Teaching Steel Connections Using an Interactive Virtual Steel Sculpture

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Abstract

Steel connections play important roles in the integrity of a structure, and many structural failures are attributed to connection failures. Connections are the glue that holds a structure together. The failures of the Hartford Coliseum in 1977, the Hyatt Regency Hotel in Kansas City in 1980, and the I-35W Bridge in Minneapolis in 2007 are all attributed to connection failures. A good connection design requires engineer to have a good understanding of the mechanics and steel behavior. The engineer also should know the fabricator's limitations and experience. In the past few decades, in order to help students better understand various connection types; many schools have acquired the steel sculptures. A steel sculpture is a physical system that shows different types of connections found in standard construction practices. Unfortunately, because of its size and location (eight feet tall, weighs nearly 2500 pounds and usually erected outdoor), students do not always have easy access to it. Moreover, today's students who belong to the Google generation are more comfortable with web-based learning tools. Through a NSF grant we have created an interactive version of the steel sculpture to provide not only an effective learning opportunity but also a 24-7 access to students and educators in the United States and abroad.

This work is the result of a collaborative effort among universities and students from different engineering programs. The virtual sculpture gives the user the freedom to rotate or pan the sculpture to view it from any direction. The user may also isolate any one of the connections for a closer view and learn more about that given connection including: description of the connection, potential failure modes (limit states), sample calculations of each limit state to determine the load carrying capacity of the connection, field examples, and finite element models of various failure modes, and a visual display of stress distribution in the connection area.

The solid model of the steel sculpture was developed using Creo and converted to a 3-D interactive PDF file. This was done to avoid the need for purchasing the Creo software. A web page was also developed from where users can download the virtual sculpture and all of the linked documents. Three survey forms were also developed with a slightly different focus to seek feedback from students, educators, and recent engineering graduates. The user may complete the online survey form after s/he has had an opportunity to explore the virtual sculpture. The capabilities of the virtual steel sculpture are presented in this paper.

Introduction

A typical steel design course includes the following topics: determination of load combinations with appropriate load factors; sizing of tension (axial), compression (columns), and flexural (beam and girder) members; and design of tension connections using mechanical fasteners and welds. In some cases, time permitting, an instructor also may be able to cover additional topics such as shear-moment connection design. Moreover, in a 15 week long semester, it is customary to teach "connections" during the last two weeks of the term.

This lack of emphasis (accounting for approximately 10% of the course) is not a reflection of the significance of connections in design, instead, it is due to time constraints and the commonly mis-held belief that connections are standardized details that could and should be left to fabricators and detailers. However, connections are the glue that holds a structure together, and as such deserve special emphasis to ensure sound structural integrity. Historically, connection failures have contributed to many structural failures. Examples include: the Hartford Civic Center in 1977 [1], the Hyatt Regency Hotel in Kansas City in 1980 [2], and, more recently, the I-35 W Bridge in Minneapolis [3]. Since the Hyatt Regency failure, many state licensing boards have made connection design the responsibility of a professional engineer. Moreover, there are situations for which standard connection types would not be applicable, and engineers are required to design connections unique to those specific structures. A good connection design requires the engineer to have a good understanding of mechanics and steel behavior and an understanding of fabrication limitations. Often, what, theoretically, may appear to be an acceptable design, in practice, may become infeasible to fabricate in the shop or in the field. AISC Code of Standard Practice [4] recommends that engineers work closely with the fabricators and detailers while designing connections. For these reasons, it is critically important that students, preparing to become practicing structural engineers, develop a good understanding of connection design, limitations, and assembly. Moreover, because of their three-dimensional nature, students have difficulty visualizing the assembly of connections of major components such as beams and columns.

The decision to create an interactive multi-media tool was made based on extensive research of the targeted audience and emerging engineers. Most faculty members who teach steel design belong to the baby boom generation. As such, they were taught using blackboards and black and white textbooks with limited illustrations. Engineers, in particular, were taught to understand and interpret orthographic views such as top, front, and side views. Today's students, as part of the Google generation are accustomed to whiteboards, multimedia presentations, multi-color textbooks with ample illustrations, and three-dimensional graphics. Most unique to the *Google generation* is the fact that they have grown up with the internet, a comprehensive tool that provides a number of resources including detailed graphics, downloading capabilities for music and movies, blogging, and tweeting. Smart phones, texting, and other electronic gadgets are also in wider use than any other time in history [5]. These societal factors are quantified in numerous surveys of college aged students in the U.S. [6-11] which show that:

- 86% own a computer
- 97% have downloaded music and other media using peer-to-peer file sharing
- 93% own a cell phone
- 76% use instant messaging and social networking sites
- 76% of college students have a Facebook profile which they use over one hour a day
- 84% own some type of portable music and/or video device such as an iPod
- 63% of college students have internet capable handheld devices
- 49% regularly download music and other media using peer-to-peer file sharing
- 34% use websites as their primary source of news
- 28% author a blog and 44% read blogs
- 15% of IM (instant messaging) users are logged on 24 hours a day/7 days a week

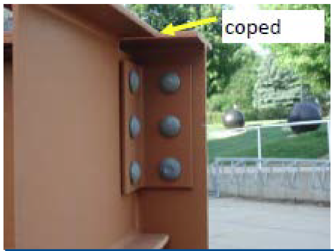


FIGURE 1a. Double bolted-angle shear connection, view 1

FIGURE 1b. Double bolted-angle shear connection, view 2

FIGURE 1c. Double bolted-angle shear connection, back of view 2

- Over one-quarter of students listed their laptop as the most important item in their bag which is almost three times the number of students who chose textbooks.

During the past two decades, there also have been many changes in the way lectures are delivered to students [12, 13]. We have seen an increase in the use of physical models to help students better understand key concepts, and have moved from black boards to white boards and then to online deliveries (e.g., Blackboard, UCompass, Desire2Learn). We have transformed our classrooms to take advantage of new technologies. These efforts were all made in an attempt to narrow the generation gap, so that we can better connect with students and their learning styles.

Also, this period has seen a great deal of research dealing with the way in which people learn [14-24]. One of the key characteristics on learning as discussed by Branford et al. [22] is that initial learning is necessary for transfer; the application of previous knowledge in acquiring new knowledge. Although it may seem obvious, these studies show, conclusively, the benefits in the thorough understanding of transfer [14, 22]. Additionally, the level of motivation a student has affects the amount of time a person is willing to spend on a subject in order to learn it. Learners are more motivated when they can see the usefulness of what they are learning [22]. Our understanding about the way people learn, in conjunction with the generational background provided the rationale for the development of an interactive multi-media tool for steel connection design.

Steel Sculpture – The Physical Model

Steel connections are primarily designed as 2-dimensional elements (x-y and y-z planes) despite the fact that their load bearing behavior is 3-dimensional. Combining two 2-D designs to yield a connection that supports a 3-D load bearing behavior is a concept that is usually very difficult for students to visualize. Figure 1 shows various views of the shear connection between a girder and two beams (Beams B3A and B3B which are connected to Girder B3) in a steel sculpture. It is common to use two angle sections to connect these structural members. One of the angles will be in the front face of beam 3A and the other angle will be placed at the back face of beam 3A. The bolts will then connect all three elements together as shown in Figure 1b.

If only the view shown in Figure 1a were presented, it would be reasonable to conclude that the connection is a single-angle bolt connection. Figure 1b allows us to see that this connection is obviously a double-angle connection. Further examination of the connection reveals that it is actually a two-double angle bolt and bolt-weld connection. The view in Figure 1c shows the back side of the view in Figure 1b. Obviously, it is cumbersome to show all of the details for this connection on a black or whiteboard. It would be even more difficult for the majority of students to visualize them.

Despite the increase usage of 3-D drafting and building information modeling (BIM), majority of the construction documents and shop drawings are still produced in 2-dimensions. Figure 2 is an example of a typical shop drawing that would be provided by a fabricator to an engineer for review and approval. Although the shop drawing depicts exactly how the connection is to be assembled, it is not easily understood by the students. The main reason for this is that students typically have a one-semester course that exposes them to computer-aided-drafing in their freshman year, at a time when the students have little engineering background. This course is often taught by an instructor who has little to no experience in structural detailing. As for the above example, if students could not visualize the existence of another set of angles at the back face of Gider B3 (view shown in Figure 1c), it could lead to two common problems. First, students would not realize the signifcance and necessity of an additional set of angles. Second, due to the visual absence of the angles, the students may forget to include it in the design calculations, and this could affect the safety and integrity of a structure. Furthermore, the sculpture shows that the flange of Beams B3A and B3B must be coped to

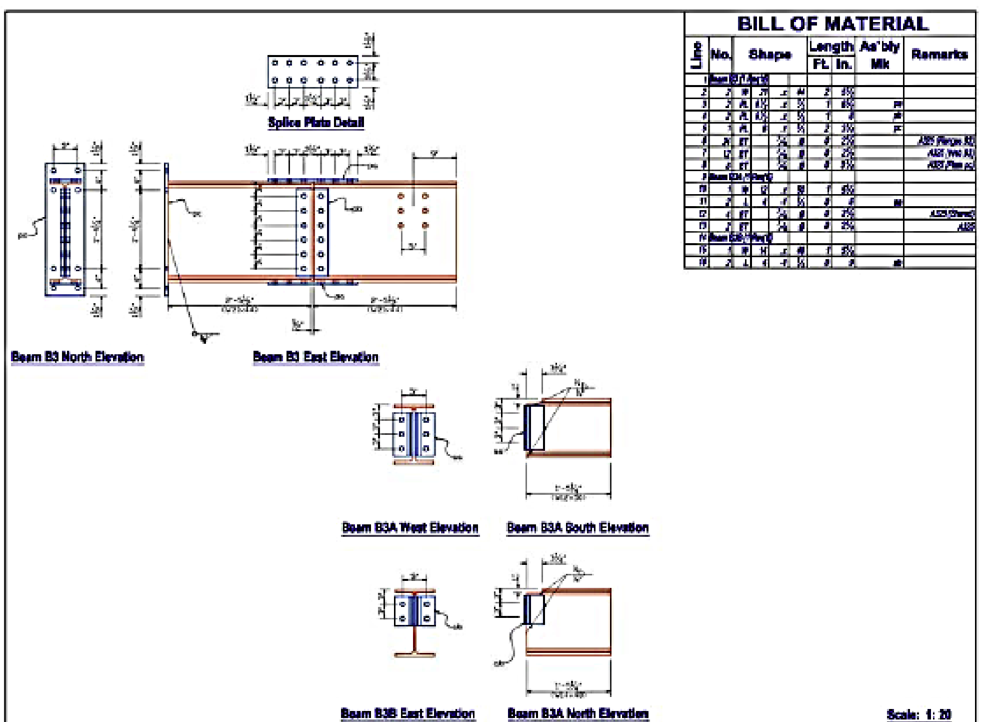


FIGURE 2. Example of a typical shop drawing for connection shown in Figure 1.

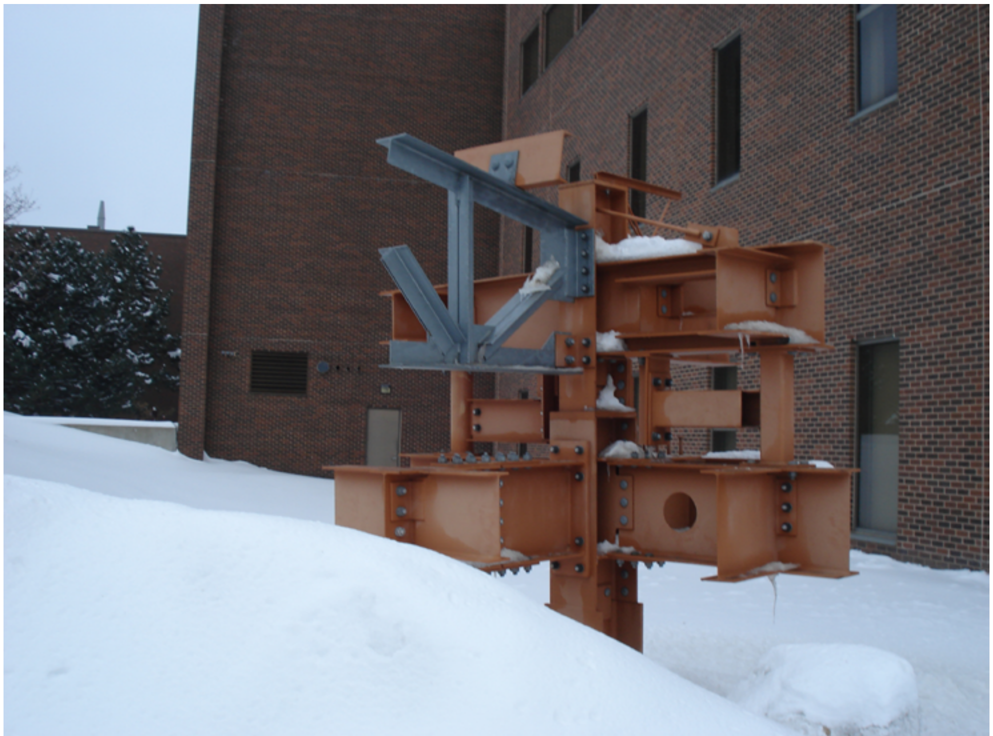


FIGURE 3. Weather could make it infeasible to use the steel sculpture in winter months

meet the top-of-steel-elevation requirement, often specified in design. This requirement refers to the necessity to have the top face of the beams and the top face of the girders on the same elevation so that roof deck and floor decks can be placed on them. From the authors' teaching experience, the coping detail in particular, is difficult for students to comprehend from 2-D sketches. Chou, Moaveni, and Drane [25] assessment results support this observation.

One way to remedy this problem is to take students to actual construction sites. Although this is a good approach, it is a major challenge to find construction projects that are nearby and installing connections that coincides with the topic being taught at the time. Additionally, liability issues may also arise and prevent the faculty from taking students to construction sites. Because of these issues, many faculty members have resorted to taking photoggraphs of connection types from construction sites and then showing them to their students. Unfortuantely, the photographs still do not show the true 3-dimensional nature of connections. In the summer of 1985, after seeing the inability of his students to visualisze even simple connections, Professor Duane Ellifritt of the University of Florida designed a steel connection sculpture as a visual aid to teach his students about the many ways steel members can be connected. The eight-feet, 2500-pounds duplicate of this sculpture has sprouted in over 150 campuses across the United States. In addition to the physical sculpture, the American Institute of Steel Construction (AISC) also has prepared a teaching guide for the connection types [26], which can be downloaded from the AISC website.

The Virtual Steel Sculpture

Due to the large size of the physical steel sculpture, many schools have erected the sculpture outdoors. The cadets at the Military Academy at West Point fabricated a miniature sculpture on wheels, and recently, a student-professor team at George Mason University used a TAZ 4 3D printer to produce a table top size steel sculpture [27]. In many parts of the country, weather also makes it infeasible to use the steel sculpture as a teaching tool in the winter months or when it is dark out (Figure 3). This means that while the steel sculpture is a very powerful tool to visualize steel connections, the lack of continuous access makes it less effective as an instructional aid. To rectify this problem, development of a virtual sculpture began in 2006 as a class project at the authors' home institution at Minnesota State University. The first generation of the virtual sculpture was basically a set of interactive PowerPoint slides which include the close-up view of each connection, sample calculations and actual field applications of selected connections [28-31]. Feedback, related to the virtual sculpture as a learning aid, from students at Minnesota State University and Ghana (West Africa) was generally very positive. The main concern of the Ghanaian students was that the file size was too large.

The current interactive virtual sculpture was developed with a few goals in mind among which are:

- a platform that is commonly available to the users without additional cost;
- a stand-alone model so that no additional software is needed; and
- a completely self-guided model so that the student can use it as tutorial or reference.

The result is a virtual sculpture that was completely rebuilt from the beginning using the original blueprints provided by the fabricator of the physical sculpture – this physical model has 48 connections – housed in Minnesota State University, Mankato. The platform chosen is Adobe's Portable Document Format (PDF). After the user downloads the sculpture files to his/her computer, s/he will then have the full use of the learning aid.

Unlike the first generation of the virtual steel sculpture where the PowerPoint slides were produced using 2-D images. The current version was developed using Creo and Adobe animation that provide full 360º view of the sculpture. Users can pan, rotate, zoom, and isolate any part of the sculpture. They can also select a connection to learn more about its design. In the following sections, we will describe the virtual sculpture in detail. Since the file for the fully animated virtual sculpture is too large to attach to this paper, readers are encouraged to visit: http://faculty.mnsu.edu/saeedmoaveni/.

The Website – When the users access the above mentioned URL, they are greeted with the home page that has an image of the interactive steel sculpture (as shown in the accompanying image). By clicking on the video button on the image, one can then view a brief video that gives background on the development and overview of the virtual steel sculpture.

The *Main Features* Page of the Website (as the name implies) explains the main features of the Virtual Sculpture. It states that a solid model of the sculpture was created from the fabrication drawings of the Steel Sculpture at Minnesota State University using Creo Elements software. This solid model was then converted into an *Interactive Three Dimensional PDF* file that looks exactly like the actual sculpture at Minnesota State (shown in Figure 4). The Interactive 3-D PDF file will allow students, instructors, and practicing engineers to manipulate the solid model; that is, one can view the model from different angles, pick a connection, zoom, pan, spin, or rotate the model. The 3-D PDF file also shows the model tree (the individual components making up the virtual steel sculpture). Moreover, while holding down the Ctrl key, if one clicks on a connection, one then will be linked to another PDF file that provides additional information for each connection type including the blue prints, close-up views, field examples, sample calculations, and Finite Element models. For those interested in the Virtual Steel Sculpture, they should send an email to virtual.steel.sculpture@gmail.com, and a link to Dropbox will be provided. From this location then the

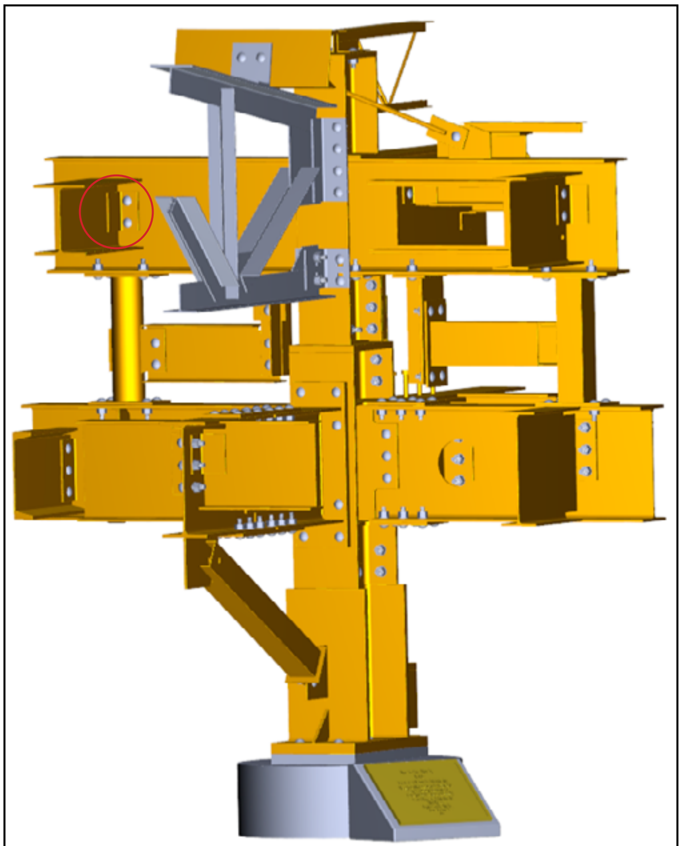


Figure 4. The 3D Interactive Sculpture

Virtual Steel Sculpture and all of the linked files could be downloaded.

The *Additional Resources* Page will take the visitor to Connection Teaching Tookkit by Perry S. Green, et al and the American Institute of Steel Construction (AISC) Website.

The *Survey Forms* Page (as the name implies) explains the survey forms. The Northwestern University Searle Center for Advancing Learning and Teaching assisted with the development of assessment instruments and data analysis. In addition to the survey forms provided on this page – intended for students, instructors, and new civil engineering graduates to provide feedback on the effectiveness and user-friendliness of the Virtual Steel Sculpture – assessment instruments consisted of quizzes specifically designed to assess recognition, analysis and evaluation skills of the student in the area of connections were also employed. The quizzes were administered before and after the tool was used to measure learning gains in these areas. Quizzes were supplemented with student interviews using think aloud protocols to assess students' conceptual understanding of the connection types.

The *Contact Us* Page encourages instructors and practicing engineers to provide additional information about a particular connection type by providing a brief note along with any images that they think students may find useful. They can send their notes with any attachments to Virtual.Steel.Sculpture@gmail.com.

The 2-D Interactive Files – As mentioned previously as users manipulate the 3-D Interactive Steel Sculpture, while holding down the Ctrl key they can click on any of the connections. Once a connection is clicked (for example, the connection circled in Figure 4), a new page is opened as shown in Figure 5. Note that a white arrow points to the location of the connection in the physical steel sculpture. On this page, the user can then choose to see the blueprints, close-up views, field examples, finite element analysis (FEA), or the sample calculations of that connection.

As you move the mouse pointer over a tab, the first page of the pertinent content is shown. For example, if you were to move the cursor over the Sample Calculations tab, you will see the first page of sample calculations as shown in Figure 5. To see or print the entire sample calculation document, with the mouse cursor over the *Sample Calculations* tab you click on the mouse right button. This action will open the sample calculation document for the given connection.

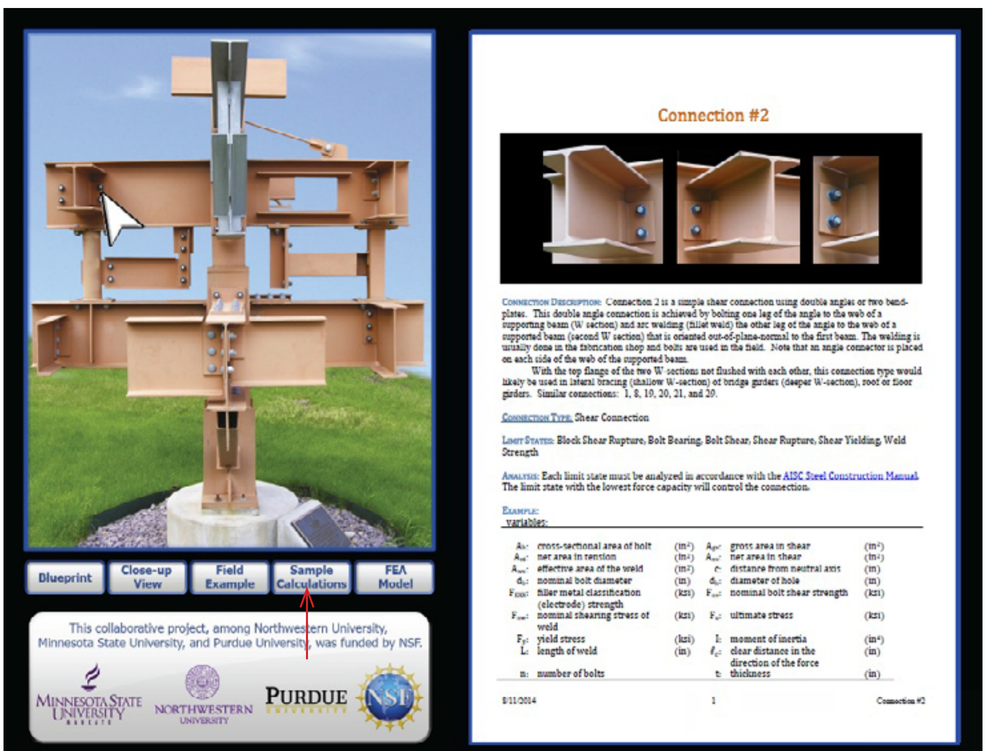


Figure 5. A screen capture of the 2-D interactive file for the connection shown in Figure 4 with the mouse pointer over the Sample calculations tab

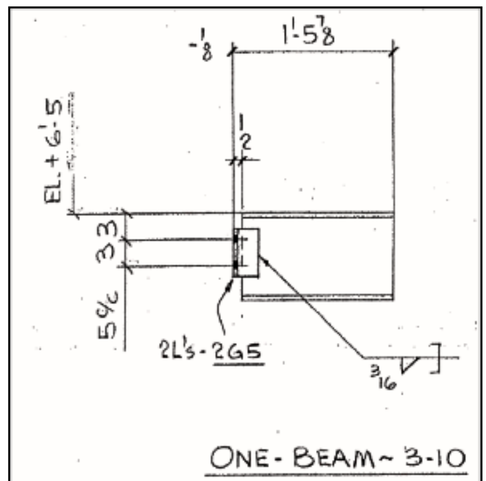


FIGURE 6. The blueprint of steel connection shown in Figure 4

Blueprints –The blueprints that were created by the fabricator to make the physical steel sculpture are available to view on this page. Figure 6 shows the blueprint of the connection shown in Figure 4. These blueprints serve a dual purpose. The blue prints present the traditional orthographic views used by engineers and fabricators. When the photograph of a connection is presented with a corresponding blueprint, students have more opportunities to learn the relationship between a 3-dimensional object and its 2-dimensional orthographic views. The second objective of showing the blueprints is to familiarize the students with construction document communication; how connection details are presented in industry. This is an important skill for students to develop. Students who are familiar with typical orthographic details will be

FIGURE 7 Close-up views of steel connection circled in Figure 4

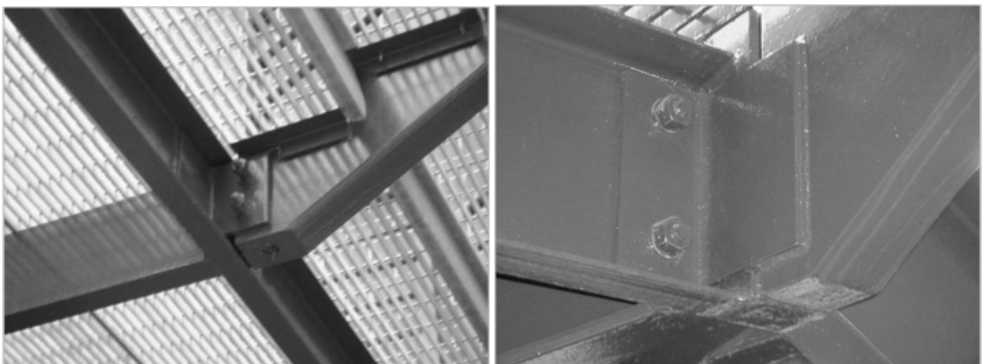
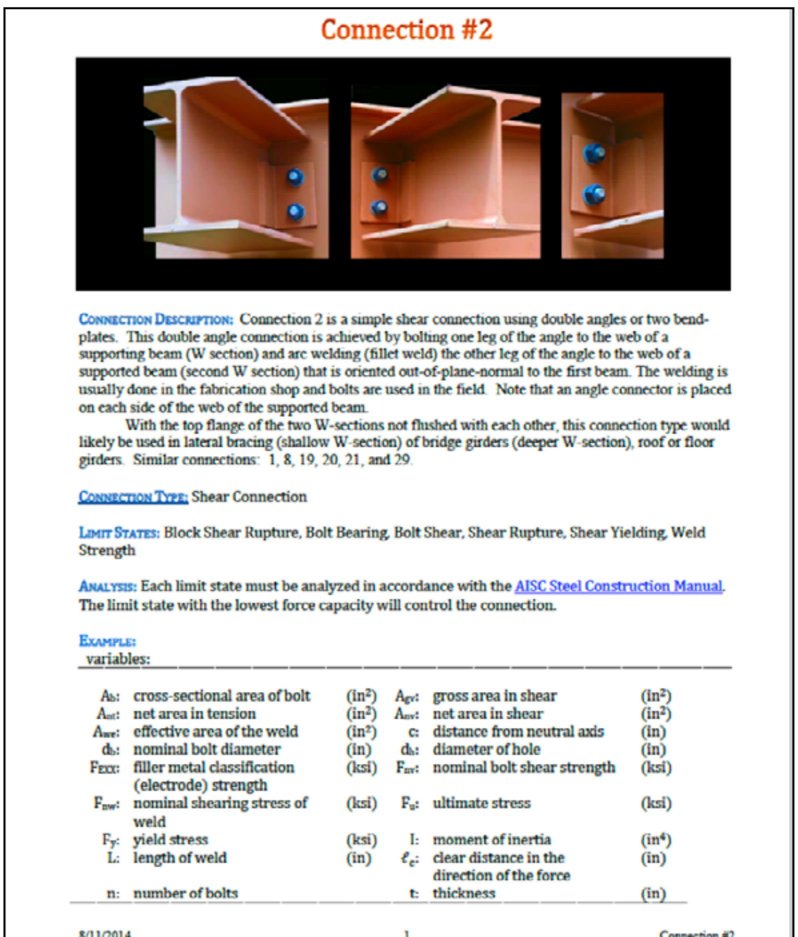


FIGURE 8 The field example of connection shown in Figure 4



Connection #2

CONNECTION DESCRIPTION: Connection 2 is a simple shear connection using double angles or two bend-plates. This double angle connection is achieved by bolting one leg of the angle to the web of a supporting beam (W section) and arc welding (fillet weld) the other leg of the angle to the web of a supported beam (second W section) that is oriented out-of-plane-normal to the first beam. The welding is usually done in the fabrication shop and bolts are used in the field. Note that an angle connector is placed on each side of the web of the supported beam.

With the top flange of the two W-sections not flushed with each other, this connection type would likely be used in lateral bracing (shallow W-section) of bridge girders (deeper W-section), roof or floor girders. Similar connections: 1, 8, 19, 20, 21, and 29.

CONNECTION TYPE: Shear Connection

LIMIT STATES: Block Shear Rupture, Bolt Bearing, Bolt Shear, Shear Rupture, Shear Yielding, Weld Strength

ANALYSIS: Each limit state must be analyzed in accordance with the AISC Steel Construction Manual. The limit state with the lowest force capacity will control the connection.

EXAMPLE:

variables:

A_b:	cross-sectional area of bolt	(in^2)	A_{gv}:	gross area in shear	(in^2)
A_{nt}:	net area in tension	(in^2)	A_{nv}:	net area in shear	(in^2)
A_{we}:	effective area of the weld	(in^2)	c:	distance from neutral axis	(in)
d_b:	nominal bolt diameter	(in)	d_h:	diameter of hole	(in)
F_{EXX}:	filler metal classification (electrode) strength	(ksi)	F_{nv}:	nominal bolt shear strength	(ksi)
F_{nw}:	nominal shearing stress of weld	(ksi)	F_u:	ultimate stress	(ksi)
F_y:	yield stress	(ksi)	I:	moment of inertia	(in^4)
L:	length of weld	(in)	ℓ_c:	clear distance in the direction of the force	(in)
n:	number of bolts		t:	thickness	(in)

8/11/2014 1 Connection #2

FIGURE 9 A screen capture of the first page of a sample calculation for the connection shown in Figure 4.

better adapted to the information presented to them in professional practice. While 3-dimensional modeling of structures, such as work done in Revit, is becoming more common, it is still the industry standard to deliver 2-dimensional plans for purposes of construction. As such, it will be incumbent upon students to understand information presented in this way.

Close-up Views– A notable feature of these close-up views is that they will provide multiple views of the connection of interest to allow the user to get a fuller picture of how, specifically, the components are connected. An example is shown in Figure 7.

Field Examples – Prior to the development of a physical sculpture, and the virtual sculpture, the only way instructors could effectively show the assembly of steel connections was through examples in actual practice. As mentioned earlier, this created numerous liability and scheduling issues. To avoid this problem, instructors would often take photographs of connections on construction sites to present in the classroom. This approach is still effective and could complement the use of the virtual sculpture that is accessible to students 24/7.

When a connection on the virtual sculpture is selected, an example from actual practice is an option that is available. This option allows the students to see how a particular connection fits into a structural system. This will also provide contextual based relevance that reinforces the need to study the “glue” that holds structures together.

Sample Calculations – Design calculation is by far the most crucial portion of connection design. From the students’ perspective, it may be the most important part as this is what they are being tested and graded for in a class. This feature of the virtual sculpture provides a comprehensive set of calculations for a given connection. All the limit states as defined in the teaching guide for the connection types [26] were considered in the sample calculation. As design is unique to each structure, the sample calculations illustrate how one would calculate the capacity of each limit state and hence the limit of a given connection. The calculations were done in accordance to design specifications of the 14th edition of the Steel Construction Manual [28]. Each set of calculations includes a problem statement, necessary free-body diagrams, and equations from the design specifications [28] used. The first page of sample calculations of the connection shown in Figure 4 (see circled connection) is shown in Figure 9. The entire sample calculation document for this connection has five pages. As mentioned previously to see or print the entire document, with the mouse cursor over the *Sample Calculations* tab you click on the mouse right button. This action will open the sample calculations document for the given connection. You can then view it or print it as you wish. Please see Chou, Moaveni, and Sapp [32] for detailed description of sample calculation documents.

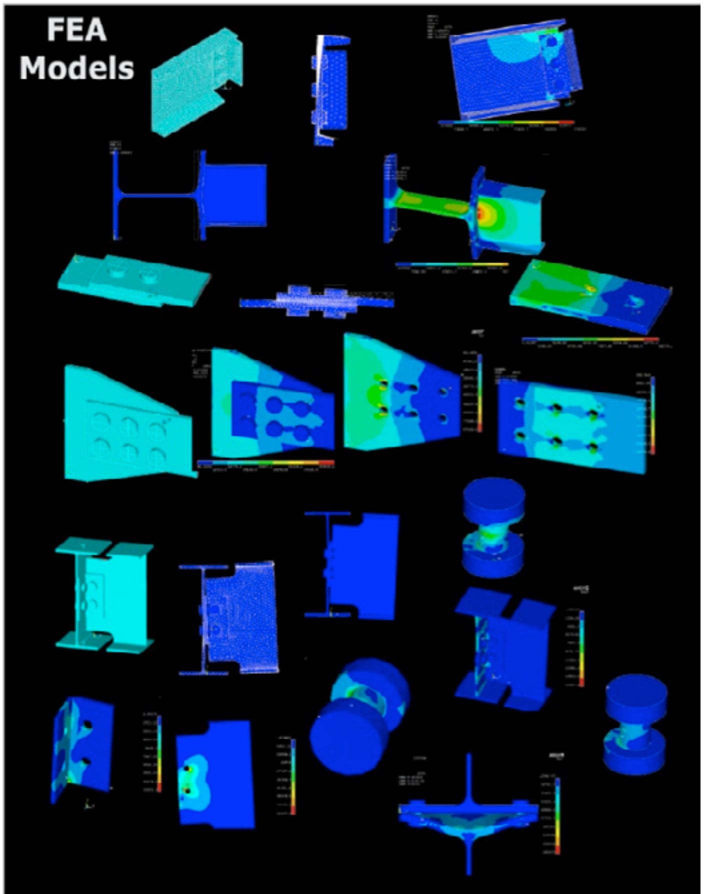
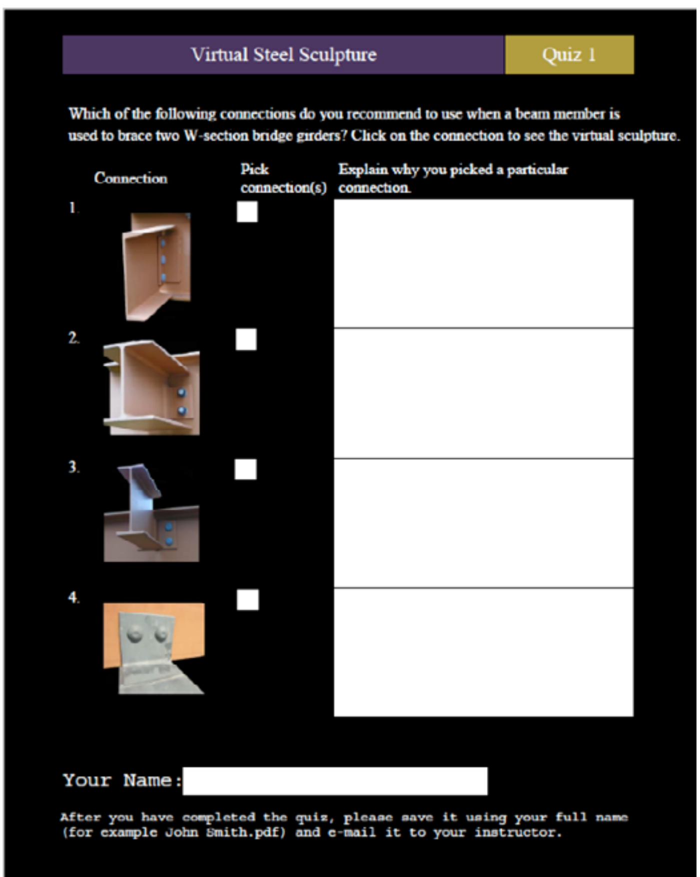


FIGURE 10 FEA Model of connection shown in Figure 3



Virtual Steel Sculpture | Quiz 1

Which of the following connections do you recommend to use when a beam member is used to brace two W-section bridge girders? Click on the connection to see the virtual sculpture.

Connection	Pick connection(s)	Explain why you picked a particular connection
1.		
2.		
3.		
4.		

Your Name:

After you have completed the quiz, please save it using your full name (for example John Smith.pdf) and e-mail it to your instructor.

Figure 11 An example of a digital quiz

FEA Models – The final feature of the virtual steel sculpture is the inclusion of the stress distribution in and within the vicinity of some connections. These FEA models allow students to visualize how stress is built up inside the connection as force is transferred from larger structural members to the connection. By providing this visualization, students will have a better understanding in identifying areas susceptible to failures.

Animation Video – On the *Main Features* Page of the Website, there is also a link to an animated video of the Virtual Sculpture that shows how different pieces of the sculpture fit together.

Learning Assessment and Interactive Quizzes

The primary objective behind the development of the Virtual Sculpture was to enhance the students' learning and knowledge in connection design. While the students may find the Virtual Sculpture fun to use, interesting, and full of technical information, its effectiveness must be evaluated. The assessment process used during the development of the Virtual Sculpture is described in a paper by Chou, Moaveni, and Drane [27]. The Northwestern University Searle Center for Advancing Learning and Teaching helped with the development of assessment instruments and data analysis. The assessment process also led to the development of twelve additional digital quizzes. The situations described in these quizzes represent the majority of connections used in regular bridge and building designs. For students who do not have the opportunity to take additional courses in steel design and for faculty members who would like to expose their students to examples of common connections that new graduates may encounter in practice, the Virtual Steel Sculpture and the quizzes combined would give students an excellent introduction to the function, assembly, and application of these connections. These quizzes are available online at http://faculty.mnsu.edu/saeedmoaveni/. The quizzes are created using pdf forms that could be easily filled and emailed to the instructor. Moreover, the images of connections on a given quiz are linked to the Virtual Sculpture to allow students to view a connection from different directions. An example of a digital quiz is shown in Figure 11.

Conclusion

Structural engineering is the oldest discipline in civil engineering. It is one of the most common areas used to fulfill ABET civil engineering program accreditation criteria. Typically, students would take a course in steel or reinforced concrete design or a combination of both after a structural analysis course to meet this proficiency requirement. An 8-ft, 2500-lb steel connection sculpture was designed and sponsored by AISC and its members to help students understand connection design. While this and other smaller models have many practical benefits, recognizing that the Google generation students are more computer savvy, an interactive (virtual) steel connection sculpture was developed as a learning tool to reach students in a way specialized to their generational acumen. Unlike the physical sculpture, this virtual sculpture is accessible 24/7. It includes a 3-D dynamic visualization, close-up views, field examples, finite element analysis, and sample calculations for each connection. This is all done in an effort to help students visualize the 3-dimensional connection and understand its design and construction. Although connection design only comprises about 10% of a typical steel design course, connections are the glue that holds members of a structure together. Their design for loads and assembly affect both safety and cost. Even when a connection is correctly designed for strength, if the assembly of the connection is complicated or practically infeasible, unnecessary errors may occur during fabrication and erection stages. This would either lead to an unsafe or extremely costly system.

Although the primary goal of the virtual steel sculpture is for a course specializing in steel design, this learning tool can help students taking other courses such as senior capstone design, statics, mechanics of materials, and structural analysis. Furthermore, this tool will benefit new engineers, architects, engineering technicians, and construction managers. With the potential of including sample calculations and field examples by colleagues from other countries, the tool also has the potential to benefit students and faculty globally.

Acknowledgements

The project was developed with the support from National Science Foundation under grant numbers: DUE-1140468 and DUE-1252371 and Program Director, Dr. Susan Finger. The student research assistants were: Lee Taylor, Thomas Gunderson, and James Sapp. JavaScript programming assistance was provided by Professor Guarionex Salivia of Computer Information Science Department at Minnesota State University. We would also like to acknowledge Central Minnesota Fabricating, Inc. in Willmar Minnesota who built and donated the physical steel sculpture.

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