Research Report

Augmented Reality in Structural Steel Fabrication

FINAL REPORT

AISC RESEARCH REPORT NO. AISC-FRR-2024-01

DATE OF PUBLICATION: MAY 2024

Project Title:	**Augmented Reality in Structural Steel Fabrication**
Primary Investigator(s):	**Dr. Hannah Blum**
Research Organization(s):	**University of Wisconsin – Madison**

DISCLAIMER

The material contained herein has been developed by researchers based on their research findings and is for general information only. The information in it should not be used without first securing competent advice with respect to its suitability for any given application. The publication of the information is not intended as a representation or warranty on the part of the American Institute of Steel Construction (AISC) or of any other person named herein, that the information is suitable for any general or particular use or of freedom from infringement of any patent or patents. Anyone making use of the information assumes all liability arising from such use.

PREFACE

The American Institute of Steel Construction (AISC), headquartered in Chicago, is a non-partisan, not-for-profit technical institute and trade association established in 1921 to serve the structural steel design community and construction industry in the United States. As part of its technical activities, AISC actively funds and supports research related to structural steel design and construction. AISC members primarily come from the structural steel construction community, including producers, fabricators, and engineers.

Many AISC members are engineers, so much of our research supports the engineering community, including maintaining and updating our technical publications such as Design Guides, The Steel Construction Manual, and our Specifications and Provisions. We distribute our specifications free for their use. The primary goal of those specifications is the reliability of structures and, through that, the safety of the public.

AISC does not use the results of research for profit, nor do we sell reports of the research or derivatives from it. Our work is performed in the interest of public safety. As such, we fund projects to, in part, support the development of next-generation steel systems for enhanced performance, safety, sustainability, and economy.

It is reasonably common for AISC research projects to receive additional direct, indirect, or in-kind support from external organizations such as federal or state agencies or member companies . As such, the partial or complete contents of this Report may also reside in the public domain of these external funding agencies.

Augmented Reality in Structural Steel Fabrication

Dr. Hannah Blum

Assistant Professor and Alain H. Peyrot Fellow in Structural Engineering

https://ssirl.cee.wisc.edu/

Department of Civil and Environmental Engineering

University of Wisconsin - Madison

January 2024

Abstract

Structural steel fabrication is a vital process in the construction industry. Fabricators make custom sections and connections which will be assembled into the main structure. Errors in the fabrication process can result in expensive delays and other undesirable costs, which will increase the overall budget of the project. To improve the competitiveness of the structural steel industry relative to other building materials, a new method to improve the fabrication process is proposed. A custom augmented reality program will be created which will assist the steel fabricator in indicating where and which fabrication operations need to be performed on the steel section using a model of the shop drawings. Additionally, the custom program can be used for quality control purposes before shipping the finished parts to the construction site. It is envisioned this will reduce costly errors and can be widely implemented in various structural steel fabricator shops.

Contents

1. Introduction

Structural steel fabrication, which involves forming custom sections and connections in a workshop prior to construction site assembly, is a vital process in the building construction industry. Errors in the fabrication process can result in expensive delays and material wastage, which increases the overall project budget. A new method to improve the fabrication process is proposed where a custom augmented / mixed reality (AR/MR) program assists the steel fabricator on the shop floor. This AR program can be used for quality control purposes before shipping the finished parts to the construction site in addition to a training tool for new fabricators. Viewing the connection with 3D holograms helps the technician visualize the assembled connection better than 2D section cuts. Mixed reality in the structural steel industry can help to increase quality, improve collaboration, and allow for shorter project timelines especially for shop processes that typically require hard to find, skilled labor, such as layout and fit up work. The developed software utilizes the 3D shop drawings and incorporates important features for the steel fabricators, including the display of dimensions, streamlined information recording, and a guide to fabrication operations. The information is displayed in the HoloLens 2 mixed reality headset which overlays holograms without blocking out the physical environment. The custom program creates a user interface where the operator can interact with the models and information without printed shop drawings or a tablet. The custom MR program is capable of a $\frac{1}{16}$ inch accuracy between the holograms and the physical steel parts. The developed program is tested on two fabricated steel bolted connections to validate the capabilities of the software including quality control check of sizes and placement of all bolts and plates, dimension inquiry, alignment, and assembly steps. This study shows the potential of implementing mixed reality into structural steel fabrication.

Extended Reality is a term for a range of emerging haptic technology that provides the user with a unique sensory experience. One category of XR is Augmented Reality (AR), which overlays holographic virtual objects onto the real environment. The virtual components can be seen superimposed on the user's actual view through wearable devices such as Google Glass or Microsoft HoloLens 2, which can run a variety of applications to display the virtual objects. Mixed Reality (MR) is another subset of XR where the holograms are not only overlaid but can interact with the present environment as well. Augmented Reality and Mixed Reality are often used interchangeably, and will hereinafter be described as "AR". Yet another technology under the XR umbrella is Virtual Reality (VR), which places users in a fully computer-generated world independent of the real environment in front of them. VR is also experienced through wearable technology. Some examples of headsets that have VR capabilities include the Oculus Rift and HTC Vive models.

2. Task 1: Selection of connections to be investigated

In consultation with AISC, two common structural steel connections were selected. One connection is representative of a bridge type connection and the other represents a beam-column style connection for steel framing. The connections were selected to have multiple features to help test the capabilities of the mixed reality process. Next, the connections were sized so that two individuals could lift and assemble the connection without needing equipment.

The details of these two connections are provided in Appendix A and images of these connections are provided in Section 8.1. The connections were created at a fabricator shop and sent to UW-Madison for the project. Upon inventorying the delivered steel parts, it was found that the angle bracket pieces of the beam-column connection were not delivered.

3. Task 2: Development of custom augmented reality program using the HoloLens headset

A custom program was developed using the HoloLens 2 headset. The program allows the user to select a dimension specified in the design on the overlaid hologram, as well as includes a step-by-step tutorial of a fabrication process. This indicates to the user which operations need to be completed to which part of the steel section and in what order. A user interface was developed to display all relevant information needed from the design files. Furthermore, a means for easily recording information, including pictures and speech, was developed. A full list of developed features is shown below:

- Validate part manufacturing/dimensions
- Accurate digital overlay alignment
- Dimension inquiry and measurements
- IFC file integration, including weld location
- Calibration/alignment update
- View shop drawings
- Table layout for quicker part validation
- Place notes on model with voice to text and photo integration
- On-device storage of models
- Interact / pull-apart model
- Step-by-step assembly guide prototype

Several video files demoing these features are uploaded to UW-Madison's KALTURA

MEDIASPACE and combined into a single playlist, AR Steel: https://mediaspace.wisc.edu/playlist/details/1_c9dutlja. The playlist has six videos:

1. open file demo
2. view PDF demo
3. pull apart demo
4. part validation demo
5. connection assembly demo
6. QA/QC demo

4. Task 3: Test custom program

The original plan was to test the custom program at Veritas Steel fabricator workshop. However, the during the early stages of the project, the point of contact at Veritas left the company and there was no replacement for the project. In lieu of testing at Veritas, the team presented the in-progress work at several conferences to obtain feedback. Most notably, there were several steel fabricators present at the North American Steel Construction Conferences, and they provided helpful feedback and guidance on desired features in the custom program during the team's presentations in the Technology track. The list of conferences where this work was presented is shown below:

- NASCC 2022, *Applications for Smart Glasses and Augmented Reality in Structural Steel*
- TRB 10th International Symposium on Visualization in Transportation 2022, *Supplementing Steel Bridge Fabrication with Immersive Augmented Reality*
- NASCC 2023, *Further Developments in AR Applications for Steel*

5. Task 4: Project summary

This report constitutes Task 4, which is a report to summarize the project. The report includes a review of the developed features in addition to potential areas of improvement should the project be expanded in the future. Much of this information is presented in Section 8. The report is listed as Task 4 as it was initially the final stage of the project (Tasks 1-4). The project was later amended to includes Tasks 5-8.

6. Task 5: Update the current program to show weld location

The program was updated to show weld locations. An example of this information is provided in Figure 6.1, where the locations of each weld is shown in a blue line. From this information, a user can check if welds are in the correct location.

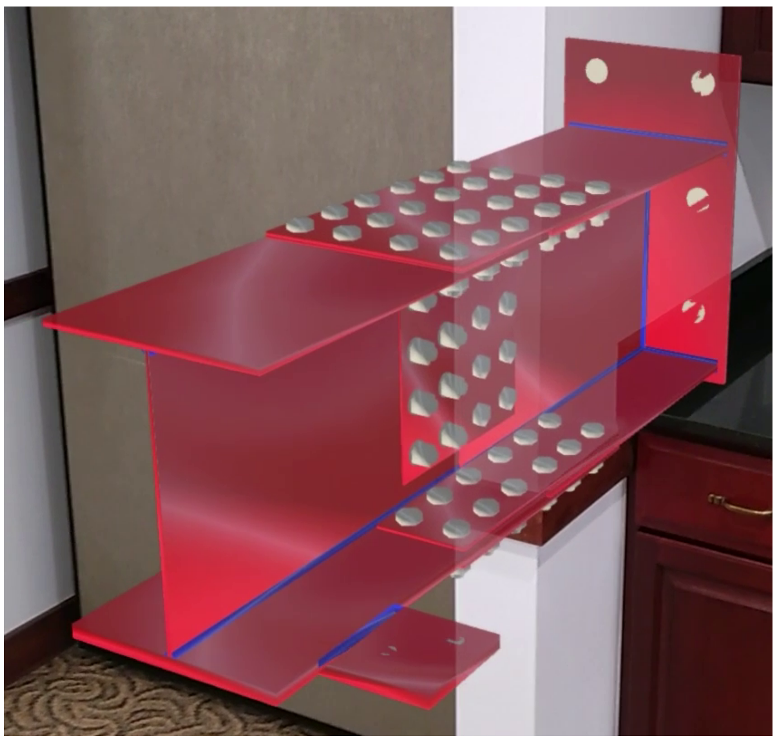


Figure 6.1: Connection showing weld locations in blue lines

7. Task 6: Automatically bringing in dimensions and information from a model file from commercial software such as Tekla or SDS2

The development team reached out to both Tekla and SDS2 for access to their Software Development Kit's (SDK's) which is the primary way to interact with proprietary file types. Tekla provided an EULA that they were unwilling to alter. For this reason, UW-Madison was not willing to move forward with the Tekla file type. The development team had a video meeting with SDS2 where it was recommended to retrieve welding information from IFC files. Once that was functioning, SDS2 confirmed that SDS2 file types provide this information as well but was unnecessary since IFC files can be exported from SDS2 software. Ultimately, it was determined that the community standard IFC files provided the relevant information for welds and dimensions removing the need to seek licensing and other agreements with private companies. The current implementation of the HoloLens application is able to automatically pull in dimensions and welding information from IFC files.

8. Task 7: Validating the developed program on two fabricated steel connection types – one representative of buildings and one representative of bridges

The AR program was validated by a three-person team consisting of the software engineer involved in developing the AR program, an individual with no prior experience using AR technology ("User 1" hereinafter), and another individual who had previously seen the program ("User 2" hereinafter). The latter two individuals were graduate students studying civil engineering. The aim was to test the overall program and specifically the step-by-step assembly instructions for both connections. The connections were assembled in the Jun and Sandy Lee Wisconsin Structures and Materials Testing Laboratory at UW-Madison.

8.1. Validation Process

The goal of the testing procedure was for User 1 to assemble two fabricated steel connections based on the steps shown in the program. The connections represented a bridge connection (Figure 8.1) and beam-column connection (Figure 8.2), and were tested separately in October 2023 and January 2024, respectively, using the same process. Based on his interpretation of the program's step-by-step 3D models showing how to assemble the connection (Figure 8.3), User 1 would verbally describe the assembly of specific parts for each step, and the other two individuals physically helped

Figure 8.1: User 1 viewing the bridge connection through the headset, and a corresponding view in the program

as needed, such as lifting larger parts or installing bolts (Figures 8.4 & 8.5). While User 1 worked through the assembly in this manner, the software engineer was monitoring the HoloLens view through a computer in order to see the process from the User 1's point of view. The goal of these testing sessions was to determine if the step-by-step guide was useful in assisting a user to assemble the connection. Prior to testing the bridge connection (first of the two connections), the software engineer gave User 1 an overview of using the HoloLens device and allowed him to get acclimated to the program before starting to use it for the assembly steps. For the second assembly test, no such refresher was done prior to testing the beam-column.

8.2. Advantages and Disadvantages of the Software

Overall, User 1 described the software's 3D models as "minimally invasive" and "not overbearing" (G. Lepak, personal communication, January 30 2024). He also gave positive feedback on some specific features of the program's steel connection model. These included the color-coded steel pieces in the model and the flashing of the next piece to be installed in each step of the program,

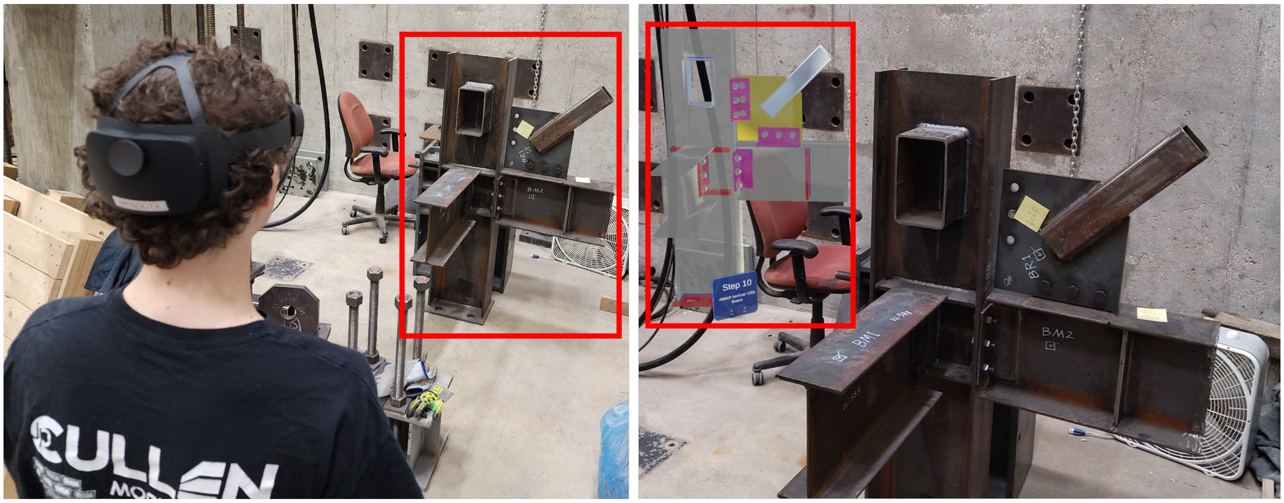


Figure 8.2: User 1 viewing the final beam-column connection (shown in in red rectangle) through the headset and a corresponding view in the program (hologram shown in red rectangle)

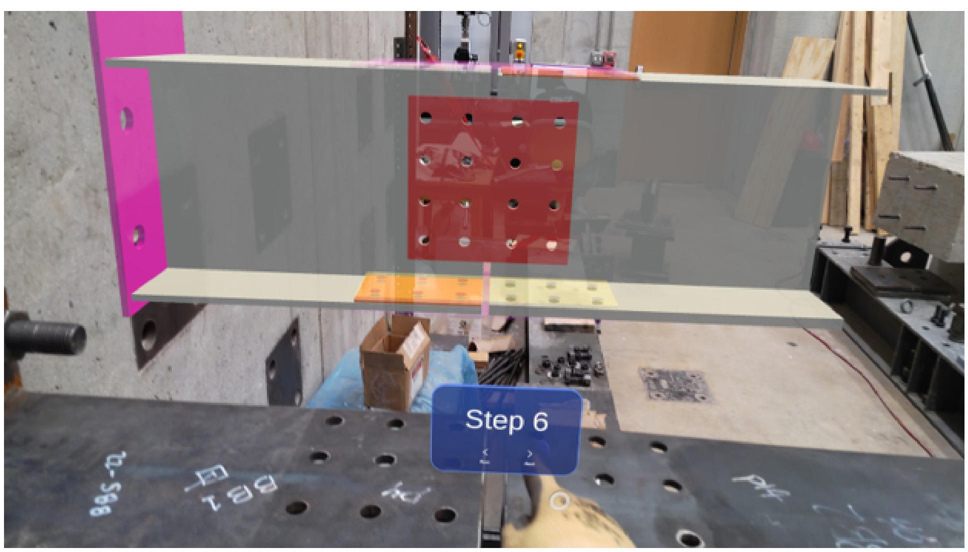


Figure 8.3: Closeup view of program model for bridge connection

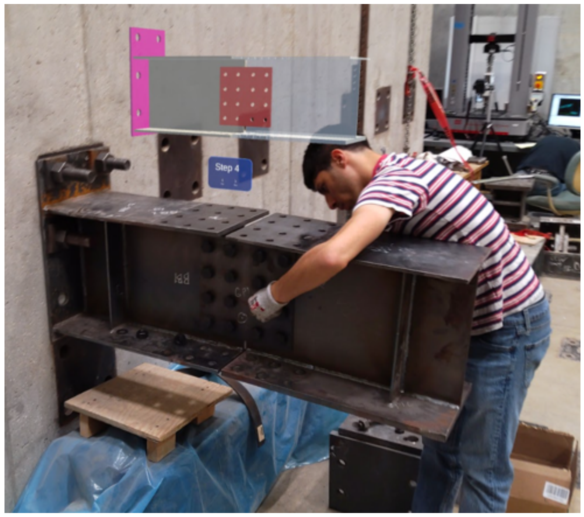


Figure 8.4: Headset view of User 1 as the bridge connection is being assembled

Figure 8.5: Users 1 and 2 assembling the beam-column

both of which made it easier to distinguish the various pieces and quickly understand which one had to be assembled at a certain point. User 1 also found it helpful that the model for the beam column connection showed the specific bolt alignments when connecting pieces, as well as the steel welds. Though the welding step did not apply during testing as the beam-column connection had been pre-welded, this feature can still be a positive aspect which would assist in determining and verifying where welds should be on a more sophisticated foundry steel assembly. Also, the angle bracket pieces of the beam-column connection were not assembled during testing since they had never been delivered with the rest of the parts. They were, however, correctly modeled for their respective step in the program. Because the angle brackets were included in the model, User 1 was able to quickly determine that those pieces were missing and move on from that step. This points to another benefit of the software's use in steel fabrication, being that the AR can help to identify discrepancies or missing components much faster than comparing the actual assembly to a manual or diagram would, provided that the model itself is accurate. Additionally, User 1 noted later in the process that he forgot he still had the headset on, indicating it would be comfortable to wear and use for long periods of time. This is useful when the technology is used in manufacturing larger or more complex pieces which would require more continuous assembly time.

As with any prototype, setbacks were also found during the validation process. For instance, as User 1 moved throughout the lab space while using the program, the software engineer noted that he frequently moved the AR model back to its original calibration. This makes the program's assembly guide less efficient and can disrupt the user's point of reference as they try to match the real assembly in front of them with what the software is projecting. Similarly when User 1 was viewing the final step of the bridge connection, which involved installing the steel plate on the top of the structure, he forgot that the AR model can be rotated while standing in the same location and tip-toed to see the plates from all angles. While this is not detrimental towards building the final intended connection, it indicates that a user who is completely new to the program would benefit from more training in using the interface. Another observation for the bridge connection was that while User 1 quickly identified the location of the parts for each step, oftentimes he initially thought them to be in the wrong orientation and had to manually inspect the real assembly to verify that parts were being placed correctly. A potential change to the program to mitigate this could be adding part IDs or dimensions to each piece overlay based on the shop drawings so that it is easier to determine their orientation in assembly.

During the beam-column assembly, User 1 also found that the HoloLens interface was not as responsive to touch commands. Switching to a thinner pair of gloves helped somewhat but it would still take multiple attempts to click the program's menu buttons compared to using bare hands. Although this has more to do with the HoloLens hardware and firmware than the program itself, it is an issue that should be mitigated, since having to remove gloves every time to engage with program options such as cycling through the models for each assembly step is not particularly efficient. While all the aforementioned issues are relatively minor, they can easily add up and lengthen the assembly process when they occur frequently. Furthermore, having several minor issues can still compromise the willingness of someone unfamiliar with AR technology to use it in this setting especially if they feel that the multiple setbacks do not contribute to overall improved productivity.

The software engineer also noted that during both assembly sessions, User 2 was consistently watching the HoloLens' view stream as User 1 viewed the program models and figured out the assembly. Indeed it did not help much to only watch User 1 look at the connection wearing the headset, which indicates that having multiple AR devices would be helpful even when one person is in charge of the assembly. While additional hardware is more expensive, having multiple individuals be able to see the same program model for one connection would limit possible errors one person could make in interpreting the orientation of parts to be assembled, as happened a few times with User 1 when they were assembling the bridge connection. With use of additional headsets for this purpose, additional training would be required which is also considered an investment towards the goal of multiple devices improving efficiency.

8.3. Outlook

Despite the drawbacks of the software as described by User 1 during the testing process, overall it was a positive experience. For the bridge connection, assembling all the parts during validation took around 90 minutes, excluding the time to configure the HoloLens device and give onboarding instructions to User 1. When the bridge connection had initially been assembled to allow the software team to accurately create each of the step models in the program, it took around four hours to build. This was done around 6 months before the validation with AR, and only the shop drawings provided by the fabricators were used as a reference. The initial assembly of the beam-column connection in a similar manner had taken around three hours, compared to only around 45 minutes during the validation process when the AR model was used. It should be noted that the beam-column had fewer parts and steps to be assembled than the bridge connection did, as well as the fact that pieces comprising one step were missing and any steps involving welding were ignored as the steel used was delivered with welding complete.

Generally, this validation showed that use of AR technology can assist in fabrication and assembly, but there are still some hindrances that reduce efficiency and must be accounted for in development. The software used for testing only showed step-by-step models of how each part should be placed to assemble the connection. The program cannot identify or detect the real parts assembled by the user, nor compare them to its 3D model to indicate any discrepancies. This means it is the user's responsibility to verify that the actual setup of the parts is correct based on their own knowledge and experience. Indeed, this points to the principle that AR technology, despite all of its benefits, is ultimately a tool and cannot replace human logic. While implementing a real time Quality Assurance addition into the software would further improve efficiency of the steel assembly process, it would involve using a third-party package with additional technology such as point cloud tracking to monitor movement and position of the real parts as they are assembled. Considering that this feature is in its infancy and would require significant funds and development time to potentially add to the current program, it is not considered a viable option in the timeline of this project. As User 1 reflected following his experience with the validation process, "the system always has to prioritize the point of view of the real world and thus too many digital features may be a detriment." Based on the fact that he found it easier to work with the software when testing the beam-column connection since he had already used the software during the previous test, he also felt that the most important step when trying to integrate such a system for steel foundry workers would be more experience and practice with the software, which comes with effective training (G. Lepak, personal communication, January 30 2024). User 1's reflection on his experience is summarized below:

> *My name is Gabriel Lepak, Professional Masters Student at UW-Madison and Project Assistant for Dr.Blum's Steel Systems Innovation Research Lab. This is my experience and perspective on the Augmented Reality testing.*
>
> *I got to test the augmented reality system twice, first on October 25th 2023 and last on January 23rd 2024. Going into the first test, I had no idea what to expect and very little experience using the augmented reality headset. The goal was to use the augmented reality headset to easily show the assembly of a steel beam without the need for drawings or any other help. The concept was easy enough to understand, I could see a 3D model of all the different parts in my POV, along with a model showing the assembly of all these pieces. Going through the steps, I was very easily able to understand how the beam was supposed to be assembled. The simple UI and colored 3D models were not overbearing and the steps were simple and easy to follow. The only difficulties I ran into was us-*

ing the hand gestures to work with the 3D models, which wasn't the easiest to do correctly.

The second test was very similar to the first; using the augmented reality headset and program to assemble a steel column. At this point, I had some experience with using the headset from the last testing, so things such as using the menu, moving the virtual steel pieces, etc, was easier than before. This makes me think that getting experience and practice with using the augmented reality system will be the most important step when trying to integrate it with actual steel workers.

Overall I think this system has a lot of potential to be used by steel workers in the industry. The program has the basics down correctly. I like that the 3D models are minimally invasive to my POV and that I can move the model around in my 3D space. Small details like the pieces needed for the current step flashing are very helpful. I think once the hardware gets better in the future (smaller, less clunky) and the gesture reading gets better (more accurate, works with gloves, etc), it could be implemented into the steel assembly industry very easily. With more development, I think it would be good to include more information and features such as assembly tips/instructions impeded into each step or even animations showing the assembly. However the system always has to prioritize the POV of the real world and thus too many digital features may be a detriment.

9. Task 8: Integration of the HoloLens built-in microphone to convert speech to text and hands-free photos

A feature was developed where the built-in microphone can be used to make a note on the model. After aligning the model to the assembled steel, the user is able to tap anywhere on the steel to add a note to that specific location. The user then speaks and the words are converted to a written note which is attached to the specific location on the model. The note dialogue is shown in Figure 9.1. In this manner, the user can leave a specific note in the program for others, without the need for a physical keyboard.

The user can also record a photo and attach it to a specific location on the model to convey information. To do so, the user either pushes the camera button (shown in the user interface) with their finger or alternatively, utilizing HoloLens eye tracking technology, the user can look at the button and speak "select" to take a photo.

Figure 9.1: User interacting with the note dialogue box by adding a note via speech-to-text to a user-specified location on a completed steel bridge connection assembly

10. List of Personnel

The following personnel were involved and contributed to the project:

- Dr. Hannah Blum, Principal Investigator
- Mihir Mehendale, Graduate Student Project Assistant, lead on Task 7
- Gabriel Lepak, Graduate Student Project Assistant, assisted with Task 7
- Dr. Ed Sippel, former Research Assistant (now Asst. Prof. MSOE), lead on Task 1
- William Kraus, Mixed Reality Engineer, lead developer
- Michael Tessmer, Mixed Reality Engineer

11. Conclusions

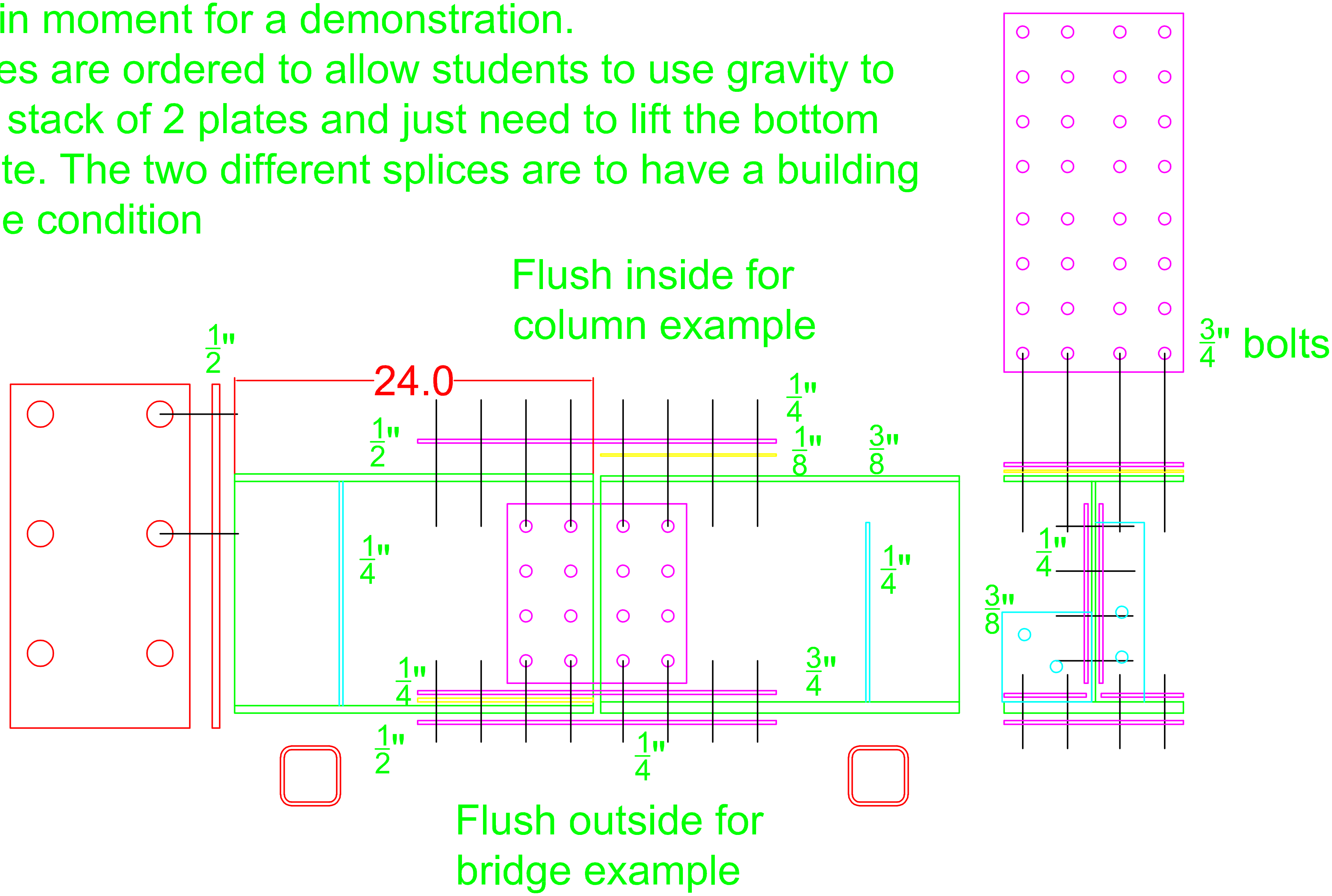
A custom augmented reality program was created in the HoloLens 2 headset to assist a user with steel assembly and fabrication. Two connections were investigated, one representing a bridge connection and one representing a beam-column connection. The overall aim of the project was to show the potential benefits of using augmented reality technology to assist in the fabrication process.

The custom program includes key features such as dimension inquiry, part validation, assembly guide, and the ability to record notes. Furthermore, it can be used to pull apart a completed connection, which may assist in training new fabricators before they begin fabrication operations. The created features are demoed in videos which are available online in the AR Steel playlist.

This investigation creates a foundation for which future developments can be conducted. It demonstrates the potential of the current hardware and shows a process that may help new fabricators. When the steel industry is ready, the software can be updated and modified to suit the needs of fabricators or others in the steel construction industry.

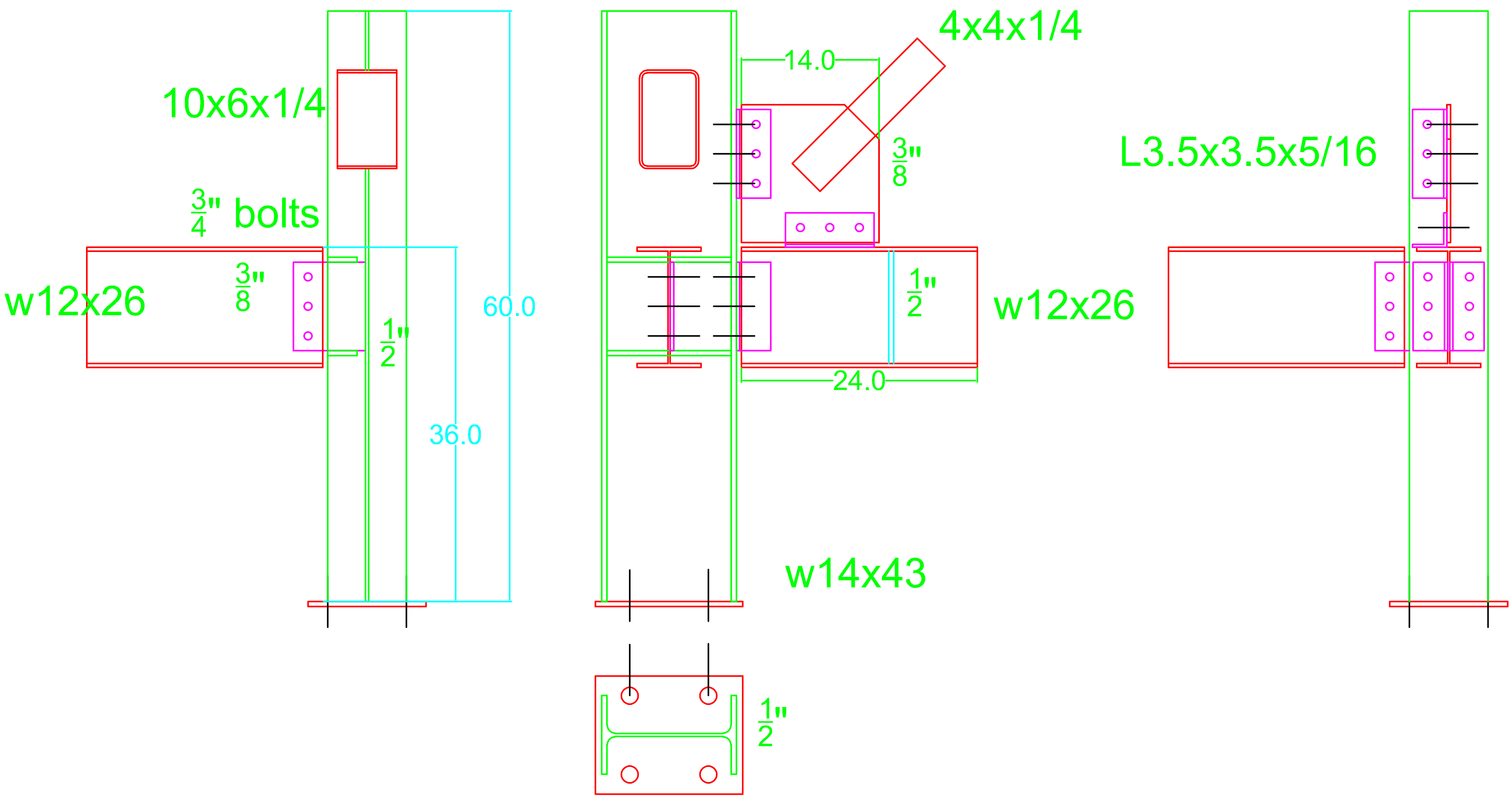
A. Connection Drawings

Plan to have end plate so can attach to strong wall if desired.
Typical position would be sitting on HSS seats on floor.
Sections will be too heavy to move freely, but expect to be able to remove flange splices and the web splice can support the ~200 lbs in moment for a demonstration.
The splices are ordered to allow students to use gravity to place the stack of 2 plates and just need to lift the bottom splice plate. The two different splices are to have a building and bridge condition



PRODUCED BY AN AUTODESK STUDENT VERSION
PRODUCED BY AN AUTODESK STUDENT VERSION
PRODUCED BY AN AUTODESK STUDENT VERSION

The final version would be 4 separate pieces. (1) The heavy column can be anchored to the strong floor. The HSS penetration will allow for a crane to be used to pick the column. (2) The I-beam on the left has an extended shear tab and no additional plates. (3) The I-beam on the right has a bolted to column, welded to beam double angle connection. The bottom angle for gusset plate would be welded to beam due to small flange. (4) The gusset plate and brace would be all bolted into place. Piece 2,3,4 should be <70 lbs and a pair of students should be able to install by hand.



130 E Randolph St, Ste 2000
Chicago, IL 60601
312.670.2400
www.aisc.org

Research Report No. AISC-FRR-2024-01