The Development of a Truly Hands-on Torsional Strength of Materials Testing Lab

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Abstract

Traditionally, strength of materials labs include tensile testing of prepared metal samples. This is normally achieved through the use of an automated tensile testing machine with data acquisition system (hardware and software). Even though students may need to load the part into the fixture manually, during the pulling process, students are mostly reduced to the role of a passive observer. This is simply due to the fact that it is impossible for human hands to pull apart a metal piece. Some education technology providers such as PASCO, Inc. sell a hand-cranked tensile testing machine that would give students some “feel” of the strength of different materials[4]. But the equipment is not suitable for torsional testing, and the “hands-on” experience it offered is still limited. In this paper, a “quick and dirty” low-budget torsional strength testing lab has been developed that would give students maximum exposure to hands-on material testing. There is no need for special fixtures - the required equipment/tools for this lab can normally be found in any machine shop. Students will have a chance to learn some basic skills using shop tools such as a lathe, a grinder, a vise, a Vernier caliper, etc. Simple torsional load calculation is required for this lab. It can also lead to a study of industrial fasteners which normally is only briefly covered in a machine component design class in the senior year.

Weakness of this lab is that a needle-type mechanical torque wrench is not very accurate. The reading of measurements of torque and twist angles would all require some “eye-balling.” But overall, the educational experience gained through this lab is well worth it for students. It facilitates student learning of various shop tools. Some assessment data is presented at the end of the paper. A poster presentation of part of this work was previously made at the 2016 ASEE North Central regional conference[10].

Introduction

“[Students] in university or college learn all the technical basics from a theoretical point of view, but they don’t really focus on the practical implementation of those learned skills into the real world,” says Robert Hardt, CEO of Siemens Canada[1]. “If you don’t know what a million tons looks like, you should," says Gary Kramer, VP of tunnels for engineering consultants Hatch Mott MacDonald.[1] "When you can look at a truck, which weighs about 60,000 kg fully loaded, then those numbers start to make more sense to you. That's the kind of practical thing you don't learn in a book," he says.

Traditionally, strength of materials labs typically include tensile testing of metal samples. This is normally achieved through the use of an automated tensile testing machine with data acquisition system (hardware and software). Examples would include *Tinus Olson*[2] and *Instron*[3] tensile testing systems. Even though students may be allowed to load the part into the fixture manually, however, during the pulling process, students are mostly standing there watching. This is simply because it is impossible for humans to pull apart a metal piece with bare hands.

Some education technology providers such as *PASCO, Inc*., provides a hand-cranked tensile testing machine that would give students some "feel" of the strength of different materials[4]. But the equipment is costly ($2,900 for the ME-8230 model or $4,900 for the ME-8244 model) considering what limited tests could be performed by it.

Abramowitz and Elliott[12] introduced a lab for junior mechanical engineering students applying torque wrenches to the testing of torsional strength of metal fasteners. They emphasized statistical data analysis and used a specialized torsional testing fixture manufactured by *Greenslade and Company*[13]. This fixture has split collets of different sizes with internal threads on them. It can be used to hold tight the screw body in the fixture, thus allowing a torque wrench to apply torque through the head of the screw and break the screw[13]. If purchased new, the fixture would cost well over $1,000 according to Abramowitz and Elliott[12].

Nagurka and Anton[15] incorporated torque wrenches in a bolt clamping force measurement lab. Again, a specially-designed testing fixture is used to measure clamping force using turn-of-nut method. The fixture includes a bushing with a mounted strain gage. Over-torqueing of bolts are performed to observe thread damage or deformation of the clamping components. This activity has been part of a Machine Design Laboratory[15].

In this paper, a "quick and dirty" low-budget torsional lab has been developed that would give students maximum exposure to hands-on material testing. There is no need of a special fixture - the required equipment/tools for this lab are normally available in a machine shop. Through 2-3 lab periods, students will have a chance to learn basic machine shop skills such as how to run a lathe, a grinder, how to use a vise for fixturing parts and calipers to measure dimensions, etc. Simple torsional load calculation is required for this lab to help students review mechanics of materials theory and correlate theory to practice. This lab can also serve as a lead-in to the study or discussion of industrial fasteners which normally is only covered briefly in a mechanical components class. It could also be used in a typical K-12 curriculum to nurture students' interest in STEM fields.

Goals

The author had taught engineering statics for many years and it has always been a little perplexing to him that many students struggle with the basic concept of torsion. So in addition to giving students more hands-on experience of the physical activity/phenomenon called "torsion" or "torqueing," the goals of this lab are (1) measure torsional material property (yield strength, ultimate strength) for regular grade steel bolts, (2) understand the use of torsion formula in data analysis and lab planning, (3) understand the use and limitations of material properties data from engineering literature/handbooks, (4) understand that material property is a statistical phenomenon, i.e., it has a spread, (5) develop a physical sense of torque and torsional strength of mechanical parts.

<u>Learning Objectives:</u>

1. Students will be able to use a lathe (either a full size lathe or a small table-top mini-lathe) to create undercuts (i.e., to cut grooves) on metal fasteners (bolts).
2. Students will be able to use a vise to fixture parts.
3. Students will be able to use a grinder to generate flat fixture surfaces.
4. Students will be able to use the torsion formula to calculate bolt torsional stress (shear) and estimate/predict yield and ultimate shear strength.
5. Students will be able to use a torque wrench to apply torque on and eventually break a bolt.
6. Students will be able to plot shear stress vs. twist angle curve using measured data.
7. Students will be able to interpret the data/plot and correlate with handbook data and discuss sources of error.

Test Sample Preparation

For this lab, some of the test samples were obtained from a local fastener supplier FASTENAL[5]. Some were purchased from Lowes. Figure 1 shows a Zinc-plated uncut bolt sample with a hexagonal head. It is critical that a hex head bolt be used as it is used to fixture the bolt for processing such as cutting of a neck and grinding a flat surface on the threaded area. The hex head is also used for torqueing with the torque wrench through an adaptor. To control the location of where the bolt breaks, a lathe would need to be used to turn a section of the bolt shank down to a smaller size, so that the diameter of the bolt at the location of the machining/turning is the smallest, making it the weakest part of the bolt, as shown in Figure 2. Once the bolt had been machined (the width of the machined groove is not critical), the diameter of this cut-down part of the shank is measured with a caliper.

Next, we need to hold the bolt in a vise so we can break it. If we simply clamp the threaded portion of the bolt in the vise, the bolt will spin in the vise when we apply a torque to the hex head. To prevent that from happening, we need to cut or grind two small flat surfaces on opposite sides of the threaded portion of the bolt. Figure 3 shows a student grinding on a small grinder. In the background is another student cutting grooves on a mini-lathe. Now a torsional strength test is ready to be performed using a torque wrench. Two needle-type torque wrenches were provided to students, one with a load range of 0-80 in-lb and the other 0-150 ft-lb, see Figures 4a (the shorter one has the smaller torque range and the longer one has a higher torque range). These torque wrenches are normally used for measuring torque applied to a nut when you are tightening it. For example, if you are working on a cylinder head of an engine, you want to make sure each nut is tightened to the same desired torque so the head doesn't warp. There are many online videos showing people how to use this type of torque wrenches[9]. Sometimes people call this type of torque wrench as beam type torque wrench. Cost ranges from $16 to $30 per piece. For more information on the correct usage of torque wrenches, please refer to an article written by Joe Greenslade for a trade journal[14].

Figure 1 An SAE bolt as obtained from vendor

Figure 2 Bolt after neck being turned down

Figure 3 Grinding flat surfaces on the bolt body

Figure 4a Torque wrenches used (front view)

Students need to do some simple calculations using torsional formulas as shown in later part of this paper to predict maximum torque needed to break the bolt. As part of the lab planning, students should cut the groove to a size that would allow maximum use of the full range of the torque wrench. This point will be discussed more in later section of this paper.

The next step is to apply torsional torque to the bolt head through the torque wrench. A proper hex head adaptor has to be used on the torque wrench, as shown in Figures 4b and 4c. This is normally available in a standard machine shop tool chest. Once the torque wrench is locked onto the hex head of the bolt the student can manually turn the black handle while another student records the angle of twist and the applied torque. Angle of twist can be read off of a standard protractor. A protractor can be copied on a piece of paper then fixed through the bolt on the vise. See Figures 5 through 7 for this process. Typically this would require three students – one would be looking at the protractor and the other applying torque via the torque wrench and read the applied torque. A third student would help record the measurements on a notepad or a piece of paper. When applying the torque manually, students are advised to apply the torque smoothly and in one direction only. If they apply the torque back and forth, it introduces work hardening effects and would cause inaccuracy and errors when later measuring and calculating tensile strength.

Figure 4b Torque wrenches (backside)

Figure 4c Torque wrenches (the top one has a hex head socket ½” drive adaptor while the bottom one needs a ¼” drive socket adaptor)

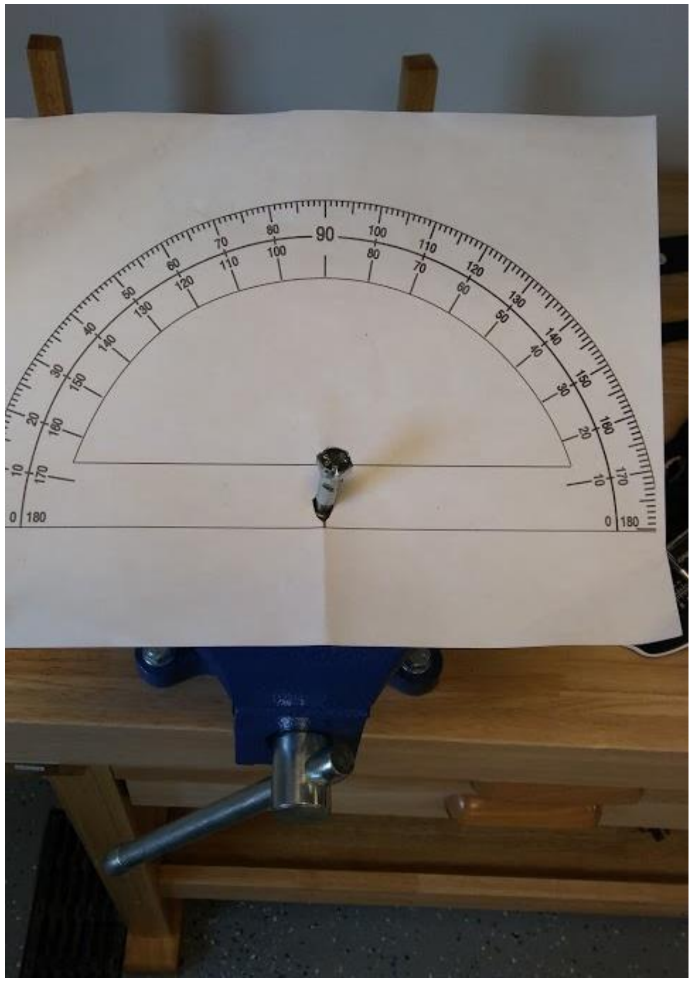

Figure 5 Protractor placed in between the bolt and the vise

Some simple calculations are needed in the data analysis stage, as well as in the selection of a proper torque wrench. To calculate torsional stress, torsion formula is needed[6],

$$\tau_{max} = \frac{Tr}{J} \qquad \text{Eq. (1)}$$

Here, τ_{max} is maximum torsion (shear) stress on the bolt, T is the applied torque on the bolt (provided by the torque wrench), r is the radius of the bolt at the breaking location (normally where the cut is) and J is the area moment of inertia along the bolt body axis. Since $J = \frac{\pi r^4}{2}$ for a solid round bar, we can rewrite the Equation (1) as

$$\tau_{max} = \frac{2T}{\pi r^3} \qquad \text{Eq. (2)}$$

In Equation (2), T and r can both be measured in the lab so a failure shear stress can be obtained by experiment. It can then be compared to the handbook data.

Figure 6 Applying torque through the torque wrench handle

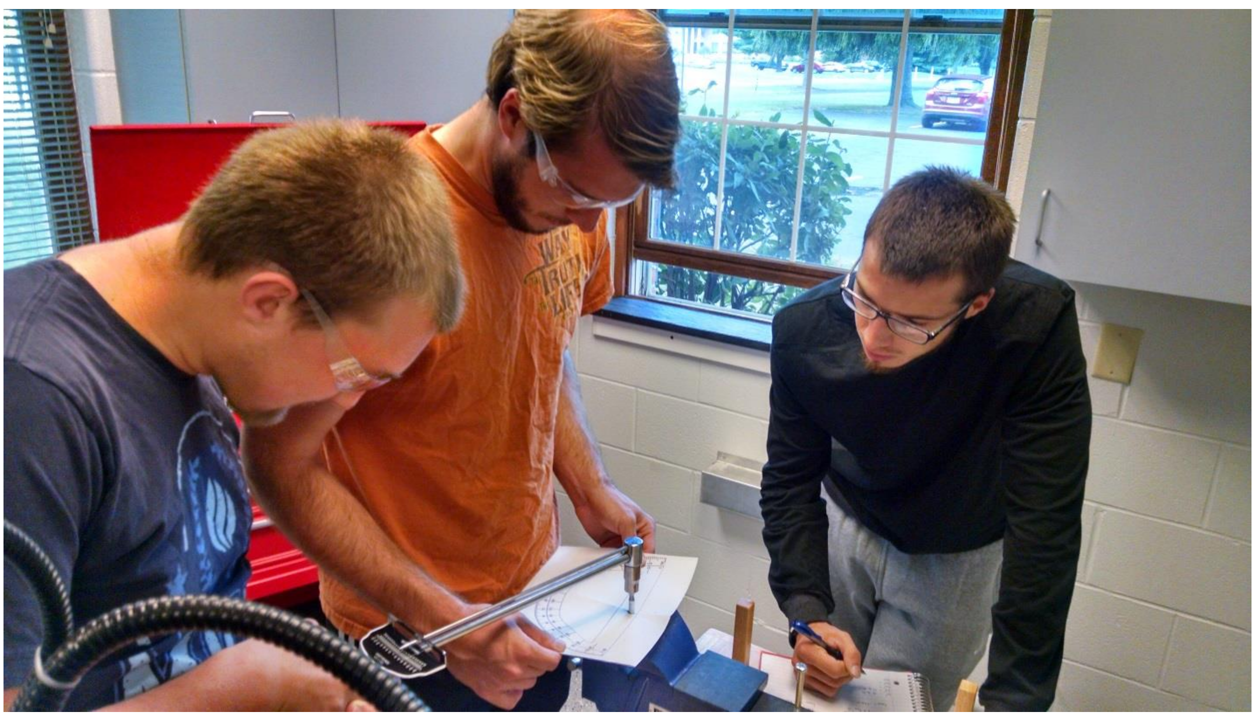

Figure 7 Recording torque applied and resulting twist angles

To obtain tensile strength, shear stress is divided by 0.577 according to strength of materials theory[7],

$$\tau_{max} = 0.577\sigma_{max} \qquad \text{Eq. (3)}$$

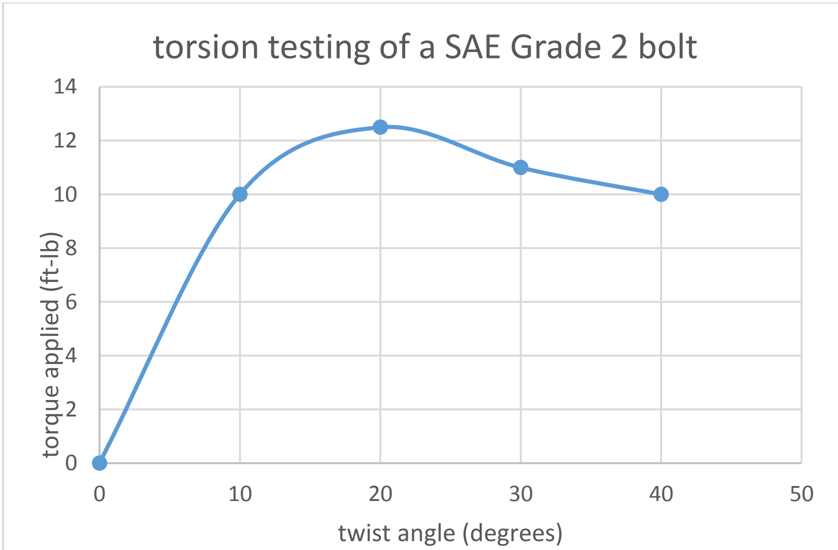

Figure 8 Torque vs. Twist Angle Curve

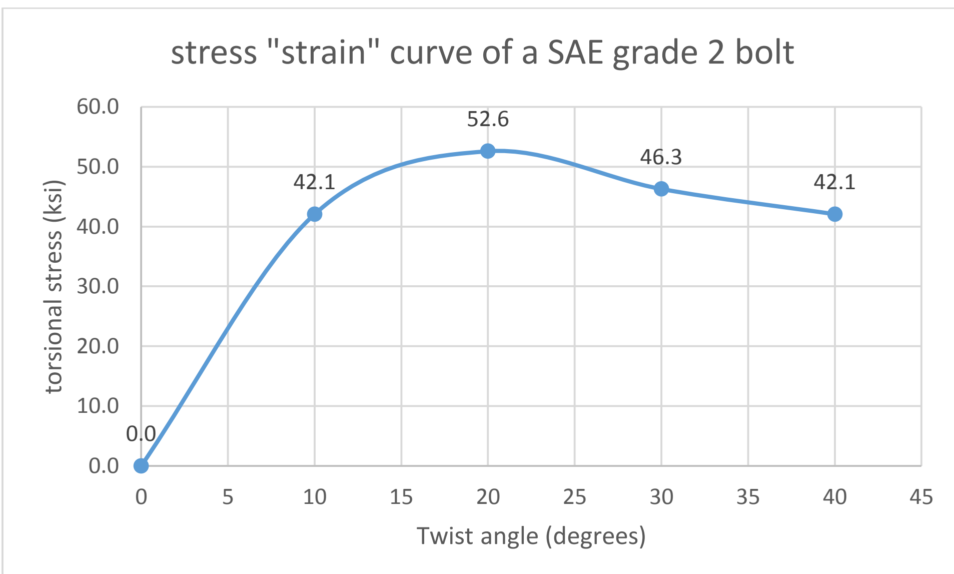

Figure 9 Torsional Stress-“Strain” Curve

Figure 8 shows the relationship between direct torque applied and angle of twist of an SAE grade 2 bolt with a diameter at the undercut/groove of 0.244 inch. Figure 9 shows the plot of a stress-

"strain" curve after the measured torque had been converted to torsional stress. Note the slope of the linear range in Figure 9 would not give shear modulus because twist angle is not equal to shear strain. But it does show similar trends of the rise and fall of torsional stress with deformation of the bolt. And it does indicate the yield strength and ultimate strength of the bolt under torsional load. Handbook data[11] indicates that for SAE Grade 2 bolts tensile yield strength is around 57 ksi and tensile ultimate strength is around 74 ksi. Converting these to shear strength using Eq. (3) we have shearing yield strength of 33 ksi and ultimate shear strength of 43 ksi. That is about 25% difference between measured and handbook data. The difference between the testing results and handbook data could be attributed to:

1. Work-hardening effect introduced by the metal cutting of the groove;
2. Case hardening from unintentional heat treat generated by the lathe and the grinder (the lathe cutting into the part and the grinder grinding the threaded area all heats up the part, then the part slowly cooled down, thereby completing a heat-treat cycle);
3. Inaccuracy introduced by the torque wrench and/or reading of the torque wrench scales with bare eyes;
4. Work-hardening due to possible repeated loading and unloading of torque on the bolt.

The first two sources of error are hard to control. The 3rd source of error could be minimized by using a smaller torque wrench that has more refined scales. But due to the wide range of shear strain introduced (see Figures 8 & 9), it is not always possible to use a single torque wrench to capture enough details while at the same time be able to break the bolt. The 4th source of error could be minimized if students are instructed to load the part slowly in one direction only and never release the load until the part fails. Even though it is not possible to get a very accurate measurement and a very good correlation between experimental data and tabulated handbook data for this lab, the mere fact that students are made aware of these errors and how these errors contributed to the difference between experimental stress limits and their handbook counterparts is tremendously valuable. It will get them to think twice when using tabulated data in the future. Another mitigating factor worth considering is, the tabulated tensile strength data had all been reported as "minimum tensile strength," which means some upward variation and thus adjustment of data is warranted. But by how much? No one knows – that is why they are statistical in nature.

A follow-up lab on identification of grades and materials of bolts/nails can be assigned also so students can learn some statistical concepts with regards to the strength of materials properties. Students were given bags of bolts/nails of different SAE grades and materials at the beginning of the lab. They needed to use torsion measurement to identify the different batches of materials for the bolts/nails. Students will be given a material property sheet for SAE grades steel bolts and copper alloys for this particular lab[8]. For aluminum, they need to obtain it online or from a textbook. Students will then need to use the lathe in the shop to cut a small groove on the bolts/nails to control where it would break in the torsion test. Using a caliper they need to measure the diameter of the groove and record this dimension. Using a torque wrench to break it on a vise (they need to grind the threads to make a flat surface for secure holding on the vise, and for the nails, they may also need to create a hex head so that you can use it on the torque wrench). Students are asked to record both the yield strength and ultimate strength.

For more accurate measurements, the selection of a proper torque wrench to use is also important. For the steel bolts, students are advised to use the larger capacity torque wrench. For the brass/copper and aluminum parts, the smaller capacity wrench might suffice. To make sure that tests would stay in the measurement range, students are advised to use an Excel spreadsheet to do some rough calculation to estimate the max torque required for the specific tests before choosing a particular torque wrench. The smaller range torque wrench will give more refined (higher resolution) readings than the larger one. This will help with measurement accuracy.

For the lab report, students are asked to include digital pictures of the fasteners in three stages: uncut state, after groove cut but before torsional break, after torsional break. They need to include all recorded measurement data in a tabulated form and include all calculations in the report. They also need to draw some conclusions and share their observations and comment on how this hands-on activity helped them gain a physical sense of strength of materials and the things engineers need to pay attention to when selecting mechanical components for design, etc.

Figure 10 Bolt broken at the threaded area

As lessons learned, Figure 10 shows the effect of groove not being cut deep enough and the bolt broke at the wrong place. This is a result of groove not being cut deep enough. When we first conducted the lab, one student did not create an undercut and he ended up breaking the adaptor of the torque wrench instead breaking the bolt! In general these activities will take up two lab sessions. It depends on how skillful students are with some of the shop tools, and also how many students are doing the lab as they might need to take turns using the machine tools. One word of caution to students should be this: even if all measurement errors were eliminated, the measurement results for material properties may still exhibit a range of values, due to differences in material composition, heat treatment received, or a history of other mechanical impact the part had endured.

Assessment

The author had used this lab as part of a Machine Component Design course in the fall of 2008 at Geneva College, and as part of a Strength of Materials lab in the fall of 2015 at Anderson University, Anderson, Indiana, and 2016 at Mount Vernon Nazarene University, Mt. Vernon, Ohio. Assessment data has been gathered through student lab report and mid-term exams. For example, one of the exam questions related to this lab is,

> ***Problem 1*** *(15%): What is the minimum torque required to twist break a ¼-20 steel bolt (SAE Grade 8)? Show your work.*

Average student performance on this test was 90.5 out of 100 and proves to be satisfactory.

Student feedback were also gathered from their lab reports. In general, students enjoyed this lab. One student shared,

> "There were a lot of human error involved in this experiment. However, the basic idea of how to test a material and how to calculate the ultimate tensile strength, was understood well."

Another student shared,

> "This activity helped me to see the effects of induced strain by machining very well. I knew that it existed but did not realize it could throw off numbers like it did here. This will help me when I design because now I have a feel for these materials."

> "Overall, this experiment helped explain the process of testing bolts and the importance in design. This will help not just in the physical sense of knowing this process, but in a theoretical sense when it comes to design parameters. Also, certain skills in the lab were acquired with using a lathe, among others."

Conclusions

In this paper, a "quick and dirty" low-budget torsional strength testing lab has been developed that would allow students maximum exposure to hands-on material testing. The required equipment list for this lab is short and affordable. Students will also have a chance to learn some basic skills using shop tools such as a lathe, a grinder, a vise and calipers, etc. Simple torsional load calculation is required for this lab to help students review mechanics of materials theory and correlate theory to practice. This lab can also serve as a lead-in to the study of industrial fasteners which normally is only briefly covered in a machine component design class. Weakness of this lab is that the torque wrench is not very accurate and would typically require a lot of "eye-balling" when reading the scales. The same is true when reading the protractor. But overall, the educational experience gained through this lab is worthwhile for students.

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