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Automated Grading of Design Problems

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Introduction

In the Department of Civil and Environmental Engineering at the University of Louisville, an automated grading system has been in use for about eight years. A recent addition to the grader represents a first step toward enhancing its ability to assess solutions for design problems. This paper describes features of the grader that are used to evaluate work done by students on design problems.

The grader is used in the course CEE 422, Fundamentals of Steel Design. Emphasis in this course is on design of steel building members (for example, beams and columns) using the AISC LRFD specification (AISC[1]). As is typical of most engineering design, there is no single building configuration that is "best", there are multiple configurations that are "satisfactory", and there are multiple design criteria that must be satisfied. Furthermore, "good" designs generally can be achieved only by global, system consideration, and not by optimizing design of individual elements.

For these reasons, evaluations of solutions to design problems offer unique challenges to an automated grading system. On the other hand, automated graders offer many advantages: the ability to assign a variety of problems; the ability to perform a more comprehensive evaluation of solutions; reduction in the workload on the instructor; assignment of individualized problems; and the ability to assign focused remedial work. Of course, all of these advantages are available with traditional grading methodology, but the work load that their use imposes on the instructor is normally prohibitive. With automated grading, there is no additional load on the instructor.

The grader used in CEE 422 is being adapted to better address design problems. Problems are presented in such a manner that students are required to make choices typical of those made by practicing designers. Choices made by the student are critiqued and alternate, possibly better, solutions are presented. Future versions of the grader will focus on requiring students to make decisions at system level.

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Existing Automated Grading Systems

Computer and Internet technologies have advanced to the point where they can be used effectively to conduct on-line automated assessment of many aspects of student performance in engineering curricula. Combining these technologies with software he has created, the author has developed a system that is capable of replicating many features of traditional, manual performance assessment. The system also has a capability to evaluate problems not having unique solutions, typical of those problems assigned in design classes.

Commercial systems that provide on-line assessment capability include Blackboard (www.blackboard.com), InternetQuiz (www.familyeducation.com), Quizzer (www.pmachine.com/quizzer), WebAssign (www.webassign.com) and WebCT (www.webct.com). Particularly relevant to this paper, the American Institute of Steel Construction (AISC[2]) offers a system of web-based quizzes and essay questions. Grading of the multiple choice quiz questions is automated, but the essay questions must be graded manually. Non-commercial experiences with on-line assessment have been reported by Crepeau[3]; Jung[4]; Murden[5]; Weigel[7,8,9].

CEE 422

The homework grading system described in this paper is currently being used in CEE 422, Fundamentals of Steel Design, taught at the University of Louisville. The automated on-line grading methodology has been used in CEE 422 for about eight years, and initial experiences with the methodology are reported by Weigel[7,8,9].

CEE 422 is offered once a year to fourth-year students in the Department of Civil and Environmental Engineering. Load and Resistance Factor methodology is taught. In most cases, it is the student's first exposure to structural design, and is a critical course in the sense that it introduces the synthesis process and establishes a basis for successful performance in subsequent design courses. More information on all aspects of CEE 422 can be found on the following web site:

www.louisville.edu/speed/civil/courses/taweig01/cee422-SteelDesign/cee422.html

Philosophy

The philosophy guiding development of the grading system was that student experience with on-line grading should be as close as possible to the experience he / she would have under a traditional, manual grading scheme. This philosophy dictated that the automated grader be able to assign meaningful partial credit.

Grader Features

The current configuration of the grader for the homework problems has these features:

- Individualized problems - each student is given a unique set of (quasi-random) data for his / her problem;

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- Immediate feedback regarding correct / incorrect answers;

- Partial credit - this is achieved (where possible) by reworking subsequent parts of the problem using incorrect intermediate answers submitted by the student;

- A specifiable tolerance for judging the accuracy of numerical answers;

- The ability to "penalize" students for multiple attempts, and even to reissue new data after a certain number of attempts. It is also possible to configure the system to impose no such penalties;

- A specifiable time window during which students can work on a problem;

- Full bookkeeping automation, including assigning of grades and partial credit, recording of grades in a database, notification (via email) to the student of his / her grade and notification (via email) to the instructor of a summary of all grades on a homework.

Example Homework Problem

A typical homework problem given in CEE 422 is shown in Figure 1. The problem requires that the student design a bolted single angle tension member. To work this problem by LRFD methodology, the student must consider the limit states of yielding, fracture, block shear rupture and bolt capacity. In order to simplify the presentation in this paper, a block shear rupture check and a bolt capacity check are not included.

The LRFD equations for the Yield Limit State and Fracture Limit State are, respectively:

Yield Limit State	Fracture Limit State
LRFD Equation D1-1 $\phi F_y A_g \geq T_u$	LRFD Equation D1-2 $\phi F_u A_e \geq T_u$

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where:	where:
$\phi = 0.9$	$\phi = 0.75$
$F_y =$ steel yield stress	$F_u =$ steel ultimate stress
A_g = angle gross area	A_e = angle effective net area = $U A_n$
T_u = the factored tensile load the angle must support	$U = 1 - \frac{\bar{x}}{L} \leq 0.9$
	$\bar{x}$ = connection eccentricity
	A_n = net angle area = A_g − deduction for bolt holes

Table 1 - Evaluation of LRFD Yield and Fracture Limit States

Intermediate Answers

For the purpose of giving partial credit and to increase the likelihood that the student understands the process involved in designing the angle (and has not simply taken his / her answer from other design software), additional information about the selected angle and design calculations is required. Figure 1 shows the required answers, taken from the AISC design requirements shown in Table 1.

In the version of the problem shown in Figure 1, in addition to selecting an angle, the student is required to provide the following additional information: the governing axial load T_u (based on the controlling ASCE 7[6] load combination), the minimum angle gross area required to satisfy the Yield Limit State, the actual gross area (A_g) provided by the selected angle, and the following quantities involved in assessing the capacity of the angle for the Fracture Limit State: minimum net area (A_n) required, the actual net area provided by the selected angle, L, $\bar{x}$, U, the required effective net area (A_e) and the actual effective net area provided by the selected angle.

Grading

A student has his / her problem graded by going to the "Grade Homework" link of the course website and logging in by entering his / her student number and password. The grader then displays the problem, as shown in Figure 1. Individualized data is given in the table. A different student accessing this problem would receive a different set of data. Future versions of the grader will show the data embedded directly in the problem statement.

The student solves his / her respective problem as he / she sees fit (calculator, pencil and paper, spreadsheet or other software), enters the answers in the input fields provided, and submits the answers for grading. The HTML form hidden behind Figure 1 collects the answers and submits them (with some help from intervening PHP code) to a C++ program that is responsible for assessing their accuracy. The HTML form has embedded JavaScript code that

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prevents the student from entering a non-numerical answer where a numerical answer is required, and also insures that a non-zero value has been entered in each field.

Partial Credit

When the C++ program detects an incorrect answer, it reworks the problem from that point forward using the incorrect value(s) submitted by the student. Student answers subsequent to his / her incorrect value(s) are compared to these recomputed values. The program is capable of managing multiple incorrect answers.

This partial credit system results in three possible classifications of answers:

- Apparently unconditionally correct (✓ - green check) ;
- Apparently conditionally correct (✓ - amber check) - these answers appear to be correct, when evaluated based on previous incorrect answer(s);
- Apparently unconditionally incorrect (✗ - red X) - these answers appear to be incorrect, even when evaluated based on previous incorrect answer(s).

Graded Results

Figure 2 shows graded results from a hypothetical student submission for the problem shown in Figure 1. The entries in the *Value* column of Figure 2 are the values entered by the student and collected from the data form shown in Figure 1.

In the case shown in Figure 2, the student has computed T_u correctly but has not selected the lightest available section (L5x5x3/8). An incorrect choice for the lightest section changes the "correct" answers for all values dependent on the properties of the selected angle (for example, A_n, U and A_e). In the scenario shown, the student has apparently generated some of these values correctly, when the properties of the incorrectly selected section (L7x4x3/8) are used as a basis for computation. These answers would be treated as conditionally correct, and for them the student is given 80% of the possible credit. When checking numerical answers, a tolerance of 1.5% is used. The instructor may set this tolerance to any desired value.

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Design of a Single Angle Tension Member

Select the lightest single angle member to resist the loads shown in the table. Consider all the applicable ASCE-7 Load Combinations.

The angle is connected to a gusset plate with row(s) of bolts installed on ***standard gage*** lines. If you select an unequal leg angle, assume that the long leg is the leg connected to the gusset plate. Further, if the attached leg will accommodate two rows of bolts, assume that your connection has two rows. If the attached leg will accommodate only one row of bolts, assume that your connection has only one row. If your connection has two rows of bolts, then you should assume them to be staggered as shown in the figure. Spacing between adjacent bolts in a given row is *s* - if two rows of bolts are used, they are staggered midway between bolts in the adjacent row.

Note that although only three bolts per row are shown, more or fewer bolts in a row may be needed, depending on the bolt size and the loads which must be carried. This is not your concern in this problem; you are only concerned with selection on the angle size. The bolt pattern is given so that you may calculate the necessary areas and the value of U. We will learn how to calculate the number of bolts required later in the semester.

You may also assume that the gusset plate does not control and you may omit a block shear rupture check.

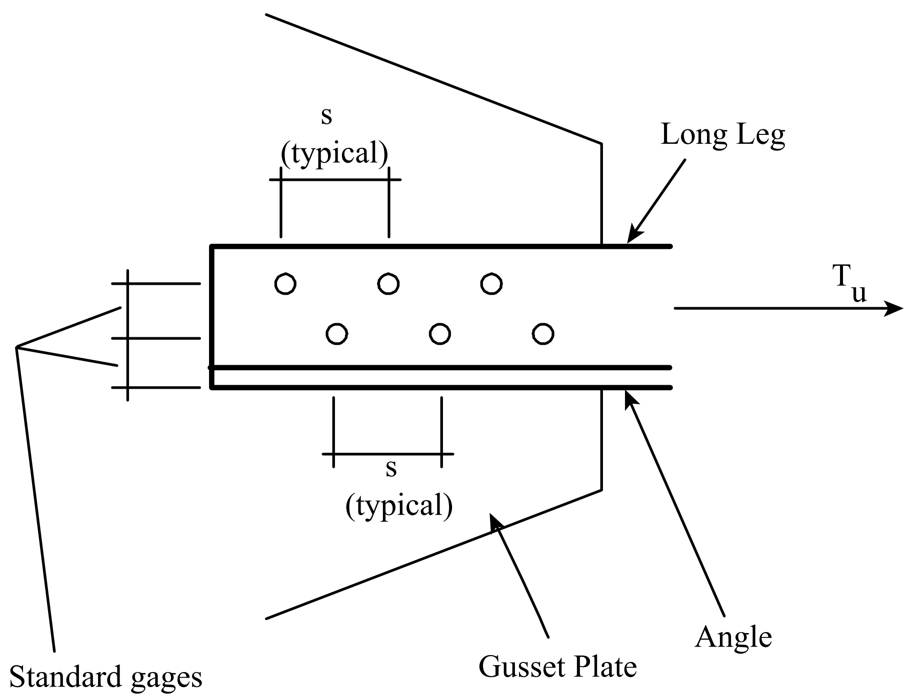

Figure 1 - Typical Homework Problem

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Do your calculations and report your answers with at least three decimal digits accuracy. Report your answers in units of kips and inches, but do not actually include units with the values you enter (that is, enter numerical values only).

Problem Data Assignment Table

Steel	s (in)	Bolt Diameter	D (k)	L (k)	L_r (k)	W (k)
A36	2	3/4	32	44	17	10

Angle section you selected

L8X8X1-1/8
L8X8X1
L8X8X7/8
L8X8X3/4
L8X8X5/8

T_u (controlling load - from the six ASCE-7 load combinations)

0

$A_{g\ reqd}$ (required gross area)

0

Enter these values for the angle you selected:

$A_{g\ prov}$ (gross area provided)

0

$A_{n\ reqd}$ (required net area)

0

$A_{n\ prov}$ (net area provided)

0

L (used in calculating U)

0

$\bar{x}$

0

U

0

$A_{e\ reqd}$ (required effective net area)

0

$A_{e\ prov}$ (effective net area provided)

0

Submit answers for grading

Figure 1 (continued) - Typical Homework Problem

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Design of a Single Tension Member January 2, 2005 13:23:58				
A ✓(green colored check) means that your answer is apparently unconditionally correct. These answers are worth a value of 1. A ✗(red colored X) means that your answer is apparently unconditionally incorrect. These answers are worth a value of 0. An ✓(amber colored check) means that your answer is apparently conditionally correct. This means that the answer appears to be correct based on one or more of your previous incorrect answers. Conditionally correct answers are worth 0.8. Selection of the correct angle section is worth 20% of the credit for this problem. The remaining 10 answers are worth 80% of the credit for this problem.				
Item	Value	Grade	Points	Help
T_u (Controlling axial load)	117	✓	1	
$A_{g\ reqd}$ (Required gross area)	3.62	✓	1	
L	4	✗	0	The value of L is the distance out-to-out of the bolts in your connection.
xbar	0.861	✓	0.8	
U	0.92	✗	0	Your value of U exceeds the maximum value permitted. The method to calculate U is found in LRFD Specification Section B3. See the example on the design of a single angle tension member.
$A_{n\ reqd}$ (Required net area)	2.94	✓	0.8	
$A_{e\ reqd}$ (Required effective net area)	2.70	✓	1	
$A_{g\ prov}$ (Gross area provided)	4.00	✓	0.8	
$A_{n\ prov}$ (Net area provided)	3.38	✓	0.8	

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$A_{e\ prov}$ (Effective net area provided)	2.21	✗	0	This value is the effective net area of the angle you selected. See the example on the design of a single angle tension member.
Selected angle	L7X4X3/8	✗	1.5	The design capacity of a L7X4X3/8 is 121.5 k and the required capacity is 117 k. This section is adequate but it is not the lightest available section. See the example on the design of a single angle tension member.
Your score on this attempt = 64.60 / 100				
If you choose to try again, the score for the number of right answers you have will be multiplied by 0.90.				

Figure 2 - Graded Problem

Individualized Data

The grader presents each student with individualized data. Data in this type of application cannot be assigned in a completely random fashion; it must be generated quasi-randomly, constrained to be within ranges that are typical of those found in engineering practice, and further constrained to produce reasonable solutions. Using purely random data may result in a problem with either a trivial solution, ludicrous solution, or even no solution.

"True" Design Problems

Even though so characterized in its description, the problem shown in Figure 1 is not a true design problem because it does not require that students make decisions typical of those made by practicing engineers. If this design was being done by a professional, he / she would have to make decisions other than selecting an angle size, and these decisions could materially affect the choice of the "best" angle. Furthermore, in the context of the total structure, the lightest angle is not necessarily the most economical selection. In order to guarantee that student answers agree with those expected by the grading system, it is necessary to make these choices in the problem for the student. This means that the problem shown in Figure 1 is artificially constrained. Specifically, the student is told which leg of the angle to connect, how many rows of bolts to use and how to space the bolt rows.

A more realistic version of this problem would have the student consider the following:

- Whether to use an equal-leg or unequal-leg angle. Steel fabricators normally do not stock unequal-leg angles, and a premium is charged if they are specified. Generally, the more economical solution is an equal leg angle;
- If an unequal-leg angle is specified, deciding whether the long leg or the short leg should be connected to the gusset plate. It is normally more efficient to connect the long leg;

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- Selecting the size and number of bolts to be used. At the point in CEE 422 that the problem shown in Figure 1 is given, bolt design has not been covered. This is not a major obstacle because the problem can provide a simple table with bolt sizes and respective capacities;
- If the connected leg of the angle is wide enough, two rows of bolts can be used. Using two rows of bolts will reduce the overall connection length but may also reduce the net area of the angle, resulting in a lower capacity for the Fracture Limit State, which in turn might require a larger angle. This area reduction potentially can be overcome if the rows are staggered as shown in Figure 3. For the case of the connected leg having a width of 5 inches or larger, the student must consider whether to stagger the bolt rows and the value of stagger (s_1) to be used;
- If two rows of bolts are used, the value of row spacing (gage) must be specified (rather than the standard gage that is currently required in Figure 1). Fabricators prefer that standard gages be used.

Modification of the grader is underway to adapt the grader to manage true design scenarios. Figure 3 shows a revised version of the problem given in Figure 1. The revised version is configured to force the student to make necessary design decisions. For this problem, the grading process is accomplished in two phases. The first phase is a sort of “pre-processor” requiring the student to make his / her design decisions. A form that allows the student to make these choices is shown in Figure 4.

As with most design situations, there are not necessarily “correct” or “incorrect” choices. Based upon the overall context of the design, some choices are, however, better than others. For example, the designer normally connects the long leg of the angle to the gusset plate because doing so results in a larger capacity for the Fracture Limit State, and reduces the connection eccentricity. However, an adequate angle configuration can be found with the short leg of the angle attached, and in certain situations this might be an acceptable or even a preferred choice. Some reason why the designer may choose to connect the short leg include: a limit state other than fracture controls the capacity of the angle; the final angle selection is made on the basis of a serviceability consideration (for example, angle stiffness); the final angle selection is made based on the fact that a large number of other (heavier) angles on the project have been selected and the designer wishes to minimize the variation in angle size used on the project. In any case, the pre-processor can permit the student to proceed with a less than optimal choice, but it should explain the ramifications of doing so. For example, if the student chooses to connect the short leg of the angle, a window such as shown in Figure 5 should popup, and the student could decide to change his / her choice based on the information provided.

Grader Extensions

Plans for extensions of the grading systems include the following:

- For design problems, add the capability to consider sections that might not be the lightest acceptable section, but could still be satisfactory choices (in some cases perhaps better choices);

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- Permit students to evaluate their solutions in a “diagnostic mode” - a student would be permitted to diagnose an incorrect solution by selecting which of the intermediate answers he / she wanted to check. This would allow the student to diagnose errors for high difficulty level problems. These are problems for which, initially, only the final answer is graded. A penalty could be imposed for each diagnostic step the student uses;

- Expand system capabilities to accept symbolic answers, for example to evaluate equilibrium equations.

Summary

An automated on-line grading system capable of evaluating design problems is under development at the University of Louisville. Initial results with the system are promising and future improvements should significantly improved its capabilities.

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Design of a Single Angle Tension Member

The single-angle tension member shown in the figure is made of *A36* steel and must resist a factored load T_u = *117* k. The fabricator stocks only equal leg angles; unequal leg angles may be had for a premium of *5*%. Because of connection requirements at parts of the structure away from this connection, the outstanding (unconnected) leg must have a dimension of at least *4* in. The table shows available bolt sizes and respective capacities. You may also assume that the gusset plate does not control and you may omit a block shear rupture check.

In this problem you must make the following decisions / selections:

The best angle to use for this situation
Whether to use an equal leg or unequal leg angle
Whether to connect the long leg or short leg of the angle to the gusset
The number and size of bolts to be used
Whether to use one or two rows of bolts
The intra-row spacing (s) between bolts
The row stagger (s_1), if you use two rows of bolts
The row gages (g_1 and g_2)

Bolt Capacities	
Bolt Size	Capacity (k)
5/8 in	11.0
¾ in	15.9
7/8 in	21.6
1 in	28.3
1-1/8 in	35.8
1-1/4 in	44.2
1-3/8 in	53.5
1-1/2 in	63.6

Figure 3 - Problem Revised to Closer Emulate the Design Process

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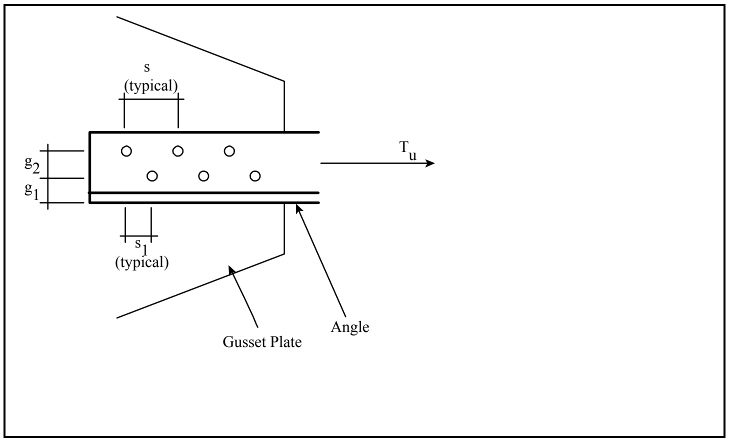

Figure 3 (continued) - Problem Revised to Closer Emulate the Design Process

<table>
<tr><td colspan="4">Design of a Single-angle Tension Member
Select Design Parameters</td></tr>
<tr><td colspan="4">Angle Parameters</td></tr>
<tr><td>Angle Type
○ Equal leg
○ Un-equal leg</td><td>Connected Leg
○ Short
○ Long</td><td colspan="2"></td></tr>
<tr><td colspan="4">Bolt Parameters</td></tr>
<tr><td>Bolt Size
○ 1/2 in
○ 5/8 in
○ 3/4 in
○ 7/8 in
○ 1 in</td><td>Number of Bolts
[ ]</td><td>Spacing
s (in)
[ ]
Stagger
s₁ (in)
[ ]</td><td>Gage
g₁ (in)
[ ]
g₂ (in)
[ ]</td></tr>
</table>

Figure 4 - Selecting Design Parameters

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Comparison of Single-Angle Fracture Limit State Capacities for Short Leg Connected Versus Long Leg Connected

The first part of the figure below shows a connection involving a single angle and a gusset plate is subjected to a moment caused by the fact that one of the forces acts at the centroid of the gusset and the other force acts at the centroid of the angle. This moment causes the connected pieces to twist and distort. The twisting moment produced is a function of the distance between the respective lines of actions of these forces (the distance between the centroids). The larger this distance is, the greater will be the moment. Connecting the long leg will reduce the twisting moment.

Furthermore, when considering the Fracture Limit State, it is normally more efficient to connect the long leg of the angle. The second part of the figure below shows why. Consider an L5X3X5/16 angle made of A36 steel. This angle has a gross area of 2.41 in^2. Assume that the bolt pattern that connects the angle to the gusset is such that the angle has a net area of 2.14 in^2 and the total connection length (L) is 6 in. The figure on the left shows the Fracture Limit State calculation when the short leg is connected, and the figure on the right gives the corresponding calculation when the long leg is connected.

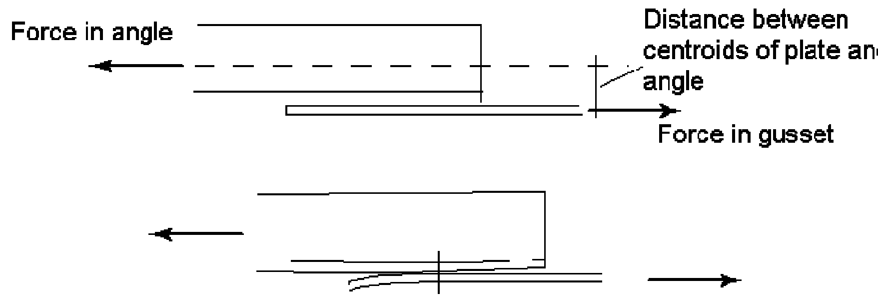

Figure 1 - Moment and Twisting in Single-Angle Connection

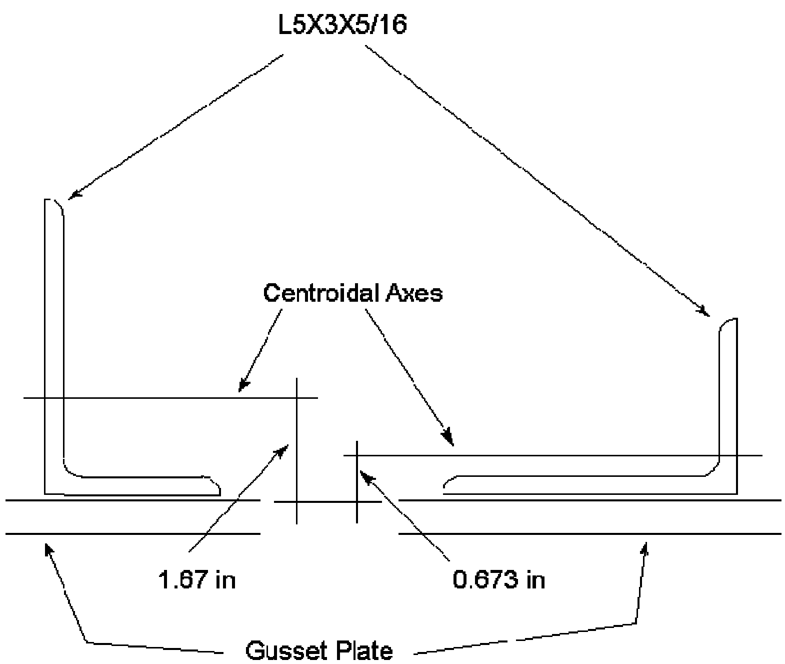

Figure 2 - Comparison of Fracture Limit State Capacities

Figure 5 - Explanation Accompanying Non-optimal Design Decision

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Short Leg Connected	Long Leg Connected
$U = 1 - \frac{\bar{x}}{L} = 1 - \frac{1.67}{6} = 0.721$	$U = 1 - \frac{\bar{x}}{L} = 1 - \frac{0.673}{6} = 0.887$
$A_e = 0.721(2.14) = 1.54\text{in}^2$	$A_e = 0.887(2.14) = 1.90\text{in}^2$
$\phi A_e F_u = 0.75(1.54)(58) = 67 \text{ k}$	$\phi A_e F_u = 0.75(1.90)(58) = 82.7 \text{ k}$

In this case, connecting the long leg results in an increase in capacity of 23% for the Fracture Limit State.

Here are some occasions when connecting the long leg does not result in added angle capacity, or situations in which connecting the short leg may be preferable. Some of these situations are:

1) The capacity of the angle is controlled by a limit state other than fracture (say, angle yield or shear rupture);
2) It is desired to have a long outstanding angle leg in order to facilitate connection of the angle to some other part of the structure;
3) Out-of-plane stiffness of the angle is a consideration;
4) For horizontal diaphragms, erection is easier with the long leg vertical, meaning that the short leg is the connected leg.

Figure 5 (continued) - Explanation Accompanying Non-optimal Design Decision

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