ASEE'S VIRTUAL CONFERENCE
At Home with Engineering Education
JUNE 22 - 26, 2020 #ASEEVC
Paper ID #31182

Yielding and Fracture in Steel Design: From Trash-Bags to Treasure

Dr. Anthony Battistini, Angelo State University

Dr. Anthony Battistini is an Assistant Professor in the David L. Hirschfeld Department of Engineering at Angelo State University. He received his BSCE (2007) degree from Lehigh University and an MS (2009) and PhD (2014) degree from The University of Texas at Austin. His expertise is in structural design, with an emphasis in steel bridge structures and connections. Prior to his current institution, Dr. Battistini also held assistant professor positions at Washington State University (2013-2014) and George Mason University (2014-2017). Throughout his career, his primary responsibility as a faculty member has been teaching students, for which he aspires to provide them with a quality and enjoyable experience.

Yielding and Fracture in Steel Design: From Trash-Bags to Treasure

Abstract

When explaining the concept of yielding and fracture to steel design students, it is best to use a visual demonstration to characterize the behavior. While performing a steel tension coupon test or full steel bolted connection test would be ideal, it is not always possible to include during class and many steel design courses do not require a laboratory component. The following paper will describe how the author uses trash bags with bolt holes to describe the concepts of yielding and fracture, while also introducing a little bit of comedy into the classroom. Answers to the most common student questions are also provided.

Motivation

For the first two or three times the author taught an introductory steel design course, he noticed that many students were not able to clearly describe yielding in materials. From previous courses in mechanics of materials and structural analysis, the students recognized that yielding, along with fracture, were both limit states to be checked, but they struggled to differentiate between the two failure modes and generally say that, "fracture happens whenever there are holes," and "fracture is worse than yielding." While these statements are true, the author felt that students should have a better grasp of why the yielding limit state needs to be checked and why it is not acceptable to allow large amounts of yielding in building design. Moreover, the author wanted students to connect the force-deformation behavior of a steel member back to the stress-strain behavior of the steel material.

Ideally, to observe yielding and fracture in steel material, students in the steel design course would perform a standard tension test on the material or better yet, a tension test on a steel member with bolted connections. However, at many universities, the introductory steel design course does not include a laboratory section and often, the instructors do not have access to a portable tension test apparatus that could be brought into the classroom or a testing frame capable of failing large steel specimens. Therefore, instruction has to rely upon the students either recalling the tension tests performed in previous semesters or video demonstrations.

The problem with remembering the tension tests is that students are typically at an intellectually different stage in their formation as engineers when they first perform a steel tension test compared to being in an upper level design course. Accordingly, students might not recognize the nuances of yielding, such as the development of Lüders bands in the metal. In addition, many universities are not equipped to test large steel members with bolted connections because even small steel specimens generally require large forces to cause failure. Finally, watching a video of a tension test is useful to observe yielding and fracture in steel, but it is not the same as physically witnessing it and experiencing it in the classroom.

Therefore, the author set out to develop a simple, portable, inexpensive model which could demonstrate the basic concepts of yielding and fracture and help correlate these concepts to the failure limit states of excessive deformations in the gross cross section and fracture at the net cross section (see Figure 1 for cross section definitions).

Physical Models

To visualize yielding, the author remembers an annoying childhood school cafeteria habit. Upon finishing a juice box or pouch, kids would bite the plastic straw and pull on it to stretch it out. In fact, the author would do this very quickly and then feel the heat dissipated while it yields by touching the stretched-out portion. Of course, the author had no idea about yielding at the time, but when trying to develop a demonstration for this concept, the author realized this habit represents a simple, but effective model to which many students can relate.

For a demonstration in the classroom though, these plastic straws are a little small to observe and/or require some pre-planning to purchase so every student can have her/his own sample. As an alternative, the author used the fact that yielding in plastic can be more readily performed in the classroom to develop a demonstration that uses trash bags to model steel member behavior. In addition to yielding, the author expanded the demonstration to include fracture on a bolted connection and also added an element of comedy into the classroom.

To prepare the samples, the instructor takes a regular trash bag and creates three models of a steel member with bolt holes on one end. Two models are one or two ply, while the other one is thicker, perhaps six ply. The width of the model is about 6 in and the bolt holes are roughly 1 in diameter. The models are shown below in Figure 1.

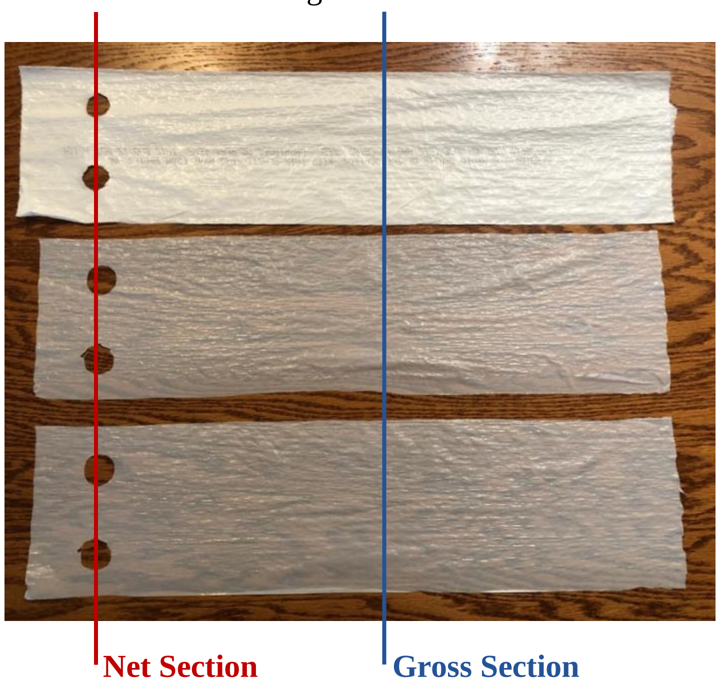

Figure 1: Trash bag models of steel members with bolt holes- six ply model (top) and one ply models (middle and bottom)

Author's Note: Usually I will cut the thinner models to size from the bag as two ply and later unfold it and cut it to one ply. To make the thicker ply model, I will use the same width and fold the remainder of the trash bag on top of itself until I use the rest of the bag. To help when cutting, apply tension to the bag transverse to the direction of cutting like wrapping paper, and allow the scissors to slide and shear the bag apart instead of needing to "cut" with the scissors. For the holes, fold the bag in half and cut a semi-circle out, like you are creating a heart valentine out of construction paper. Don't worry if the holes are not perfect or about the length of the model, the demonstration will still work fine.

Prior to the demonstration, have a sample stress vs strain curve for steel available to reference throughout the demonstration. To begin the demonstration, ask for a student volunteer to come to the front of the room. Based on the interpersonal rapport the instructor has with the volunteer student, the instructor can make the decision whether or not the demonstration will include an element of comedy.

Demonstration (without Comedy)

Using a one ply trash bag member, ask the student to hold the end without holes with two hands to apply a roughly uniform stress distribution. The instructor will do the same on the end with holes, making sure to grasp the bag in front of the hole locations. Then, have the student pull gently on the trash bag at first, and then with more force to cause yielding to form along much of the length of the member (see Figure 2).

> *Teaching Point #1:* Explain that at low forces, steel remains elastic and returns to its original shape when unloaded.
>
> *Teaching Point #2:* Explain to the class that the yielding limit state occurs along the entire length of the member. Depending on the plastic bag, you may even be able to point out examples of Lüders bands.
>
> *Question:* Is the member capable of sustaining the applied load?
> *Answer:* Yes, yielding does not mean the member cannot hold more load. Demonstrate the member can still sustain force and refer to stress-strain curve.
>
> *Question:* Is the member still usable in the structure?
> *Answer:* No, yielding has left the member much longer than its initial length, so the structure is now permanently deformed. The yielded member will need to be repaired for the structure to return to its initial, designed state.

Figure 2: Member with yielding in the gross section

Now that the member has yielded and is no longer useful, you can discard it to the floor. Next, grab the second one ply trash bag member and have the student hold the two bolt holes while the instructor holds the other end of the member, ready to apply uniform stress.

> *Question:* What will happen to this member?
> *Answer:* Students will generally answer that it will fracture or rip apart at the holes.

Pull gently until you get yielding to occur at the net section, but not fracture (see Figure 3).

> *Teaching Point #3:* Explain that yielding first occurs at the net section because the stress is higher in that region of the member. If done well, the net section will show signs of stretching.

> *Question:* Is the member still usable in the structure?
> *Answer:* Yes, while it is slightly deformed at the bolt holes, it is still generally the same length. Recall that the net section can still reach an ultimate stress level higher than the yield stress, so it can still sustain more load and engineers allow this to occur in steel connection design.

Figure 3: Member with yielding in the net section

Finally, instruct the student to pull until failure, which is likely to be fracture of the net section (see Figure 4).

> *Teaching Point #4:* Now, two possibilities will occur: (1) the net section will enter the strain hardening region and will eventually reach the ultimate stress and fracture will occur, or (2) the net section will enter strain hardening region, but then the gross section will enter yielding prior to the net section reaching the ultimate stress. For these reasons, engineers must check both limit states.

Figure 4: Member with fracture in the net section

The demonstration is now complete. Have the class applaud the volunteer student!

Demonstration (with Comedy)

Based on your interpersonal rapport with the first volunteer student, the instructor can opt to add a comedic element to this demonstration. To do this, make sure one of the one ply trash bag members is hidden from the students' sight.

Author's Note: Usually I place the six ply trash bag member and a one ply member flat on the table at the front of my room. I will then place the other one ply model on the floor behind the podium station or underneath a table at the front of the room, perhaps using my backpack and other items to block it from view as necessary.

Begin the demonstration of the yielding limit state as previously described, but now using the six ply trash bag member. Even though its plastic, it will be very difficult to get any substantial yielding along the length of the member.

> *Comedic Act:* Encourage the student to pull harder. C'mon, it's just a trash bag. Why can't you do it? Do we need someone stronger? Ask the student to sit back down and get a new volunteer.

At some point, while the first volunteer is sitting down and a second volunteer is being selected, the instructor needs to inadvertently drop the six ply member on the floor hidden from sight. The instructor should then pick up the pre-placed, secret one ply member and pretend that nothing has happened. With the second volunteer, complete the entire demonstration as outlined in the previous section.

While the thickness difference is easily seen on a flat surface like in Figure 1, it is not as discernible when being held in the air during the demonstrations. In the author's opinion, using the demonstration with comedy adds a little fun to this classroom activity without detracting from the learning experience. However, it is very important that the instructor has some existing interpersonal rapport with the first student volunteer so as not to offend him/her when claiming he/she is "not strong enough" to cause the yielding in the member and that he/she will not be offended when being asked to sit down and a different volunteer come forward.

Author's Note: The demonstration with comedy has especially worked well when the first volunteer is one of the student-athletes who the class knows is relatively strong and who has an outgoing personality, which is often the case with the students who are most eager to volunteer for demonstrations. As long as I know the first student will not be terribly offended if I joke about her/his strength, then I will do the comedy act, and then try to select the second volunteer as someone who seems visibly less strong than the first student, although it is not required. Once the demonstration is complete, I will ask the students to applaud both volunteers and I will pick up the six ply bag off the floor, revealing to the whole class my trick, and hand it off to the first volunteer so they know the whole comedy act was planned. This helps to maintain good rapport with the first student volunteer.

Author's Note: Again, I will make a decision on-the-fly as to whether or not I will do the comedy bit. At my current institution, I typically have had the students in my steel design course in at least 2-3 previous courses, so I generally know the students and their demeanors and can predict if the comedic act will be well received. However, I have chosen not to do the comedy act before, so then I will do the yielding demonstration with the one ply trash bag member from the table. If that is the case, when I discard the yielded member to the floor, I will grab the other one ply member from the floor for the fracture demonstration and just not ever use or discuss the six ply member on the table.

Common Student Questions

This section lists a couple of the common questions students have during this demonstration.

> *Student Question:* Why do we need to check both yielding and fracture limit states?
> *Answer:* Refer back to the demonstration to explain how engineers need to check for yielding in the gross section, which leads to excessive deformation, which is not acceptable. Additionally, while engineers will accept small amounts of yielding in the net section, it is unacceptable for fracture to occur here as that leads to total member separation and potentially catastrophic failure.
>
> *Student Question:* Will fracture always control?
> *Answer:* No, both yielding and fracture limit states must be checked and depending on the member geometry and material, either one can control.
>
> *Student Question:* Why do engineers allow yielding in the connections?
> *Answer:* The state of stress in simple bolted connections is complex and not easily determined due to various stress concentrations and changing geometry. However, connection tests and previous experience show that using the ultimate strength on the net cross sectional area produces safe designs. Remember, steel material fails at the ultimate stress and not the yield stress. (Depending on time and the student asking, one can add that once the steel material begins to yield in the connection, some of the stress will redistribute to other portions of the cross section. There are also the load factors and reduction factors in LRFD to increase the margin of safety.)

Student Question: Do we need to check for both yielding and fracture in tension members with welded connections?
Answer: Yes, we still need to check both limit states in the tension member because yielding and fracture have different reduction factors in LRFD design. Depending on the ratio of the ultimate stress to yield stress, one limit state could control over the other.
Note: This question is rare, as students usually have not discussed welded connections by this point in the semester.

Demonstration- Revisited

In addition to using this trash bag demonstration for yielding and fracture, it is also possible to extend its application to the connection limit states of bearing strength and tearing strength at bolt holes, as currently stipulated in AISC 360-16 Chapter J3.10 [1]. In a typical steel undergraduate class, the author expects that bearing and tearout strength would be presented in a lesson subsequent to the previously described introduction to yielding and fracture limit states. While the author currently utilizes a different physical model for bearing and tearout strength (consisting of 3-hole punched paper and a pencil), it is recognized that the trash bag demonstration could also be used. The following paragraphs detail one possible implementation of using the trash bag model for bearing and tearout strengths the author might attempt in a future semester.

Prepare trash bag tension members with bolt holes as outlined in the "Physical Models" section of this paper, but with an extra line of bolts- i.e. the member will now have four bolt holes at the end. For bearing strength, locate the bolt holes in a similar location as needed for the yielding and fracture samples with an appropriate spacing to the next bolt line. For tearout strength, locate the bolt holes closer to the back edge of the trash bag member so that the holes are unusually close to the edge and to one another. Figure 5 shows the two completed models with the approximate location of bolt holes.

Figure 5: Trash bag models of steel members for bearing strength (top) and tearout strength (bottom)

Using the tearout strength member, ask a student to place a thumb inside each of the edge bolt holes to represent bolts.

Teaching Point #1: Explain that in a simple bolted connection, it is assumed that all bolts will act to resist the applied load. In addition to yielding, fracture, and block shear limit states, engineers must check bolt related limit states.

Question: If a tension load is applied to the member, what is expected to happen?
Answer: Due to the short distance between the hole and the edge of the plate member, the student's thumbs are likely to tear through to the edge of the plate- this is known as a tearout failure for the bolt hole.

Pull on the tension member, resulting in tearout failure. Ask the student to now place a thumb inside each of the bolt holes in the forward line of the connection.

Question: Now, consider the next line of bolts. If a tension load is applied to the member now, what is expected to happen? Will fracture occur?
Answer: No. Due to the short longitudinal spacing or stagger between the holes, the bolts in the forward line will tear through the member into the back line. Again, tearout failure of these bolts will control.

Teaching Point #2: Explain to the class that an appropriate formula will be developed in class to check the tearout strength of the member by considering the shear strength of the block of material ripped out in the tearout failure- similar to the mechanics principles use to calculate block shear strength. Also point out that the tearout strength of this bolt line is different from the edge bolt line because of the different amounts of material resisting the tension.

Question: Was tearout failure a gradual failure like yielding, or a more sudden rupture like fracture?
Answer: Tearout strength is a rupture limit state like fracture. Therefore, a similar reduction factor is used in LRFD design.

Question: How can engineers prevent tearout failures from controlling their design?
Answer: Tearout strength can be improved by increasing the edge distance to the centerline of the bolts as well as increasing the longitudinal spacing from bolt to bolt.

Teaching Point #3: Explain that AISC has minimum requirements for these distances to help minimize the impact of shear tearout failures, but engineers still need to calculate this limit state. Compare the geometry of the tearout strength member to the more typically spaced bearing strength member to show how small edge distances lead to tearout. Tell students these construction limits will be covered in the upcoming lesson(s) on bolt limit states.

Now have the student volunteer place a thumb inside each of the edge bolt holes in the bearing strength member and put the member into some tension- enough to cause some deformation at the bolt holes but not fracture or tearout.

Question: What will happen if tension is applied to this member? Will the bolt holes experience tearout?
Answer: No, since there is a longer edge distance, tearout does not occur.

Teaching Point #4: While these bolts did not tearout, the bolt holes are now elongated and stretched. This is known as a bearing failure and is also considered an ultimate limit state. Like tearout, the bearing strength for each bolt hole in the connection needs to be calculated. Since every bolt hole can have its own tearout and bearing strength for each connecting member, along with the shear strength of the bolt itself, designers need to find the minimum of all these values at each bolt hole. To find the final strength of all the bolts acting together, add up the total available resistance of each bolt/bolt hole in the connection.

Future Improvement

While the demonstration is well received by the students, the author recognizes the need for assessment data. The author plans to implement a pre-test/post-test mechanism in the next course offering to measure student learning. In a homework previous to the lesson and after the lesson, the instructor will ask the same set of questions regarding the importance of yielding and fracture in design. Students will also be given a picture of a bolted steel tension member and asked to identify at what location in the member the limit states apply. Students should have the basic knowledge of these two limit states to properly answer the questions from the pre-requisite Structural Analysis I course. Quantitative measurements can then be obtained for the impact to student learning. In addition, qualitative data will be obtained via open-ended response questions specifically referencing the in-class demonstration in the post-test assessment. The qualitative data will allow the students to self-identify the perceived impact of the demonstration to their learning and make suggestions for improvement.

References

[1] American Institute of Steel Construction (AISC), *AISC 360-16: Specification for Structural Steel Buildings*, AISC, 2016.