Title

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Developing an Effective and Engaging Concept-driven Approach to Teaching Structural Design

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Dr. Joel Lanning specializes in seismic design of civil structures such as bridges and buildings. His research focuses on the development of tools and methods used in structural design and those used in experimental physical testing aimed at improving structural resilience during an earthquake. He is passionate about teaching and is also focused on research and development of strategies to use in the classroom. His teaching philosophy includes building a strong learning community within each class and the use of high-impact practices to engage and challenge his students.

Developing an Effective and Engaging Concept-Driven Approach to Teaching Structural Design

Abstract

Structural engineering students are expected to have a very well developed understanding of structural design upon graduating. However, many students achieve only a low level of understanding with design abilities amounting to “plug-and-chug”. This might be the product of the combination of two factors. First, commonly instructors only use traditional teacher-centered direct instructional practices (e.g. only lecturing and writing out equations/problems). Second, many instructors try to cover too many different topics and scenarios, necessitating a focus on *process* and on picking the correct design equations. Perhaps this is in an attempt to prepare students for practice where structures can take on any shape, and there a plethora of design items to check.

However, this instructional style combined with an overemphasis on application of prescribed design equations sends students the wrong message - *design is about knowing how to apply equations*. Not only is this style *disengaging* but it misdirects study away from developing a strong conceptual understanding of the *basic* design equations, of their parts, and of design philosophy overall. A solid conceptual knowledge will ultimately allow students to navigate more complex problems and more intricate portions of design specifications later on in their professional careers.

With this opinion in mind, this paper discusses and outlines an approach to teaching structural design courses rooted in methods that are well documented in education research. This includes changing the focus of lectures to the underlying physical concepts behind design specification equations, assigning homework problems which emphasize analyzing trends within and between structural behavior and specification equations, and adding concept-targeted lab experiments (or data analysis assignments to mimic experiments). Examples are provided for a course in steel design, but this approach is certainly applicable to design courses on other structural materials, like reinforced concrete or timber.

Going beyond simply making course material suggestions, this paper seeks interested collaborators to join the author in a larger research and dissemination effort. The goal is to have this group develop and distribute two nation-wide surveys to understand and document (i) what design skills are desired by the industry of newly graduated engineers, (ii) what and how instructors are teaching, and (iii) how these two align. Additionally, this group will collaborate on developing (i) concept-focused course materials and methods, (ii) a standardized structural design concept inventory for pre- and post-course assessment, and (iii) course assessment data collection over a wide range of institutions.

The goal of all these efforts is to establish an effective and engaging concept-driven approach to teaching structural design which is backed up by convincing quantitative and qualitative evidence.

Introduction

Structural engineering students are like any others, some are very naturally engaged and arrive in upper-level courses well prepared to take the next steps. However, based on experience and observation, many are not well prepared and struggle to connect prerequisite material to successfully form a meaningful understanding of structural design. But immediately upon graduation these new engineers are expected to be extremely well prepared to take on design tasks[1][2] which require skills beyond *simple operation* of design specifications, which is commonly the focus of undergraduate design courses. Skills in generating preliminary designs from "scratch", verifying computer analyses and design output, and having a "feeling" for the structure and its components are generally left to the students to figure out on their own *in their first job* [2].

Further, design specifications change, and new research constantly affects design equations and methodologies. However, what rarely, or never, changes are the underlying principles of structural mechanics behind design procedures. Mechanics, both academically and intuitively derived, can be integrated to impart a "feeling" and an understanding of the physical meaning *together* with the specification equations. Cultivating this ability before entering the work force could be highly impactful for the career trajectory of new engineers.

Just as there is variability in student preparation, there is variability in structural design instructors. Some are well prepared to skillfully blend lessons in structural behavior and the details of the design specification, while others are not and may tend to fall into the common trap of assigning a linear presumption to the amount of material they cram into their course. This is a well-recognized problem in engineering courses, as wonderfully described and analyzed by Professor Emeritus David Bella of Oregon State University [3], where the focus is on productivity – the more topics covered in a course, the better the course. This is likely in an attempt to better prepare students for entering the industry by giving them a full toolbox to utilize once they graduate. But, as Bella points out, this assumes a linear relationship that simply does not always apply to human behavior and learning. Covering *too many topics*, combined with the *use of less effective traditional teaching strategies* can do students a real disservice.

Arguably structural design courses may be especially at risk to these *two teaching problems*. The increased focus on research at most universities has driven down the practical experience of faculty[2],[4]. Further, ABET encourages design courses to be taught by licensed engineers [5]. So, departments often hire part-time, or adjunct faculty, who are full-time practicing engineers who may not have much teaching experience or training but *do* have extensive professional experience. Among these there are most certainly many excellent instructors. However, it is no stretch of the imagination to think that many will "teach the way they were taught" and rely on poor instructional practices like teaching only by transmission. Further, experienced practitioners can be susceptible to expert blindness[6], just as university faculty can, and may mistakenly assume students are far more experienced than they actually are and that students will be bored by the fundamentals. Then, in a somewhat misguided attempt to provide value to their course, adjunct faculty may try to cover as much material as possible and include complex versions of basic design problems (different situations and geometries). It is not disputed that this has vocational value. But teaching by transmission *and* overemphasizing code operation over understanding structural behavior will likely lead to, as Bella [3] called it, "plug and chug, cram, and flush".

It is likely more important to focus on the basic design philosophy and to guide students into developing a deeper more concept-connected understanding in terms of the underlying mechanical principles and how they relate to the primary design specifications. Just having a large number of tools is not helpful if you do not understand how to use them or for what use they are intended. Rather than learning to plug-and-chug many prescribed design equations, students will be much better prepared for their careers if they have a solid fundamental understanding of a few key behaviors to use as a platform from which they can learn more complex, detailed, or newly developed design tasks and procedures. This can prepare students to more confidently carry out their work early in their careers and more easily adapt to new methods in the future.

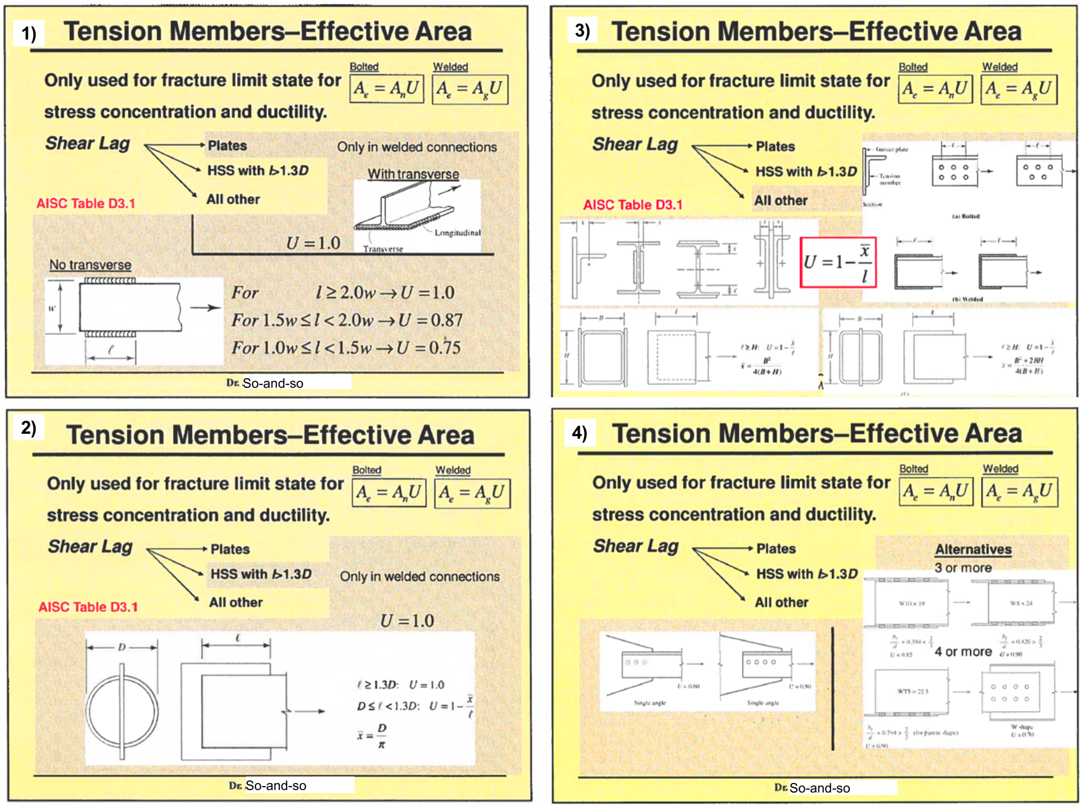
Concentrating on concepts and linking to the specification equations may open instructors to assigning students tasks that will represent a liminal space, the utility of which Phillips [6] describes as a crucial part in experiencing learning, where students must utilize their knowledge of "what's going on" to solve a design problem in concept and link to the specification being taught. For instance, if students understand the physical meaning behind, and the name of, lateral torsional buckling in steel beams, then a design problem could be framed where the parameters *should* lead students to independently find the appropriate provisions in the steel specification. In general, though, students may *not* walk away from this type of course knowing all the code equations, but they will be better equipped to fluctuate in and out of liminal space later in their career.

Teaching in this way may be more the purview of the typical university professor, who is less likely to have an abundance of professional design experience, but for whom the more theoretical and historical aspects tend to be strengths. They (arguably) may also have more time to focus on course development. However, professors also certainly fall victim to the same poor instructional practices and can have expert blindness, again leading students to "plug, chug, cram, and flush". So, whether adjunct or full-time university faculty, whomever is teaching structural design a concept-focused approach should be considered.

All these aspects describe the basic philosophy of the author on a concept-focused approach to teaching structural design. This paper presents some specific examples of corresponding course materials for a steel design course under development by the author. The strategy includes three parts which on their own are not novel pedagogical ideas, but are inspired by this philosophy. These parts are (i) concept-focused lectures with (ii) concept- and trend-focused homework assignments, and (iii) small concept-focused lab experiments all designed to relate structural mechanics concepts, structural design concepts, and structural design equations.

Focusing on Concepts in Lecture

Here, a few examples of typical lecture slides are used to illustrate how a conventionally taught steel design course may present a few topics. Although the instructor may or may not stop there in their coverage of the underlying concepts, the point to be made is that even with a few more slides students can be provided a much more meaningful physical explanation from which to develop a "feeling". A few slides from a typical tension member lecture are shown in Figure 1. These very efficiently summarize the AISC [8] treatment of the shear lag phenomenon in tension members . But, in this particular presentation the very next slide, the last one on this topic, is a calculation example. Presumably, this is the extent of coverage for shear lag. But, any discussion in class about the *concept* of shear lag that may have occurred is, at minimum, not passed on to



1) Tension Members–Effective Area

Only used for fracture limit state for stress concentration and ductility.

Bolted $A_e = A_n U$ Welded $A_e = A_g U$

Shear Lag → Plates / HSS with $l \geq 1.3D$ / All other

AISC Table D3.1

Only in welded connections

With transverse

$U = 1.0$

No transverse

$For \quad l \geq 2.0w \rightarrow U = 1.0$

$For \; 1.5w \leq l < 2.0w \rightarrow U = 0.87$

$For \; 1.0w \leq l < 1.5w \rightarrow U = 0.75$

Dr. So-and-so

2) Tension Members–Effective Area

Only used for fracture limit state for stress concentration and ductility.

Bolted $A_e = A_n U$ Welded $A_e = A_g U$

Shear Lag → Plates / HSS with $l \geq 1.3D$ / All other

AISC Table D3.1

Only in welded connections

$U = 1.0$

$\ell \geq 1.3D$: $U = 1.0$

$D \leq \ell < 1.3D$: $U = 1 - \frac{\bar{x}}{\ell}$

$\bar{x} = \frac{D}{\pi}$

Dr. So-and-so

3) Tension Members–Effective Area

Only used for fracture limit state for stress concentration and ductility.

Bolted $A_e = A_n U$ Welded $A_e = A_g U$

Shear Lag → Plates / HSS with $l \geq 1.3D$ / All other

AISC Table D3.1

$U = 1 - \frac{\bar{x}}{l}$

4) Tension Members–Effective Area

Only used for fracture limit state for stress concentration and ductility.

Bolted $A_e = A_n U$ Welded $A_e = A_g U$

Shear Lag → Plates / HSS with $l \geq 1.3D$ / All other

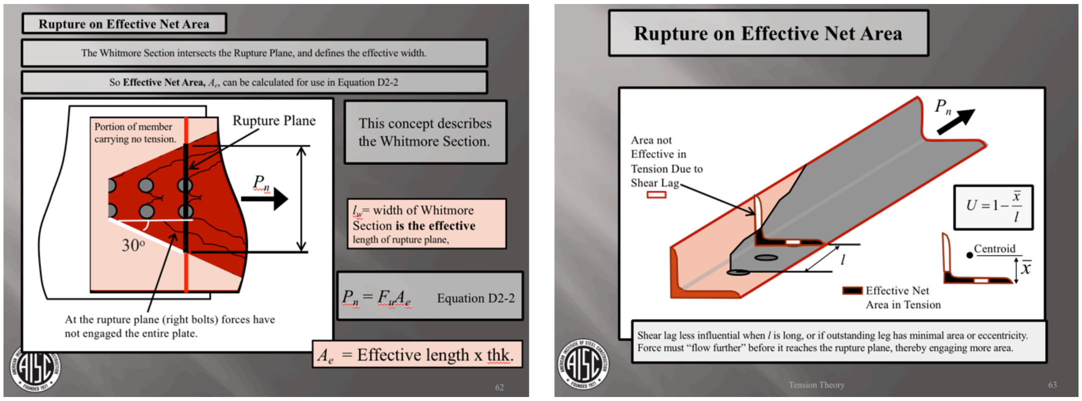
Alternatives

3 or more

4 or more

Dr. So-and-so

Figure 1 Slides from a typical steel design lecture describing shear lag



Rupture on Effective Net Area

The Whitmore Section intersects the Rupture Plane, and defines the effective width.

So **Effective Net Area,** A_e, can be calculated for use in Equation D2-2

This concept describes the Whitmore Section.

l_w = width of Whitmore Section **is the effective** length of rupture plane,

$P_n = F_u A_e$ Equation D2-2

A_e = Effective length x thk.

At the rupture plane (right bolts) forces have not engaged the entire plate.

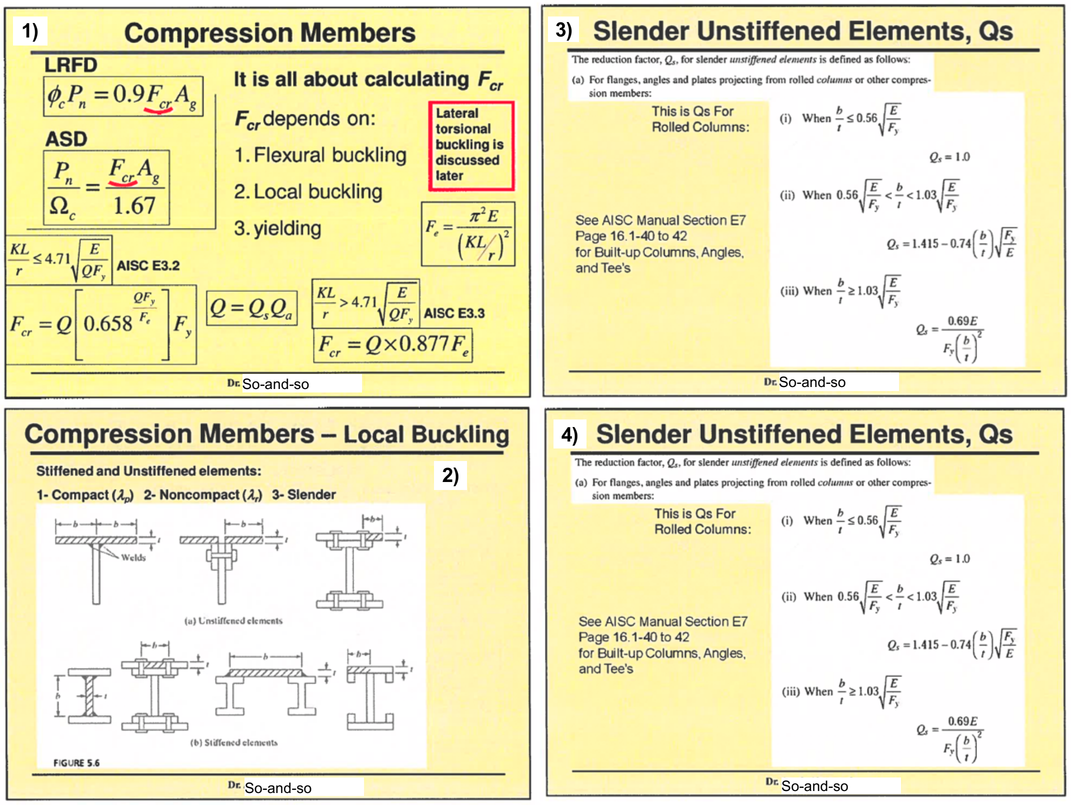
Rupture on Effective Net Area

$U = 1 - \frac{\bar{x}}{l}$

Shear lag less influential when l is long, or if outstanding leg has minimal area or eccentricity. Force must "flow further" before it reaches the rupture plane, thereby engaging more area.

Figure 2 Concept-focused slides providing students a feeling for shear lag (Derived from Civjan [9])

the students in these slides assuming they are provided after lecture. This material potentially gives no expert guidance about the *physical meaning* of shear lag. To the busy student, it could easily become *just some design "thing"* that must be accounted for in tension member design. However, just two additional slides, shown in Figure 2, can provide students with a better *feeling* for the physical meaning of shear lag (although these are condensed forms of what should probably be given in class). *Is this particular concept immediately important to engineers hiring newly graduates?* Probably not, but as a new engineer they may be more likely to properly account for shear lag and feel more confident in their early work. This affects their career trajectory and ultimately promotes higher quality work (less mistakes are made, so less must be caught and less must be taught on the job, etc.). Instructors may skip this concept, though, in order to show more examples *in an effort* to achieve the same overall goal. This may risk the student simply knowing how to apply the equations and “plugging-and-chugging” their way through this type of problem.



1) **Compression Members**

LRFD

$$\phi_c P_n = 0.9 F_{cr} A_g$$

ASD

$$\frac{P_n}{\Omega_c} = \frac{F_{cr} A_g}{1.67}$$

It is all about calculating F_{cr}

F_{cr} depends on:

1. Flexural buckling
2. Local buckling
3. yielding

Lateral torsional buckling is discussed later

$$F_e = \frac{\pi^2 E}{\left(KL/r\right)^2}$$

$$\frac{KL}{r} \le 4.71\sqrt{\frac{E}{QF_y}}$$ AISC E3.2

$$F_{cr} = Q\left[0.658^{\frac{QF_y}{F_e}}\right]F_y$$

$$Q = Q_s Q_a$$

$$\frac{KL}{r} > 4.71\sqrt{\frac{E}{QF_y}}$$ AISC E3.3

$$F_{cr} = Q \times 0.877 F_e$$

Dr. So-and-so

Compression Members – Local Buckling 2)

Stiffened and Unstiffened elements:

1- Compact (λ_p) 2- Noncompact (λ_r) 3- Slender

FIGURE 5.6

Dr. So-and-so

3) **Slender Unstiffened Elements, Qs**

The reduction factor, Q_s, for slender *unstiffened elements* is defined as follows:

(a) For flanges, angles and plates projecting from rolled *columns* or other compression members:

This is Qs For Rolled Columns:

(i) When $\frac{b}{t} \le 0.56\sqrt{\frac{E}{F_y}}$

$$Q_s = 1.0$$

(ii) When $0.56\sqrt{\frac{E}{F_y}} < \frac{b}{t} < 1.03\sqrt{\frac{E}{F_y}}$

$$Q_s = 1.415 - 0.74\left(\frac{b}{t}\right)\sqrt{\frac{F_y}{E}}$$

(iii) When $\frac{b}{t} \ge 1.03\sqrt{\frac{E}{F_y}}$

$$Q_s = \frac{0.69E}{F_y\left(\frac{b}{t}\right)^2}$$

See AISC Manual Section E7 Page 16.1-40 to 42 for Built-up Columns, Angles, and Tee's

Dr. So-and-so

4) **Slender Unstiffened Elements, Qs**

The reduction factor, Q_s, for slender *unstiffened elements* is defined as follows:

(a) For flanges, angles and plates projecting from rolled *columns* or other compression members:

This is Qs For Rolled Columns:

(i) When $\frac{b}{t} \le 0.56\sqrt{\frac{E}{F_y}}$

$$Q_s = 1.0$$

(ii) When $0.56\sqrt{\frac{E}{F_y}} < \frac{b}{t} < 1.03\sqrt{\frac{E}{F_y}}$

$$Q_s = 1.415 - 0.74\left(\frac{b}{t}\right)\sqrt{\frac{F_y}{E}}$$

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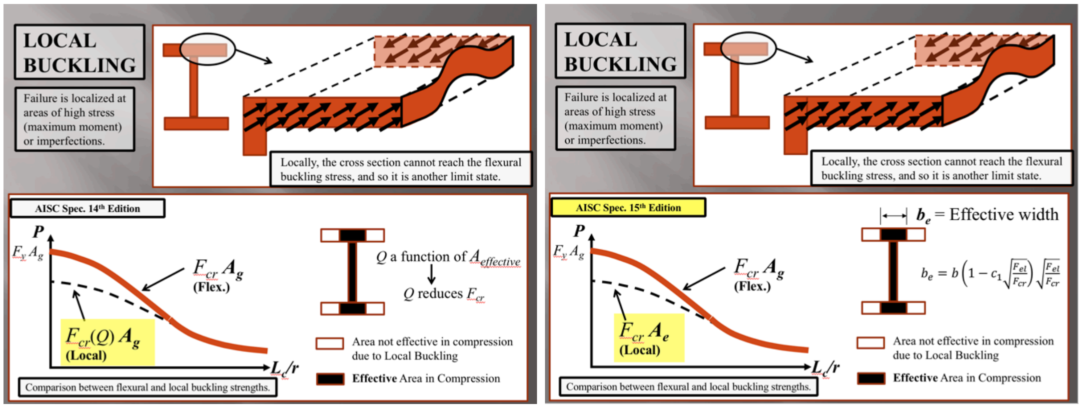
See AISC Manual Section E7 Page 16.1-40 to 42 for Built-up Columns, Angles, and Tee's

Dr. So-and-so

Figure 3 Slides from a typical steel design lecture describing local buckling



LOCAL BUCKLING

Failure is localized at areas of high stress (maximum moment) or imperfections.

Locally, the cross section cannot reach the flexural buckling stress, and so it is another limit state.

AISC Spec. 14th Edition

Q a function of $A_{effective}$ ↓ Q reduces F_{cr}

☐ Area not effective in compression due to Local Buckling

■ **Effective** Area in Compression

Comparison between flexural and local buckling strengths.

LOCAL BUCKLING

Failure is localized at areas of high stress (maximum moment) or imperfections.

Locally, the cross section cannot reach the flexural buckling stress, and so it is another limit state.

AISC Spec. 15th Edition

b_e = Effective width

$$b_e = b\left(1 - c_1\sqrt{\frac{F_{el}}{F_{cr}}}\right)\sqrt{\frac{F_{el}}{F_{cr}}}$$

☐ Area not effective in compression due to Local Buckling

■ **Effective** Area in Compression

Comparison between flexural and local buckling strengths.

Figure 4 Concept-focused slides relating *new* and *old* methods for local buckling using the same underlying concept (Derived from Civjan [9])

Another example is provided using the topic of local buckling. Here, the same issue is observed from the example lecture slides for compression. The first slide in Figure 3 summarizes the AISC equations[8] for flexural and local buckling, again efficiently and necessarily. These four slides are presented along with a few others showing the AISC slenderness ratio tables, which accompany the equations, and then immediately are followed by example problems. Again, students are left with no explanation of the phenomenon and get no feeling for what exactly is happening during local buckling. The simple figure at the top of each slide in Figure 4 effectively provides a visualization for what happens during local buckling.

Furthermore, the method for calculating local buckling strength has changed in the most recent edition of the AISC Specification; this is not an uncommon occurrence in structural design specifications. The plots shown in the two concept-focused slides of Figure 4 provide a very simplified summary and comparison of the old and new methodologies. Students are shown that in the past local buckling strength was arrived at through a modification of the flexural buckling stress, F_{cr}, via a Q-factor which was a function (in part) of the effective area of the cross section of slender elements. These equations are shown in Figure 3, the typical lecture slides, as they should be. However, especially to the inexperienced student, this is likely just a mess of meaningless equations which they will simply follow blindly. Providing even a little context – making a connection between Q and the flexural buckling strength curve – at minimum will give students a better feeling for what the equations *do*. Similarly, the new method overall strategy shown in Figure 4, and it is clear that in concept *nothing changed* between old and new methods. This, again, instills confidence in the future designer. When students are empowered by an understanding of the basic underlying physical meaning of the design equations and methods, they will be much better equipped to tackle updated versions throughout their careers.

The author has approached lectures in this way with excellent feedback from students. Example student feedback include comments like:

> "[the instructor] explains complicated topics and concepts using pictures, drawings and example[s]…"
>
> "… [the instructor] tries to make everyone think about the concept behind the equations, instead of just plugging and chugging numbers…"
>
> "… [the instructor] encourages students to graph and look at trends and realize what is actually going on…"
>
> "Does a good job teaching concepts and how material applies to real world applications…"
>
> "[the instructor] always relates the theoretical aspect of the subject to how it works in actuality."

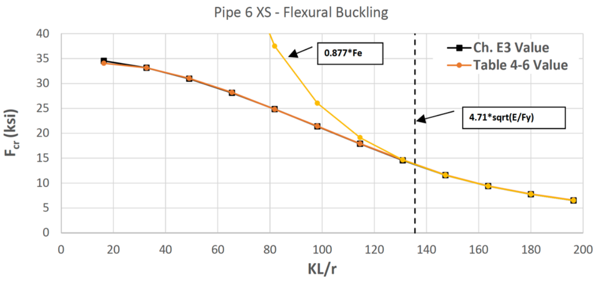
Students clearly appreciate incorporating the conceptual information as they identify it with "the real world" and "how things work". Whether this experience actually benefits them further on their careers is not known for certain. This is acknowledged by the Collaboration Section, below.

Concept-Focused Homework

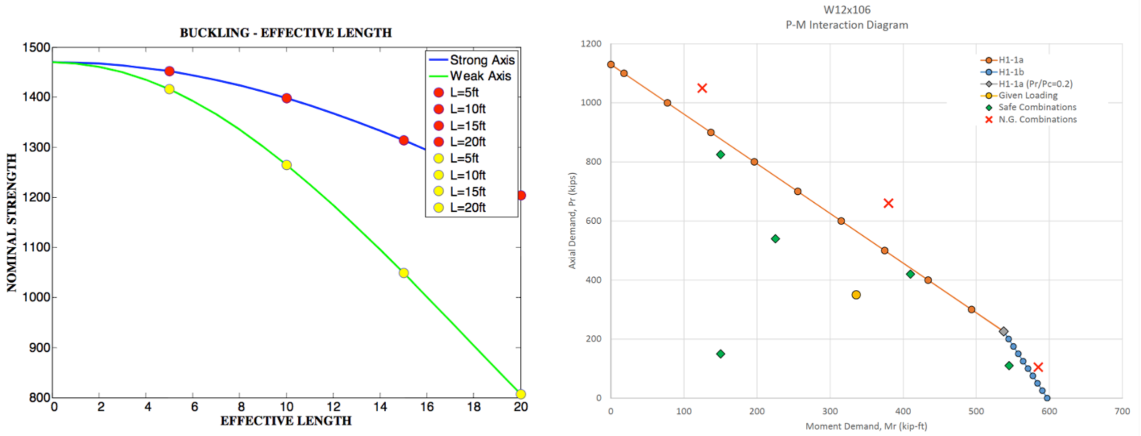
In one comment, above, a student mentions graphing and examining trends. This is in reference to a type of homework problem used and written by the author to build upon the emphasis on concepts in lectures. Understanding the trends associated with the specification equations provides students a valuable perspective which can quickly build up their engineering experience and intuition. This was recognized by Rafiq [1], who pointed out that by utilizing common structural software, students can almost instantly learn the change in analysis results over a wide parameter range which previously required large amounts of engineering experience.

Of course, this idea can be easily implemented in structural design without special software. For example, when introducing flexural buckling AISC Specification[8] equations and design table values (which summarize specification equation results for common shapes - i.e., a design aid) the students are required to use a spreadsheet to calculate an entire range of values and compare to what is simply listed in the AISC Manual, as shown in Figure 5(a). This builds confidence with the theory, specification equations, and the design tables. Further, often a conceptual lesson is highlighted in this type of assignment, such as the critical difference between x- and y-axis flexural buckling, highlighted in Figure 5(b).

When introducing combined axial and bending forces, students often do not have a good idea of how the relative magnitudes of axial and bending loads affect the overall capacity of the member. In one simple problem added to the normal assignment, students generate essentially random pairings of loads for a given section and plot them against the corresponding specification equations, as in Figure 5(c). Through inspecting a range of values, exploring how the design equations change within practical ranges, and discovering what is reasonable and what is not, students build their intuition about structural design.



(a) Comparison of flexural buckling stresses



(b) Comparison of strong- and weak-axis flexural buckling strength

(c) Comparison of various Moment and Axial force combinations and H1-1a,b

Figure 5 Examples of plots requested as part of homework assignments designed to highlight concepts and connect concepts to the design specification (AISC [8])

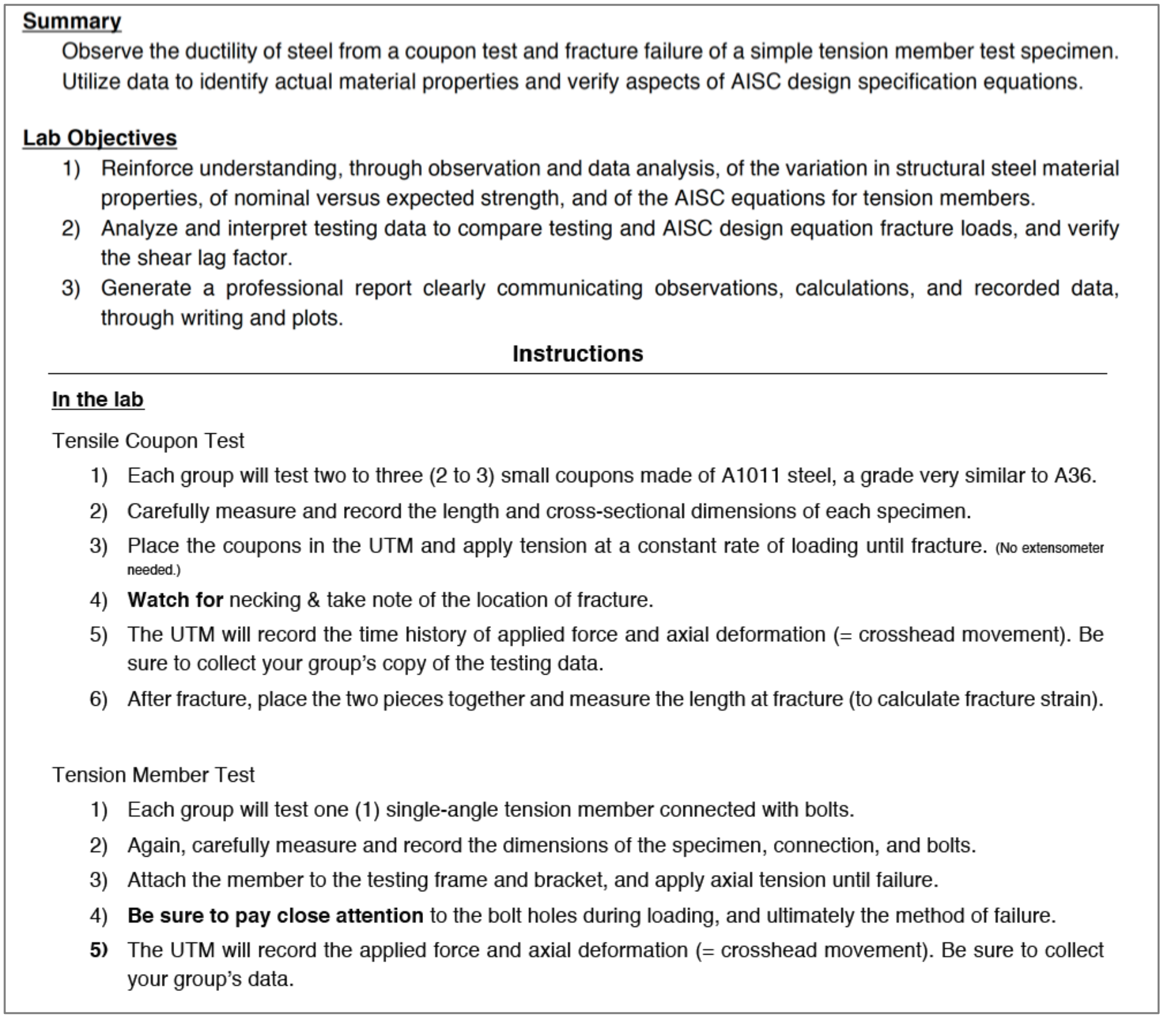
Concept-Focused Labs

It is no secret that lab experiences are great for teaching. Some instructors use them to bridge the gap between theory and practice, like Hale [10] in a reinforced concrete (R.C.) design course. To get students to learn the difficulties in tying rebar and placing rebar chairs *is* a valuable design lesson that can almost only effectively taught via experience. Further, tracking the progression of failure during physical testing in lockstep with the theoretical failure modes also provides an experience that will remain with the students far beyond the class (e.g. cannot really be crammed and hopefully not flushed). Although lab experiments are not always within the course "budget", whether in terms of time or resources, even simple experimental results can be used to deeply connect fundamentals, specification equations, and principles of mechanics. Or, conceptual models can be made ahead of time for presentation or can be made by the students, as an assignment or in-class "lab", in order to solidify the concept at hand. Behrouzi [11] developed very low-cost R.C. conceptual and practice-oriented models demonstrating the stress distribution in beams and rebar cage layouts of various R.C. components.

Along these lines, yet focusing more on connection of theory, reality, and specification equations, a few mini-labs using small inexpensive components are presented here. These experiments have not yet been carried out in a course by the author but they will be for an upcoming class. In the examples, the intent is to have students generate data and arrive at a useful comparison between the data being analyzed and the theoretical or design specification results. In lieu of generating the data through a physical lab experiment, a data set could be analyzed by the students to discover the theoretical results (more on this below in the Collaboration Section). Again, examples here are provided from a steel design course and the concepts discussed above are included for continuity.

As is somewhat typical, students conduct a simple tensile coupon test and a buckling test in their prerequisite strength of materials course. Here, once the particular topic has been covered for steel design in lecture, the students will conduct a lab experiment to partially recreate some portions of either the theory or design specification equations discussed in class. After a lecture in tension design students then participate in the lab shown in Figure 6, which culminates in their independently arrival at a shear lag factor, U. First, a steel coupon is pulled to refresh the memory about ductility and to also collect the necessary actual material yield and ultimate strengths, F_y and F_u, needed to properly compare the specification equations and the test data. Then a single angle (or similar) connected by one row of bolts (i.e., a tension member which will exhibit shear lag) is subjected to tension and the failure loading is (hopefully) fracture of the net section. Fracture of the net section (equation shown in Figure 6) is directly related to the net area, which students can measure themselves, modified by the shear lag factor. If all goes well, students will arrive at approximately the same shear lag factor that is prescribed by the AISC Specification[8] via back-calculation from the data. The reader is invited to review the instructions for further clarification.

Another example is provided for compression members in Figure 7, where students can connect the theoretical (yet approximate) method for calculating the inelastic Euler buckling strength. Although there are several methods of various accuracy for calculating the inelastic buckling load, one simple iterative method uses the tangent Modulus of Elasticity within the elastic Euler formula. This method can provide students great insight into the AISC Specification equations for inelastic flexural buckling. So using a provided stub column curve (see Figure 7) together with axial stress data recorded during lab, students analyze the two data sets to make a comparison and prediction as to the theoretical, observed, and the specification values for their specimens. Again, the reader is invited to review the instructions for a more thorough explanation of the steel-specific content. But for brevity, the point of the lab is to plunge students into some real data that will hopefully show them the connections between theory, design concepts, and design equations.



Summary

Observe the ductility of steel from a coupon test and fracture failure of a simple tension member test specimen. Utilize data to identify actual material properties and verify aspects of AISC design specification equations.

Lab Objectives

1) Reinforce understanding, through observation and data analysis, of the variation in structural steel material properties, of nominal versus expected strength, and of the AISC equations for tension members.
2) Analyze and interpret testing data to compare testing and AISC design equation fracture loads, and verify the shear lag factor.
3) Generate a professional report clearly communicating observations, calculations, and recorded data, through writing and plots.

Instructions

In the lab

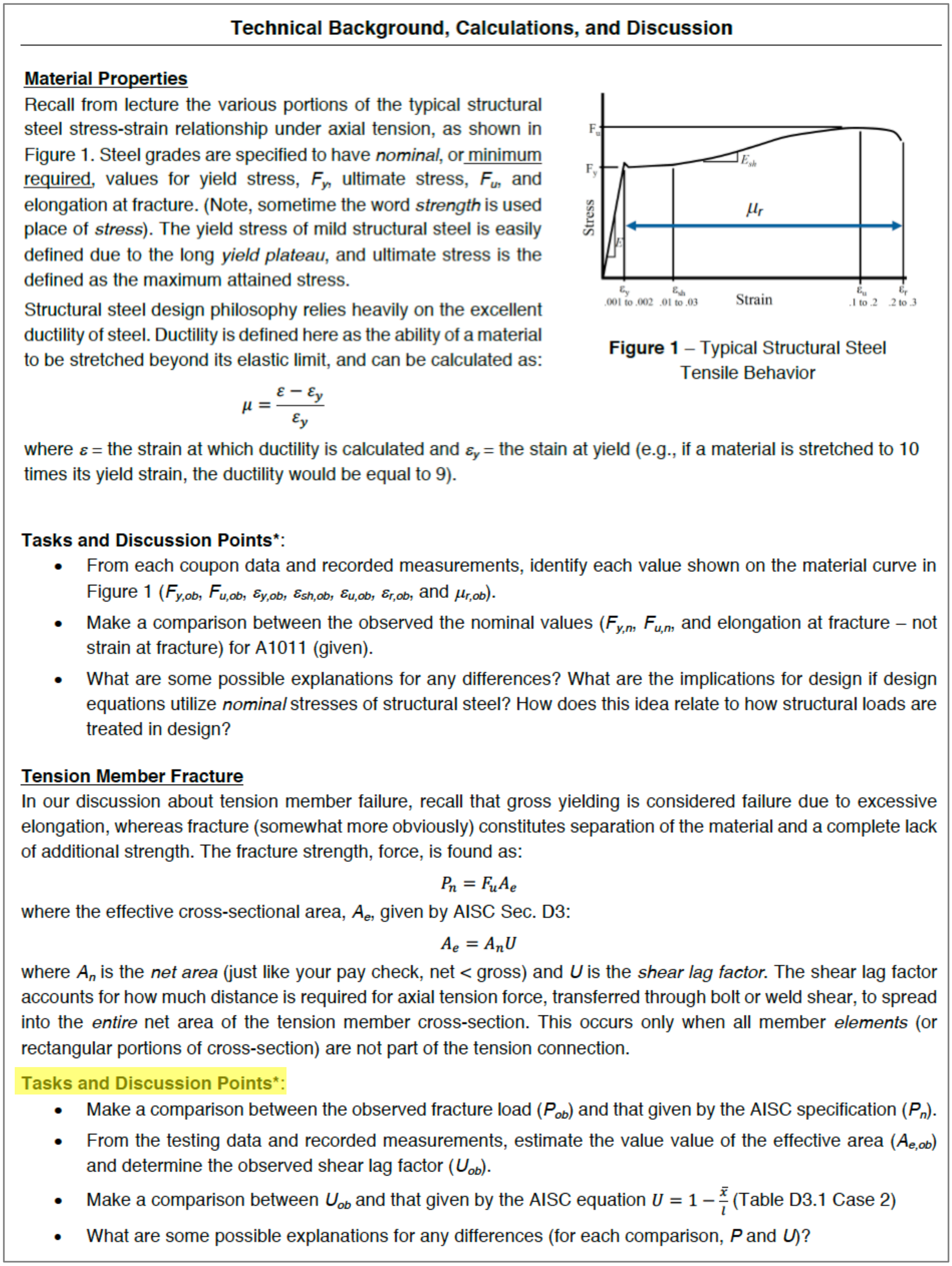
Tensile Coupon Test

1) Each group will test two to three (2 to 3) small coupons made of A1011 steel, a grade very similar to A36.
2) Carefully measure and record the length and cross-sectional dimensions of each specimen.
3) Place the coupons in the UTM and apply tension at a constant rate of loading until fracture. (No extensometer needed.)
4) **Watch for** necking & take note of the location of fracture.
5) The UTM will record the time history of applied force and axial deformation (= crosshead movement). Be sure to collect your group's copy of the testing data.
6) After fracture, place the two pieces together and measure the length at fracture (to calculate fracture strain).

Tension Member Test

1) Each group will test one (1) single-angle tension member connected with bolts.
2) Again, carefully measure and record the dimensions of the specimen, connection, and bolts.
3) Attach the member to the testing frame and bracket, and apply axial tension until failure.
4) **Be sure to pay close attention** to the bolt holes during loading, and ultimately the method of failure.
5) The UTM will record the applied force and axial deformation (= crosshead movement). Be sure to collect your group's data.

Figure 6 Concept-focused lab assignment highlighting ductility and shear lag



Technical Background, Calculations, and Discussion

Material Properties

Recall from lecture the various portions of the typical structural steel stress-strain relationship under axial tension, as shown in Figure 1. Steel grades are specified to have *nominal*, or minimum required, values for yield stress, F_y, ultimate stress, F_u, and elongation at fracture. (Note, sometime the word *strength* is used place of *stress*). The yield stress of mild structural steel is easily defined due to the long *yield plateau*, and ultimate stress is the defined as the maximum attained stress.

Structural steel design philosophy relies heavily on the excellent ductility of steel. Ductility is defined here as the ability of a material to be stretched beyond its elastic limit, and can be calculated as:

Figure 1 – Typical Structural Steel Tensile Behavior

$$\mu = \frac{\varepsilon - \varepsilon_y}{\varepsilon_y}$$

where ε = the strain at which ductility is calculated and ε_y = the stain at yield (e.g., if a material is stretched to 10 times its yield strain, the ductility would be equal to 9).

Tasks and Discussion Points*:

- From each coupon data and recorded measurements, identify each value shown on the material curve in Figure 1 ($F_{y,ob}$, $F_{u,ob}$, $\varepsilon_{y,ob}$, $\varepsilon_{sh,ob}$, $\varepsilon_{u,ob}$, $\varepsilon_{r,ob}$, and $\mu_{r,ob}$).
- Make a comparison between the observed the nominal values ($F_{y,n}$, $F_{u,n}$, and elongation at fracture – not strain at fracture) for A1011 (given).
- What are some possible explanations for any differences? What are the implications for design if design equations utilize *nominal* stresses of structural steel? How does this idea relate to how structural loads are treated in design?

Tension Member Fracture

In our discussion about tension member failure, recall that gross yielding is considered failure due to excessive elongation, whereas fracture (somewhat more obviously) constitutes separation of the material and a complete lack of additional strength. The fracture strength, force, is found as:

$$P_n = F_u A_e$$

where the effective cross-sectional area, A_e, given by AISC Sec. D3:

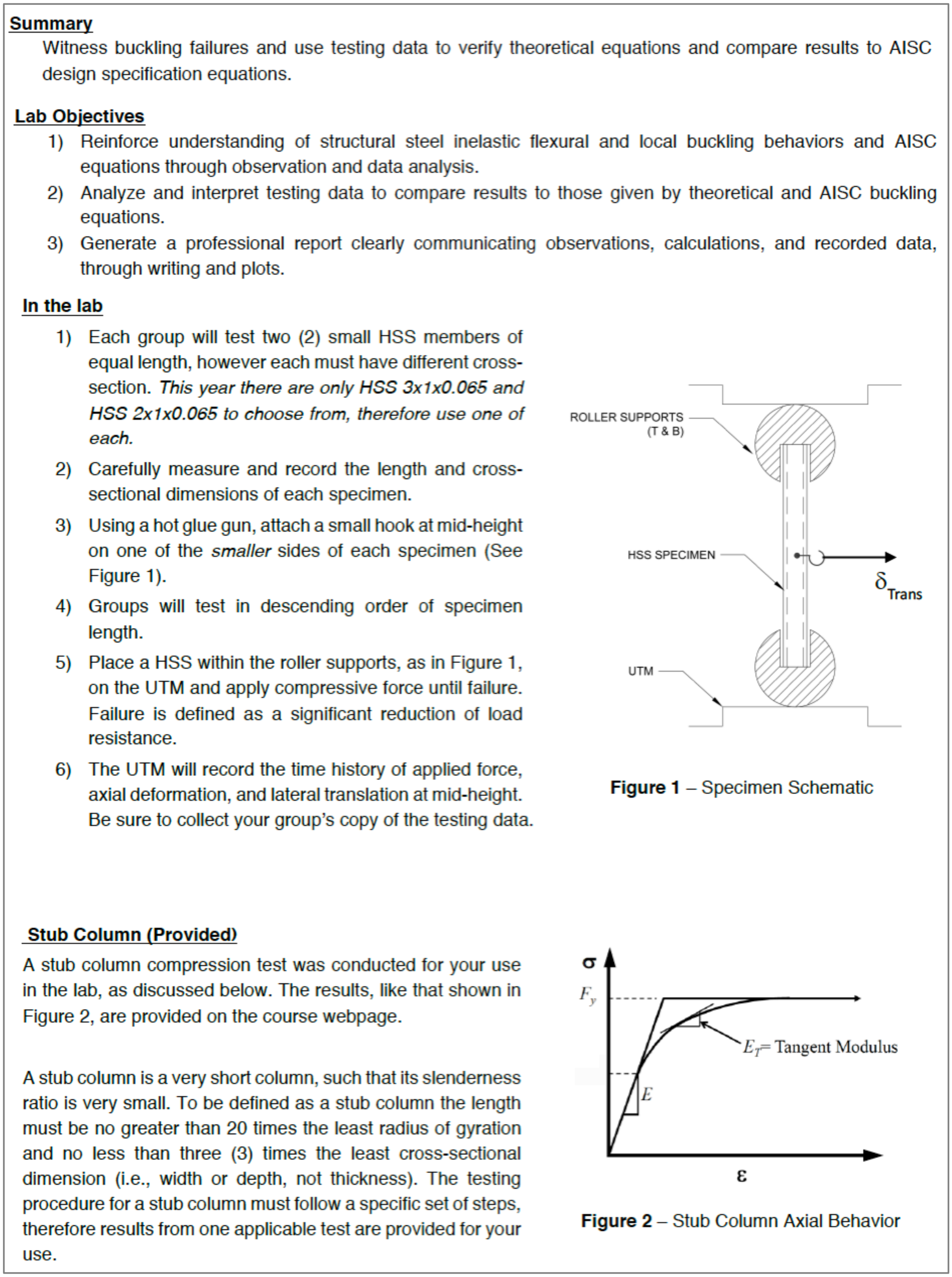
$$A_e = A_n U$$

where A_n is the *net area* (just like your pay check, net < gross) and U is the *shear lag factor*. The shear lag factor accounts for how much distance is required for axial tension force, transferred through bolt or weld shear, to spread into the *entire* net area of the tension member cross-section. This occurs only when all member *elements* (or rectangular portions of cross-section) are not part of the tension connection.

Tasks and Discussion Points*:

- Make a comparison between the observed fracture load (P_{ob}) and that given by the AISC specification (P_n).
- From the testing data and recorded measurements, estimate the value value of the effective area ($A_{e,ob}$) and determine the observed shear lag factor (U_{ob}).
- Make a comparison between U_{ob} and that given by the AISC equation $U = 1 - \frac{\bar{x}}{l}$ (Table D3.1 Case 2)
- What are some possible explanations for any differences (for each comparison, P and U)?

Figure 6 (continued) Concept-focused lab assignment highlighting ductility and shear lag



Summary

Witness buckling failures and use testing data to verify theoretical equations and compare results to AISC design specification equations.

Lab Objectives

1) Reinforce understanding of structural steel inelastic flexural and local buckling behaviors and AISC equations through observation and data analysis.
2) Analyze and interpret testing data to compare results to those given by theoretical and AISC buckling equations.
3) Generate a professional report clearly communicating observations, calculations, and recorded data, through writing and plots.

In the lab

1) Each group will test two (2) small HSS members of equal length, however each must have different cross-section. *This year there are only HSS 3x1x0.065 and HSS 2x1x0.065 to choose from, therefore use one of each.*
2) Carefully measure and record the length and cross-sectional dimensions of each specimen.
3) Using a hot glue gun, attach a small hook at mid-height on one of the *smaller* sides of each specimen (See Figure 1).
4) Groups will test in descending order of specimen length.
5) Place a HSS within the roller supports, as in Figure 1, on the UTM and apply compressive force until failure. Failure is defined as a significant reduction of load resistance.
6) The UTM will record the time history of applied force, axial deformation, and lateral translation at mid-height. Be sure to collect your group's copy of the testing data.

Figure 1 – Specimen Schematic

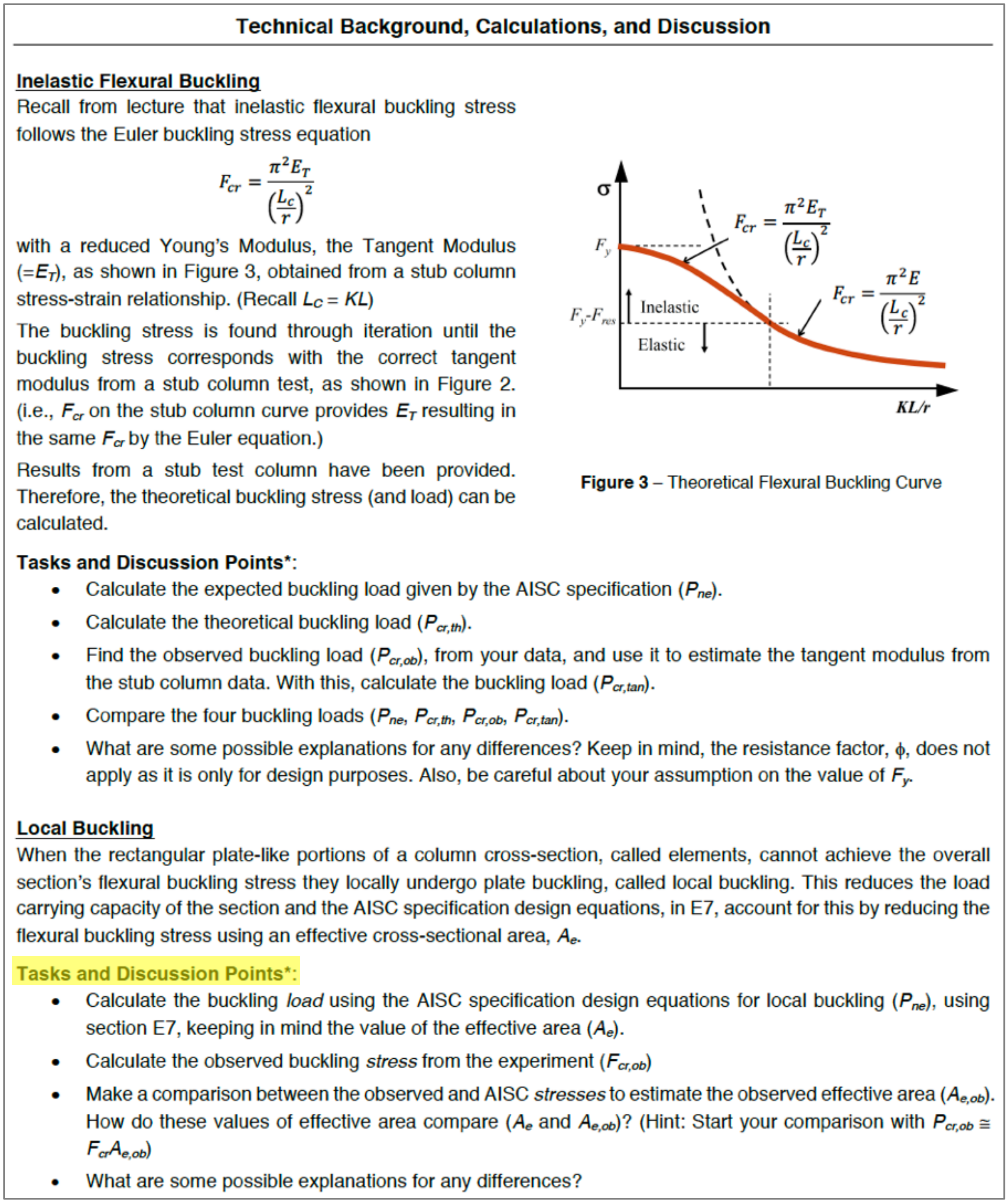
Stub Column (Provided)

A stub column compression test was conducted for your use in the lab, as discussed below. The results, like that shown in Figure 2, are provided on the course webpage.

A stub column is a very short column, such that its slenderness ratio is very small. To be defined as a stub column the length must be no greater than 20 times the least radius of gyration and no less than three (3) times the least cross-sectional dimension (i.e., width or depth, not thickness). The testing procedure for a stub column must follow a specific set of steps, therefore results from one applicable test are provided for your use.

Figure 2 – Stub Column Axial Behavior

Figure 7 Concept-focused lab assignment highlighting inelastic flexural and local buckling



Technical Background, Calculations, and Discussion

Inelastic Flexural Buckling

Recall from lecture that inelastic flexural buckling stress follows the Euler buckling stress equation

$$F_{cr} = \frac{\pi^2 E_T}{\left(\frac{L_c}{r}\right)^2}$$

with a reduced Young's Modulus, the Tangent Modulus ($=E_T$), as shown in Figure 3, obtained from a stub column stress-strain relationship. (Recall $L_C = KL$)

The buckling stress is found through iteration until the buckling stress corresponds with the correct tangent modulus from a stub column test, as shown in Figure 2. (i.e., F_{cr} on the stub column curve provides E_T resulting in the same F_{cr} by the Euler equation.)

Results from a stub test column have been provided. Therefore, the theoretical buckling stress (and load) can be calculated.

Figure 3 – Theoretical Flexural Buckling Curve

Tasks and Discussion Points*:

- Calculate the expected buckling load given by the AISC specification (P_{ne}).
- Calculate the theoretical buckling load ($P_{cr,th}$).
- Find the observed buckling load ($P_{cr,ob}$), from your data, and use it to estimate the tangent modulus from the stub column data. With this, calculate the buckling load ($P_{cr,tan}$).
- Compare the four buckling loads (P_{ne}, $P_{cr,th}$, $P_{cr,ob}$, $P_{cr,tan}$).
- What are some possible explanations for any differences? Keep in mind, the resistance factor, ϕ, does not apply as it is only for design purposes. Also, be careful about your assumption on the value of F_y.

Local Buckling

When the rectangular plate-like portions of a column cross-section, called elements, cannot achieve the overall section's flexural buckling stress they locally undergo plate buckling, called local buckling. This reduces the load carrying capacity of the section and the AISC specification design equations, in E7, account for this by reducing the flexural buckling stress using an effective cross-sectional area, A_e.

Tasks and Discussion Points*:

- Calculate the buckling *load* using the AISC specification design equations for local buckling (P_{ne}), using section E7, keeping in mind the value of the effective area (A_e).
- Calculate the observed buckling *stress* from the experiment ($F_{cr,ob}$)
- Make a comparison between the observed and AISC *stresses* to estimate the observed effective area ($A_{e,ob}$). How do these values of effective area compare (A_e and $A_{e,ob}$)? (Hint: Start your comparison with $P_{cr,ob} \cong F_{cr}A_{e,ob}$)
- What are some possible explanations for any differences?

Figure 7 (continued) Concept-focused lab assignment highlighting inelastic flexural and local buckling

Collaboration and Assessment

A course involving these, and other, materials following a concept-focused approach is certainly a work-in-progress. Addition building materials such as reinforced concrete and timber are perhaps even more widely taught than steel, and both have their own structural mechanics concepts to be highlighted. Therefore, this paper first calls for collaborators to join together to develop concept-focused course materials in order to promote this style of teaching through sharing of resources across all common building materials.

However, without assessment tools and results, the importance or effectiveness of a concept-focused approach is mostly an opinion. This problem is two-fold. First, a consistent tool for measuring conceptual student learning in structural design courses should be developed. A concept inventory test must be carefully developed and tested to ensure statistical relevance, such as that conducted by Steif [13] for statics concepts. These types of questions hone in on a particular concept where a number of scenarios are presented and a question is posed in a way such that a misconception may be emphasized. For example, several simple supported beams with various cross-sections and loadings are shown and the student is asked to match a given deflected shape and cross-section figure which exhibits lateral torsional buckling (LTB). The provided choices would include those which clearly indicate a lack of understanding of when and how a beam will experience LTB. A series of this type of purely conceptual, physical “feeling”, type problems will isolate the identified crucial concepts in structural design.

In order to identify the appropriate concepts, practicing structural engineers should be polled about what concepts and concept-dependent skills are important to them and to the career trajectory of new engineers. This, of course, will not be the first industry survey about structural engineering education. The most relevant found in the literature was by Robertson [12] in 2002. This comprehensive industry survey which focused on the skills of new structural engineers across both a wide range of engineering and workplace skills (e.g. ability to communicate, work on a team, take direction) and some specific to structural engineering (e.g. knowledge of timber design, ability to visualize a deflected shape). But, the survey did not probe into the more detailed conceptual understanding and skills related to structural behavior and design specifications (e.g. on a 1-10 scale rate the importance of new engineers to be familiar with *how to prevent* LTB versus be familiar with the specification equation providing LTB strength). With survey results in hand, a concept inventory assessment tool (test) can then be properly developed to ensure that this approach indeed works to effectively teach the desired skills. Finally, the content being taught and the delivery methods being used by structural design instructors should also be investigated. This second survey will mimic that given to industry, but will also include instructional details.

So, collaborators are sought to join the author in generating (i) additional concept-focused course materials across various design materials (steel, R.C., timber). In addition to steel design, the author teaches timber design and an introduction to seismic design every year. The group will also work together in (ii) developing and distributing industry surveys to determine the skills which are valuable in new engineers and relate those skills to their corresponding structural design concepts. Finally, this group will work together in (iii) developing a Structural Design Concept Inventory to be used to measure the effectiveness of the teaching method. These tasks are large in scope and necessitate collaborators.

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