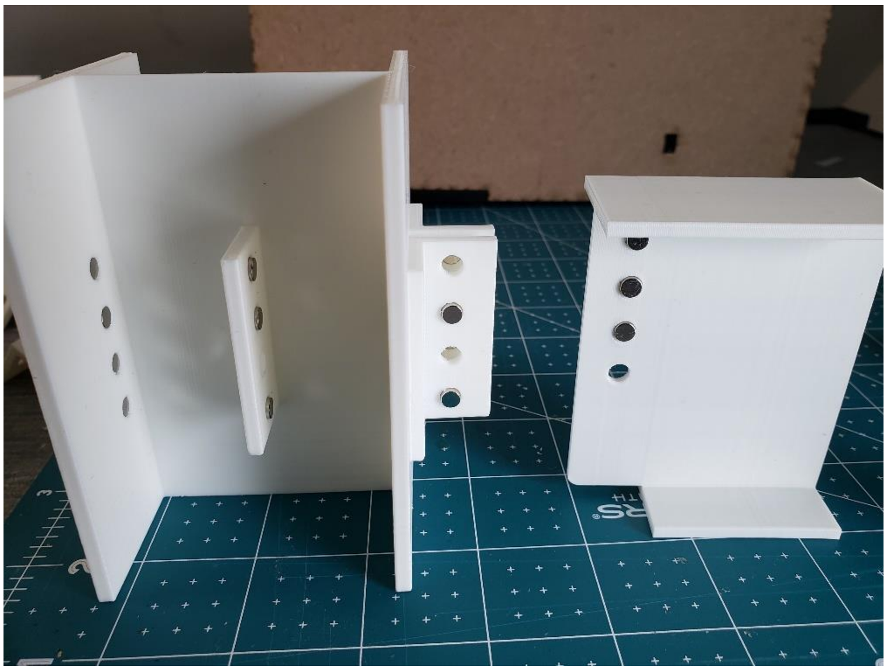
3D-Printed Connections

Instructions



September 2021 (Rev 1)

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Funded by: AISC Teaching Aid Development Program

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Introduction

Steel connection design and detailing is highly three-dimensional and can be difficult to visualize using two-dimensional graphics and/or photographs. Helping students develop the ability to visualize how the connections are constructed is crucial to making informed decisions during steel connection detailing and design.

This teaching aid contains files for instructors to produce 3D-printed connections for use as demos in their lectures that can be passed around the classroom. There are four connection models that illustrate different types of connections, and these models have components that measure approximately 3 in. to 6 in. long. The end of this document includes some key points for each connection to discuss during your class as the models are shared.

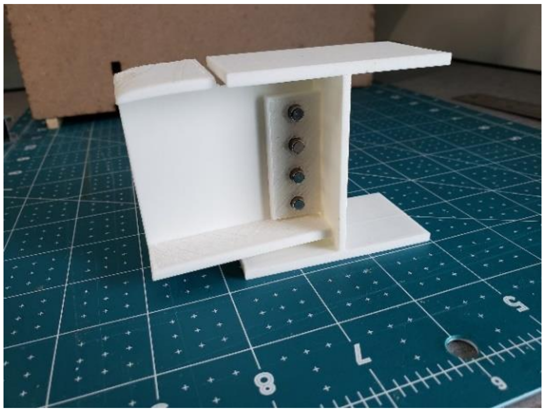
We hope that you find these 3D-printed connection models to be helpful in your classroom!

File Structure

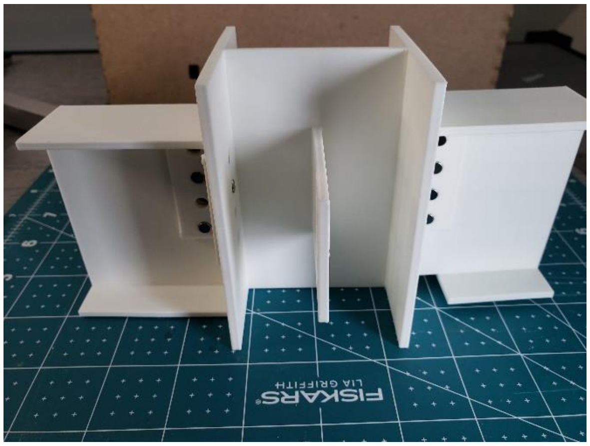
This project contains the files and instructions necessary to create a 3D-printed example of several steel connections for the purposes of education. The files were created in the educational version of Fusion360 and exported into stl files that are compatible with any slicer. These stl files are editable should there be any desired minor modifications.

Extensive modification may require the initial Fusion360 file, which is provided with the file name: *AISC_Complete_File.obj*. Other connections can be created and modeled using this approach.

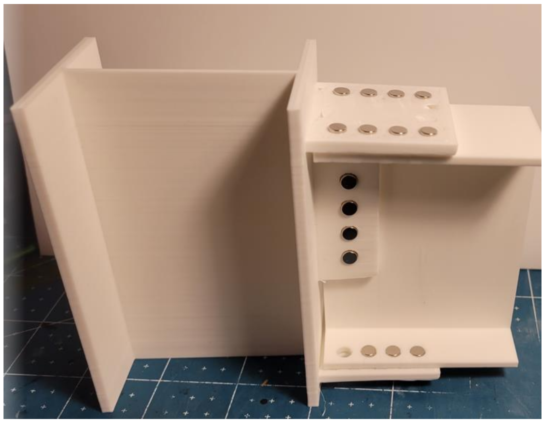
There are six models as part of this set, as shown in Figure 1.



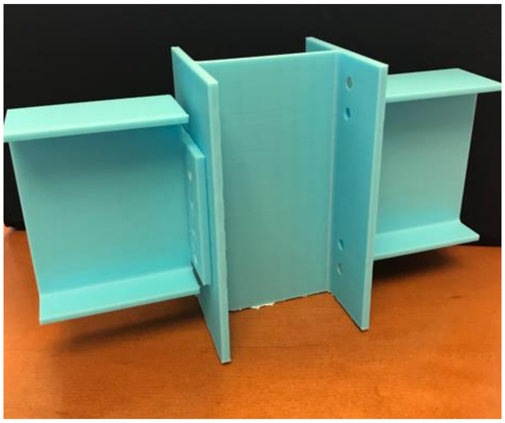
(a) Connection 1 – Beam-Girder



(b) Connection 2 – Column Connections



(c) Connection 3 – Moment Connection



(d) Connection 4 – End-plate Moment Connection

(e) Connection 5 – Unstiffened Seated Connection

(f) Connection 6 – Moment Connections to Column Web

Figure 1: Connection types that can be printed

Folder Contents

Each connection has its own folder within the directory that contains the following information:

- Photos of the 3D-printed connections.
- stl files for each part to be printed. Each part is intended to be individually printed, and the part is already oriented in the proposed printing orientation. (Note: If you open the file using the program Print3D, please disregard the cost that may be shown at the bottom left of the screen. It does not reflect the cost of either the actual steel connection or the 3D-printed connections. This is an unknown quantity generated by the program that serves no meaning for our purposes).
- stl file showing the connection digitally assembled (this is not meant for printing, but for digital visualization if 3D printing is not possible). These files are designated by *AISC_(connection type nomenclature)_Virtual*.

Model Index

The Model Index (below) uses nomenclature to identify the connection types and the parts to be printed for each connection. The file nomenclature is *AISC (Connection type)_(Part)*, and this nomenclature also matches the folder directory.

1) AISC Beam-to-Girder Connection (BG)
   A. Girder
   B. Coped beam
   C. Deeper beam coped on top and bottom flange

2) AISC Column Connection (CC)
   A. Column
   B. Double angles
   C. Beam with the bottom flange coped
   D. Standard beam (use w/ bolted-bolted angles and shear tab to column web or print 2 copies)
   E. Wide beam

3) AISC Moment Connection (MC)
   A. Beam
   B. Column and stiffener plate

4) AISC Moment and Shear End-Plate Connection (EP)
   A. Column
   B. Beam (moment connection)
   C. Beam (shear connection)

5) AISC Unstiffened Seated Connection (SC)
   A. Column
   B. Beam
   C. Stabilizing angle
   D. Seat angle

6) AISC Moment Connections to Column Web (WMC)
   A. Column
   B. Beam (CJP weld)
   C. Beam (bolted flange)

For example: AISC BG_A is the Girder piece (listed as "A") for the Beam-to-Girder (BG) Connection.

3D Printing Requirements

The 3D printing of these "proof-of-concept" models were performed using an Ender 3 printer with a 0.4mm nozzle. It was sliced in Cura 4.7 using 1.75mm Inland brand polylactic acid (PLA) material at 215°C. All prints utilized tree-style supports and were printed in a vertical orientation to limit overhangs. These connections were also printed using a FlashForge Creator Pro with a 0.4mm nozzle. It was sliced in FlashPrint using 1.75mm Inland brand acrylonitrile butadiene styrene (ABS) material at 225 degrees Celsius with a platform temperature of 110 degrees Celsius.

The user is not limited to these specific parameters, but these are provided for reference. Decisions regarding specific printing details, such as type and brand of filament, print temperatures, support style, and print orientation, should be left to the printer operator, as they are the most knowledgeable on their own machine. With that said, the stl files should be usable by any fused deposition modeling (fdm) machine with any slicer. Any program that can slice stl files, such as Cura, Prusaslicer, Slic3r, Simplify3d, or other free open source or paid software, should be adequate for slicing stl files for a fdm printer.

The printer bed must be capable of printing pieces up to 5 in. tall and 4 in. wide.
Note that these models were printed in white, cyan, and red, but any color filament can be used. You may also choose to print the different parts (i.e. beam or column) in different colors, as shown in the Beam Girder Connection photos.

3D Printing Process

The pieces were primarily printed in a longitudinal orientation of the wide-flange member, and the stl files reflect this recommended print orientation. They were printed with a 15% infill using a tree style scaffolding. However, ordinary support should be sufficient, and there is no indication that different print orientations would cause a failure. The infill of 15% was found to be fragile, and there is potential of breakage when removing the supports and inserting magnets. 15% was selected to minimize printing time and material use, and this value should be considered the minimum recommended infill percentage. For less likelihood of a breakage, a slightly higher percentage (20-25%) of infill is suggested. Note: piece AISC_WMC_A require additional supports beyond automated supports because of the complexity of the part.

Importing the stl file into your printer's software should not result in any type of scaling of the pieces. However, if you would like to double check the scaling and print a test piece, we recommend that you first load the piece AISC CC_D into your software. This piece should have overall dimensions as follows: flange width (33.67 mm), beam depth (77.63 mm), and beam length (60.64 mm). This piece should take approximately two hours to print. After printing this piece, you can check if the magnets fit sufficiently within the holes. Refer to the next section for tips on installing the magnets.

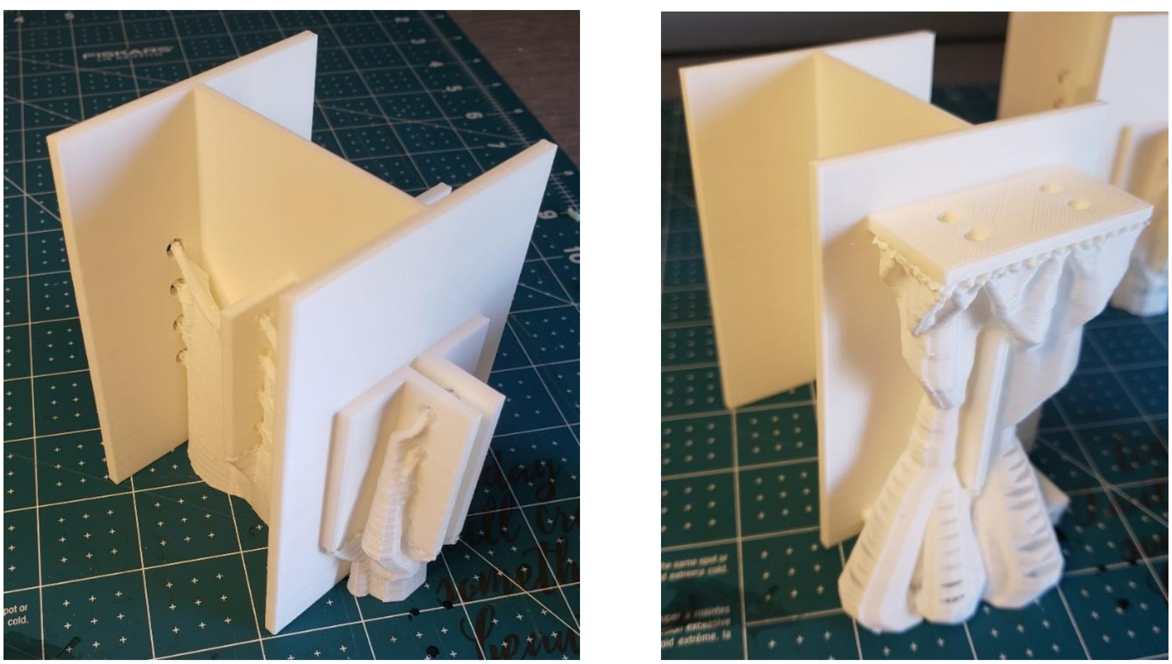
The column connection is the largest model and has a footprint of 3.5 in. x 3.5 in. and is 4 in. tall. The end-plate connection has a height of 5 in. but a smaller footprint. Print times for most beams are two hours. Column prints range from four to six hours, with the larger pieces reaching eight hours. The column for WMC (AISC_WMC_A) can take 15+ hrs to print due to the need for extensive supports.

Modifications of the basic printing settings may increase or decrease print time along with possible changes to the overall quality, and these decisions should be left up to the machine's operator.

Post-Printing Assembly

Once printed, the supports must be pruned off all overhangs. Figure 2 shows tools that may be useful for post-printing assembly (wood chisel, screwdriver, pliers, Allen wrench). A pair of small pliers or scissors should be sufficient to remove the supports; a wood chisel can also be useful for this. To clean out the holes, you may want to use a 1/8" Allen wrench. Regardless of the method you use to remove supports, this should be done delicately, as this is the most likely time that a breakage of the model may happen. Figure 3 shows examples of these supports for the (a) vertical shear tab and angle connectors and (b) horizontal flange plates.

Figure 2 – Recommended tools for post-printing assembly



(a) (b)

Figure 3: Printed pieces that show supports (necessary for printing the connection plates) to be removed post-printing

Once the supports have been removed, the pieces can be connected using magnets to represent the bolts. The prints include holes for 3/16-in. diameter magnets, and these magnets are intended to fit snugly into the hole without the need for glue. Depending on printer tolerances, it is possible that hole sizes may vary slightly from the magnet size. If the holes in the models are not large enough to insert the magnet, a file or screwdriver (3/16-in. diameter) can be inserted into the hole and twisted, removing any excess filament and expanding the hole. If the hole is too large and the magnet slides out with little resistance, glue can be used to adhere the magnet to the print.

Installing the magnets may take some time and patience until you get accustomed to the process. The magnet should be inserted into the hole so that the correct pole of the magnet is facing outwards and can connect it to its counterpart. One strategy for installation is to place the magnets on a metallic surface so that they are all facing the same direction and then push the model down onto the magnets. The thinner side of a table (or some other metallic surface with a smaller width) can be used to install magnets in the holes of the web or other areas that would not be reachable by a table face.

There are many bolt holes provided in the models, but due to the lightweight nature of these models, one or two magnets should be enough to support the connection. While the magnets are symbolic of the bolts in a real connection, a significant portion of the holes could be left unfilled, and the models would still be stable.

216 magnets are needed if you plan to build each of the six connections and include magnets at each bolt location. However, because of the force in the magnets (1.37 lbs/magnet), this is not recommended. It is recommended that you first start with only a couple of the magnets in each connection and then gradually increase if you would like to install more. Using too many magnets may make it difficult to detach the pieces from one another and you may risk damaging the printed parts. This is particularly true for the bolted flange plate moment connection where there are a large number of magnets. Only one or two magnets are needed at each web and flange of members to allow for east of assembly and detachment of the pieces. If you use only enough magnets to maintain stability of the connections, then you only need to order about 120 magnets.

The magnets used in the prototypes were 3/16 x 1/8-in. disc/cylinder magnets purchased from kjmagnetics.com (*noted as product D32 on their website in September 2021*).

Frequently Asked Questions

What does it cost? As of September 2021, each magnet cost $0.25. For a total of 120 magnets plus USPS shipping, the cost was approximately $36. Less than one reel of filament was used to print all of the parts, and each reel generally costs about $15-$25, depending on whether ABS or PLA material is used. (Note: reels are typically ~1080 linear feet in length.) Therefore, to complete printing of all the connections, the approximate cost is $50-60.

What if I don't have access to a 3D printer? Many universities have access to 3D printers. PLA and ABS printers are the intended materials for printing these connections. These printers are very common and even relatively affordable, so you may even know someone that personally owns a printer. If you cannot find someone you know to print it, there are a variety of companies online that offer 3D printing services, though these are expected to be more costly options. Even if you decide not to print these models, the stl files can still be used as 3D digital models to show the connections from different directions.

How can I save time and material to print more quickly? Each stl file is set up to print one piece at the time but you may find it more efficient to print multiple pieces on the platform at once. This can speed up the time of printing. It is recommended that you still print the more complicated pieces (i.e. the columns with angles and plates attached) individually. Additionally, you need not use supports as robust as what are shown in Figure 3. A smaller tree-like support system, as shown in Figure 4 below, may also suffice and save printing time. However, when plates are oriented horizontally (like the flange plates on the MC column connection or the WMC connection), more robust supports will likely be needed.

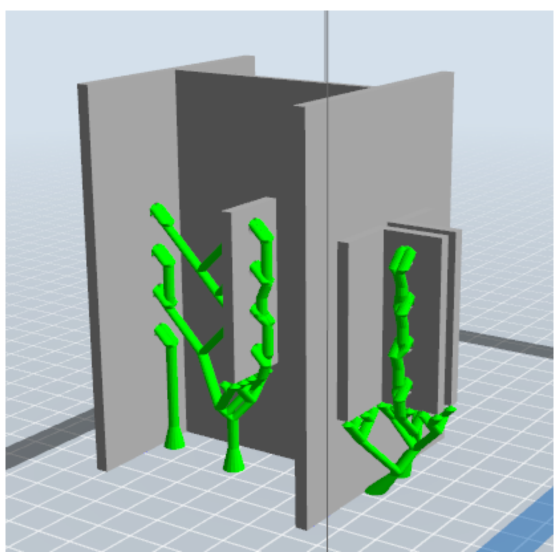


Figure 4: Model that shows alternative supports system (in contrast to Figure 3a)

Finally, you do not need to print every beam piece as some of the beams are duplicates. Instead, you can print only 1 copy of the piece and then use them to demonstrate multiple connections. Duplicates are:

- AISC CC_D and CC_E
- AISC CC_C and BG_B (not exactly the same but similar)

Talking Points for Instructors

Below are some potential talking points for each connection.

Connection 1: Beam-to-girder shear tab connection

There are two different beam options that can be printed and used to frame into the girder. One beam is a deep beam that requires a top and bottom cope to connect to the girder. The other is a shallower beam that only needs a top cope. You can take this opportunity to discuss how complexity of connections should be considered when designing beams: whenever possible, a good designer wants to avoid large copes and complicated, expensive connections. It is often good practice to use larger girder depths and shallower beam depths, even if that is not the most economic design for the member. The depth of the connection has to be at least half the depth of the supported beam, and the coped section has to be checked and possibly braced at the end of the cope.

Connection 2: Beam-to-column shear connections

This connection shows a few different options for framing beams into columns.

To the flange:

The beam framing into the column flange uses a double-angle connection. Whether the angles are welded or bolted to the supported member (the beam) or the supporting member (the column) can vary. The choice of whether connections are shop attached to the beam or column may depend on the thickness of the column flanges and the shop equipment.

The beam framing into the column with the bottom cope shows the angles shop-welded to the column and field bolted to the beam. To make this connection, the beam needs to be lowered into place from above, and the web must be knifed between the double angles that are already in place. Thus, the bottom flange needs to be coped in order to make this possible. Any adjustability to accommodate the length of the beam and any gaps or overruns in length need to be accounted for in the size of the bolt holes.

The double-angle connection could alternatively be bolted-bolted. For this connection, no coping of the beam is required, and no welding is required.

If the double-angle connection were welded to the beam and bolted to the column (not shown in a 3D image), then no coping of the beam would be required. Double angles that are shop attached to the beam are very common and typically do not need to be shimmed. Shimming is not typically required because member tolerances are within reason: column depths are usually overrun and beams are typically detailed short, which results in a connection that does not require excessive shimming. However, if a building has many bays, the beam tolerances can accumulate, and shimming may be required.

To the web:

When connecting a beam into the web of the column, the designer must consider the width of the beam flange relative to the depth of the column. If the beam is too wide, it will not fit within the column flanges. If that is the case, then either an extended shear tab connection could be used or the beam flanges would need to be notched to get the end of the beam closer to the column web.

The connection on the other side of the web shows a conventional shear tab connection since the beam can fit within the column. While field-bolting is relatively easy to do, it can be challenging to get a wrench into tight spaces and have enough room to tighten bolts. Thus, it is typically preferable to use an extended configuration, even if the beam width fits within the column flanges. Alternatively, a seated connection (Connection 5 - SC) can be used. The conventional shear tab to column web connection shown in this instance is rarely used because of the complexity in erection, but it is included to illustrate the difficulty in erecting this type of connection.

Connection 3: Bolted-flange moment connection

This connection shows an example of a moment connection. There are several types of moment connections, but they all restrain the flanges in some way. In this connection, the top and bottom flanges are clamped by the flange plates, and this limits the rotation and causes bending moments at the beam end. The flanges act as force couples to carry tension and compression, and the connection at the web carries shear. Stiffener plates (sometimes called continuity plates) are often added to stiffen the column and prevent local buckling and other concentrated limit states from occurring on the column web or column flange.

The bolted flange plate may need to be very long in order to develop the full force in the beam flange. While an eight-bolt flange plate is realistic, it is very possible that even longer plates and more bolts may be needed. The vertical spacing of the flange plates must accommodate the beam depth plus tolerances. This can be an important consideration for this connection type, especially with very long flange plates. To make matters worse, out of plane distortions can occur during welding. In order to prevent these issues, plates may need to be jacked together by snugging and tensioning the bolts. Shims may be needed and designed to comply with ASTM A6 tolerances for the beam. Modifications to the weld detailing and weld sequence can reduce the out of plane distortion. The plate can also be heat straightened after welding if necessary.

A cost comparison with a field welded moment connection could be worthwhile, but there is no one-size-fits-all answer. Where field welding is in short supply or expensive, the bolted connection may be the more economical solution over the welded condition, and you may get different answers in different regions of the country. While not required, it is good practice to allow at least a 1/2-in. difference in width on each side of the flange plate relative to the beam flange. This allows sufficient shelf dimension to place longitudinal fillet welds to compensate for the lack of bolts if the bolt holes misalign.

Connection 4: End-plate moment connection

This connection is an end-plate connection. If designed adequately, this connection serves as a moment connection. If the plate and bolts are only in the web region of the beam, then it behaves like a shear connection. If the bolts and the plate extend above and below the beam flanges, then it behaves like a moment connection. These connections are relatively easy to install but require precision in beam length. They also require that the end-plates are square (i.e. perpendicular to the beam and without a skew that would make it difficult to connect to the supporting member).

Connection 5: Unstiffened Seated Connection

This connection can be used for beam-to-column flange or beam-to-column web connections. These connections are a good option for beam-to-column web connections because bolting is easily accessible, and it avoids the shear tab problems discussed in Connection 2. The unstiffened seated connection includes a seated angle below the beam and a stabilizing angle above the beam. The seated angle is designed to carry the entire shear demand from the beam. The top angle is just meant to stabilize the beam during erection before the floor is installed. If the stabilizing angle is welded to the column, only the top of the angle can be welded (not the sides) in order to permit beam end rotation.

Generally, the seat angle is stiffer than the stabilizing angle because the outstanding leg is sized to resist bending moments from the reaction of the beam. It is welded on its sides with a short return at the top. The top angle is shipped loose or finger tight bolted to the beam flange. The stabilizing angle can be bolted or welded to the column and the beam. If bolted, provisions must be made for beam depth tolerances, usually in the form of vertical short slots. The connection is called “unstiffened” because the seat is an angle that does not include stiffener plates. In order to obtain more shear capacity in the connection, the designer may need to use plates and stiffeners plates as the seat for the beam. Stiffened seats can resist significantly higher loads than unstiffened seats. In many cases the beams need to be trimmed back to allow for field assembly without interference from attachments in the web of the column.

Connection 6: Moment Connections to Column Web

A moment connection framing into the web of a column is used when bi-axial bending of the column is needed. The web is not prone to the same concentrated limit states as the flange-connected moment connection (Connection 3), but the web-connected connection may be limited by the weak axis moment capacity of the column. These web connections are not nearly as common as moment connections to the flange. Two connection types are provided in this model. One is a CJP-welded connection and the other is a flange-bolted connection. The CJP welding of the beam flange to the continuity plate would need to be performed in the field. The flange-bolted connection is a field-bolted option that eliminates field welding. In both cases, the shear tabs extend beyond the column flanges in order to allow for placement of the beam and room for bolt tightening. Again, beam depth tolerances are accommodated with a filler plate between the top flange and the top connection plate.

The instructor should refer to Part 12 of the AISC *Steel Construction Manual* for more information about these types of connections, which includes tips about extending the continuity plate beyond the column flange toes and welding the continuity plate to the column web.

Version Updates

VERSION	DATE	UPDATES
--	July 2021	• Connections 1-4 provided
Rev 1	September 2021	• Connections 5-6 provided • Added fillets to WF shapes • Minor tweaks to connections 1-4 (i.e. shifting shear tabs in column connection, widening beam flange in moment connection to prevent cracking) • Beam-girder connection model modified so both beams can frame into the girder from either side • Added a fixed connection to end plate connection model • Updates to INSTRUCTIONS document for more clarity and tips on construction