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Autonomous Guided Vehicle Frame for Outdoor Use

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Thomas McGrath

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Introduction and Background

The idea of an Autonomous Guided Vehicle (AGV) is far from new, but as sensing and computing technology continues to advance, so does the scope of applications for these vehicles. The size of an AGV can range from a small cleaning robot not unlike one you may have at home to the largest heavy equipment found in major mining operations, and all sizes in between. Applications are typically related to material handling, hauling, or cleaning, but can also include security, healthcare, and transportation. The application that is the primary focus of this project is hauling, specifically in a larger scale for mining or large construction.

Research

There are several companies that are branching into the realm of autonomous guided vehicles for applications like mining and earth moving. CAT and Komatsu both have large scale autonomous hauler trucks that can move up to 400 tons in one trip. Making these vehicles autonomous "…boosts safety, productivity and availability on busy mine sites, especially those in difficult or remote locations" (*cat.com*). Despite the autonomous capability of these vehicles, they still include a cab and controls for a human operator. Komatsu has demonstrated an autonomous driverless truck with no cab, called the "Autonomous Haulage System dump truck" (Liszewski). This vehicle was debuted in 2016, but there does not appear to be a date for when they will be available.

Another company implementing autonomous technology into heavy equipment is Built Robotics. Their approach is "upgrading off-the-shelf heavy equipment with AI guidance systems, enabling it to operate fully autonomously" (*builtrobotics.com*). This is the same approach taken by CAT and Komatsu, just with different equipment. Built Robotics creates autonomous dozers, excavators, and compact track loaders. Their application goes outside the realm of mining to include grading, clearing, compacting, and other operations related to all types of construction.

Based on the direction taken by existing companies, it was determined that the best course of action would be to base the frame design on existing vehicle frames for a similar style vehicle.

Design Considerations

A goal when designing the vehicle frame was to create a frame that could be used for a vehicle that could compete with a commonly available commercial dump truck. The length of the frame was chosen as 25ft, which is a common size for a larger single unit dump truck. Next, the number of axles on the vehicle is four so that it is consistent with a typical large single-unit dump truck. The distance between the extremes of groups of axles was chosen as 18ft, again following what is commonly available in a larger commercial dump truck. Using a table provided by the US Department of Transportation Federal Highway Administration at *ops.fhwa.dot.gov*, the permissible gross weight of the vehicle was determined to be 54,000lbs for a 4-axle truck with 18ft between the extremes of any group of 2 or more consecutive axles. By following these guidelines, the autonomous vehicle will be legally permitted to drive on roads and highways in the United States.

Another goal for the vehicle frame was to be able to operate in off-road conditions. To accommodate this the frame was analyzed with a design factor of 3, as well as other considerations to improve the strength and durability of the frame. A design factor of 3 was selected based on a ductile material "under dynamic loading with uncertainty about loads, material properties, stress analysis, or the environment", taken from page 189 of *Machine Elements in Mechanical Design*.

Design Process

Material Selection

To select a material, research was done to determine what types of steel should be considered. It quickly became clear that a High Strength Low Alloy (HSLA) steel would be the best option for several reasons. First, *ASM Handbook Volume 1: Properties and Selection: Irons, Steels, and High-Performance Alloys* notes that "HSLA steels have fatigue properties equivalent or superior to those of hot-rolled low-carbon steel" (413). Fatigue properties are important for a vehicle frame because the vehicle will be subjected to repeated stresses over the course of its life. Another consideration is the ability of the material to be formed into desired shapes, and according to the ASM Handbook, "… high-strength steels have good formability, and straight bends can be made to relatively tight bend radii" (*ASM Handbook Volume 1,* 413). This was important to consider because the frame components will be more complex than flat plates. Finally, "High-strength low-alloy steels are readily welded by any of the welding processes used for plain carbon structural steels" (*ASM Handbook Volume 1*, 414). Weldability of the material is necessary as welding is commonly used in vehicle manufacturing. *ASM Handbook Volume 1* goes on to mention that HSLA steels used in automotive applications provide opportunities for weight reduction, gage reduction, and increased payloads without sacrificed fuel efficiency (415-417).

Three HSLA steels were considered: SAE HSLA 950A, ASTM A656 Grade 80, and Timken Steel Microtec 2W60. Of the three options, ASTM A656 Grade 80 was selected because it was indicated on *ASM Handbook Volume 1* page 399 as being used for truck frames. With a yield strength of 80ksi, ASTM A656 Grade 80 is well suited for use in off road conditions that the frame may encounter.

Frame Rail

With a material selected, calculations were made to determine the required size of the frame rails. Based on frames of commercially available dump trucks, a C-channel was selected as the channel style for the frame rails. “Volvo Body Builder Instructions” published by Volvo Trucks North America provides some rationale for the channel style. “The steel channel frame is popular because components can be attached to it easily, and it exhibits relatively high strength compared to other shapes” (“Volvo Body Builder Instructions” 18). All calculations are available in Appendix 1.

The process that the calculations would follow would be finding moments at each axle, finding a required section modulus, and then using allowable deflection to determine a required moment of inertia. This process was taken from chapter 16 of *Applied Statics and Strength of Materials*.

To begin calculations, a diagram was drawn indicating the locations of the front and rear axles, as well as the load that would be placed on the rail. Each rail was designed to hold the total vehicle weight. This was done intentionally to create a stronger than necessary part to decrease the chance of failure in extreme conditions. The moment at each axle was found using formulas taken from figure 22 of “Beam

Design Formulas with Shear and Moment Diagrams" published by the American Forest & Paper Association. The larger moment was used when determining the section modulus.

When finding the section modulus, the design stress of the material was cut in half from 80ksi to 40ksi. This was done for two reasons, the first being to add additional strength to the design by creating a larger section modulus, and second to increase the size of the frame rail cross section. When using 80ksi, the frame rail cross section was smaller than expected and would have likely caused issues when designing crossmembers, such as creating a crossmember with adequate strength that can still fit within the frame rail. The section modulus was calculated using the following formula:

$$S = \frac{M}{\sigma_D}$$

This formula was taken from page 105 of *Machine Elements in Mechanical Design*. M is the maximum bending moment and sigma is the design stress.

With the section modulus calculated, a channel was chosen from the table 15-4 in the appendix of *Machine Elements in Mechanical Design*. The required section modulus found was approximately $S = 8.1in^3$, so the channel C8x11.5 was selected.

The bending moment was calculated using the weight of the selected channel and added to the previous bending moment. The section modulus was calculated again, and had increased enough to require the next size channel, C8x18.75.

Next, deflection calculations were used to determine a required moment of inertia. To find the allowable deflection in the span, the following equation was used:

$$\Delta_{Limit} = \frac{Span}{360}$$

This formula was taken from page 338 of *Applied Statics and Strength of Materials.* After finding the allowable deflection, two more formulas from table A14-1 were used to find the required moment of inertia. One equation solved the deflection at the center of the beam, and the other solved for deflection at the ends of the beam. Using these equations, two moments of inertia were found, the larger being $I = 69.16in^4$. The previously selected C8x18.75 channel only has a moment of inertia of $I = 44.0in^4$, so a new channel was chosen. The new channel selected was C10x20.

During the design of the frame crossmembers, it was determined that the shape of the C-channels was not optimal. The inside of the C channel has a taper that makes it difficult to place a cross member inside and flush against the surfaces. Because of this, a U-channel that met the required section modulus and moment of inertia was chosen from table 15-6 in the appendix of *Machine Elements in Mechanical Design.* The selected channel has a 9in depth and 4in width. Drawings of the frame rail can be found in appendix 3.

Crossmembers

When designing the crossmembers of the frame, the goal was simply to create parts that fit within the frame rail for easy attachment. For the majority of crossmembers used in the frame, a W8x15 steel beam was used. This size beam fits inside of the chosen frame rail size, and because of its standard size should be easier to produce. Drawings of this beam can be found in appendix 3. In order to attach the W8x15 beams to the frame rail a joining part was designed. The inclusion of this part creates a better attachment method than would be possible with just the W8x15 beam. Drawings of the joiner part are available in appendix 3, and an assembly drawing with the joiner part attached to both ends of the W8x15 can be found in appendix 2.

For the ends of the frame it did not seem that the best option was to use the W8x15 due to the open sides of an I shaped beam. A U-shaped channel was designed to be used on both ends of the frame rail. This channel was designed to fit within the frame rail, similar to the W8x15. The flanges of the channel were wider at each end and narrower in the middle. This was done to accommodate a mounting bracket, similar to the joiner piece that was used with the W8x15. A drawing of the closing channel is available in appendix 3, and an assembly drawing with the bracket attached to both ends can be found in appendix 2.

Joining Methods

The two joining methods considered for assembling the frame were welding and using fasteners. HSLA steels can be welded in many ways, and welding is often used in automotive manufacturing. However, it is recommended to avoid welding on the frame rails as well as heating steel frame rails to minimize frame failure ("Volvo Body Builder Instructions" 29). Furthermore, the *ASM Handbook Volume 6: Welding, Brazing, and Soldering* states that "The successful welding of HSLA structural steels requires consideration of a preheat. […] If the preheat temperature is not sufficiently high, weld cracking can occur" (664). For this reason, fasteners were chosen as the joining method for the frame.

The Volvo guide recommends “property class 10.9 bolts and property class 10 nuts” on page 5, and also recommends M14 and M16 bolts for joining crossmembers to the frame. M14 bolts were used to join the mounting brackets to the closing crossmembers and W8x15 crossmembers. M16 bolts were used to join all crossmembers to the frame rails. The chosen nuts and bolts were found on the McMaster-Carr website, and drawings of each part can be found in appendix 3.

Some further considerations to minimize frame failure listed in the Volvo guide, page 29, include not drilling holes in the frame rail flanges and spacing holes in the web section of the frame rail at least 2 inches apart. The suggestions were followed in the design of the various frame parts. Avoiding drilling in the frame rail flanges is what prompted the inclusion of brackets for the attachment of the frame crossmembers.

Analysis

Simulations were run on three different frame parts to evaluate their ability to withstand the loads that they would be subjected to. Calculations used to determine the loads to apply are available in appendix 1. Note that the calculations include the design factor of 3 mentioned previously in design considerations. ANSYS student software was used to perform analysis on the frame rail, W8x15 crossmember, and closing crossmember. Due to limitations of the student edition, analysis was kept to applying pressures to different faces of the part while fixing others in place. Assemblies were not able to be simulated due to the higher quantity of surfaces/faces in the 3D models.

To preform analysis on the frame rail, a section was tested instead of the entire length of the rail. This was done because the student version of ANSYS was not able to accommodate the entire frame rail.

For the analysis, parts were fixed in place using their bolt holes, as well as on surfaces that would be supported in the final assembly. Pressure was applied to the top faces of the parts and the simulation was run. Appendix 4 includes screenshots of the results for the deformation, stress, and strain of each part simulated.

Conclusions

Based on the results of the ANSYS analysis, the goal of designing a frame that would be reliable after repeated uses in an off-road environment has been achieved. On the parts tested, the deformation was negligible and the stresses applied (after including the design factor of 3) were well within the acceptable range for the material being used. Although the ANSYS models may look dramatic, the values are not. The intentional over-designing of the parts resulted in the creation of a frame that will withstand the stresses of its intended use.

The look and design of the frame is similar to that which would be found in a commercially available dump truck. It follows many of the same conventions, and as a result should be easy and cost effective to manufacture and implement into a vehicle.

Recommendations

Based on the results of the analysis, investigation of other materials would be recommended to hone the design. The material should still be an HSLA steel, but it could be one with a lower yield strength.

To truly affirm that the frame can withstand the abuse of its applications, more simulation would need to be performed. Use of a full version of ANSYS could allow simulation of the complete assembly and sub-assemblies, which would provide a much better idea as to how the frame will perform.

References

ASM Handbook Volume 1: Properties and Selection: Irons, Steels, and High-Performance Alloys. ASM International, 1990.

ASM Handbook Volume 6: Welding, Brazing, and Soldering. ASM International, 1993.

"Beam Design Formulas with Shear and Moment Diagrams." *American Forest & Paper Association*, 2007, www.awc.org/pdf/codes-standards/publications/design-aids/AWC-DA6-BeamFormulas-0710.pdf.

"Bridge Formula Weights." *U.S. Department of Transportation Federal Highway Administration*, August 2019, ops.fhwa.dot.gov/freight/publications/brdg_frm_wghts/index.htm.

Built Robotics. Built Robotics Inc., 2020, www.builtrobotics.com.

"CAT Command for Hauling.", *CAT*, www.cat.com/en_US/by-industry/mining/surface-mining/surface-technology/command/command-for-hauling.html.

Limbrunner, George F. and D'Allaird, Craig T. *Applied Statics and Strength of Materials*. 6th ed., Pearson, 2016.

Liszewski, Andrew. "This Giant Autonomous Dump Truck Doesn't Have a Front or Back." *Gizmodo*, 27 Sept. 2016, gizmodo.com/this-giant-autonomous-dump-truck-doesn-t-have-a-front-o-1787133684.

Mott, Robert L., et al. *Machine Elements in Mechanical Design*. 6th ed., Pearson, 2018.

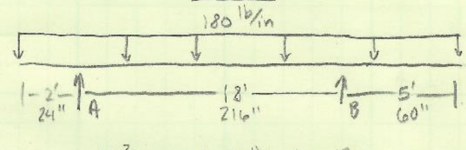
"Volvo Body Builder Instructions." *Volvo Trucks North America*, Jan 2017, www.volvotrucks.us/-/media/vtna/files/shared/body-builder/manuals/volvo_section-7-frame.pdf.

Appendix 1, Calculations

Thomas McGrath
1/29/2020

Front Axle (A)
Rear Axle (B)
Vehicle Length = 25 ft = 300 in
Gross Vehicle Weight = 54,000 lb

Moment



$a = 24"$ $b = 216"$ $c = 60"$
$w = 180\ \text{lb/in}$ $L = 300"$

$$M_A = -\frac{wa^2}{2} = -\left(\frac{-180\ \text{lb/in} \cdot (24\ \text{in})^2}{2}\right) = 51840\ \text{lb-in}$$

$$M_B = -\frac{wc^2}{2} = -\left(\frac{-180\ \text{lb/in} \cdot (60\ \text{in})^2}{2}\right) = 324000\ \text{lb-in}$$

Section Modulus

$$S = \frac{M_B}{\sigma_D} = \frac{324000\ \text{lb-in}}{40000\ \text{lb/in}^2} = 8.1\ \text{in}^3 \qquad \sigma_D = 40000\ \text{lb/in}^2$$

Choose C8 × 11.5 channel ($S = 8.14\ \text{in}^3$)

$$11.5\ \text{lb/ft} \times \frac{1\ \text{ft}}{12\ \text{in}} = .958\ \text{lb/in}$$

Moment of Weight of Channel

$$M_c = -\frac{wc^2}{2} = -\left(\frac{-.958 \cdot (60\ \text{in})^2}{2}\right) = 1724.4\ \text{lb-in}$$

Total $M_B = 324000 + 1724.4 = 325724.4\ \text{lb-in}$

Section Modulus with Channel

$$S = \frac{M_B}{\sigma_D} = \frac{325724.4\ \text{lb-in}}{40000\ \text{lb/in}^2} = 8.14\ \text{in}^3$$

$$8.14\ \text{in}^3 = 8.14\ \text{in}^3$$

To be safe, we will go the next size up C8 × 18.75 ($S = 11.0\ \text{in}^3$)

Thomas McGrath
2/3/2020

Deflection allowable in span = $\frac{span}{360}$

$$\Delta_{Limit} = \frac{span}{360} = \frac{300in}{360} = .833in$$

To find deflection at the center of the beam:

$$\Delta_{Limit} = \frac{W(L-2a)^3}{384EI}\left(\frac{5}{L}(L-2a) - \frac{24}{L}\left(\frac{a^2}{L-2a}\right)\right)$$ table A14-1
Machine Elements in Mech. Design

$\Delta_{Limit} = 0.833in$ $W = 54000lb$ $L = 300in$ $E = 3\times10^7 psi$ $a = 24in$

$$0.833in = \frac{54000lb(300in - 2(24in))^3}{384(3\times10^7)psi(I)}\left(\frac{5}{300in}(300in-2(24in)) - \frac{24in}{300in}\left(\frac{(24in)^2}{300in - 2(24in)}\right)\right)$$

$$0.833in = \frac{54000lb(252in)^3}{(1.152\times10^{10}psi)I}(.768)$$

$$0.833in = \frac{54000lb(12290310.14in^3)}{(1.152\times10^{10}\ lb/in^2)I}$$

$$(9696160000\ lb/in)I = 54000lb(12290310.14in^3)$$

$$I = 69.16in^4$$

To find deflection at the ends of the beam:

$$\Delta_{Limit} = \frac{-W(L-2a)^3a}{24EIL}\left(-1+6\left(\frac{a}{L-2a}\right)^2 + 3\left(\frac{a}{L-2a}\right)^3\right)$$ table A14-1

$\Delta_{Limit} = 0.833in$ $W = 54000lb$ $L = 300in$ $E = 3\times10^7 psi$ $a = 60in$

$$0.833in = \frac{-54000lb(300in - 2(60in))^3(60in)}{24(3\times10^7psi)(300in)I}\left(-1+6\left(\frac{60in}{300in-2(60in)}\right)^2 + 3\left(\frac{60in}{300in-2(60in)}\right)^3\right)$$

$$0.833in = \frac{-54000lb(349920000in^4)}{(2.16\times10^{11}\ lb/in)I}(-1+.667+.111)$$

$$0.833in = \frac{4.1948\times10^{12}\ lb\text{-}in^4}{(2.16\times10^{11}\ lb/in)I}$$

$$(1.7993\times10^{11}\ lb)I = 4.1948\times10^{12}\ lb\text{-}in^4$$

$$I = 23.3in^4$$

Required $I = 69.16in^4$ $C8\times18.75$ $I = 44.0in^4$
$69.16 > 44.0$
Choose Larger Size

Choose $C10\times20$ $I = 78.9in^4$

Thomas McGrath
2/10/2020

C - Channel shape not well suited for mounting of cross members. As a result will use calculated section modulus and moment of inertia to select a better suited channel.

Required $I = 69.16 in^4$
Required $S = 8.14 in^3$

Choose channel with 9" depth and 4" width

$I = 78.31 in^4$
$S = 17.40 in^3$

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3/31/2020

Estimation of Loads for ANSYS Analysis

Gross Vehicle weight = 54,000 lb

Approximately 2/3 of total weight on rear axle -> 36,000 lb,

Approximately 1/3 of total weight on front axle -> 18,000 lb

9 total crossmembers
- 3 in "front"
- 6 in "rear"

Each member regardless of position must hold up to 6000 lb

If using a design factor of 3, each must hold 18,000 lb

Surface Area of top of W8×15 crossmember = 128.5 in^2

Surface Area of top of End crossmember = 158.1 in^2

W8×15

Required psi = 6000 lb/128.5 in^2 = 46.7 psi

Design Factor psi = 18000 lb/128.5 in^2 = 140.1 psi

Closing Crossmember

Required psi = 6000 lb / 158.1 in^2 = 38.0 psi

Design factor psi = 18000 lb/158.1 in^2 = 113.9 psi

9x4 Channel

Surface Area Top = 1200 in^2

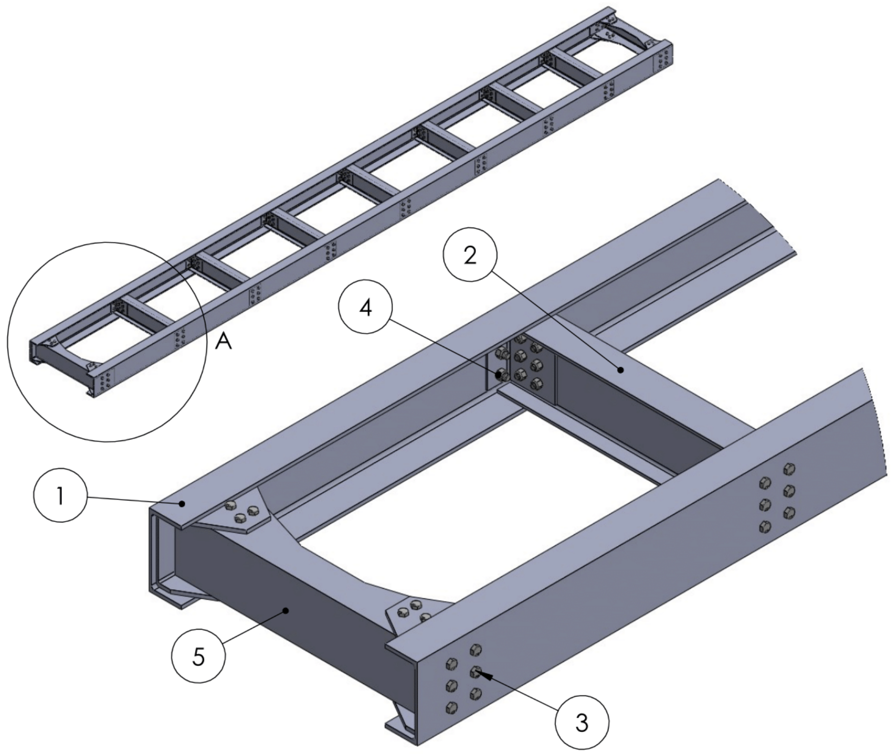
54,000 lb / 2 channels = 27,000 lb / channel

Design factor of 3 -> 27,000 lb × 3 = 81,000 lb

Required psi = 27,000 lb / 1200 in^2 = 22.5 psi

Design Factor psi = 81,000 lb / 1200 in^2 = 67.5 psi

Appendix 2, Assembly Drawings



DETAIL A
SCALE 1 : 12

ITEM NO.	PART NUMBER	MATERIAL	QTY.
1	9x4 Channel	STEEL - ASTM A656 GRADE 80	2
2	W8x15 with Joiner	SEE SUBASSEMBLY DRAWING	7
3	M16 x 2mm Hex Screw	ZINC YELLOW-CHROMATE PLATED STEEL	108
4	M16 x 2mm Locknut	HIGH-STRENGTH STEEL WITH NYLON INSERT	108
5	Closing Member with Joiner	SEE SUBASSEMBLY DRAWING	2

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
FINISH:
DEBURR AND BREAK SHARP EDGES
DO NOT SCALE DRAWING
REVISION

	NAME	SIGNATURE	DATE
DRAWN	T MCGRATH		3/2/2020
CHK'D			
APPV'D			
MFG			
Q.A			

MATERIAL:
WEIGHT:
TITLE:
Frame Assembly
DWG NO.
A4
SCALE 1:50
SHEET 1 OF 1

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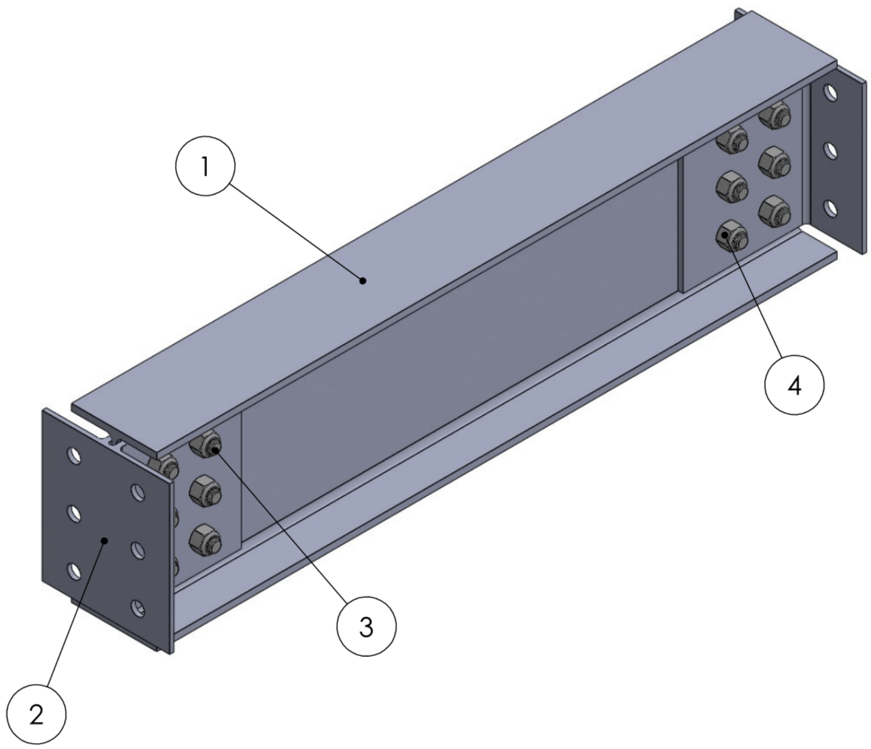


ITEM NO.	PART NUMBER	MATERIAL	QTY.
1	W8x15	STEEL - ASTM A656 GRADE 80	1
2	W8x15 Joiner	STEEL - ASTM A656 GRADE 80	2
3	M14 x 2mm Hex Screw	ZINC YELLOW-CHROMATE PLATED STEEL	12
4	M14 x 2mm Locknut	HIGH-STRENGTH STEEL WITH NYLON INSERT	12

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN	T MCGRATH		3/2/2020
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

W8x15 with Joiner

MATERIAL:

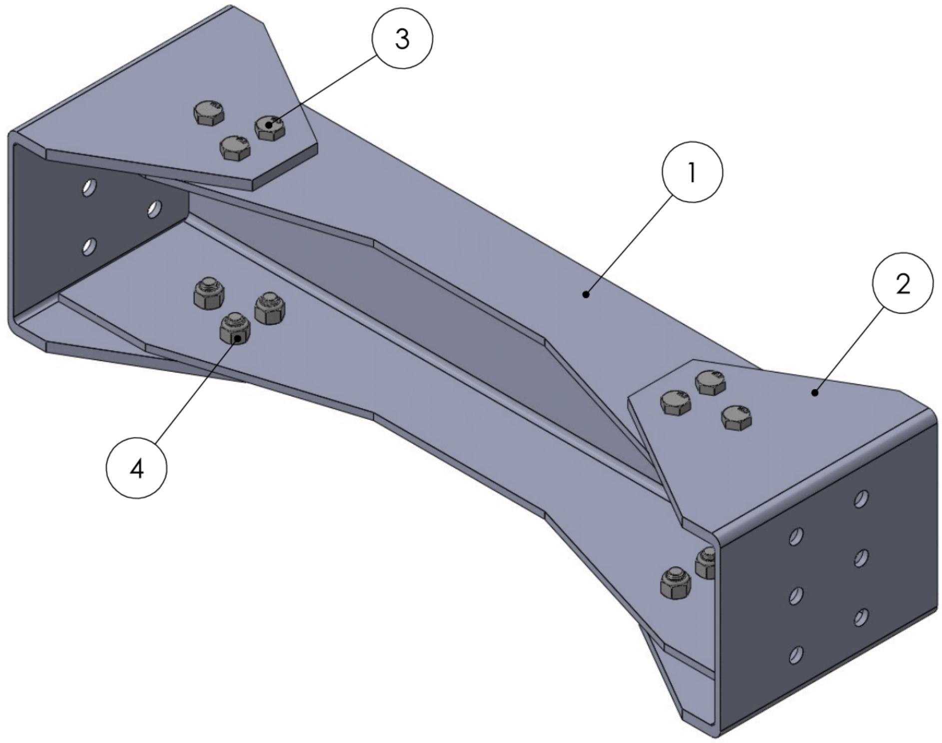
DWG NO.

A4

WEIGHT:

SCALE:1:5

SHEET 1 OF 1



ITEM NO.	PART NUMBER	MATERIAL	QTY.
1	Closing Member	STEEL - ASTM A656 GRADE 80	1
2	Closing Member Joiner	STEEL - ASTM A656 GRADE 80	2
3	M14 x 2mm Hex Screw	ZINC YELLOW-CHROMATE PLATED STEEL	12
4	M14 x 2mm Locknut	HIGH-STRENGTH STEEL WITH NYLON INSERT	12

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN	T MCGRATH		3/2/2020
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

Closing Member with Joiner

MATERIAL:
STEEL - ASTM A656 GRADE 80

DWG NO.

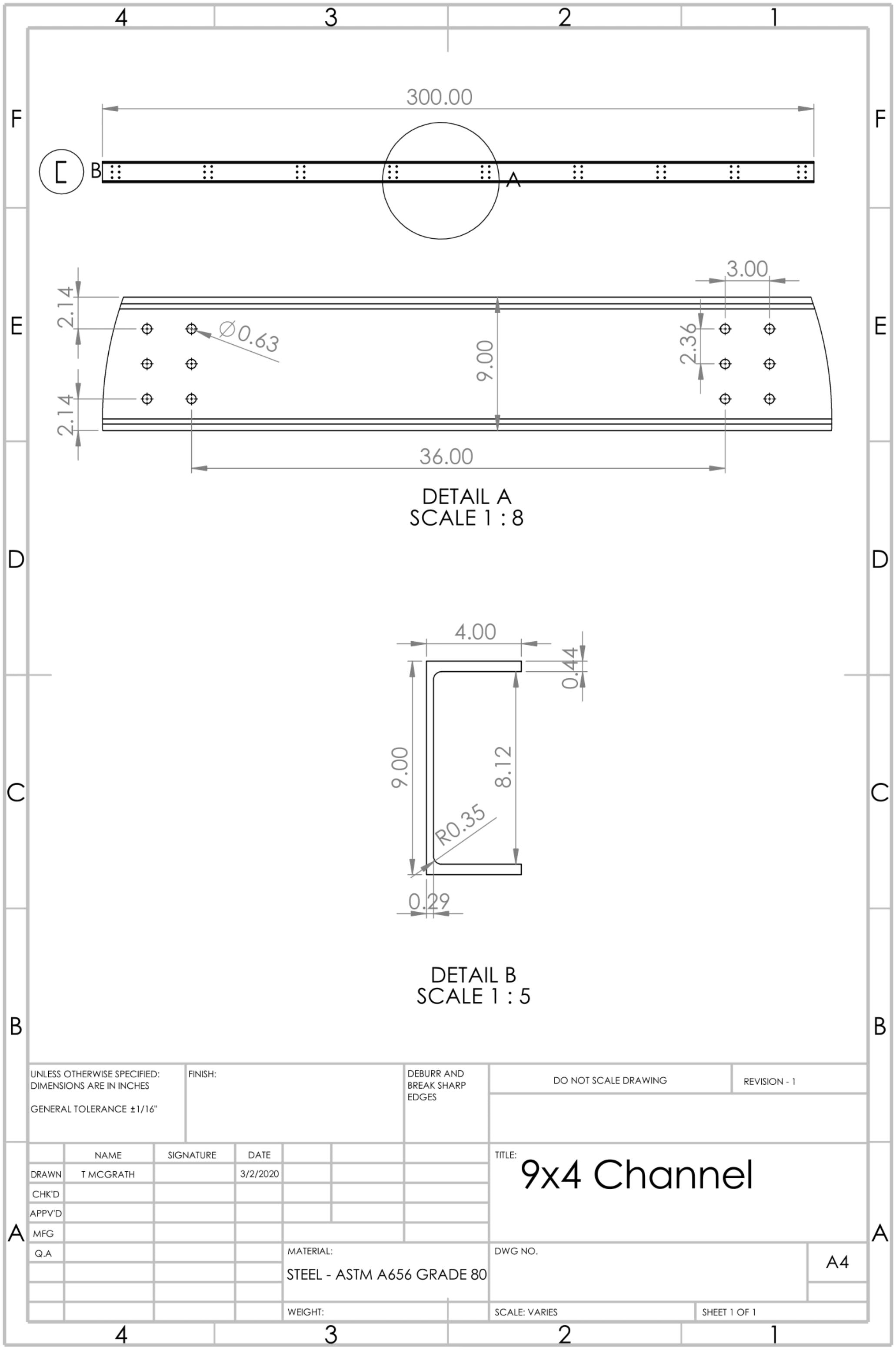
A4

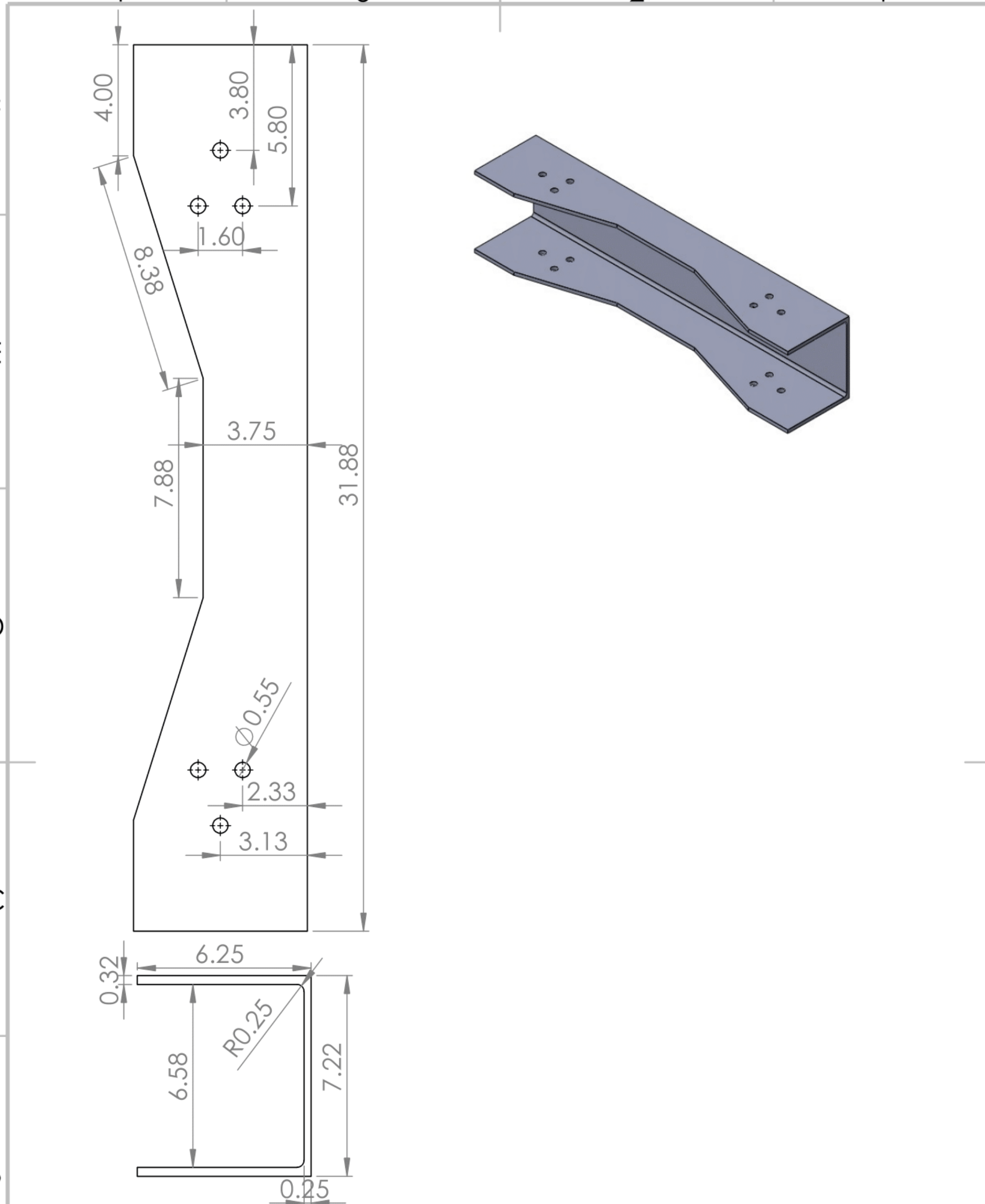
WEIGHT:

SCALE 1:5

SHEET 1 OF 1

Appendix 3, Part Drawings





UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES

GENERAL TOLERANCE ±1/16"

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN	T MCGRATH		3/2/2020
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

Closing Member

MATERIAL:
STEEL - ASTM A656 GRADE 80

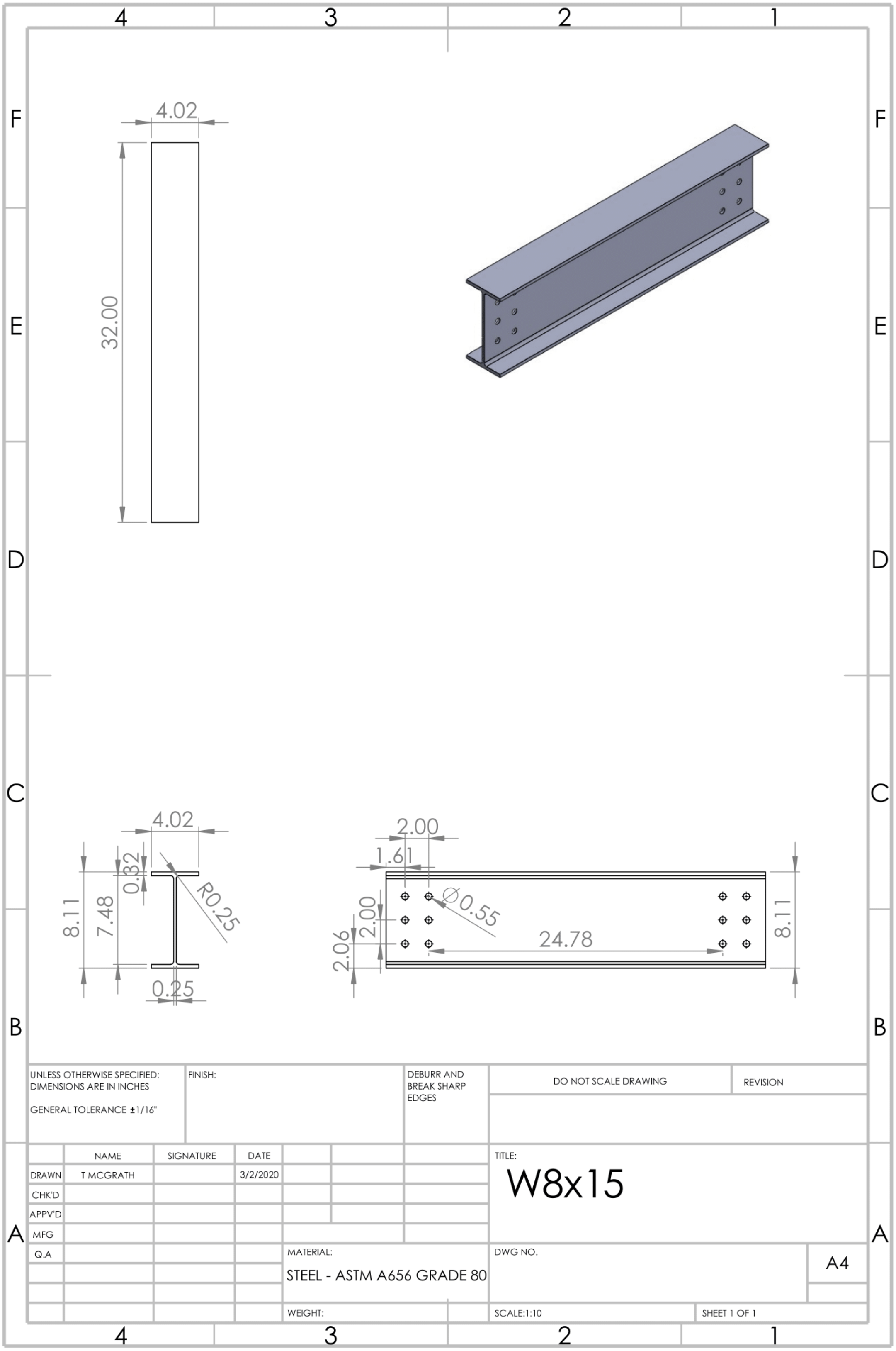
DWG NO.

A4

WEIGHT:

SCALE:1:10

SHEET 1 OF 1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8.11
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∅0.55
2.00
2.06
24.78
8.11
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
GENERAL TOLERANCE ±1/16"
FINISH:
DEBURR AND BREAK SHARP EDGES
DO NOT SCALE DRAWING
REVISION
NAME
SIGNATURE
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DRAWN
T MCGRATH
3/2/2020
CHK'D
APPV'D
MFG
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DWG NO.
A4
WEIGHT:
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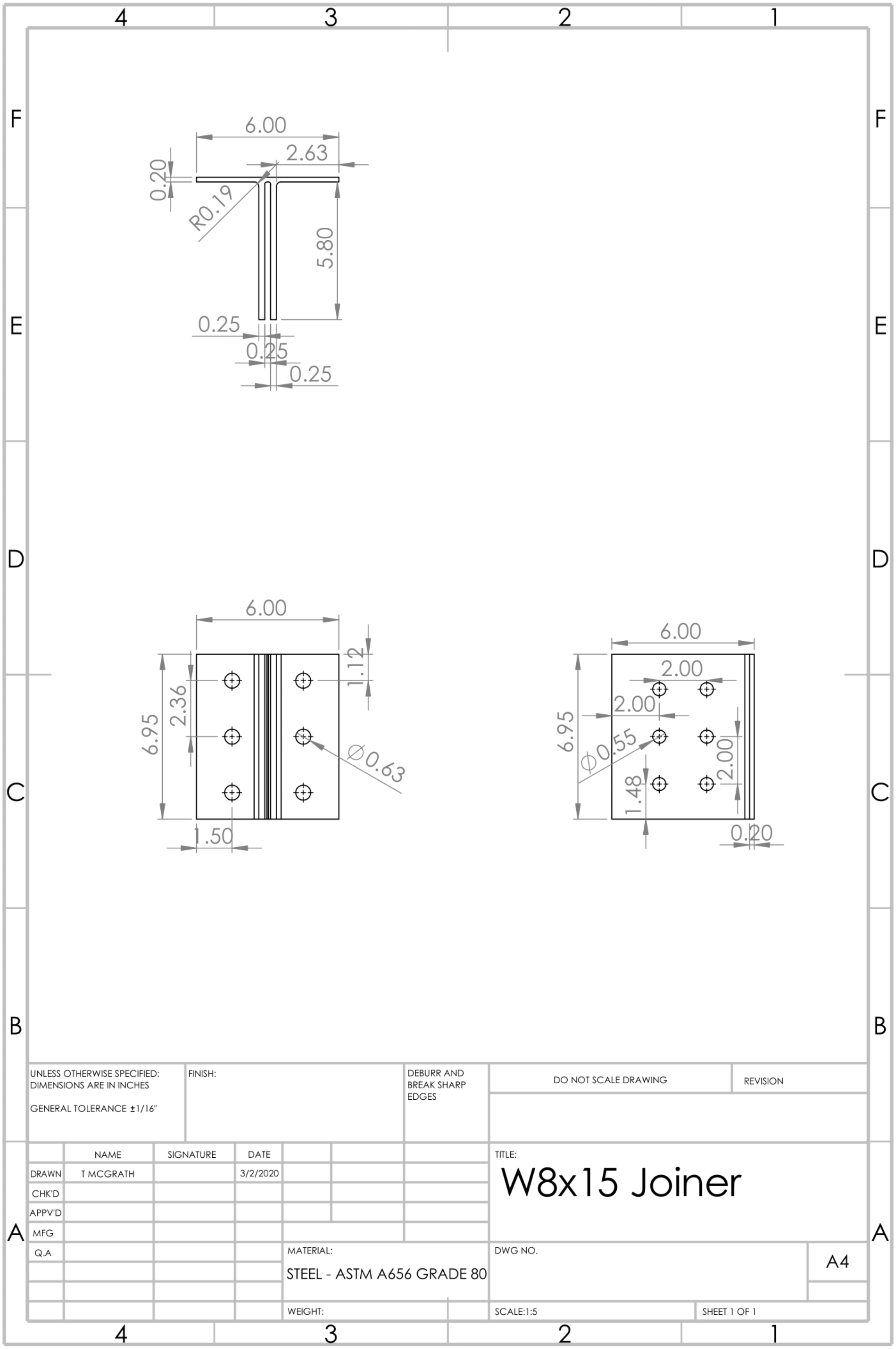
SHEET 1 OF 1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0.20
R0.19
5.80
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⌀0.63
1.50
6.00
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6.95
⌀0.55
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1.48
0.20
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
GENERAL TOLERANCE ±1/16"
FINISH:
DEBURR AND BREAK SHARP EDGES
DO NOT SCALE DRAWING
REVISION
NAME
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DATE
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T MCGRATH
3/2/2020
CHK'D
APPV'D
MFG
Q.A
TITLE:
W8x15 Joiner
MATERIAL:
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DWG NO.
A4
WEIGHT:
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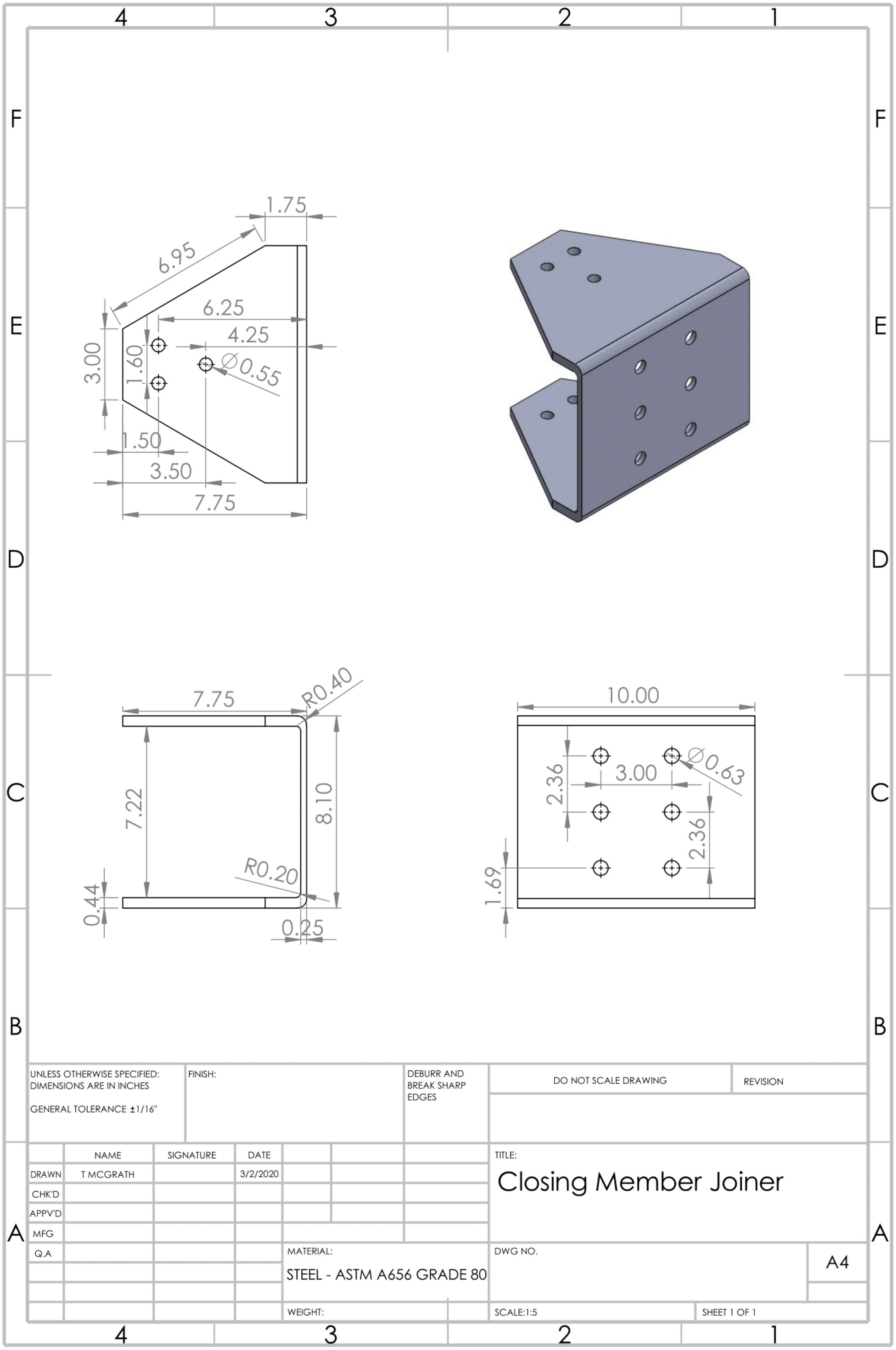
SHEET 1 OF 1



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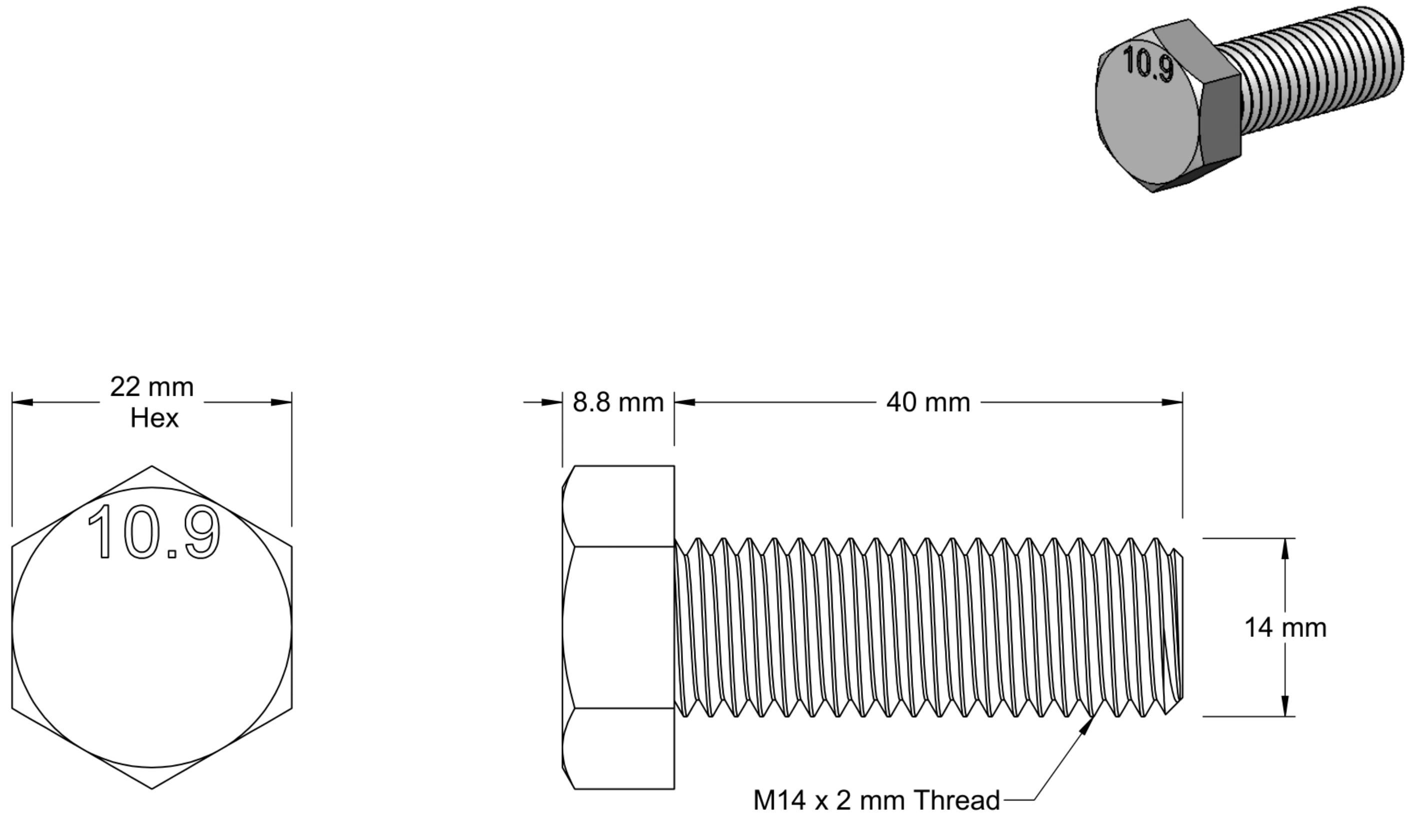
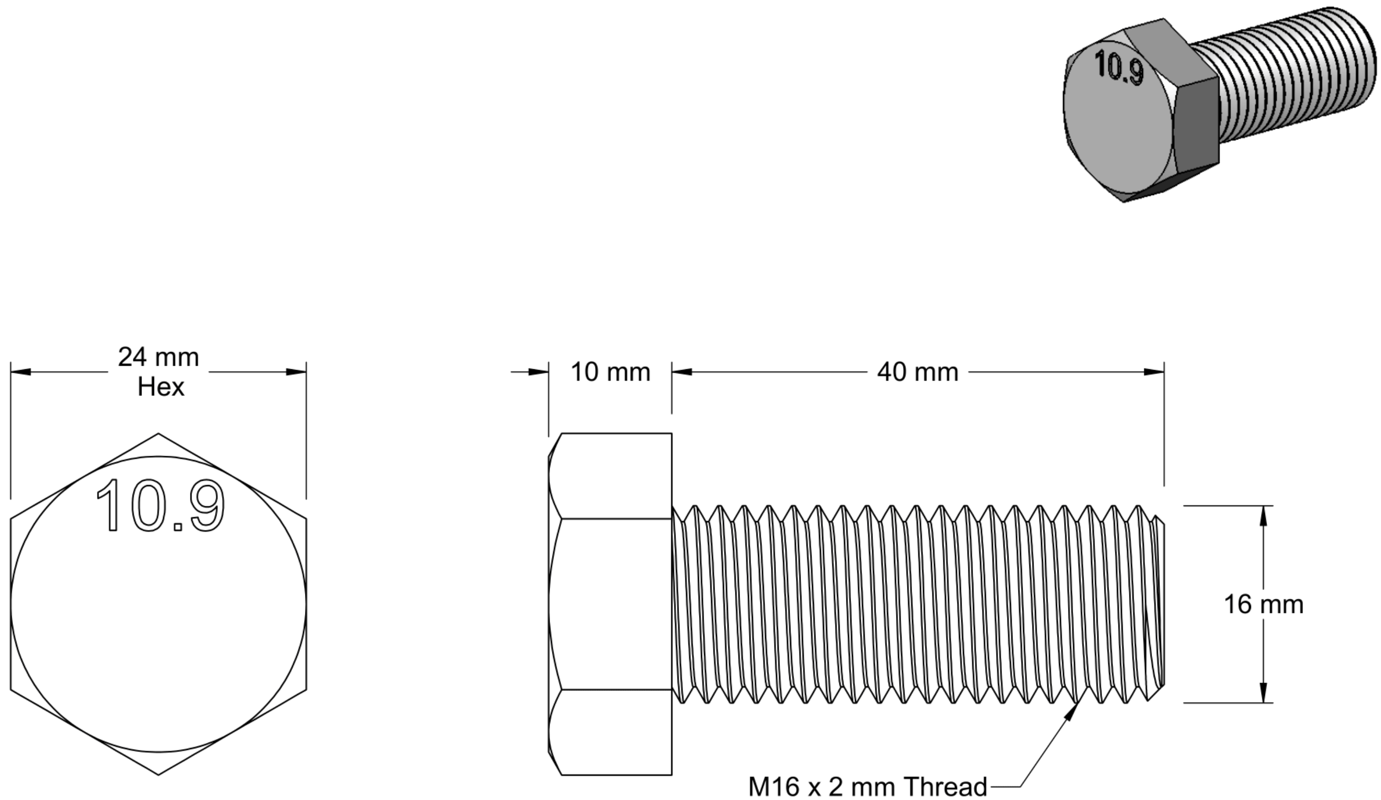


McMASTER-CARR® CAD	PART NUMBER	90854A261
http://www.mcmaster.com © 2014 McMaster-Carr Supply Company	Metric High-Strength Steel Cap Screw -Class 10.9	
Information in this drawing is provided for reference only.		



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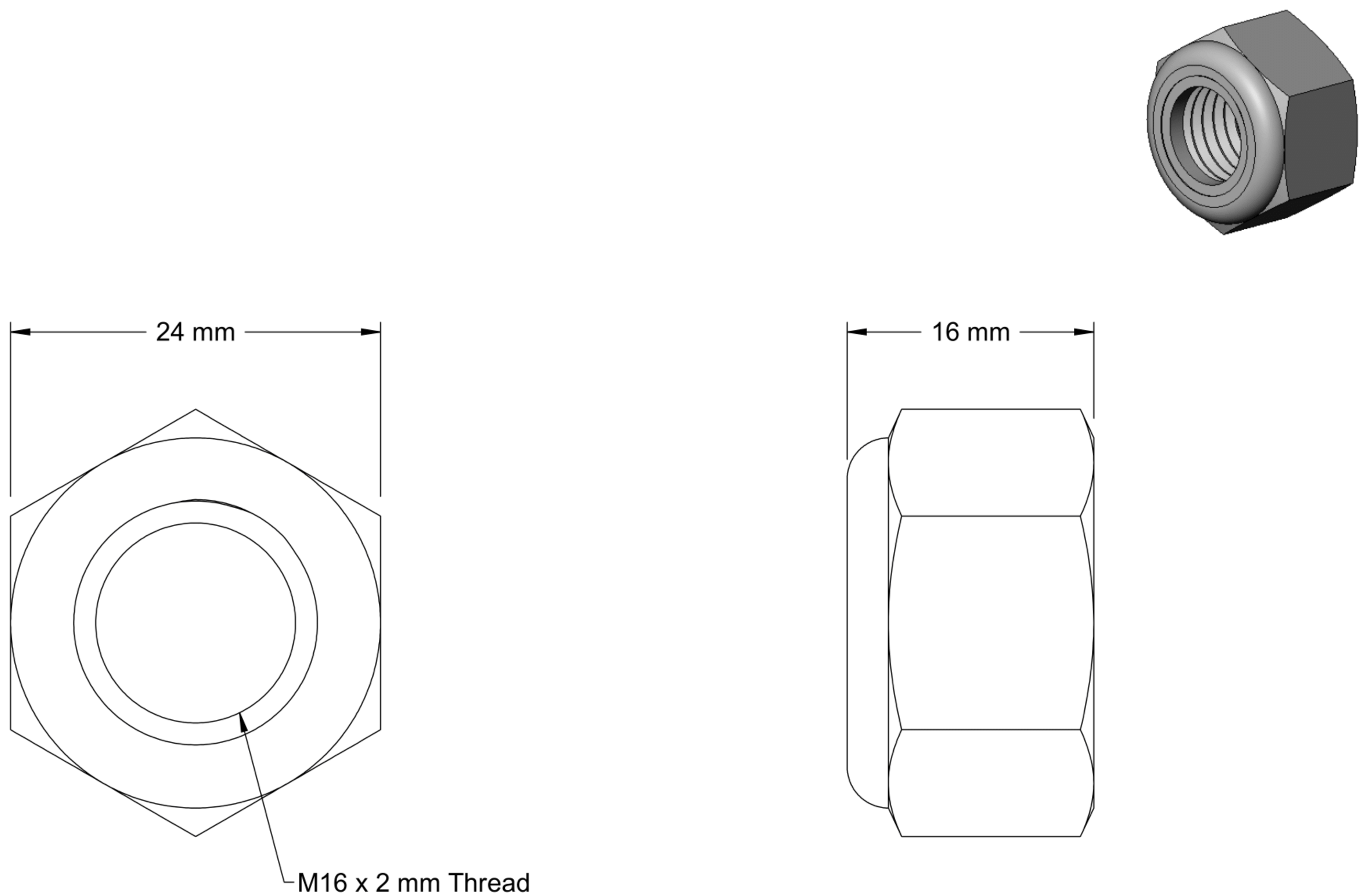
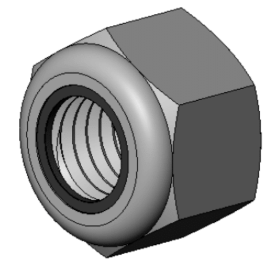
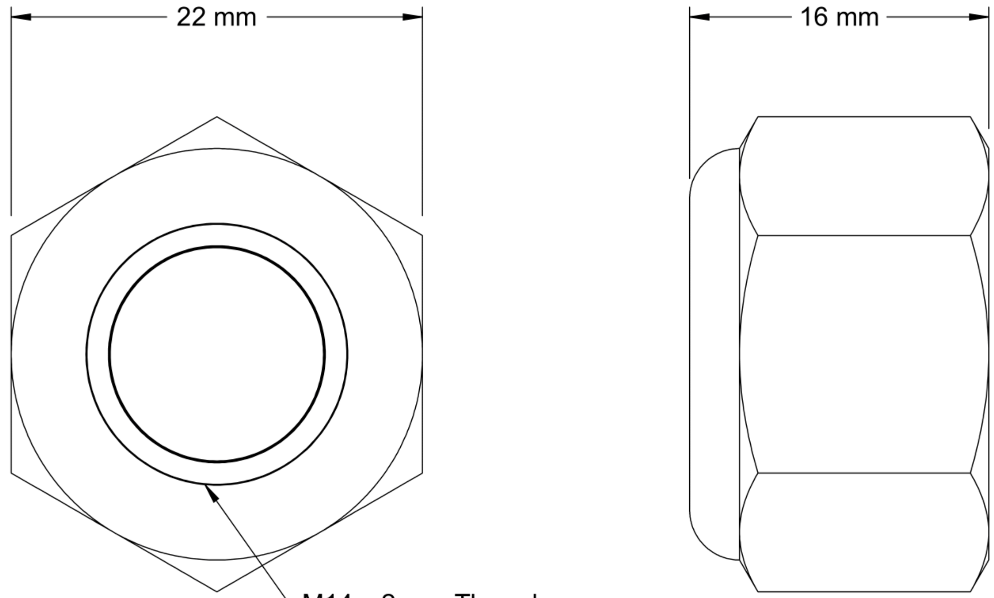
http://www.mcmaster.com © 2014 McMaster-Carr Supply Company Information in this drawing is provided for reference only.	Metric High-Strength Steel Cap Screw -Class 10.9



McMASTER-CARR® CAD	PART NUMBER	94645A250
http://www.mcmaster.com © 2019 McMaster-Carr Supply Company Information in this drawing is provided for reference only.	Metric High-Strength Steel Nylon-Insert Locknut	

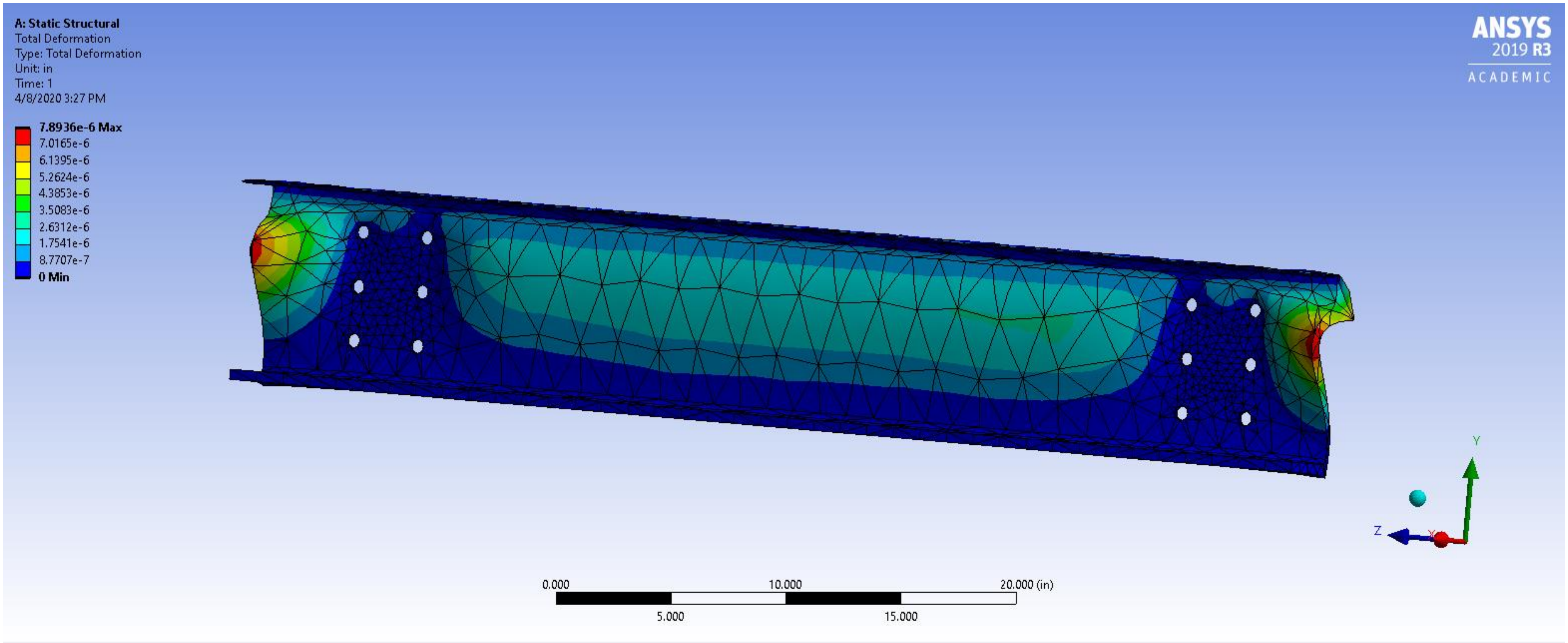




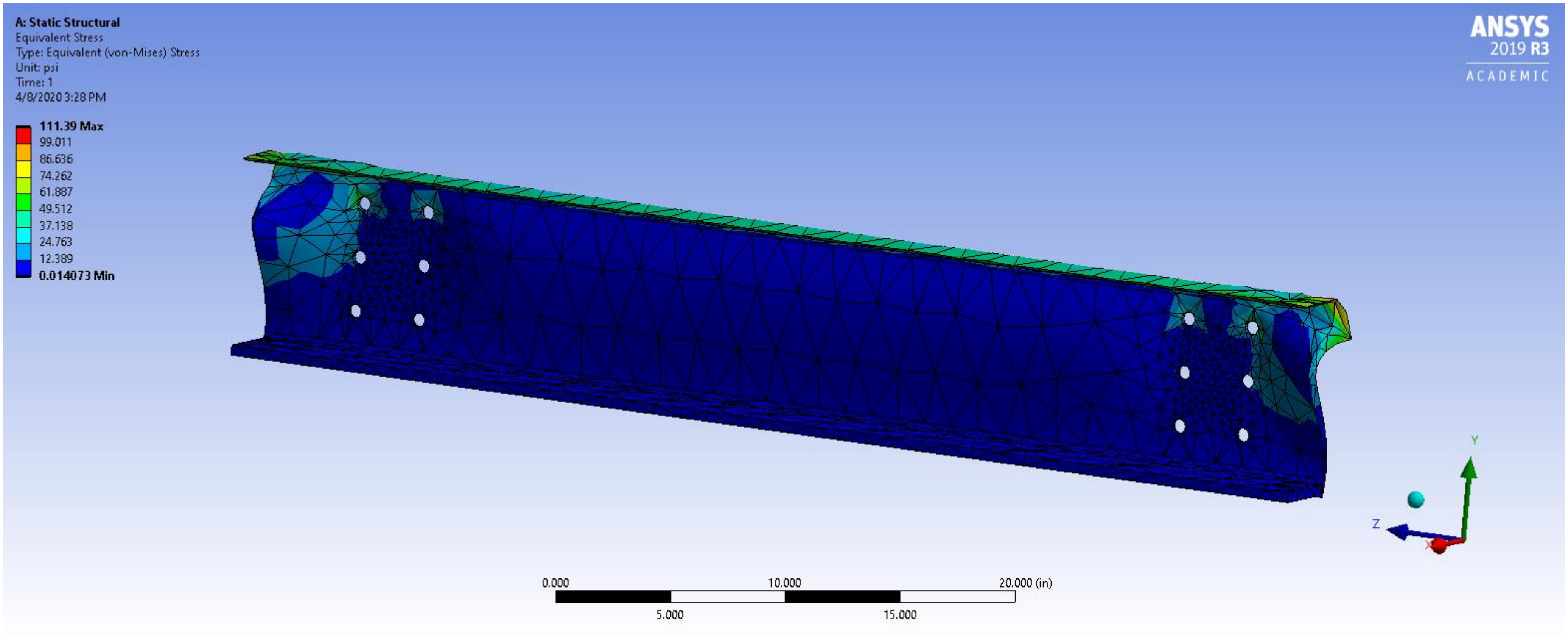
McMASTER-CARR® CAD	PART NUMBER **97260A105**
http://www.mcmaster.com © 2019 McMaster-Carr Supply Company Information in this drawing is provided for reference only.	Metric High-Strength Steel Nylon-Insert Locknut

Appendix 4, Analysis Screenshots

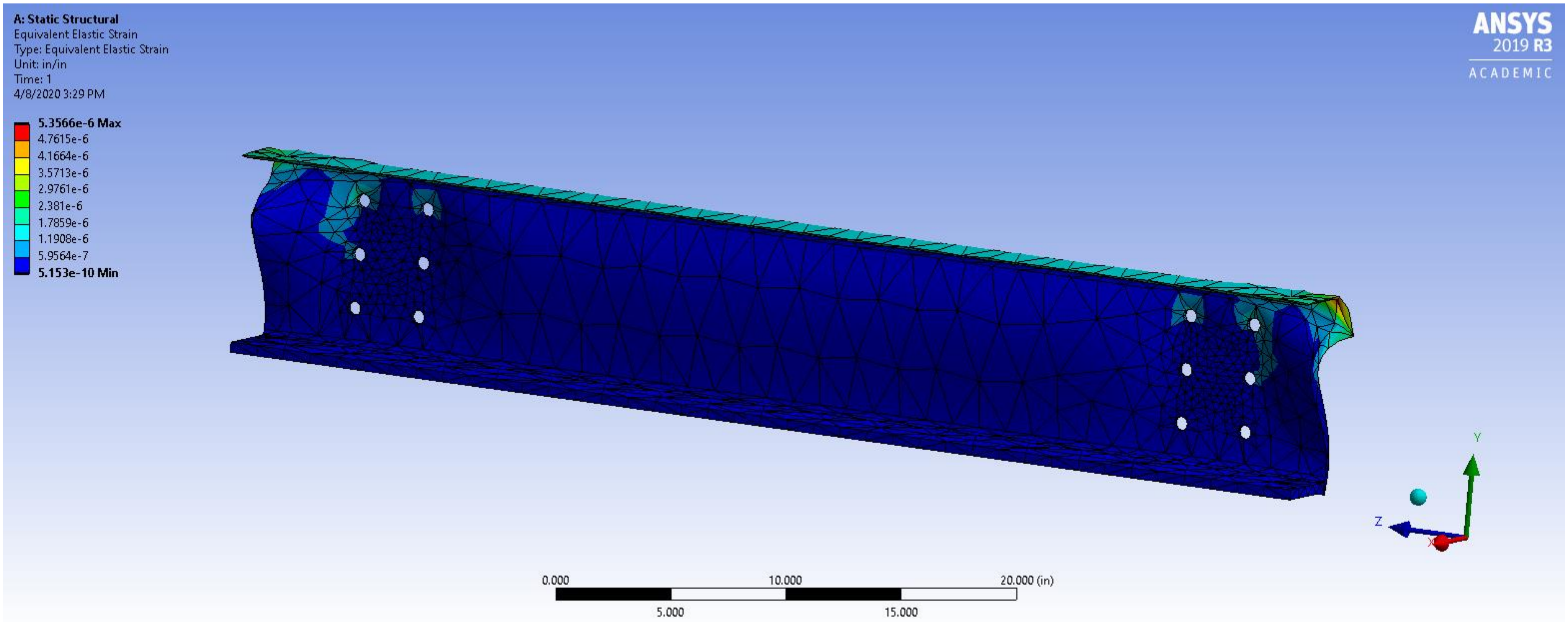
Frame Rail Deformation



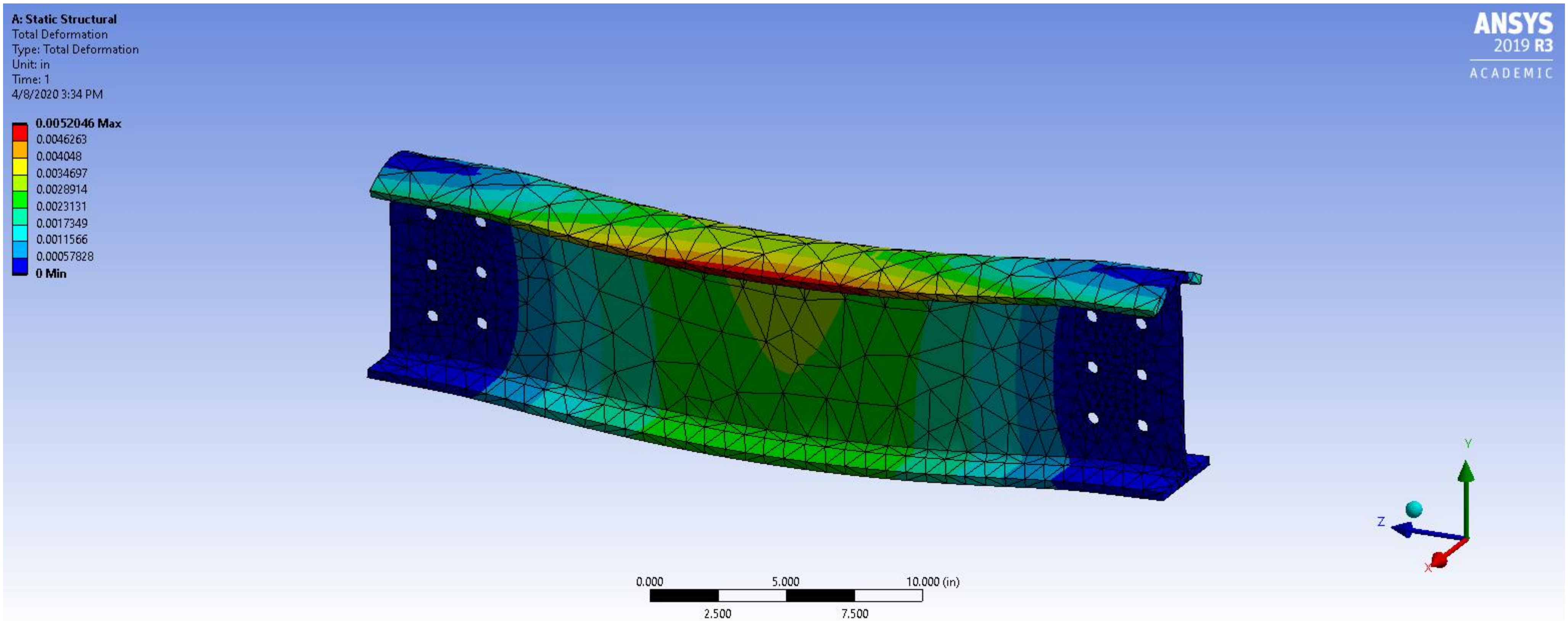
Frame Rail Stress



Frame Rail Strain



W8x15 Deformation



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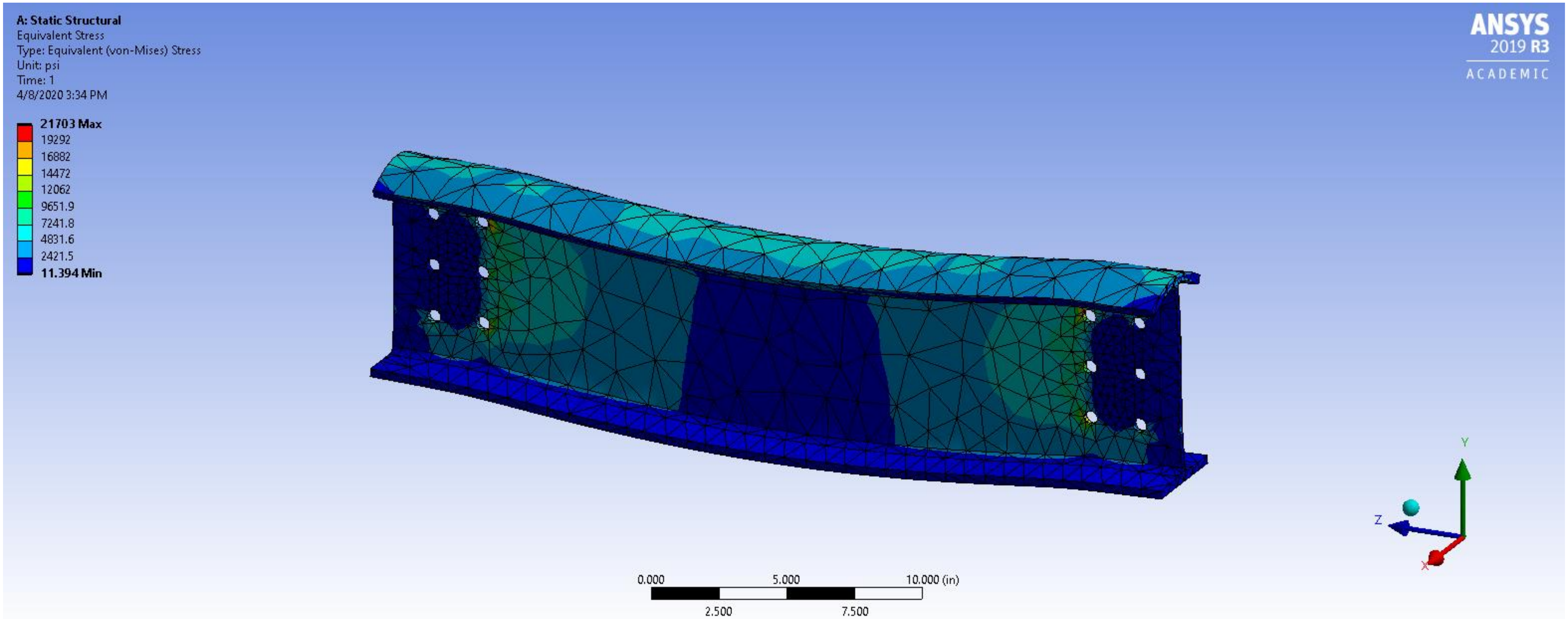
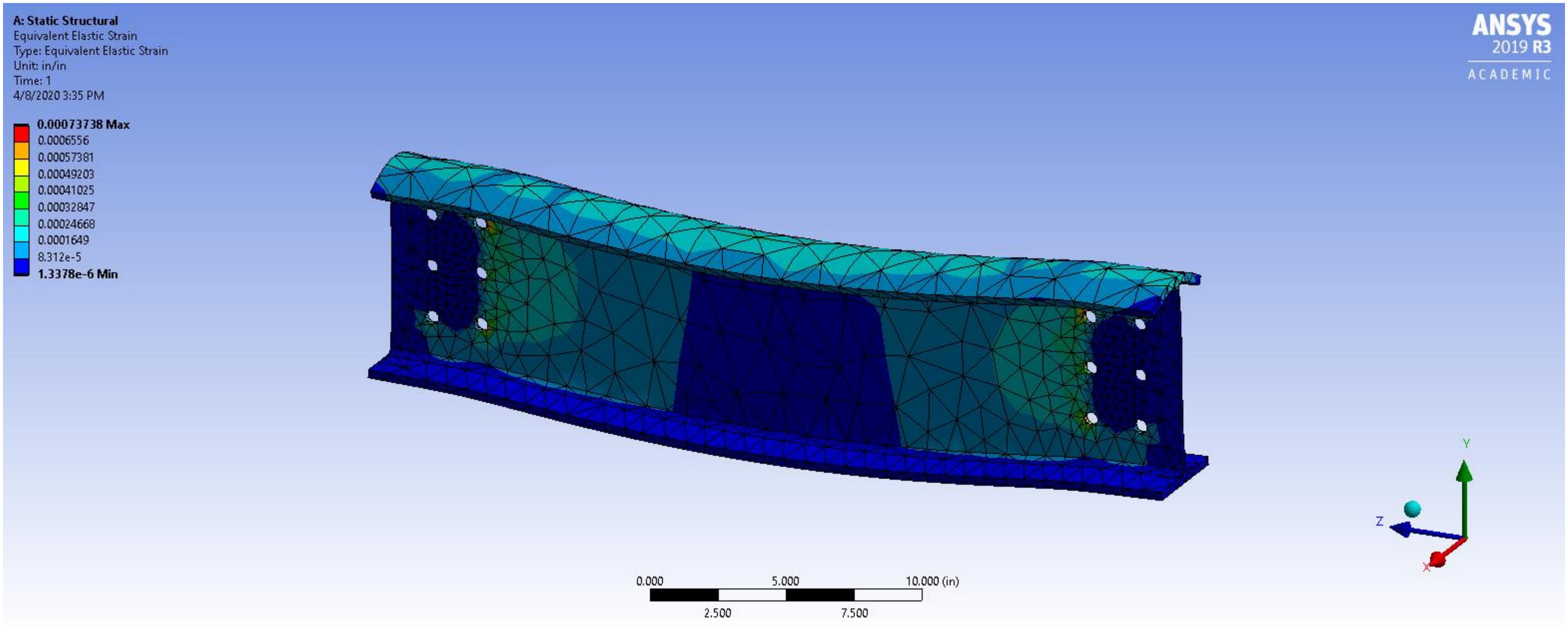
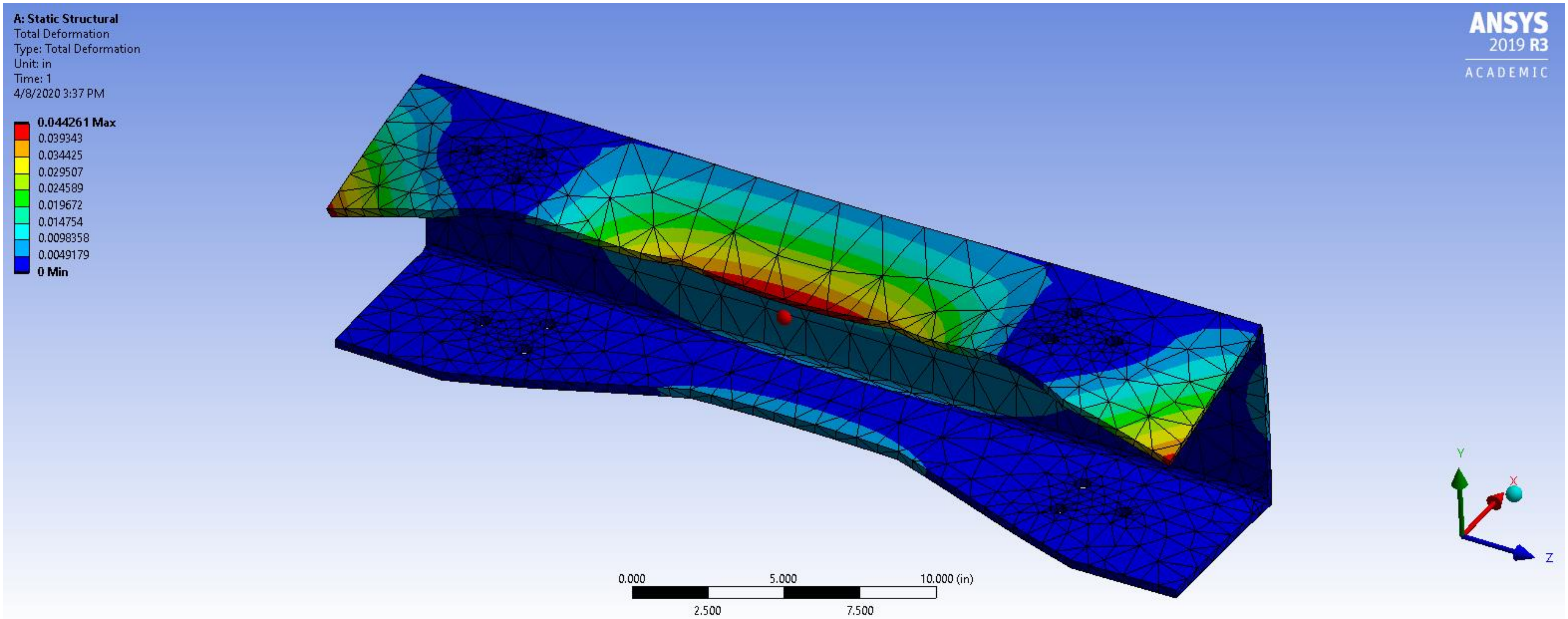


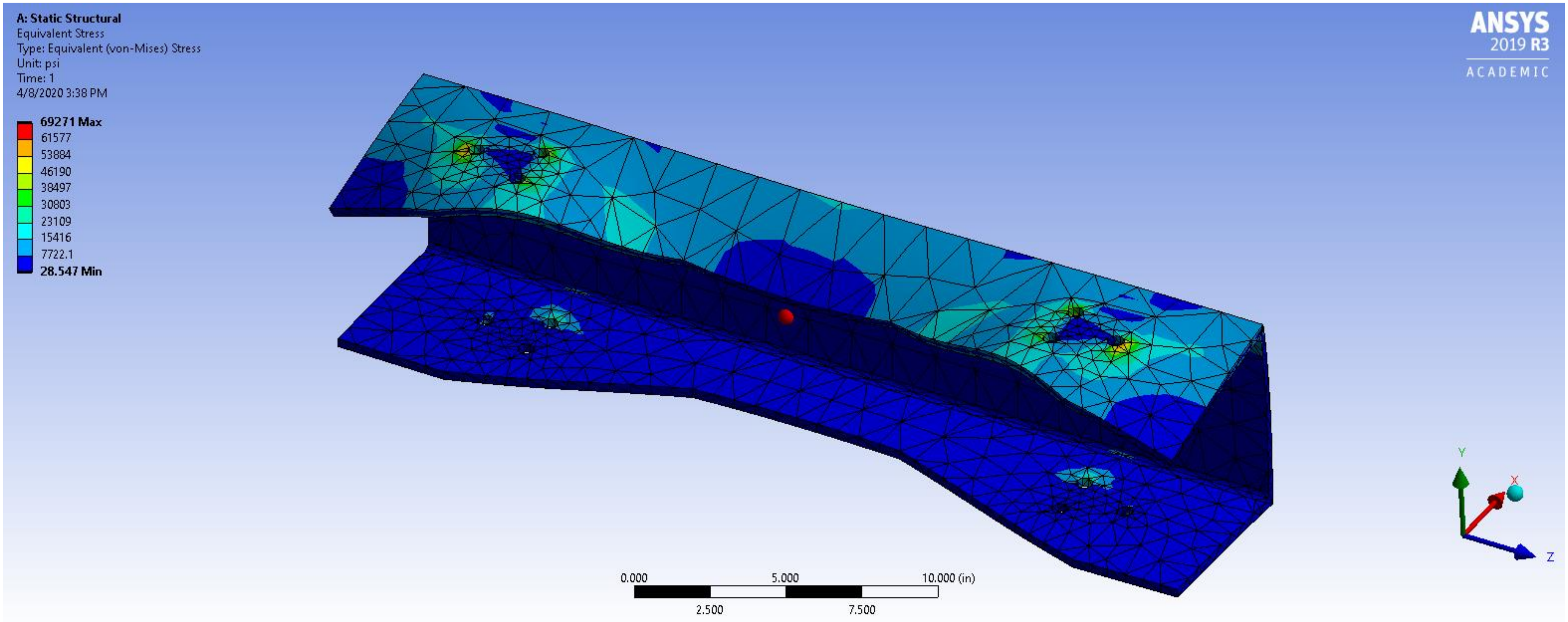
W8x15 Strain



Closing Crossmember Deformation



Closing Crossmember Stress



Closing Crossmember Strain