or } 270^\circ, \text{ and}$$

$$\theta = \pm 45^\circ. \quad (\text{A-6})$$

This result shows that for the case of pure shear, the principal axes for linear strain are at ± 45 degrees to the axis of rotation. (θ is measured positive in the anticlockwise direction.)

Examining Equations A-4a and A-4b for the case of pure shear, where ϵ_x and ϵ_y vanish, gives:

$$|\epsilon_1| = \frac{\gamma_{xy}}{2} \text{ and } |\epsilon_2| = \frac{\gamma_{xy}}{2}, \text{ then}$$

$$|\epsilon_1| + |\epsilon_2| = \gamma_{xy}. \quad (\text{A-7})$$

Therefore, the sums of the absolute values of the magnitudes of the linear strains along the principal axis will equal the magnitude of the shear strain.

The previous analysis shows that if a symmetrical specimen is tested, if two strain gages are placed at ± 45 degrees to the axis of rotation, and if the magnitudes of the strains are added in the wheatstone bridge network, the output of the bridge will be equal to the shear strain in the specimen.

Angle Error in the Gage Location

The output of the wheatstone bridge represents the algebraic sum of the linear strains measured by the two strain gages. Recalling that ϵ_x and ϵ_y will vanish in the case of pure torsion, and examining Equation A-1 for linear strain, it is seen that:

$$2\epsilon_\theta = \gamma_{xy} \sin 2\theta.$$

Therefore, if it is assumed that the specimen is perfectly symmetrical and that a pure torsion test exists, then the strain gages must be placed at exactly ± 45 degrees for the shear strain to equal twice the linear strain. The error then, in misplacing the strain gages, will be a function of the sine of twice the angle.⁽⁴⁾

For example, if there was a four-degree error in the location of the strain gage, the output of the wheatstone bridge would be:

$$2\epsilon_\theta = \gamma_{xy} \sin 82^\circ = 0.990 \gamma_{xy}$$

and the result would be a 1.0 percent error in the shear strain measurement.

It should be noted that, since the strain gages used were 90-degree rosettes, the principal measuring axes will remain perpendicular regardless of the way the gage is located on the specimen. An error of four degrees then will result in a positive-angle error in one gage and a minus-angle error in the other gage. One gage will be located at 41 degrees to the axis of rotation and the other gage will be located at 49 degrees. Equation A-8 involves the sine of twice the angle; therefore, since work is done around the angle of 45 degrees, it does not matter which angle is used in the error calculation. This fact can be shown as follows:

Let:

$$\theta' = 45^\circ \pm \alpha,$$

where α is the angle error in the gage location.

Then:

$$\sin 2\theta' = \sin 2(45^\circ \pm \alpha), \text{ and} \quad (\text{A-8})$$

$$\sin (90^\circ \pm 2\alpha) = \cos 2\alpha.$$

APPENDIX B

EQUATIONS AND TECHNIQUES USED IN SOFTWARE

The software used for data acquisition and reduction in torsion testing performs four basic calculations: (1) it converts torque to shear stress using the equation for a hollow cylinder (see Table 1), (2) it calculates the shear modulus, (3) it calculates the yield strength at 0.2 percent offset, and (4) it calculates the energy to the yield point.

The calculations are made using the theory for the best fit of a straight line.⁽⁵⁾ The equation for a straight line is:

$$Y = a + bX,$$

where:

a represents the intercept on the Y axis, and

b the slope of the line.

The shear modulus is the slope of the linear portion of the shear stress-strain curve. Therefore, letting X represent the strain axis and Y the stress axis, the shear modulus can be determined by:

$$\text{Shear Modulus} = \frac{k \sum (X_n Y_n) - \sum X_n \sum Y_n}{k \sum X_n^2 - (\sum X_n)^2}. \quad (\text{B-1})$$

This calculation involves only the data points along the linear portion of the curve (see Figure B-1), and the number of points used may be arranged to fit the material being tested. Usually between ten and fifteen points are sufficient.

The yield strength at the 0.2 percent offset (Figure B-1) is determined using Equation B-5. The values of the Y intercept and modulus are required for this approximation. The modulus is determined by Equation B-1; the Y intercept is determined using the equation:

$$\text{Y Intercept} = \frac{\sum X_n^2 \sum Y_n - \sum X_n \sum (X_n Y_n)}{k \sum X_n^2 - (\sum X_n)^2}. \quad (\text{B-2})$$

Figure B-1. SHEAR STRESS-STRAIN CURVE.

A theoretical strain value (X'_n) is determined, using the stress values of the data points located in computer memory along with the calculated Y intercept and modulus, thus:

$$\text{Theoretical Strain} = X'_n = \frac{Y_n - Y \text{ Intercept}}{\text{Modulus}}. \quad (\text{B-3})$$

Each theoretical value is then compared with the true strain value (X_n), located in the computer memory, as follows:

$$(X_n - X'_n - 0.2\%) > 0. \quad (\text{B-4})$$

Once Equation B-4 becomes positive, the yield point is approximated from the last two data points used in the comparison.

The 0.2% offset yield strength is then determined as follows:

$$\text{Yield Strength} = \left(\frac{Y_n - Y_{n-1}}{X_n - X_{n-1}} \right) (X'_n + 0.2\% - X_{n-1}) + Y_{n-1}. \quad (\text{B-5})$$

The energy to the yield point is the area under the curve to this point. The value is determined through summation of the areas of the trapezoids formed by the data points using the following equation:

$$\text{Area to Yield Point} = \frac{1}{2} \sum (Y_{n-1} + Y_n) (X_{n+1} - X_n). \quad (\text{B-6})$$

In these equations, k represents the total number of pairs of values sampled. All summations are taken from $n = 1$ to $n = k$.

APPENDIX C

SHUNT RESISTANCE FOR STRAIN CALIBRATION

It is often desirable to check a strain circuit by applying a known amount of strain at the input and calibrating to get the same value at the output of the circuit. When testing specimens, it is usually impractical or undesirable to produce a real strain in the specimen to make this check; therefore, some virtual strain must be generated. The shunt-resistance method is a good technique for producing this calibration strain.⁽⁶⁾ The method is to place a shunt resistance in parallel with the leg of the wheatstone bridge that contains the strain gage, as indicated in Figure C-1.

Figure C-1. SHUNT RESISTOR.

There are several advantages to using a fixed resistor for the shunt. The resistance is not likely to change, provided the environmental conditions remain stable, and the possible error due to "knob twisters" is eliminated. High-precision, fixed resistors are also more readily available and less expensive to buy than equivalent variable resistors.

The method for determining the value of the shunt resistance is developed in the statements that follow.

The gage factor (GF) of a strain gage is:

$$GF = \frac{\Delta R/R_g}{\Delta l/l} = \frac{1}{\epsilon} \frac{\Delta R}{R_g}, \quad (C-1)$$

where:

R_g represents the resistance of the gage,

ϵ the strain,

l the gage length,

ΔR the change in resistance, and

Δl the change in gage length.

The resistance, R_g , is balanced out in the wheatstone bridge and only the change in resistance, ΔR , is observed.

If a fixed accurate resistance, R , is connected in parallel with the gage resistance, R_g , the new resistance, R_t , of the bridge leg will be:

$$R_t = \frac{R_g R}{R_g + R}. \quad (C-2)$$

The change in resistance, ΔR , then will be:

$$\Delta R = R_g - R_t,$$

where:

$$\Delta R = R_g - \frac{R_g R}{R_g + R}, \text{ and}$$

$$\Delta R = R_g \left(\frac{R_g}{R_g + R} \right). \quad (C-3)$$

Recall that in a wheatstone bridge, R_g is balanced out and only ΔR is observed; therefore, substituting this value for ΔR (Equation C-3) into the equation for the gage factor (Equation C-1) gives:

$$GF = \frac{1}{\epsilon} \frac{\Delta R}{R_g} = \frac{1}{\epsilon} \left(\frac{R_g}{R_g + R} \right).$$

Then:

$$R_g + R = \frac{1}{\epsilon} \frac{R_g}{GF}, \text{ or}$$

$$R = R_g \left[\frac{1}{GF} \left(\frac{1}{\epsilon} \right) - 1 \right], \text{ and}$$

$$R = R_g \left[\frac{1 - GF (\epsilon)}{GF (\epsilon)} \right]. \quad (C-4)$$

Equation C-4 gives the value for shunt resistance for a particular strain if the gage factor and the gage resistance are known. R and R_g are expressed in ohms and ϵ is expressed in inches per inch. GF is a constant.

The gage factor and gage resistance are furnished by the manufacturers of all strain gages; therefore, Equation C-4 is an easy one to solve, as shown in the example to follow.

Example

Assume $GF = 2.0$, $R_g = 120$ ohms, and $\epsilon = 0.001$ in/in, Equation C-4 gives a resistance value of:

$$R = 120 \left[\frac{1 - 2 (0.001)}{2 (0.001)} \right], \text{ or}$$

$$R = 120 \times 499 = 59,880 \text{ ohms.}$$

The shunt resistance for other strain values can be derived in a similar manner. Table C-1 was constructed using the gage factor and gage resistance used in the example.

Table C-1

SHUNT RESISTANCES AT VARIOUS STRAINS

Strain (μ in/in)	Shunt Resistance (ohms)
100	599,880
1,000	59,880
10,000	5,880
100,000	480

REFERENCES

- (1) Poorman, A. P.; Strength of Materials; McGraw-Hill Book Company, New York, NY (1945).
- (2) Smith, J. H.; Application of a Digital Computer to Mechanical Testing, Y-1663; Union Carbide Corporation-Nuclear Division, Oak Ridge Y-12 Plant, Oak Ridge, Tennessee; February 27, 1969.
- (3) Murray, W. M.; Stress and Strain Relations, Part of a Series of Lectures Presented at the University of Houston, March 23-26, 1970.
- (4) Poore, M. W.; The Effect of Angular Variation of Strain Gages on the Shear Modulus, Y-DL-28; Union Carbide Corporation-Nuclear Division, Oak Ridge Y-12 Plant, Oak Ridge, Tennessee; November 15, 1968.
- (5) Beers, Y.; Introduction to the Theory of Error; Addison-Wesley Publishing Company, Reading, Mass (1957).
- (6) Perry, C. C. and Lissner, H. R.; The Strain Gage Primer; McGraw-Hill Book Company, New York, NY (1962).

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