STEEL LAB

The steel lab consists of two weeks of tension tests conducted on specimens machined from a batch of 3/4 inch diameter normalized 1020 steel rods. Week One: Ten student lab groups each conducted two replicate tension tests, each employing a conventional (nominally) 0.505 inch diameter threaded specimen. Week Two: The same ten student lab groups (i) first conducted two replicate tension tests employing a threaded specimen with a sharp V-shaped circumferential groove at its mid-length, and (ii) stopping a third tension test just prior to failure to demonstrate that a crack originates at the root of the sharp V-shaped circumferential groove and slowly grows inward toward the center of the specimen.

CONVENTIONAL 0.505 INCH DIAMETER THREADED NORMALIZED 1020 STEEL (UNNOTCHED) SPECIMENS:

Table S.1. Tensile ultimate strength datum values for two replicate tension tests conducted on normalized 1020 unnotched steel specimens — calculated as the maximum load divided by the original cross-sectional area.

<table>
<thead>
<tr>
<th>student lab group</th>
<th>replicate one</th>
<th>replicate two</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>69646</td>
<td>69995</td>
</tr>
<tr>
<td>2</td>
<td>69903</td>
<td>68729</td>
</tr>
<tr>
<td>3</td>
<td>68410</td>
<td>69722</td>
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<tr>
<td>4</td>
<td>71300</td>
<td>68141</td>
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<td>5</td>
<td>68569</td>
<td>68379</td>
</tr>
<tr>
<td>6</td>
<td>72574</td>
<td>72829</td>
</tr>
<tr>
<td>7</td>
<td>70385</td>
<td>70843</td>
</tr>
<tr>
<td>8</td>
<td>68577</td>
<td>67317</td>
</tr>
<tr>
<td>9</td>
<td>70903</td>
<td>69422</td>
</tr>
<tr>
<td>10</td>
<td>70332</td>
<td>69901</td>
</tr>
</tbody>
</table>

The null hypothesis is that all student lab groups have the same effect on the median (mean) of the presumed normal tensile ultimate strength distribution, whereas the alternative hypothesis is that not all student lab groups have the same effect on the median (mean) of the presumed normal tensile ultimate strength distribution. Given the data in microcomputer file $USTUSDTA$, microcomputer program $ANOVA$ computed the null hypothesis rejection probability as 0.0224. Thus we opt to reject the null hypothesis and assert that instead the student lab group effects do differ. Accordingly, we cannot properly employ the average of all 20 datum values to estimate the actual value for the median (mean) of the presumed normal tensile ultimate strength distribution for conventional 0.505 inch diameter (unnotched) specimens machined from the given batch of normalized 1020 steel rods; nor can we properly aggregate the 9 estimated student group effects with the 10 replicate datum value effects (i) to estimate the standard deviation of this tensile ultimate strength distribution using all 20 aggregated datum
values, and (ii) in turn to compute the shortest \(100(\text{scp})\%\) (two-sided) statistical confidence interval that allegedly includes the actual value for the median (mean) of this normal tensile ultimate strength distribution.

*Remark One:* The test outcome that the *between* groups (MS) markedly exceeds the *within* groups (MS) is not surprising; rather it is the usual test outcome. On the other hand, it would have been very surprising if the *within* groups (MS) had exceeded the *between* groups (MS).

*Remark Two:* The ANOVA above pertains to a CRD experiment test program in which student group effects are regarded as treatment effects before the null hypothesis is rejected, and after as block effects. The estimate of the actual value for the median (mean) of the presumed normal distribution always includes an unknown material batch (block) effect in a CRD experiment test program (as well as typically several other aggregated block effects). Moreover, in this case, if computed the estimate would also include the respective aggregated student group (block) effects.

*Remark Three:* Given the data in microcomputer files *USSLGENT* and *USREPENT*, microcomputer program *NORTEST* computed the respective null hypothesis rejection probabilities as 0.4792 and 0.8029. Thus there is no statistical basis for concern regarding the credibility of the respective presumptions of normality. (Recall however that the statistical power for microcomputer program *NORTEST* is quite poor for detecting non-normality given a small data set).

**Fracture Appearance and Failure Mode:**

Conventional 0.505 inch diameter (unnotched) threaded specimens of normalized 1020 steel rods display the well known cup-and-cone fracture appearance in which the cup portion of the fracture surface is initiated by growth and coalescence of voids that create a center disc-shaped crack that expands in diameter until abrupt failure occurs along the circumferential shear lip that forms the cone portion of the fracture surface. Examination of the cup-and-cone failure using a scanning electron microscope indicates that the only difference between the (plane strain) cup and the (plane stress) cone is that in the voids are markedly elongated in the direction of sliding along the cone.

*Remark One:* We will demonstrate in the forthcoming Aluminum Lab that the crack that eventually leads to failure originates at the center of the specimen. (This demonstration is virtually impossible for steel tension specimens.)

*Remark Two:* Tensile failures terminate with a shear lip for a very wide range of crystalline and non-crystalline materials.
THREADED STEEL SPECIMENS NOTCHED WITH A SHARP CIRCUMFERENTIAL V-GROOVE

Table S.2. Tensile ultimate strength datum values for two replicate tension tests conducted on normalized 1020 steel specimens with a sharp circumferential V-groove notch — calculated as the maximum load divided by the original cross-sectional area at the root of the notch.

<table>
<thead>
<tr>
<th>student lab group</th>
<th>replicate one</th>
<th>replicate two</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>93000</td>
<td>93100</td>
</tr>
<tr>
<td>2</td>
<td>101000</td>
<td>93000</td>
</tr>
<tr>
<td>3</td>
<td>10200</td>
<td>91000</td>
</tr>
<tr>
<td>4</td>
<td>94000</td>
<td>104000</td>
</tr>
<tr>
<td>5</td>
<td>120500</td>
<td>125000</td>
</tr>
<tr>
<td>6</td>
<td>101500</td>
<td>104500</td>
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<tr>
<td>7</td>
<td>92500</td>
<td>92750</td>
</tr>
<tr>
<td>8</td>
<td>115500</td>
<td>101200</td>
</tr>
<tr>
<td>9</td>
<td>94500</td>
<td>94000</td>
</tr>
<tr>
<td>10</td>
<td>98000</td>
<td>96000</td>
</tr>
</tbody>
</table>

The null hypothesis is that all student lab groups have the same effect on the median (mean) of the presumed normal tensile ultimate strength distribution, whereas the alternative hypothesis is that not all student lab groups have the same effect on the median (mean) of the presumed normal tensile ultimate strength distribution. Given the data in microcomputer file NSTUSDTA, microcomputer program ANOVA computed the null hypothesis rejection probability as 0.0037. Thus we again opt to reject the null hypothesis and assert that the student lab group effects differ. Accordingly, we cannot properly employ the average of all 20 datum values to estimate the actual value for the median (mean) of the tensile ultimate strength distribution for threaded specimens with a sharp circumferential V-notch machined from the given batch of normalized 1020 steel rods; nor can we properly aggregate the estimated student group effects with the 10 replicate datum value effects (i) to estimate the standard deviation of this tensile ultimate strength distribution using all 20 aggregated datum values, and (ii) in turn to compute the shortest 100(scp)% (two-sided) statistical confidence interval that allegedly includes the actual value for the median (mean) of this normal tensile ultimate strength distribution.

Remark One: The diameter at the root of the sharp circumferential V-notch was not convenient for students to measure. Accordingly it was presumed to be 0.505 inches, viz., the cross-sectional area at the root was presumed to be exactly 0.2000 square inches. In contrast, for unnotched specimens the diameter was measured and the cross-sectional area was computed to four decimal places. In turn, when the associated tensile ultimate strength value was computed , it was recorded up to the decimal point.
Remark Two: Given the data in microcomputer files NSSLGENT and NSREPENT, microcomputer program NORTEST computed the respective null hypothesis rejection probabilities as 0.0621 and 0.5338. Thus there is a rational basis for concern regarding the statistical credibility of the presumption of normality for the student lab group effects, but there is no rational basis for concern regarding the credibility of the presumption of normality for the replicate effects.

Fracture Appearance and Failure Mode:

The tensile fracture of a threaded 1020 normalized steel specimen with a sharp circumferential V-notch is almost flat and lies in the plane of minimum cross-section. The crack that ultimately leads to abrupt failure initiates along the root (throat) of the sharp circumferential V-notch and grows slowly inward toward the center of the specimen. Visually, the fracture surface exhibits two distinct modes of failure, separated by a distinct boundary. The failure surface is much darker in the slow-growth crack region than in the abrupt, typically more or less elliptical, final fracture region. Failure surface examination using a scanning electron microscope indicates that the slow-growth crack regions is a ductile (growth and coalescence of voids) failure whereas the abrupt final fracture region is a brittle (cleavage) failure. Moreover, as illustrated below, the transition from growth and coalescence of voids to cleavage is not actually distinct, but typically is a small region consisting of mixture of these two modes of failure.

SEM micrograph 300X (Transition Region)
SEM micrograph 300X (Cleavage Region)
FILE USTUSDTA  (UNNOTCHED 1020 NORMALIZED STEEL, TENSILE ULTIMATE STRENGTH
DATA FOR ANOVA ANALYSIS, PERTAINING TO 10 STUDENT LAB
GROUPS EACH CONDUCTING 2 REPLICATE TENSION TESTS)
MICROCOMPUTER PROGRAM ANOVA (R.E.LITTLE)

This program presumes that the transpose of the relevant orthogonal augmented contrast array appears in microcomputer file ARRAY and the corresponding appropriately ordered experiment test program datum values appear in microcomputer file DATA.

Input the adjacent column vectors in the estimated complete analytical model that are aggregated to compute the desired between[est(cte`s)]SS (e.g., for columns 6 through 8, type 6 space 8)

2 10

Input the adjacent column vectors in the estimated complete analytical model that are aggregated to compute the desired within[est(CRHNDEE`s)]SS, (e.g., for columns 9 through 20, type 9 space 20)

11 20

\[
\text{Between[est(cte`s)]SS} = .3064232605D+08
\]

\[
\text{[est(cte`s)]n(sub)sdf} = 9
\]

\[
\text{Between[est(cte`s)]MS} = .3404702894D+07
\]

\[
\text{Within[est(CRHNDEE`s)]SS} = .8714156500D+07
\]

\[
\text{[est(CRHNDEE`s)]n(sub)sdf} = 10
\]

\[
\text{Within[est(CRHNDEE`s)]MS} = .8714156500D+06
\]

The data-based value of Snedecor`s central F(9,10) test statistic for the outcome of the experiment test program that was actually conducted is equal to .390709D+01.

Given the null hypothesis that the actual value(s) for the ctesc(s) of specific interest is (are) equal to zero and given that the experiment test program datum values are random, homoscedastic, and normally distributed, this data-based value of Snedecor`s central F(9,10) test statistic can statistically be viewed as having been randomly selected from Snedecor`s central F(9,10) conceptual sampling distribution. Thus the probability that a randomly selected outcome of this experiment test program when continually replicated will have its data-based value of Snedecor`s central F(9,10) test statistic equal to or greater than .390709D+01 is equal to .0224. When this probability is sufficiently small, reject the null hypothesis in favor of the composite alternative hypothesis that the actual value(s) for the ctesc(s) of specific interest is (are) not equal to zero.
10
.2765000000D+02
-.4768500000D+03
-.7268500000D+03
-.7235000000D+02
-.1318850000D+04
.2908650000D+04
.8211500000D+03
-.1855850000D+04
.3696500000D+03
.3236500000D+03
10000
317 857 555

FILE USSLGENT  (UNNOTCHED STEEL, NON-REPEATED STUDENT LAB GROUP EFFECTS FOR TESTING NORMALITY BY RUNNING MICROCOMPUTER PROGRAM NORTEST)
MICROCOMPUTER PROGRAM NORTEST (R.E.LITTLE)

The data-based value of our modified Michael`s MDSPP test statistic for the 10 replicate (allegedly replicate) datum values of specific interest is equal to .0906

This microcomputer program generated 10000 sets of 10 normally distributed replicate datum values. The number of these data sets that had our modified Michael`s MDSPP test statistic value equal to or greater than .0906 is equal to 4792. Thus, given the null hypothesis of normality, the simulation-based probability that a randomly selected set of 10 replicate datum values will have our modified Michael`s MDSPP test statistic value equal to or greater than .0906 is equal to .4792. When this probability is sufficiently small, reject the null hypothesis in favor of the (omnibus) alternative hypothesis of non-normality
FILE USREPENT (UNNOTCHED STEEL, NON-REPEATED REPLICATE EFFECTS FOR TESTING NORMALITY BY RUNNING MICROCOMPUTER PROGRAM NORTEST)
The data-based value of our modified Michael's MDSPP test statistic for the 10 replicate (allegedly replicate) datum values of specific interest is equal to .0695

This microcomputer program generated 10000 sets of 10 normally distributed replicate datum values. The number of these data sets that had our modified Michael's MDSPP test statistic value equal to or greater than .0695 is equal to 8029. Thus, given the null hypothesis of normality, the simulation-based probability that a randomly selected set of 10 replicate datum values will have our modified Michael's MDSPP test statistic value equal to or greater than .0695 is equal to .8029. When this probability is sufficiently small, reject the null hypothesis in favor of the (omnibus) alternative hypothesis of non-normality.
FILE NSTUSDTA (NOTCHED 1020 NORMALIZED STEEL, TENSILE ULTIMATE STRENGTH DATA FOR ANOVA ANALYSIS, PERTAINING TO 10 STUDENT LAB GROUPS EACH CONDUCTING 2 REPLICATE TENSION TESTS)
This program presumes that the transpose of the relevant orthogonal augmented contrast array appears in microcomputer file ARRAY and the corresponding appropriately ordered experiment test program datum values appear in microcomputer file DATA

Input the adjacent column vectors in the estimated complete analytical model that are aggregated to compute the desired between[est(c-te's)]SS (e.g., for columns 6 through 8, type 6 space 8)

\[ \begin{array}{c}
2 \\
10 
\end{array} \]

Input the adjacent column vectors in the estimated complete analytical model that are aggregated to compute the desired within[est(CRHNDDEE's)]SS, (e.g., for columns 9 through 20, type 9 space 20)

\[ \begin{array}{c}
11 \\
20 
\end{array} \]

\[
\text{Between}[\text{est}(c-te's)]SS = 0.1524096125D+10
\]

\[
[\text{est}(c-te's)]n(sub)sdf = 9
\]

\[
\text{Between}[\text{est}(c-te's)]MS = 0.1693440139D+09
\]

\[
\text{Within}[\text{est}(\text{CRHNDEE's})]SS = 0.2615312500D+09
\]

\[
[\text{est}(\text{CRHNDEE's})]n(sub)sdf = 10
\]

\[
\text{Within}[\text{est}(\text{CRHNDEE's})]MS = 0.2615312500D+08
\]

The data-based value of Snedecor's central F(9,10) test statistic for the outcome of the experiment test program that was actually conducted is equal to $0.647510D+01$

Given the null hypothesis that the actual value(s) for the ctesc(s) of specific interest is (are) equal to zero and given that the experiment test program datum values are random, homoscedastic, and normally distributed, this data-based value of Snedecor's central F(9,10) test statistic can statistically be viewed as having been randomly selected from Snedecor's central F(9,10) conceptual sampling distribution. Thus the probability that a randomly selected outcome of this experiment test program when continually replicated will have its data-based value of Snedecor's central F(9,10) test statistic equal to or greater than $0.647510D+01$ is equal to $0.0037$. When this probability is sufficiently small, reject the null hypothesis in favor of the composite alternative hypothesis that the actual value(s) for the ctesc(s) of specific interest is (are) not equal to zero.
FILE NSSLGENT (NOTCHED STEEL, NON-REPEATED STUDENT LAB GROUP EFFECTS FOR TESTING NORMALITY BY RUNNING MICROCOMPUTER PROGRAM NORTEST)
The data-based value of our modified Michael's MDSP test statistic for the 10 replicate (allegedly replicate) datum values of specific interest is equal to .1367

This microcomputer program generated 10000 sets of 10 normally distributed replicate datum values. The number of these data sets that had our modified Michael's MDSP test statistic value equal to or greater than .1367 is equal to 621. Thus, given the null hypothesis of normality, the simulation-based probability that a randomly selected set of 10 replicate datum values will have our modified Michael's MDSP test statistic value equal to or greater than .1367 is equal to .0621. When this probability is sufficiently small, reject the null hypothesis in favor of the (omnibus) alternative hypothesis of non-normality.
10
-.5000000000D+02
.4000000000D+04
.5500000000D+04
-.5000000000D+04
-.2250000000D+04
-.1500000000D+04
-.1250000000D+03
.7150000000D+04
.2500000000D+03
.1000000000D+04
10000
275 619 975

FILE NSREPENT (NOTCHED STEEL, NON-REPEATED REPLICATE EFFECTS FOR TESTING NORMALITY BY RUNNING MICROCOMPUTER PROGRAM NORTEST)
MICROCOMPUTER PROGRAM NORTEST (R.E.LITTLE)

The data-based value of our modified Michael's MDSPP test statistic for the 10 replicate (allegedly replicate) datum values of specific interest is equal to .0875.

This microcomputer program generated 10000 sets of 10 normally distributed replicate datum values. The number of these data sets that had our modified Michael's MDSPP test statistic value equal to or greater than .0875 is equal to 5338. Thus, given the null hypothesis of normality, the simulation-based probability that a randomly selected set of 10 replicate datum values will have our modified Michael's MDSPP test statistic value equal to or greater than .0875 is equal to .5338. When this probability is sufficiently small, reject the null hypothesis in favor of the (omnibus) alternative hypothesis of non-normality.
Yielding (ostensibly) occurs in a conventional tension test on 1020 normalized steel when the first Lüder’s band forms and the load drops sharply. The microhardness across this band of plastically deformed steel is relatively uniform and its axial deformation is approximately equal to the so-called yield point elongation. The remainder of the specimen remains (ostensibly) perfectly elastic, viz., the deformation on one side of the Lüder’s band is elastic and is plastic on the other side. In turn, as the elongation of the specimen increases, more and more Lüder’s bands are formed causing the load to fluctuate up and down until the entire gauge length of the specimen is plastically deformed. However, the largest load during this yield point elongation portion of the tension test is always (much) smaller than the so-called upper yield point load. Subsequently the load increases monotonically as the steel strain hardens until necking occurs.

Remark: The value of the so-called upper yield point load markedly depends on the shape of the specimen, its fillets and surface finish, and on the test machine. This load, under optimal conditions, can reach the maximum value that would occur in a conventional tension test.

The steel lab consisted of two replicate tension tests conducted on conventional 0.505 inch diameter (unnotched) threaded specimens machined from a batch of 3/4 inch diameter 1020 normalized steel rods. Subsequently, a third tension test is conducted on a properly polished specimen, but stopped (immediately) as soon as the load drops from its upper yield point value. Then visual inspection of the polished specimen will demonstrate the existence of one or more (typically a few) Lüder’s bands.

Remark One: The third unnotched 1020 normalized steel specimen should be polished as follows: first polish circumferentially using coarse emery cloth to eliminate deep machining marks and then use a finer emery cloth to polish longitudinally. In turn, use an even finer emery clock to polish circumferentially and then use an even finer emery cloth to polish longitudinally, etc., finishing by polishing in the longitudinal direction to obtain a fine (but not necessarily shiny) surface finish. (It is important use clean emery cloth and to polish by cutting not smearing.)

Remark Two: Plastic deformation is, for practical purposes, a constant volume process. Thus each Lüder’s band that forms leaves a slight but distinct depression in a properly polished surface that is clearly visible when the specimen is viewed at slight angle.

Remark Three: If the specimen is work hardened and then unloaded, Lüder’s bands will not occur upon reloading. However, given sufficient time depending on the temperature, say several weeks or more, Lüder’s bands will again be observed in a tension test on a properly re-polished specimen.
The aluminum lab consisted of two replicate tension tests conducted on conventional 0.505 inch diameter (unnotched) threaded specimens machined from a batch of 3/4 inch diameter 1100-F aluminum rods. Subsequently, a third tension test is conducted, but stopped just prior to failure. Then the necked-down portion of the specimen is sectioned longitudinally to demonstrate that the crack that eventually leads to failure initiates at the center of the specimen.

Longitudinal section through the neck of a 1100-F aluminum specimen. (The internal crack was formed by growth and coalescence of voids.)