

## **Improving Visualization and Sketching Skills for Structural Engineering Students**

### **Abstract**

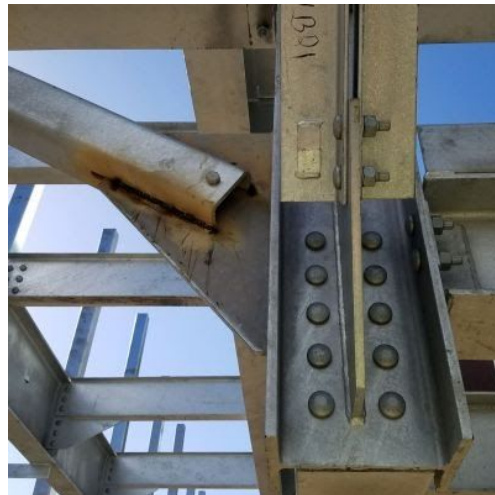
The ability to visualize in structural engineering is a crucial skill. Analyzing and visualizing different perspectives of existing drawings and images is important and structural engineers must be able to sketch their own images to convey their designs to others. Students tend to struggle with skills such as visualizing and sketching section cuts and details, correlating various 2D views of 3D structures and components, conceptually connecting cross-sectional properties to member behavior (e.g., cross-sections of strong- and weak-axes determining tensile, bending, and buckling behaviors), and properly understanding the flow of forces through a structure and its components. Skills such as these aid in growing a student's understanding of design methods and developing their engineering intuition.

In the authors' experience, using static figures, pictures, and structural drawings is only so effective in teaching these skills. Practicing sketching is likely a more effective way to improve these skills, yet many instructors of structural design courses, typically junior- or senior-level classes, may not spend time emphasizing these necessary skills. Many instructors may expect students to already have developed their sketching and visualization skills in lower-level engineering courses. But, lower-level courses usually only cover visualizing and sketching various views of generic block shapes. Structural engineering students need to understand and develop detailed visuals such as section cuts, elevation views, and plan views of structures and their components. These advanced visualization and sketching skills still seem to be difficult even for senior-level students.

Therefore, this paper evaluates the authors' experience in providing students the opportunity to practice visualization and sketching tasks that are more applicable to structural engineering in a structural steel design course. After observing a lack of visualization skills, a simple and easily implemented assignment was given to the students and student performance before and after this intervention is analyzed.

## Introduction

In structural engineering, visualization skills are a core component of understanding the geometry, organization, and relative dimensions of complex structures and their components. A structural engineer is required to analyze and design connections, structural members, and other components of a structure. During structural engineering education, specifically in steel design courses, students are expected to visualize cross-sections, various orientations and views of connections, and plan and elevation views of buildings. For example, for the steel connection shown in Figure 1, it is important to know the number and location of bolts to analyze the member for its tensile capacity and mode of failure. Understanding the location of small components, such as bolts, welds, rebars, and nails, promotes the comprehension of the flow of forces and cross-sectional properties that are preliminary in analyzing and designing members for tension, compression, bending, and combined loading.



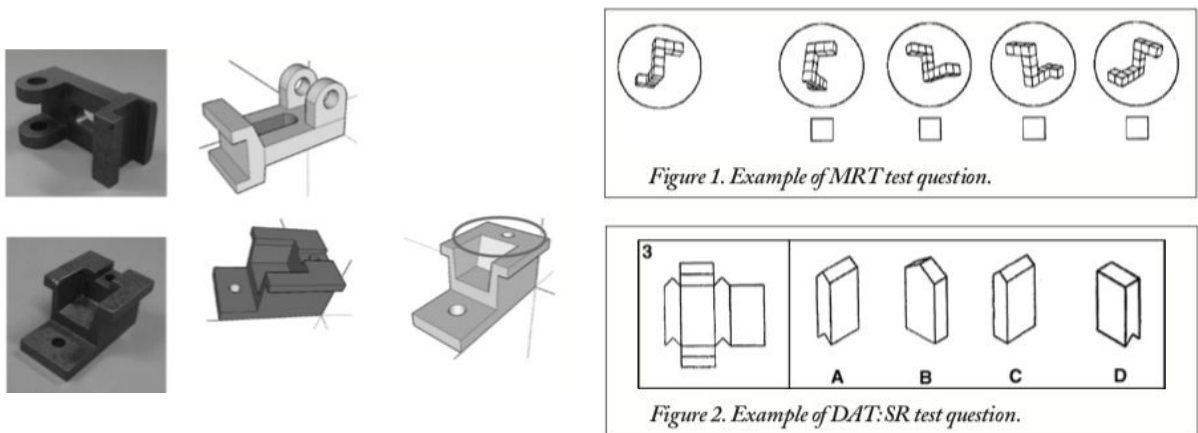
(Photo taken from Southern Steel Engineers, southernsteelengineers.com)

**Figure 1** A sample steel connection with details to be visualized, including bolts, plates, and connections

Spatial visualization is a complex cognitive skill utilized in engineering via sketches, computer generated drawings, and 3D renderings of engineered components, all of which are forms of graphic communication<sup>1</sup>. This skill includes performing mental transformations and cuts<sup>2,3</sup> of different angles in order to analyze configurations<sup>3</sup>. In addition to comprehending engineering drawings, this skill helps to communicate preliminary design ideas through sketching and computer models. Many have addressed improving visualization skills for freshman engineering students using remedial courses, pencil- paper exercises, web-based tools and physical models<sup>4,5</sup>. In order to assess how these interventions affect student performance, researchers use Purdue Spatial Visualization Test (PSVT), Mental Cutting Test (MCT), Mental Rotation Test (MRT) and Differential Aptitude Test (DAT) as measuring tools. Samples of these types of visualization

tests are shown in Figure 2. These tests involve shapes such as generic blocks with simple flat surfaces and limited applicability to components used in structural engineering which have greater detail in their connections and cross-sectional shapes.

Few studies were found in the literature addressing visualization skills specific to structural steel components. A paper, by Meyer, et. al, suggests using physical models as a means to illustrate steel design concepts to students. The paper describes various ways of communicating steel member behavior through physical models, yet the effect on student performance was not assessed<sup>8</sup>.



(a) Physical and CAD models utilized in a first-year program in a remedial course<sup>5</sup>

(b) Typical MRT<sup>6</sup> and DAT:SR<sup>7</sup> test questions for assessing spatial ability<sup>4</sup>

**Figure 2** Examples of the kinds of objects in typical visualization exercises conducted early in engineering curricula.

The goal of this study was to improve the visualization skills of structural engineering seniors in a steel design course. In a recent course offering, the first of two exams revealed student weakness in sketching and visualizing various views and cross-sections. The graders observed student drawing errors including missing elements and incorrect orientation or placement of components. These mistakes are consistent with mistakes seen by the instructor in the past several years in this and other structural design courses.

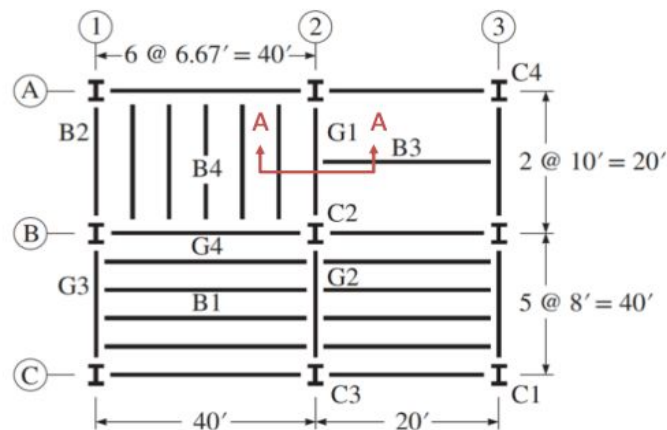
Therefore, a sketching assignment was initiated between the two exams as an intervention to encourage students to practice visualizing and drawing various views of connections, floor plans, and detailed 3D structural steel components. The final exam, then, included questions testing the students visualization and drawing skills. The questions involving drawing on the first and final

exams were analyzed using similar rubrics to evaluate an improvement of students' visualization skills.

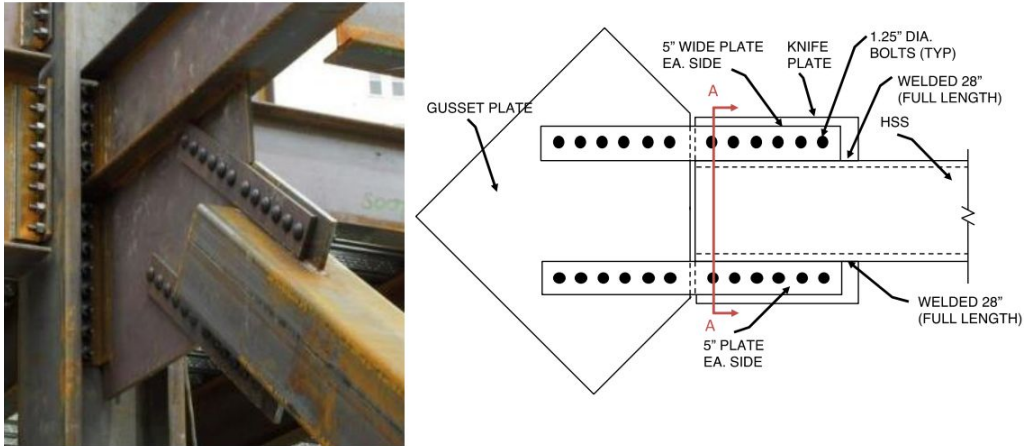
## Background

The University of California, Irvine Department of Civil & Environmental Engineering (CEE) offers Structural Steel Design as the second structural design course in the undergraduate curriculum (following Concrete Design). Steel Design is typically taken in the first term of students' senior year. The course covers topics such as the flow of forces through a gravity system and analyzing and designing members in tension, compression, bending, and combine loading, as well as their connections. Drawing cross-sections is a tool used to understand the flow of forces from one steel component to another and to evaluate properties needed to design or analyze those components. For example, the rupture failure mode of a tensile member is dependent on its net area and drawing a cross-section of the connection illustrates that area.

In Fall 2019, a midterm (Exam 1) and final exam (Exam 2) were administered to the students of the design course. Exam 1 contained six questions, four of which required visualization skills. These questions ask students to draw the following: an elevation view of a W-shape column from a written description, a 2D perspective of a C-shape from a given 3D figure, a cross-section of a floor plan from a given plan view (see Figure 3), and a cross-section of a detailed connection from a given 2D and 3D figure (see Figure 4).



**Figure 3** A floor plan given in a question from Exam 1 asking students to draw cross-section A-A, including all structural components participating in the flow of forces



**Figure 4** A 3D and 2D view of a connection given in a question from Exam 1 asking students to draw cross-section A-A, including all structural components participating in the flow of forces

Midterm results revealed students' weaknesses in visualization skills. In the example of the cross-section of the detailed connection, students' drawings were missing welds, bolts, and plates, incorrectly orienting plates, and misplacing the knife plate (see **Figure 4**). Mistakes such as these led to miscalculations of net area and capacity.

The students in this course have taken a class in the beginning of their college careers to teach them a level of drawing skills. This level of drawing includes the ability to draw generic block shapes from different perspectives. The level of drawing required in the steel design course includes the ability to draw complex cross-sections of floor plans and connections with detailed components like bolts and welds (again, see **Figure 3** and **Figure 4**).

After Exam 1, a sketching assignment was assigned to the students to initiate practice of visualizing and drawing complex figures, similar to those on Exam 1. Exam 2 would be administered after the assignment was given and would include questions having the students draw complex figures similar to those on Exam 1 and the sketching assignment.

### Sketching Assignment

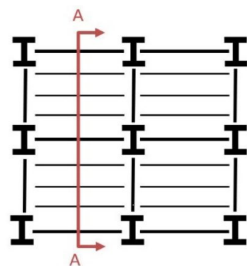
The sketching assignment was sectioned into three parts based on the type of visualization as shown in **Figures 5** through **7**. The first part of the assignment was titled "Drawing Cross-Sections from a Side View." This portion included a table with three columns, shown in **Figure 5**, including side view figures of structural connections, a place to list the elements in the section cut, and a place to draw the cross-section. The first row of the table contains an example demonstrating the process.

#	Side View	List of Elements to be in Cross-Section A-A	Cross-Section
Ex.		<ul style="list-style-type: none"> <li>• 4 Plates</li> <li>• Knife Plate</li> <li>• HSS</li> <li>• Bolts</li> <li>• Welds</li> </ul>	

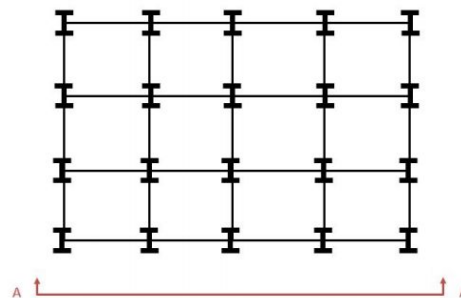
Figure 5 Example problem given in part 1.

The second part was titled “Drawing from a Plan or 3D View,” and instructed students to draw cross-sections, elevation views, and plan views from either a floor plan or 3D view, **Figures 6** and **7**, respectively. Sketches were to include beams, girders, columns, and decking when appropriate. The 3D representation of a multistory building, in **Figure 8**, was included to initiate students to sketching the plan view. A problem such as this is similar to those taught in lower-level courses, with a generic block shape and are more simple than drawing cross-sections of floor plans or connections. This was the only problem on the assignment that constitutes a review of the basic visualization skills already practiced by the students before the steel design course.

The third part of the assignment was titled “Drawing from a Description” and asks students to draw the side view or cross-section of a connection based on a given written description. This part utilizes course-related terminology in the description, initiating students to visualize fully without a given figure.

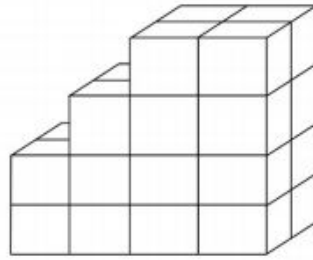


(a) Students to draw cross-section A-A



(b) Students to draw elevation A-A

Figure 6 Floor Plans given in Part 2 of Sketching Assignment



**Figure 7** 3D View given in Part 2 of Sketching Assignment

## **Methods**

The drawing assignment was given to encourage students to practice drawing detailed figures with the goal of improving students' visualization skills. Exam 2 included drawing problems similar to those on Exam 1 and the sketching assignment. Exam 2 was used to evaluate the improvement in student skill when drawing figures after the students have had specific drawing practice. Exam 1 and Exam 2 were analyzed using rubrics.

The rubrics were created to evaluate and quantify accuracy of drawings. Rubrics were made based on the possible errors that could be made in each of the drawings. Since each question given in Exam 1 and Exam 2 varies in difficulty and contains different components, the rubric must be different for each drawing problem. The rubrics are created with the same methodology for both Exam 1 and Exam 2, and are shown in **Figure 8**.

The rubric is broken down into sections including presence, location, orientation, correct quantity of elements, and miscellaneous mistakes when appropriate. The "Presence of" section aims to account for the inclusion of items in the sketch, such as structural components, hidden lines, and appropriate spacing of components. The "Location of" section is graded according to the correct placement of elements, including decking, bolts, and plates. The "Orientation of" section accounts for the members and details drawn in the correct orientation (e.g. depicting w-shapes in the correct orientation using lines to show the flanges or web). The "Correct Quantity of" section addresses the number of structural elements required by the drawing, including the number of welds, plates, and bolts. The "Miscellaneous" section accounts for additional errors not defined in the rubric. These errors include, but are not limited to, incorrect perspective drawings (e.g. drawing a plan view when an elevation view was asked for) and adding details that are not given in the problem description (e.g. adding a pin support, girder, or decking at the base of an elevation drawing when incorrect).

The elements of each section are graded by giving a 1 or 0 to each error, and a total score and percentage is computed for each visualization question. An example of a student's work and solution is shown below in **Figure 8**. Scores will be calculated and pre- and post-intervention results will be compared to evaluate improvement in student performance.

Presence of:	Beam 1	0
	Beam 2	1
	Girder	0
	Decking	0
	Concrete Slab	0
Location of:	Decking	0
Orientation of:	Beam 1	0
	Beam 2	0
	Girder	0
	Decking	0
Miscellaneous:		1
Total (out of 11)		2
Score		0.18

Presence of:	HSS	1
	Knife Plate (through HSS)	1
	Welds	0
	Wide Plates	1
	Bolts	1
Location of:	Knife Plate	1
Orientation of:	Wide Plates	1
Correct # of:	Welds	0
	Wide Plates	1
Miscellaneous:		1
Total (out of 10)		8
Score		0.80

Presence of:	Columns	1
	Girders	0
	Decking	1
	Concrete Slab	1
	Three Floors	1
	Appropriate spacing between floors	1
Location of:	Decking	0
Orientation of:	Columns	1
	Girders	1
	Decking	0
Miscellaneous:		0
Total (out of 11)		7
Score		0.64

Presence of:	W-Shape	1
	½" Plate	1
	1" Plate	1
	Vertical Bolts	1
	Horizontal Bolts	1
	Web Plates	1
Location of:	Horizontal Bolts	1
	Vertical Bolts	1
Correct # of:	Horizontal Bolts	1
	Vertical Bolts	1
	Web Plates	1
Miscellaneous:		1
Total (out of 12)		12
Score		1.00

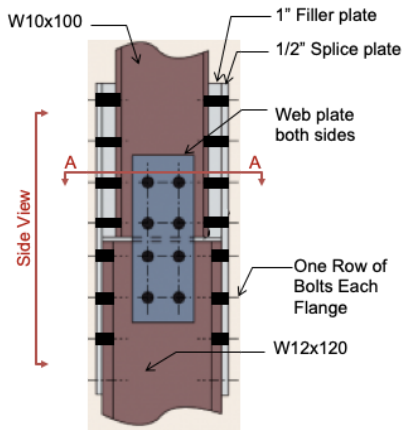
(a) Elevation/Cross-Section of Floor

(b) Cross-Section of Connection

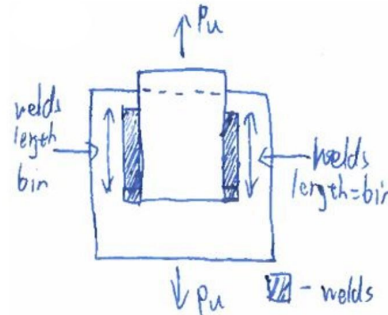
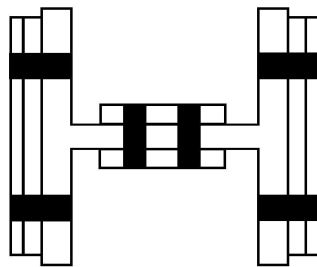
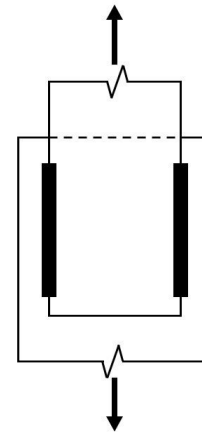
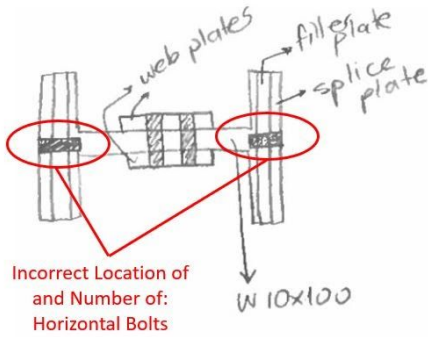
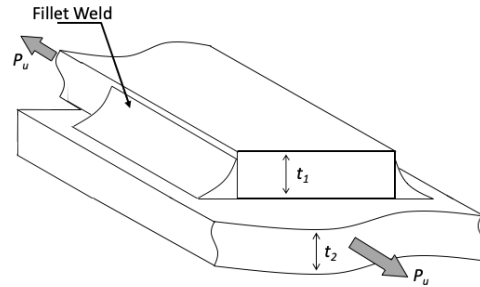
**Figure 8** Sample rubrics used to score problems on Exam 1 (top) and Exam 2 (bottom)



**Draw a sketch** of the cross-section A-A with the column web drawn horizontally.



**Draw a top down view** of the connection including any hidden lines. On sketch, **label** the length of the welds **and** include the force arrows.



**Figure 9** Sample problem statements (top row), student drawings (middle row), and the expected solutions (bottom row).

## Limitations

After analyzing the results certain limitations of this study were realized. One limitation is the lack of a control group (ie., a group not given the specific sketching assignment to increase practice). Since the intervention came about as an immediate corrective measure in response to observed student weaknesses, the immediate goal was to improve student performance rather than observe the effectiveness of practice. Therefore, the study began mid-term, after observing errors in the drawing questions in Exam 1.

Since there is no control group, this study cannot detect the reason for a change in student performance and the change cannot be directly attributed to either the effectiveness of the sketching assignment nor the presence of additional drawing practice. Further, their relative contributions to performance change also cannot be determined.

Exam 1 and 2 were evaluated after the term finished. Exam 2 was analyzed immediately after it was completed and therefore results include the whole class. Exam 1 was returned to the students before it was able to be analyzed for this study and only 18 tests were able to be recovered and scored with the rubrics. Since approximately half of the Exam 1 results were available, there is a limited depiction of the total change from Exam 1 to Exam 2.

## Results

In this course, the instructor did not provide sketching and visualization homework or example problems before Exam 1 and did not announce that visualization problems would be included in the exam. Therefore, the results observed in the Exam 1, shown in Table 1, can be reasonably assumed to closely represent the students' actual level of visualization skill prior to the intervention.

As seen in **Table 1** and **Figure 10**, the first and second exams had questions that fell into two categories. Category 1 questions are those related to a skill level assumed to have been obtained from lower level classes (e.g., generic blocks). Category 2 questions are those related to a skill needed in upper level design courses. Examples of Category 2 are drawing cross-sections of a floor plan, marked in green on **Table 1**, and drawing detailed steel connections, marked in purple on **Table 1**. The results for Exam 1 and 2 can be seen in the table and figures below.

**Table 1** Summary of Student Performance Before and After Intervention Assignment

## (a) Exam 1 Results

	Question Type (N)	Min (%)	Max (%)	Average (%)
Category 1	1. Column Side View (17)	57	100	87
	2. C-Shape Side View (18)	63	88	80
Category 2	<b>3. Cross-Section: Floor in Building (16)</b>	<b>18</b>	<b>100</b>	<b>60</b>
	<b>4. Knife Plate Cross-Section (16)</b>	<b>30</b>	<b>90</b>	<b>71</b>

N = Number of responses

## (b) Exam 2 Results

	Question Type (N)	Min (%)*	Max (%)	Average (%)
Category 1	1. Welded Plate Cross-Section (48)	83	100	99
	2. Welded Plate Plan View (48)	86	100	95
	3. Welded Plate Side View (47)	20	100	91
Category 2	<b>4. Elevation and Cross-Section of Floors in Building (47)</b>	<b>36</b>	<b>100</b>	<b>75</b>
	<b>5. W- Shape Cross Section (47)</b>	<b>50</b>	<b>100</b>	<b>86</b>
	<b>6. W-Shape Side View (46)</b>	<b>38</b>	<b>100</b>	<b>71</b>

N = Number of responses

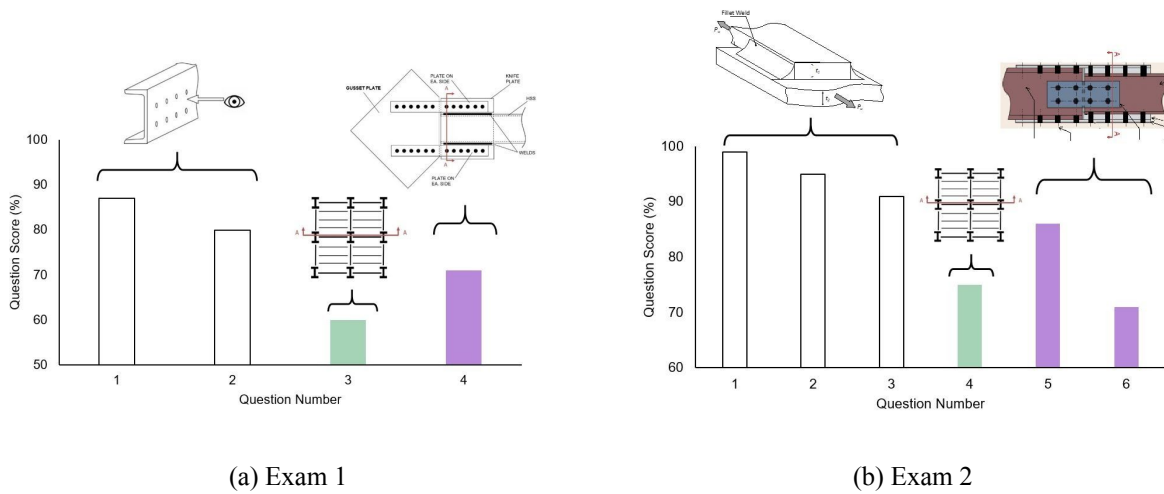
\*Does not include scores of 0, which were left blank.

## (c) Exam 1 vs. Exam 2 Average Scores by Question Type

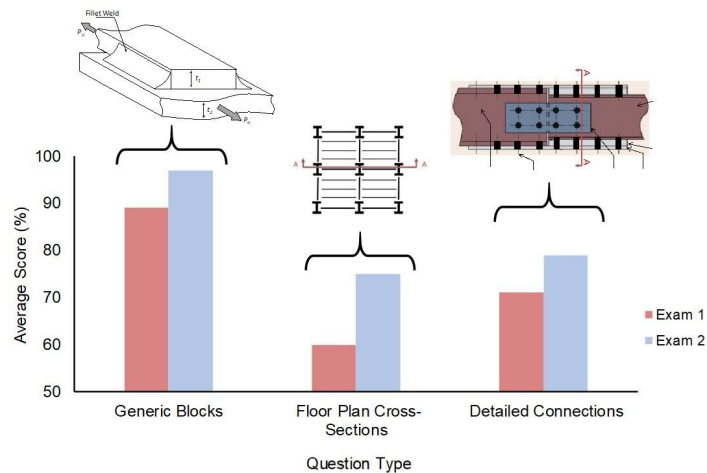
	Question Type	Exam 1 Averages (%)	Exam 2 Averages (%)	Improvement (%)
Category 1	Generic Blocks	89	97	8
Category 2	<b>Cross-Section of Floors in Building</b>	<b>60</b>	<b>75</b>	<b>15</b>
	<b>Detailed Connection</b>	<b>71</b>	<b>79</b>	<b>8</b>

In Exam 1, students received higher scores in Category 1 than in Category 2, showing their previously learned skill in visualizing and drawing generic block shapes is relatively strong. However, students performance was much weaker in Category 2 with some students scoring as low as 18% and 30%, for cross-sections of a floor plan and detailed connections, respectively, showing their lack of visualization skills needed in upper-level design courses.

After practicing these skills on the intervention assignment, students showed improvement in both categories and in each question type on Exam 2 compared to Exam 1. These improvements are observed in **Figure 11** and **Table 1(c)**.



**Figure 10** Averages scores from exams



**Figure 11** Averages scores from Exam 1 and 2 by Question Type

## Conclusion

The ability to visualize in structural engineering is crucial. From analyzing section cuts and details to correlating various 2D views of 3D structures and components, to the ability to connect cross-sectional properties to member behavior, these skills help students build an understanding of design methods and engineering intuition.

In the past several years of the instructor's experience student weakness in sketching and visualization in structural steel design has been obvious. In a recent offering of the course, an assignment was implemented after particularly poor performance was observed in the first of two exams. This intervention provided students the opportunity to practice visualizing and drawing various views of connections, floor plans, and detailed 3D structural steel components (i.e., visualization and sketching skills more complicated than those typically practiced in early courses of an engineering curriculum).

After encouraging students to complete detailed and specific drawing and visualization practice, their drawing scores improved on the following exam. Students scored higher in both Category 1 and 2 items, but showed more significant improvement sketching more complex items (Category 2).

Although scores were indeed higher for Category 1 items (+8%), Exam 1 scores were already very high at nearly 90% (nearly an A-grade). This improvement shows that practice was not necessarily needed for simple Category 1 sketching and visualization. So, instructors' assumption that students already are capable of performing these tasks, due to prior instruction, may be well founded.

However, overall larger gains (+11.5%) in Category 2 items shows that students benefited from practice. Although the improvement in score is not significantly higher, the total average score is much more acceptable, having improved from about 65% (a D-grade) up to about 77% (nearly a B-grade). Therefore, it may not be productive for instructors to assume that students are already well equipped to perform and understand these more complex drawings.

Is it surprising that additional practice seems to have caused students to improve? No, but it does show that instructors of structural design courses may want to consider explicitly providing students with the resources and opportunities to practice sketching, drawing section cuts, and visualizing more detailed and complex structural components. Further, they ought not rely on the fact that an earlier course covered sketching and visualization. For this class, more practice was effective in improving students' abilities in drawing realistic, practical, and complicated structural components, connections, and building sections.

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