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Design and Analysis of a Mobile Arm Support for Patients with Degenerative Muscle Disorders

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Design and Analysis of a Mobile Arm Support for Patients with Degenerative Muscular Disorders

by

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Table of Contents

Abstract

The purpose of this project was to create Computer Aided Design (CAD) drawings and to perform a Finite Element Analysis (FEA) of a mobile arm support system for patients with degenerative muscular disorders. Two previous mobile arm support designs were produced by Mechanical and Aerospace Engineering (MAE) Capstone Design teams at The University of Alabama in Huntsville (UAH) in 2016, and have recently been re-designed and merged into a single, upgraded design. The system was designed to support upper arm shoulder and forearm movements and reduce stress on the patient's arm from normal usage. Specifically, the arm support allows for 30 degree shoulder flexion and extension, full elbow flexion and extension, and 60 degree horizontal abduction and adduction. Analysis of the system was performed to enable the determination of high stress areas and deformations caused by loads on the system. FEA allowed for evaluation of the loading limits and margins of safety of critical areas on the product. The CAD drawings were created using Solid Edge® and the analysis was performed using Patran® and Nastran®. The analysis provided stress and weight limits of the system and was used to determine the level of safety for use by patients.

Introduction

The purpose of this project was to design and analyze a Mobile Arm Support (MAS) that will support upper arm, shoulder, and forearm movements in order to encourage upper extremity use, which will allow for greater distal function and increased activity participation for a five-year-old girl with Type 2 Spinal Muscular Atrophy. [3]

Type 2 Spinal Muscular Atrophy (SMA) is a degenerative genetic condition that affects the motor neurons within the body. It causes weakness in muscles that will progressively get worse throughout the lifetime of an individual. Figure 1 shows an example of the decrease in the biceps. [3]

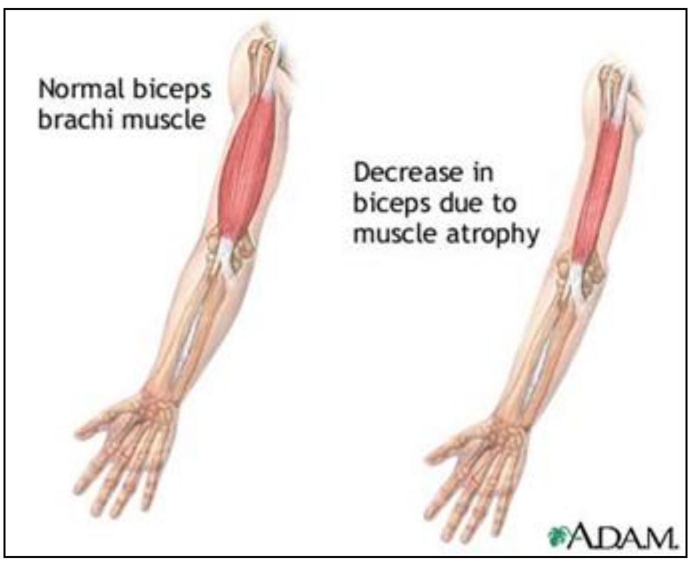

Figure 1: SMA Weakened Muscle ("Medical Encyclopedia.")

SMA is caused by a deficiency of a motor neuron known as the "Survival Motor Neuron (SMN)". Figure 2 shows an example of a nerve and muscle affected by SMA.

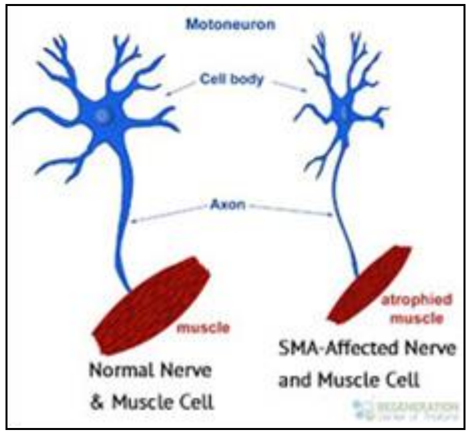

Figure 2: SMA Neuron ("Stem Cells for Spinal Muscular Atrophy SMA Therapy.")

The disease will typically have more of an effect on the muscles closest to the center of the body, which can cause difficulty with breathing. There are four types of SMA with Type 1, onset as an infant, being the worst and Type 4, onset as an adult, being the mildest form. The earlier the onset of the disease, the greater the impact it will have. [3]

A Mobile Arm Support is "a forearm support device that enables people with upper extremity disabilities to fulfill some activities of daily living" ("Mobile Arm Support"). An arm support can allow an individual to move more freely without expending as much energy as is required for unassisted motion. This type of device would be ideal for the patient because it would allow her to participate in more daily activities without wearing herself out as quickly. [3]

Computer Aided Design, CAD, is "the use of computer technology for design and design documentation." [4] CAD models provide images of 3D devices and their individual components. The CAD software used to model the arm support system for this project was Solid Edge®.

Stress analysis is a method of analyzing a system and its components to determine stresses, strains, and deflections on the system from the given loading conditions. One common form of stress analysis is the Finite Element Analysis (FEA). FEA is a method of breaking up a structure into a finite number of elements and nodes and analyzing the effects on the loads on each of the elements. The stresses across all the elements are used to represent the stresses on the model as a whole. The software used to perform a FEA for this project was Patran® and Nastran®. Patran® can be used for pre- and post-processing. It can be used to first create the model and then to output the results into a user-friendly form after they have been analyzed in Nastran®.

Chapter 1: Mobile Arm Support Design

The mobile arm support that was analyzed for this project was designed based on two previous models that were produced by Capstone Design teams at UAH. One design, the Arm Super't, was a freestanding lateral arm device that used a series of springs to reduce the forces on the arm [3]. The other design was an over hanging device that fit around the patients chair and held the arm from above to reduced the effects of gravity on the patients arms. The new model uses a clamp to attach it to a tabletop or other surface rather than sitting on the floor. It utilizes a dog grooming arm design as the main structure. A CAD model and drawing of the support designed in Solid Edge® can be seen in Figures 3 and 4.

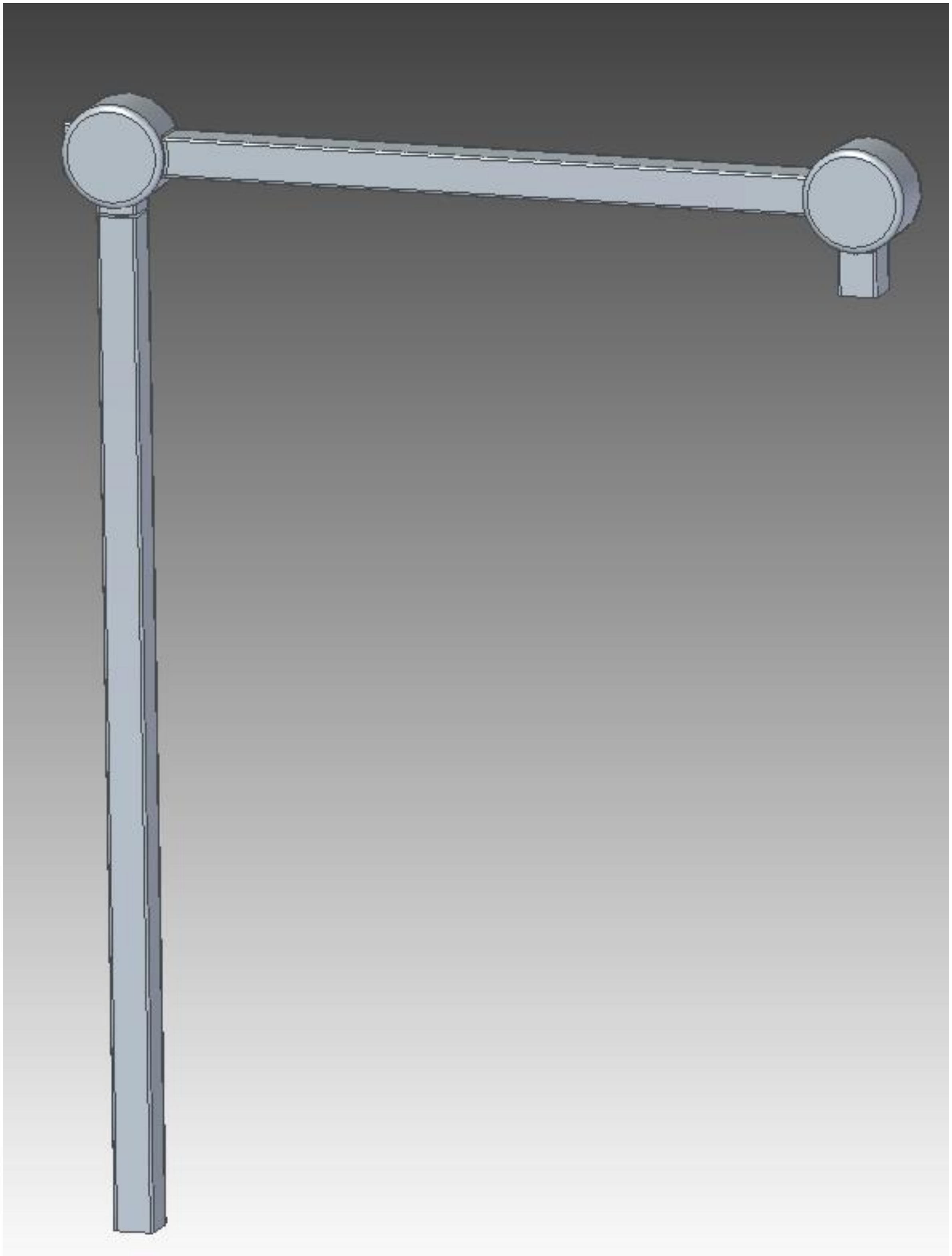

Figure 3: Mobile Arm Support Model

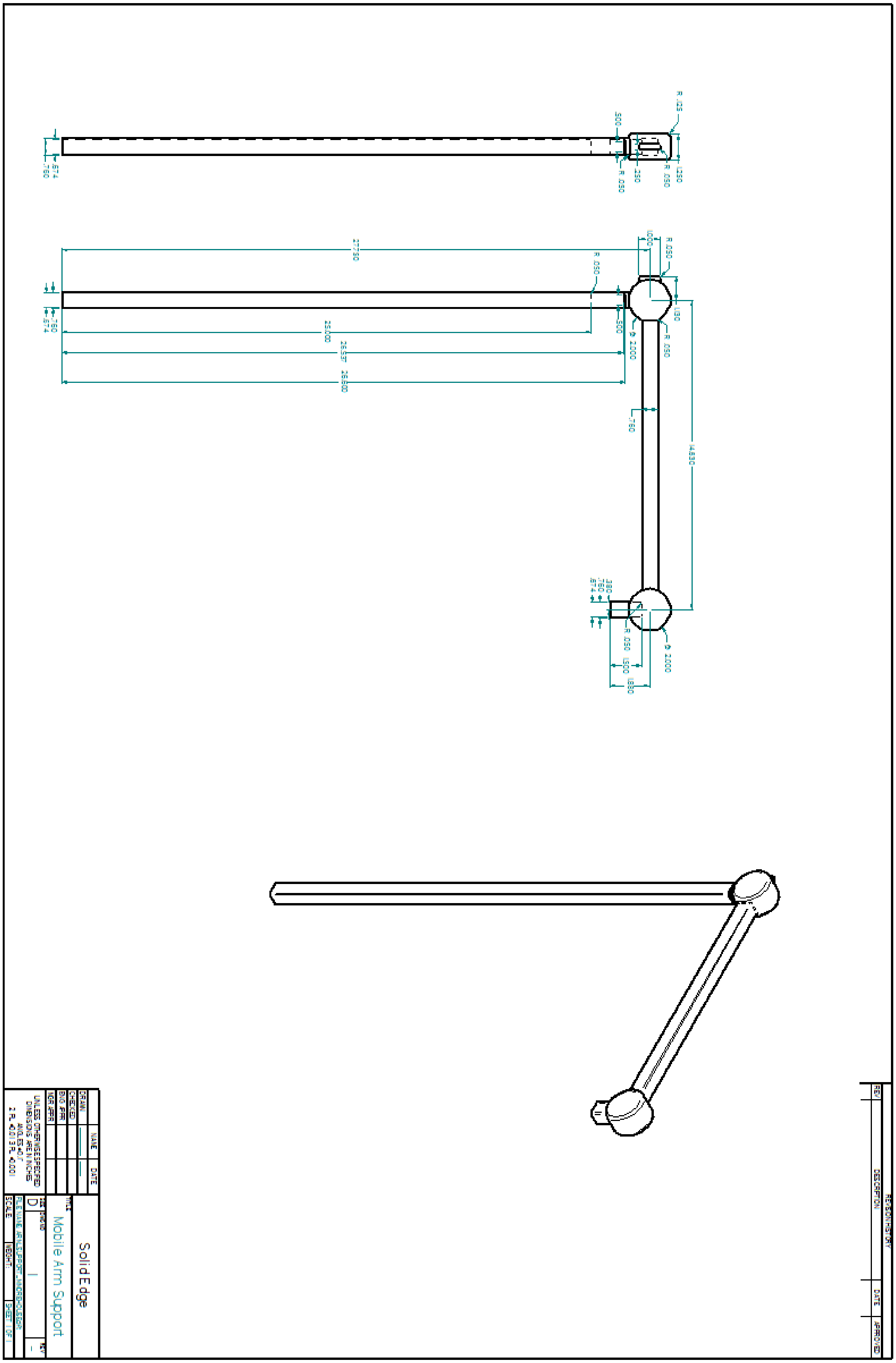

Figure 4: CAD Drawing

Chapter 2: Analysis of the Mobile Arm Support

The arm support was modeled in Patran® using 1D elements and assigning beam properties to them. The model utilized eight nodes and seven bar elements. A force load was applied to the node at the end of the model to represent the weight of the patients arm. The weight of a persons arm is on average approximately 5.3% of their body weight [1]. A chart on average body weights by age can be found in Appendix A [2]. The average weight for a 5-year-old girl is 40 – 44 pounds. So for an average five year old girl the weight of her arm would be approximately 2.23 pounds. The system was also analyzed at the maximum loading weight of 10 pounds. The base of the model was fixed where the clamp would attach the beam to the table and the node that attached the horizontal portion of the arm support to the vertical portion had all translations and rotations fixed except the y-rotations. This would allow the device to move with the patient. The 1D model can be seen in Figure 5 below. Each element was then assigned beam properties. The vertical and horizontal bars were assigned square tube properties and the elements at the joints were assigned solid cylindrical properties. An image of the 3D model can be seen in Figure 6. The material used for the device was aluminum. After creating the model and pre-processing, the analysis was run through Nastran®. A copy of the output file from Nastran® (f06 files) for both loading conditions can be found in Appendix B. The f06 file contains all the analysis data and results. Next, the analysis was read back into Patran® and plots were generated showing the maximum stress and deformation locations and values. The plots can be seen in Appendix C.

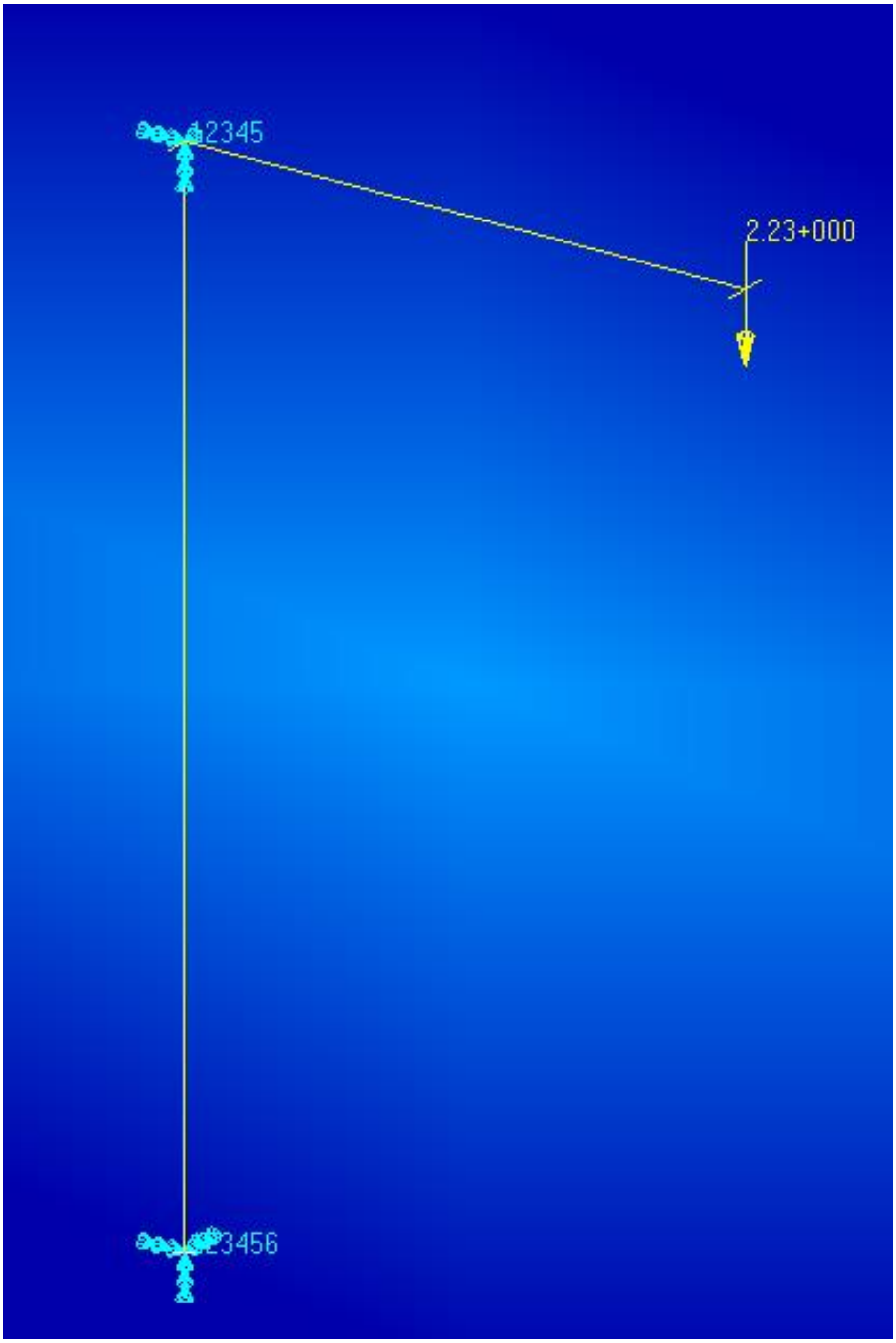

Figure 5: 1D Model and Loading

Figure 6: 3D Model

Another useful calculation in analyzing a system is a margin of safety. The margin of safety is a measure of the load capacity of a system beyond its actual loading. In other words it measures how much stronger the system is than it needs to be. The margin of safety is a ratio between the ultimate stress and the actual stress of a system. After running a stress analysis, the margin of safety can be computed using the maximum stress on the system and the known ultimate stress of the material used.

Chapter 3: Results

Two load cases were analyzed for this project, one with the current loading condition of the system and one with the intended maximum loading of the system. The results of the analysis on the system can be seen in Table 1 below. For the current load case, 2.23 lbs, the maximum stress on the system was located at the joint between the vertical and horizontal beams and had a value of 1,119 psi. The maximum deflection was located at the end of the support where the arm weight was applied and had a value of 0.0453 in and the margin of safety was 24.13. For the maximum load case, 10 lbs, the maximum stress was at the same location as the current load case with a value of 5,240 psi. The maximum deflection was again at the end of the support where the load was applied and had a value of 0.212 in. The margin of safety for the 10 lb load case was 5.15.

Table 1: Summary of Results

Load/Results	**Max Stress (psi)**	**Max Deformation (in)**	**Yield Stress (psi)**	**Ultimate Stress (psi)**	**Margin of Safety (for yield stress)**	**Margin of Safety (for ultimate stress)**
2.23 (lbs)	1,119	0.0453	21000	27000	18.77	24.13
10 (lbs)	5,240	0.212	21000	27000	4.01	5.15

The margin of safety is very similar to the factor of safety. The factor of safety (FoS) is the system's load capacity beyond the actual or expected loading, in other words how much stronger the system is than it needs to be. It is used to account for imperfections in materials, unexpected stresses in the system, flaws in the assembly, or other unforeseen circumstances. The margin of safety is the system's load capacity at the largest load the device should see, in other words how many more loads of the same force it can withstand before failing. Most designs attempt to incorporate a factor of safety between 2.0 and 2.5. Buildings typically have a FoS of 2.0. Cars and aircraft typically have a FoS of 3.0 and 1.2 - 3.0, respectively. A value of 4 or above is incorporated when failure could result in serious injury or death.

Conclusion

Through careful modeling and analysis of the arm support system, the level of safety of the device was able to be evaluated. The high stress area of the device lies at the joint where the horizontal and vertical beams meet. At the highest intended loading of the system, the stress value still maintains a margin of safety of more than 5. The amount of vertical deflection at this loading would be about 0.2 in. With this level of a margin of safety and only force loads due to arm weight the device will be safe to use on patients. Some suggestions to improve future designs could include lowering the factor of safety incorporated to help reduce the cost and making the joint a more gradual curve rather than a 90 degree angle to reduce the stress at that location. Some important things that can be learned from this analysis include recognizing how sharp angles can cause areas of high stress concentration and that analysis and testing is a very important factor when human well-being is involved.

Reference List

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2. "Average Height to Weight Chart - Babies to Teenagers." *Disabled World Towards Tomorrow*. Disabled World, 2004. Web. 28 Apr. 2017. <https://www.disabled-world.com/artman/publish/height-weight-teens.shtml>.

3. Morehouse, Moriah, Taylor Reed, Jonathan Bosse, Thomas Robertson, and Blake Muzny. *Arm Super't*. Rep. Huntsville, AL: U of Alabama in Huntsville, 2016. Print.

4. "CAD Software | 2D And 3D Computer-Aided Design | Autodesk." Autodesk 2D and 3D Design and Engineering Software. Autodesk, 2017. Web. 30 Apr. 2017. <http://www.autodesk.com/solutions/cad-software>.

Appendices

Appendix A: Average Body Weight by Age

Height to Weight Ratio for Male Babies		
Age	Weight	Length
0 mth	7.4 lb (3.3 kg)	19.6" (49.8 cm)
1 mth	9.8 lb (4.4 kg)	21.6" (54.8 cm)
2 mth	12.3 lb (5.6 kg)	23.0" (58.4 cm)
3 mth	14.1 lb (6.4 kg)	24.2" (61.4 cm)
4 mth	15.4 lb (7 kg)	25.2" (64 cm)
5 mth	16.6 lb (7.5 kg)	26.0" (66 cm)
6 mth	17.5 lb (7.9 kg)	26.6" (67.5 cm)
7 mth	18.3 lb (8.3 kg)	27.2" (69 cm)
8 yrs	19.0 lb (8.6 kg)	27.8" (70.6 cm)
9 mth	19.6 lb (8.9 kg)	28.3" (71.8 cm)
10 mth	20.1 lb (9.1 kg)	28.8" (73.1 cm)
11 mth	20.8 lb (9.4 kg)	29.3" (74.4 cm)

Height to Weight Ratio for Male Toddlers		
Age	Weight	Length
12 mth	21.3 lb (9.6 kg)	29.8" (75.7 cm)
13 mth	21.8 lb (9.9 kg)	30.3" (76.9 cm)
14 mth	22.3 lb (10.1 kg)	30.7" (77.9 cm)
15 mth	22.7 lb (10.3 kg)	31.2" (79.2 cm)
16 mth	23.2 lb (10.5 kg)	31.6" (80.2 cm)
17 mth	23.7 lb (10.7 kg)	32.0" (81.2 cm)
18 mth	24.1 lb (10.9 kg)	32.4" (82.2 cm)
19 mth	24.6 lb (11.2 kg)	32.8" (83.3 cm)
20 mth	25.0 lb (11.3 kg)	33.1" (84 cm)
21 mth	25.5 lb (11.5 kg)	33.5" (85 cm)
22 mth	25.9 lb (11.7 kg)	33.9" (86.1 cm)
23 mth	26.3 lb (11.9 kg)	34.2" (86.8 cm)

Height to Weight Ratio for Male Children		
Age	Weight	Height
2 yrs	27.5 lb (12.5 kg)	34.2" (86.8 cm)
3 yrs	31.0 lb (14.0 kg)	37.5" (95.2 cm)
4 yrs	36.0 lb (16.3 kg)	40.3" (102.3 cm)
5 yrs	40.5 lb (18.4 kg)	43.0" (109.2 cm)
6 yrs	45.5 lb (20.6 kg)	45.5" (115.5 cm)
7 yrs	50.5 lb (22.9 kg)	48.0" (121.9 cm)
8 yrs	56.5 lb (25.6 kg)	50.4" (128 cm)
9 yrs	63.0 lb (28.6 kg)	52.5" (133.3 cm)
10 yrs	70.5 lb (32 kg)	54.5" (138.4 cm)
11 yrs	78.5 lb (35.6 kg)	56.5" (143.5 cm)
12 yrs	88.0 lb (39.9 kg)	58.7" (149.1 cm)

Height to Weight Ratio for Male Teenagers		
Age	Weight	Height
13 yrs	100.0 lb (45.3 kg)	61.5" (156.2 cm)
14 yrs	112.0 lb (50.8 kg)	64.5" (163.8 cm)
15 yrs	123.5 lb (56.0 kg)	67.0" (170.1 cm)
16 yrs	134.0 lb (60.8 kg)	68.3" (173.4 cm)
17 yrs	142.0 lb (64.4 kg)	69.0" (175.2 cm)
18 yrs	147.5 lb (66.9 kg)	69.2" (175.7 cm)
19 yrs	152.0 lb (68.9 kg)	69.5" (176.5 cm)
20 yrs	155.0 lb (70.3 kg)	69.7" (177 cm)

Height to Weight Ratio for Female Babies		
Age	Weight	Length
0 mth	7.3 lb (3.3 kg)	19.4" (49.2 cm)
1 mth	9.6 lb (4.3 kg)	21.2" (53.8 cm)
2 mth	11.7 lb (5.3 kg)	22.1" (56.1 cm)
3 mth	13.3 lb (6.0 kg)	23.6" (59.9 cm)
4 mth	14.6 lb (6.6 kg)	24.5" (62.2 cm)
5 mth	15.8 lb (7.1 kg)	25.3" (64.2 cm)
6 mth	16.6 lb (7.5 kg)	25.9" (64.1 cm)
7 mth	17.4 lb (7.9 kg)	26.5" (67.3 cm)
8 mth	18.1 lb (8.2 kg)	27.1" (68.8 cm)
9 mth	18.8 lb (8.5 kg)	27.6" (70.1 cm)
10 mth	19.4 lb (8.8 kg)	28.2" (71.6 cm)
11 mth	19.9 lb (9.0 kg)	28.7" (72.8 cm)

Height to Weight Ratio for Female Toddlers		
Age	Weight	Length
12 mth	20.4 lb (9.2 kg)	29.2" (74.1 cm)
13 mth	21.0 lb (9.5 kg)	29.6" (75.1 cm)
14 mth	21.5 lb (9.7 kg)	30.1" (76.4 cm)
15 mth	22.0 lb (9.9 kg)	30.6" (77.7 cm)
16 mth	22.5 lb (10.2 kg)	30.9" (78.4 cm)
17 mth	23.0 lb (10.4 kg)	31.4" (79.7 cm)
18 mth	23.4 lb (10.6 kg)	31.8" (80.7 cm)
19 mth	23.9 lb (10.8 kg)	32.2" (81.7 cm)
20 mth	24.4 lb (11 kg)	32.6" (82.8 cm)
21 mth	24.9 lb (11.3 kg)	32.9" (83.5 cm)
22 mth	25.4 lb (11.5 kg)	33.4" (84.8 cm)
23 mth	25.9 lb (11.7 kg)	33.5" (85.1 cm)

Height to Weight Ratio for Female Children		
Age	Weight	Height
2 yrs	26.5 lb (12.0 kg)	33.7" (85.5 cm)
3 yrs	31.5 lb (14.2 kg)	37.0" (94 cm)
4 yrs	34.0 lb (15.4 kg)	39.5" (100.3 cm)
5 yrs	39.5 lb (17.9 kg)	42.5" (107.9 cm)
6 yrs	44.0 lb (19.9 kg)	45.5" (115.5 cm)
7 yrs	49.5 lb (22.4 kg)	47.7" (121.1 cm)
8 yrs	57.0 lb (25.8 kg)	50.5" (128.2 cm)
9 yrs	62.0 lb (28.1 kg)	52.5" (133.3 cm)
10 yrs	70.5 lb (31.9 kg)	54.5" (138.4 cm)
11 yrs	81.5 lb (36.9 kg)	56.7" (144 cm)
12 yrs	91.5 lb (41.5 kg)	59.0" (149.8 cm)

Height to Weight Ratio for Female Teenagers		
Age	Weight	Height
13 yrs	101.0 lb (45.8 kg)	61.7" (156.7 cm)
14 yrs	105.0 lb (47.6 kg)	62.5" (158.7 cm)
15 yrs	115.0 lb (52.1 kg)	62.9" (159.7 cm)
16 yrs	118.0 lb (53.5 kg)	64.0" (162.5 cm)
17 yrs	120.0 lb (54.4 kg)	64.0" (162.5 cm)
18 yrs	125.0 lb (56.7 kg)	64.2" (163 cm)
19 yrs	126.0 lb (57.1 kg)	64.2" (163 cm)
20 yrs	128.0 lb (58.0 kg)	64.3" (163.3 cm)

Figure 7: Height to Weight Ratios

https://www.disabled-world.com/artman/publish/height-weight-teens.shtml

Appendix B: f06 Nastran® Output Files

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                  Warning: This computer program is protected by copyright law and international treaties.
                Unauthorized use, reproduction or distribution of this computer program, or any portion of it, may
                                       result in severe civil and criminal penalties.
                     Copyright (C) 2014 MSC Software Corporation and its licensors. All rights reserved.

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1 News file -  (March 25, 2014):

               Welcome to MSC Nastran 2013.1.1


   The MSC Nastran 2013.1.1 contains defect corrections associated with the
   2013.1 release. Some of these defects are significant in that they result
   in erroneous results. The list of defects is available in the Fixed Defect
   file.
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The Release Guide is available online and in the installation documentation
  sub-directory.
Additional information can be found at the MSC Nastran Product Support page:

   http://simcompanion.mscsoftware.com


The support page provides links to these valuable information:
   * A searchable Knowledge Base containing examples and answers to thousands
     of frequently asked questions written by MSC Software subject-matter
     experts.
   * Peer-to-peer Discussion Forums enabling you to post questions for your
     MSC Software products and receive answers from other users worldwide.
   * A list of known issues with the product and any workarounds.
   * Instructions on how to contact technical support
   * A mechanism for sending us product feedback or enhancement requests.
   * Hardware and software requirements.
   * Examples and Tutorials
   * and much more.

For information on training, please visit our Training web site

   http://www.mscsoftware.com/Contents/Services/Training/

MSC Nastran brings powerful new features and enhancements for engineering
solutions.

The highlights for the MSC Nastran 2013.1 release include:

 ò   HPC
    û   ACMS Performance Improvements which reduces Wall time.

 ò   Dynamics
    û   New Axisymmetric Rotor Dynamics model
    -   Rotors may be included in external Superelements

 ò   Advanced Nonlinear Implicit (SOL 400)
    - Stress recovery with advanced elements for perturbation load cases.
    -   Improve Contact User Interface Improvements to make input file more
      readable and reduce the amount of input for models with many contact
1     bodies.
    - Sequential thermal-mechanical analysis for 3-D thermal shell elements
    - Interface to Digimat for Advanced Composites


 ò   Explicit Dynamics (SOL 700)
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     û Support for User Subroutines

   ò  Ease of Use
      - User Defined Services (UDS) Enhancements to simplify usage.
      - Extension to Monitor Points to allow results in local coordinate system



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               FY       ----      -1.044500E+01     ----       0.000000E+00     ----      -1.462300E+02
               FZ       ----          ----       0.000000E+00  0.000000E+00  0.000000E+00     ----
               MX       ----          ----          ----       0.000000E+00     ----          ----
               MY       ----          ----          ----          ----       0.000000E+00     ----
               MZ       ----          ----          ----          ----          ----       0.000000E+00
             TOTALS  0.000000E+00 -1.044500E+01  0.000000E+00  0.000000E+00  0.000000E+00 -1.462300E+02
0        2     FX    0.000000E+00     ----          ----          ----       0.000000E+00  0.000000E+00
               FY       ----      -2.230000E+00     ----       0.000000E+00     ----      -3.122000E+01
               FZ       ----          ----       0.000000E+00  0.000000E+00  0.000000E+00     ----
               MX       ----          ----          ----       0.000000E+00     ----          ----
               MY       ----          ----          ----          ----       0.000000E+00     ----
               MZ       ----          ----          ----          ----          ----       0.000000E+00
             TOTALS  0.000000E+00 -2.230000E+00  0.000000E+00  0.000000E+00  0.000000E+00 -3.122000E+01
0        3     FX    0.000000E+00     ----          ----          ----       0.000000E+00  0.000000E+00
               FY       ----      -8.215000E+00     ----       0.000000E+00     ----      -1.150100E+02
               FZ       ----          ----       0.000000E+00  0.000000E+00  0.000000E+00     ----
               MX       ----          ----          ----       0.000000E+00     ----          ----
               MY       ----          ----          ----          ----       0.000000E+00     ----
               MZ       ----          ----          ----          ----          ----       0.000000E+00
             TOTALS  0.000000E+00 -8.215000E+00  0.000000E+00  0.000000E+00  0.000000E+00 -1.150100E+02

 *** SYSTEM INFORMATION MESSAGE 4159 (DFMSA)
     THE DECOMPOSITION OF KLL      YIELDS A MAXIMUM MATRIX-TO-FACTOR-DIAGONAL RATIO OF    2.467855E+05
1    MSC.NASTRAN JOB CREATED ON 28-APR-17 AT 20:33:53                        APRIL  28, 2017  MSC Nastran  3/14/14
PAGE     6

0                                                                                                   SUBCASE 1
 *** USER INFORMATION MESSAGE 5293 (SSG3A)
    FOR DATA BLOCK KLL
    LOAD SEQ. NO.             EPSILON              EXTERNAL WORK      EPSILONS LARGER THAN 0.001 ARE FLAGGED WITH
ASTERISKS
                1         -5.1027457E-11          1.1091620E+00
                2          3.4630486E-12          5.0557755E-02
                3         -7.6409205E-11          6.8610913E-01
1    MSC.NASTRAN JOB CREATED ON 28-APR-17 AT 20:33:53                        APRIL  28, 2017  MSC Nastran  3/14/14
PAGE     7
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0
 *** USER INFORMATION MESSAGE 7310 (VECPRN)
     ORIGIN OF SUPERELEMENT BASIC COORDINATE SYSTEM WILL BE USED AS REFERENCE LOCATION.
     RESULTANTS ABOUT ORIGIN OF SUPERELEMENT BASIC COORDINATE SYSTEM IN SUPERELEMENT BASIC SYSTEM COORDINATES.
0                                                  SPCFORCE RESULTANT
  SUBCASE/    LOAD
  DAREA ID    TYPE       T1            T2            T3            R1            R2            R3
0        1     FX   -3.552714E-15     ----          ----          ----       0.000000E+00  2.187983E+02
               FY       ----      1.044500E+01     ----       0.000000E+00     ----       0.000000E+00
               FZ       ----          ----      6.793128E-27  1.698282E-25  0.000000E+00     ----
               MX       ----          ----          ----     -1.977818E-10     ----          ----
               MY       ----          ----          ----          ----      7.544776E-16     ----
               MZ       ----          ----          ----          ----          ----     -7.256833E+01
             TOTALS -3.552714E-15  1.044500E+01  6.793128E-27 -1.977818E-10  7.544776E-16  1.462300E+02
0        2     FX   -6.661338E-16     ----          ----          ----       0.000000E+00  4.671329E+01
               FY       ----      2.230000E+00     ----       0.000000E+00     ----       0.000000E+00
               FZ       ----          ----      1.450321E-27  3.625802E-26  0.000000E+00     ----
               MX       ----          ----          ----     -4.222627E-11     ----          ----
               MY       ----          ----          ----          ----      1.610804E-16     ----
               MZ       ----          ----          ----          ----          ----     -1.549329E+01
             TOTALS -6.661338E-16  2.230000E+00  1.450321E-27 -4.222627E-11  1.610804E-16  3.122000E+01
0        3     FX   -2.664535E-15     ----          ----          ----       0.000000E+00  1.720851E+02
               FY       ----      8.215000E+00     ----       0.000000E+00     ----       0.000000E+00
               FZ       ----          ----      5.342807E-27  1.335702E-25  0.000000E+00     ----
               MX       ----          ----          ----     -1.555555E-10     ----          ----
               MY       ----          ----          ----          ----      5.933971E-16     ----
               MZ       ----          ----          ----          ----          ----     -5.707504E+01
             TOTALS -2.664535E-15  8.215000E+00  5.342807E-27 -1.555555E-10  5.933971E-16  1.150100E+02
1    MSC.NASTRAN JOB CREATED ON 28-APR-17 AT 20:33:53                        APRIL  28, 2017  MSC Nastran  3/14/14
PAGE     8

0
0                                                  MAXIMUM  SPCFORCES
  SUBCASE/
  DAREA ID        T1             T2             T3             R1             R2             R3
0        1   8.7519331E+00  1.0445001E+01  6.7931278E-27  1.9778179E-10  7.5447755E-16  7.2568329E+01
0        2   1.8685315E+00  2.2300000E+00  1.4503208E-27  4.2226271E-11  1.6108041E-16  1.5493286E+01
0        3   6.8834019E+00  8.2150002E+00  5.3428070E-27  1.5555553E-10  5.9339714E-16  5.7075043E+01
1    MSC.NASTRAN JOB CREATED ON 28-APR-17 AT 20:33:53                        APRIL  28, 2017  MSC Nastran  3/14/14
PAGE     9

0
0                                                  MAXIMUM  DISPLACEMENTS
  SUBCASE/
  DAREA ID        T1             T2             T3             R1             R2             R3
0        1   3.2086737E-02  2.1238141E-01  7.7220836E-14  4.4139541E-14  9.9654229E-20  1.8335279E-02
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0        2   6.8504959E-03  4.5343276E-02  1.6486593E-14  9.4237599E-15  2.1276106E-20  3.9145690E-03
0        3   2.5236243E-02  1.6703813E-01  6.0734248E-14  3.4715781E-14  7.8378122E-20  1.4420711E-02
1    MSC.NASTRAN JOB CREATED ON 28-APR-17 AT 20:33:53                        APRIL  28, 2017  MSC Nastran  3/14/14
PAGE    10

0
0                                                  MAXIMUM  APPLIED LOADS
  SUBCASE/
  DAREA ID        T1             T2             T3             R1             R2             R3
0        1   0.0000000E+00  1.0445000E+01  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
0        2   0.0000000E+00  2.2300000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
0        3   0.0000000E+00  8.2150002E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00  0.0000000E+00
1    MSC.NASTRAN JOB CREATED ON 28-APR-17 AT 20:33:53                        APRIL  28, 2017  MSC Nastran  3/14/14
PAGE    11
     DEFAULT
0                                                                                                            SUBCASE 1

                                             D I S P L A C E M E N T   V E C T O R

      POINT ID.   TYPE          T1             T2             T3             R1             R2             R3
             1      G      0.0            0.0            0.0            0.0            0.0            0.0
             2      G      0.0            0.0            0.0            0.0            0.0           -8.682759E-03
             6      G      0.0            0.0            0.0            0.0            0.0           -8.682759E-03
             7      G      0.0            0.0            0.0            0.0            0.0           -8.682759E-03
             8      G      3.425996E-20  -2.123666E-01   6.972338E-19   4.412659E-14  -9.960484E-20  -1.833528E-02
             9      G     -2.795209E-20  -2.123666E-01   6.972338E-19   4.411364E-14  -9.955544E-20  -1.833528E-02
            10      G      9.635000E-20  -2.123666E-01   6.972338E-19   4.413954E-14  -9.965423E-20  -1.833528E-02
            11      G     -3.208674E-02  -2.123814E-01  -7.722084E-14   4.412659E-14  -9.960484E-20  -1.833528E-02
1    MSC.NASTRAN JOB CREATED ON 28-APR-17 AT 20:33:53                        APRIL  28, 2017  MSC Nastran  3/14/14
PAGE    12
     F5
0                                                                                                            SUBCASE 2

                                             D I S P L A C E M E N T   V E C T O R

      POINT ID.   TYPE          T1             T2             T3             R1             R2             R3
             1      G      0.0            0.0            0.0            0.0            0.0            0.0
             2      G      0.0            0.0            0.0            0.0            0.0           -1.853763E-03
             6      G      0.0            0.0            0.0            0.0            0.0           -1.853763E-03
             7      G      0.0            0.0            0.0            0.0            0.0           -1.853763E-03
             8      G      7.314476E-21  -4.534011E-02   1.488589E-19   9.420995E-15  -2.126556E-20  -3.914569E-03
             9      G     -5.929231E-21  -4.534011E-02   1.488589E-19   9.418231E-15  -2.125501E-20  -3.914569E-03
            10      G      2.064643E-20  -4.534011E-02   1.488589E-19   9.423760E-15  -2.127611E-20  -3.914569E-03
            11      G     -6.850496E-03  -4.534328E-02  -1.648659E-14   9.420995E-15  -2.126556E-20  -3.914569E-03
1    MSC.NASTRAN JOB CREATED ON 28-APR-17 AT 20:33:53                        APRIL  28, 2017  MSC Nastran  3/14/14
PAGE    13
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     M20
0                                                                                                             SUBCASE 3

                                                D I S P L A C E M E N T   V E C T O R

      POINT ID.   TYPE          T1             T2             T3             R1             R2             R3
             1      G      0.0            0.0            0.0            0.0            0.0            0.0
             2      G      0.0            0.0            0.0            0.0            0.0           -6.828996E-03
             6      G      0.0            0.0            0.0            0.0            0.0           -6.828996E-03
             7      G      0.0            0.0            0.0            0.0            0.0           -6.828996E-03
             8      G      2.694548E-20  -1.670265E-01   5.483749E-19   3.470560E-14  -7.833928E-20  -1.442071E-02
             9      G     -2.191698E-20  -1.670265E-01   5.483749E-19   3.469541E-14  -7.830043E-20  -1.442071E-02
            10      G      7.580945E-20  -1.670265E-01   5.483749E-19   3.471578E-14  -7.837812E-20  -1.442071E-02
            11      G     -2.523624E-02  -1.670381E-01  -6.073425E-14   3.470560E-14  -7.833928E-20  -1.442071E-02
1    MSC.NASTRAN JOB CREATED ON 28-APR-17 AT 20:33:53                         APRIL  28, 2017  MSC Nastran  3/14/14
PAGE    14
     DEFAULT
0                                                                                                             SUBCASE 1

                                   F O R C E S   O F   S I N G L E - P O I N T   C O N S T R A I N T

      POINT ID.   TYPE          T1             T2             T3             R1             R2             R3
             1      G      8.751933E+00   0.0            0.0            0.0            0.0           -7.256833E+01
             2      G     -8.751933E+00   1.044500E+01   6.793128E-27  -1.977818E-10   7.544776E-16   0.0
1    MSC.NASTRAN JOB CREATED ON 28-APR-17 AT 20:33:53                         APRIL  28, 2017  MSC Nastran  3/14/14
PAGE    15
     F5
0                                                                                                             SUBCASE 2

                                   F O R C E S   O F   S I N G L E - P O I N T   C O N S T R A I N T

      POINT ID.   TYPE          T1             T2             T3             R1             R2             R3
             1      G      1.868531E+00   0.0            0.0            0.0            0.0           -1.549329E+01
             2      G     -1.868531E+00   2.230000E+00   1.450321E-27  -4.222627E-11   1.610804E-16   0.0
1    MSC.NASTRAN JOB CREATED ON 28-APR-17 AT 20:33:53                         APRIL  28, 2017  MSC Nastran  3/14/14
PAGE    16
     M20
0                                                                                                             SUBCASE 3

                                   F O R C E S   O F   S I N G L E - P O I N T   C O N S T R A I N T

      POINT ID.   TYPE          T1             T2             T3             R1             R2             R3
             1      G      6.883402E+00   0.0            0.0            0.0            0.0           -5.707504E+01
             2      G     -6.883402E+00   8.215000E+00   5.342807E-27  -1.555555E-10   5.933971E-16   0.0
1    MSC.NASTRAN JOB CREATED ON 28-APR-17 AT 20:33:53                         APRIL  28, 2017  MSC Nastran  3/14/14
PAGE    17
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     F5
0                                                                                                           SUBCASE 2

                                  S T R A I N S    I N   B A R   E L E M E N T S         ( C B A R )
  ELEMENT        SA1            SA2            SA3            SA4           AXIAL          SA-MAX         SA-MIN
M.S.-T
    ID.          SB1            SB2            SB3            SB4           STRAIN         SB-MAX         SB-MIN
M.S.-C
0       1    5.551794E-05  -5.551793E-05  -5.551793E-05   5.551794E-05   0.0            5.551794E-05  -5.551793E-05
            -1.118723E-04   1.118723E-04   1.118723E-04  -1.118723E-04                  1.118723E-04  -1.118723E-04
0       2    0.0            0.0            0.0            0.0            0.0            0.0            0.0
             0.0            0.0            0.0            0.0                           0.0            0.0
0       3    0.0            0.0            0.0            0.0            0.0            0.0            0.0
             0.0            0.0            0.0            0.0                           0.0            0.0
0       4    2.998122E-17  -2.998006E-17  -2.998121E-17   2.998007E-17   5.224626E-22   2.998174E-17  -2.998069E-17
             1.118723E-04  -1.118723E-04  -1.118723E-04   1.118723E-04                  1.118723E-04  -1.118723E-04
0       5    0.0            3.201050E-18   0.0           -3.201050E-18   0.0            3.201050E-18  -3.201050E-18
             0.0            3.201050E-18   0.0           -3.201050E-18                  3.201050E-18  -3.201050E-18
0       6   -3.201050E-18   3.201050E-18   3.201050E-18  -3.201050E-18   0.0            3.201050E-18  -3.201050E-18
            -3.201050E-18   3.201050E-18   3.201050E-18  -3.201050E-18                  3.201050E-18  -3.201050E-18
0       7   -1.798202E-19   1.798202E-19   1.798202E-19  -1.798202E-19   1.808245E-06   1.808245E-06   1.808245E-06
            -1.798202E-19   1.798202E-19   1.798202E-19  -1.798202E-19                  1.808245E-06   1.808245E-06
1    MSC.NASTRAN JOB CREATED ON 28-APR-17 AT 20:33:53                         APRIL  28, 2017  MSC Nastran  3/14/14
PAGE    18
     M20
0                                                                                                           SUBCASE 3

                                  S T R A I N S    I N   B A R   E L E M E N T S         ( C B A R )
  ELEMENT        SA1            SA2            SA3            SA4           AXIAL          SA-MAX         SA-MIN
M.S.-T
    ID.          SB1            SB2            SB3            SB4           STRAIN         SB-MAX         SB-MIN
M.S.-C
0       1    2.045201E-04  -2.045201E-04  -2.045201E-04   2.045201E-04   0.0            2.045201E-04  -2.045201E-04
            -4.121216E-04   4.121216E-04   4.121216E-04  -4.121216E-04                  4.121216E-04  -4.121216E-04
0       2    0.0            0.0            0.0            0.0            0.0            0.0            0.0
             0.0            0.0            0.0            0.0                           0.0            0.0
0       3    0.0            0.0            0.0            0.0            0.0            0.0            0.0
             0.0            0.0            0.0            0.0                           0.0            0.0
0       4    1.099948E-16  -1.099905E-16  -1.099948E-16   1.099906E-16   1.924677E-21   1.099967E-16  -1.099929E-16
             4.121216E-04  -4.121216E-04  -4.121216E-04   4.121216E-04                  4.121216E-04  -4.121216E-04
0       5    0.0            1.280420E-17   0.0           -1.280420E-17   0.0            1.280420E-17  -1.280420E-17
            -1.600525E-17   1.280420E-17   1.600525E-17  -1.280420E-17                  1.600525E-17  -1.600525E-17
0       6   -2.560840E-17   1.280420E-17   2.560840E-17  -1.280420E-17   0.0            2.560840E-17  -2.560840E-17
             6.402100E-18  -3.201050E-18  -6.402100E-18   3.201050E-18                  6.402100E-18  -6.402100E-18
0       7   -1.018451E-19   1.018451E-19   1.018451E-19  -1.018451E-19   6.661315E-06   6.661315E-06   6.661315E-06
             6.110704E-19  -6.110703E-19  -6.110703E-19   6.110704E-19                  6.661315E-06   6.661315E-06
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1    MSC.NASTRAN JOB CREATED ON 28-APR-17 AT 20:33:53                        APRIL  28, 2017  MSC Nastran  3/14/14
PAGE    19
     DEFAULT
0                                                                                                                   SUBCASE 1

                                 S T R E S S E S   I N   B A R   E L E M E N T S         ( C B A R )
  ELEMENT        SA1            SA2            SA3            SA4           AXIAL          SA-MAX         SA-MIN
M.S.-T
    ID.          SB1            SB2            SB3            SB4           STRESS         SB-MAX         SB-MIN
M.S.-C
0       1    2.600381E+03  -2.600380E+03  -2.600380E+03   2.600381E+03   0.0            2.600381E+03  -2.600380E+03
            -5.239940E+03   5.239939E+03   5.239939E+03  -5.239940E+03                  5.239939E+03  -5.239940E+03
0       2    0.0            0.0            0.0            0.0            0.0            0.0            0.0
             0.0            0.0            0.0            0.0                           0.0            0.0
0       3    0.0            0.0            0.0            0.0            0.0            0.0            0.0
             0.0            0.0            0.0            0.0                           0.0            0.0
0       4    1.401924E-09  -1.401870E-09  -1.401924E-09   1.401870E-09   2.447140E-14   1.401949E-09  -1.401900E-09
             5.239940E+03  -5.239939E+03  -5.239939E+03   5.239940E+03                  5.239940E+03  -5.239939E+03
0       5   -1.280420E-10   1.280420E-10   1.280420E-10  -1.280420E-10   0.0            1.280420E-10  -1.280420E-10
            -1.280420E-10   1.280420E-10   1.280420E-10  -1.280420E-10                  1.280420E-10  -1.280420E-10
0       6   -2.560840E-10   2.560840E-10   2.560840E-10  -2.560840E-10   0.0            2.560840E-10  -2.560840E-10
             6.402100E-11  -6.402100E-11  -6.402100E-11   6.402100E-11                  6.402100E-11  -6.402100E-11
0       7    5.283213E-12  -5.283212E-12  -5.283212E-12   5.283213E-12   8.469560E+01   8.469560E+01   8.469560E+01
             1.954152E-11  -1.954152E-11  -1.954152E-11   1.954152E-11                  8.469560E+01   8.469560E+01
1    MSC.NASTRAN JOB CREATED ON 28-APR-17 AT 20:33:53                        APRIL  28, 2017  MSC Nastran  3/14/14
PAGE    20
     F5
0                                                                                                                   SUBCASE 2

                                 S T R E S S E S   I N   B A R   E L E M E N T S         ( C B A R )
  ELEMENT        SA1            SA2            SA3            SA4           AXIAL          SA-MAX         SA-MIN
M.S.-T
    ID.          SB1            SB2            SB3            SB4           STRESS         SB-MAX         SB-MIN
M.S.-C
0       1    5.551794E+02  -5.551793E+02  -5.551793E+02   5.551794E+02   0.0            5.551794E+02  -5.551793E+02
            -1.118723E+03   1.118723E+03   1.118723E+03  -1.118723E+03                  1.118723E+03  -1.118723E+03
0       2    0.0            0.0            0.0            0.0            0.0            0.0            0.0
             0.0            0.0            0.0            0.0                           0.0            0.0
0       3    0.0            0.0            0.0            0.0            0.0            0.0            0.0
             0.0            0.0            0.0            0.0                           0.0            0.0
0       4    2.998122E-10  -2.998006E-10  -2.998121E-10   2.998007E-10   5.224626E-15   2.998174E-10  -2.998069E-10
             1.118723E+03  -1.118723E+03  -1.118723E+03   1.118723E+03                  1.118723E+03  -1.118723E+03
0       5    0.0            3.201050E-11   0.0           -3.201050E-11   0.0            3.201050E-11  -3.201050E-11
             0.0            3.201050E-11   0.0           -3.201050E-11                  3.201050E-11  -3.201050E-11
0       6   -3.201050E-11   3.201050E-11   3.201050E-11  -3.201050E-11   0.0            3.201050E-11  -3.201050E-11
            -3.201050E-11   3.201050E-11   3.201050E-11  -3.201050E-11                  3.201050E-11  -3.201050E-11
```

```
0       7   -1.798202E-12   1.798202E-12   1.798202E-12  -1.798202E-12   1.808245E+01   1.808245E+01   1.808245E+01
            -1.798202E-12   1.798202E-12   1.798202E-12  -1.798202E-12                  1.808245E+01   1.808245E+01
1    MSC.NASTRAN JOB CREATED ON 28-APR-17 AT 20:33:53                        APRIL  28, 2017  MSC Nastran  3/14/14
PAGE    21
     M20
0                                                                                                           SUBCASE 3

                                S T R E S S E S   I N   B A R   E L E M E N T S         ( C B A R )
  ELEMENT        SA1            SA2            SA3            SA4           AXIAL          SA-MAX         SA-MIN
M.S.-T
    ID.          SB1            SB2            SB3            SB4           STRESS         SB-MAX         SB-MIN
M.S.-C
0       1    2.045201E+03  -2.045201E+03  -2.045201E+03   2.045201E+03   0.0            2.045201E+03  -2.045201E+03
            -4.121216E+03   4.121216E+03   4.121216E+03  -4.121216E+03                  4.121216E+03  -4.121216E+03
0       2    0.0            0.0            0.0            0.0            0.0            0.0            0.0
             0.0            0.0            0.0            0.0                           0.0            0.0
0       3    0.0            0.0            0.0            0.0            0.0            0.0            0.0
             0.0            0.0            0.0            0.0                           0.0            0.0
0       4    1.099948E-09  -1.099905E-09  -1.099948E-09   1.099906E-09   1.924677E-14   1.099967E-09  -1.099929E-09
             4.121216E+03  -4.121216E+03  -4.121216E+03   4.121216E+03                  4.121216E+03  -4.121216E+03
0       5    0.0            1.280420E-10   0.0           -1.280420E-10   0.0            1.280420E-10  -1.280420E-10
            -1.600525E-10   1.280420E-10   1.600525E-10  -1.280420E-10                  1.600525E-10  -1.600525E-10
0       6   -2.560840E-10   1.280420E-10   2.560840E-10  -1.280420E-10   0.0            2.560840E-10  -2.560840E-10
             6.402100E-11  -3.201050E-11  -6.402100E-11   3.201050E-11                  6.402100E-11  -6.402100E-11
0       7   -1.018451E-12   1.018451E-12   1.018451E-12  -1.018451E-12   6.661315E+01   6.661315E+01   6.661315E+01
             6.110704E-12  -6.110703E-12  -6.110703E-12   6.110704E-12                  6.661315E+01   6.661315E+01
1    MSC.NASTRAN JOB CREATED ON 28-APR-17 AT 20:33:53                        APRIL  28, 2017  MSC Nastran  3/14/14
PAGE    22

0
 * * * *  D B D I C T   P R I N T  * * * *      SUBDMAP = PRTSUM  ,  DMAP STATEMENT NO.     41



0                                  * * * *  A N A L Y S I S  S U M M A R Y  T A B L E  * * * *
0 SEID  PEID PROJ VERS APRCH      SEMG SEMR SEKR SELG SELR MODES DYNRED SOLLIN PVALID SOLNL LOOPID DESIGN CYCLE
SENSITIVITY
 ------------------------------------------------------------------------------------------------------------------------
---
     0     0    1    1 '        '    T    T    T    T    T     F      F      T      0     F     -1            0
F
0SEID = SUPERELEMENT ID.
 PEID = PRIMARY SUPERELEMENT ID OF IMAGE SUPERELEMENT.
 PROJ = PROJECT ID NUMBER.
 VERS = VERSION ID.
 APRCH = BLANK FOR STRUCTURAL ANALYSIS.  HEAT FOR HEAT TRANSFER ANALYSIS.
```

```
SEMG = STIFFNESS AND MASS MATRIX GENERATION STEP.
SEMR = MASS MATRIX REDUCTION STEP (INCLUDES EIGENVALUE SOLUTION FOR MODES).
SEKR = STIFFNESS MATRIX REDUCTION STEP.
SELG = LOAD MATRIX GENERATION STEP.
SELR = LOAD MATRIX REDUCTION STEP.
MODES = T (TRUE) IF NORMAL MODES OR BUCKLING MODES CALCULATED.
DYNRED = T (TRUE) MEANS GENERALIZED DYNAMIC AND/OR COMPONENT MODE REDUCTION PERFORMED.
SOLLIN = T (TRUE) IF LINEAR SOLUTION EXISTS IN DATABASE.
PVALID = P-DISTRIBUTION ID OF P-VALUE FOR P-ELEMENTS
LOOPID = THE LAST LOOPID VALUE USED IN THE NONLINEAR ANALYSIS.  USEFUL FOR RESTARTS.
SOLNL = T (TRUE) IF NONLINEAR SOLUTION EXISTS IN DATABASE.
DESIGN CYCLE = THE LAST DESIGN CYCLE (ONLY VALID IN OPTIMIZATION).
SENSITIVITY = SENSITIVITY MATRIX GENERATION FLAG.

No PARAM values were set in the Control File.

1                                        * * * END OF JOB * * *


No Symbolic Replacement variables or values were specified.
```

f06 File

Appendix C: Stress and Deformation Plots

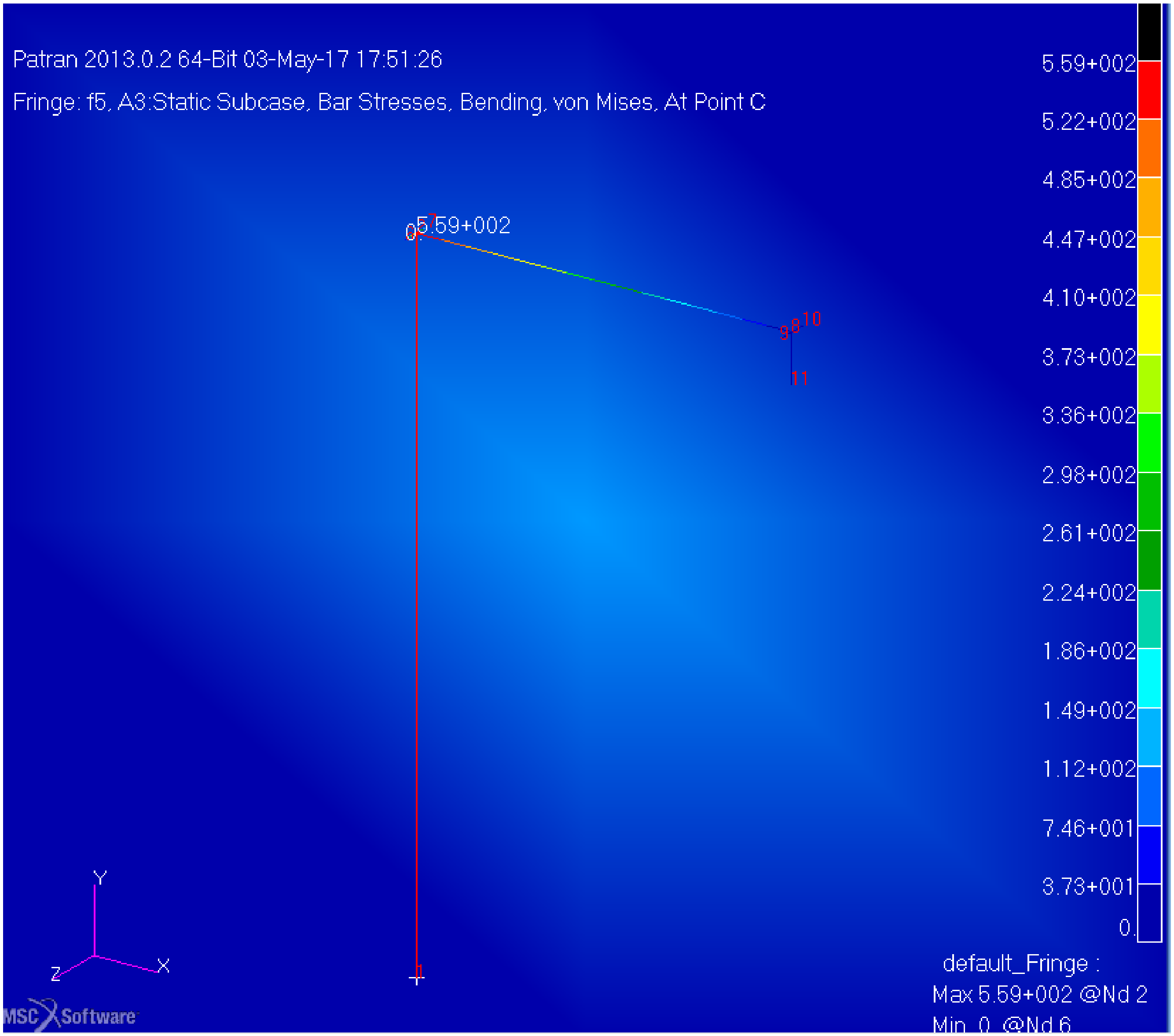

Figure 8: Stress for 2.23lb Load

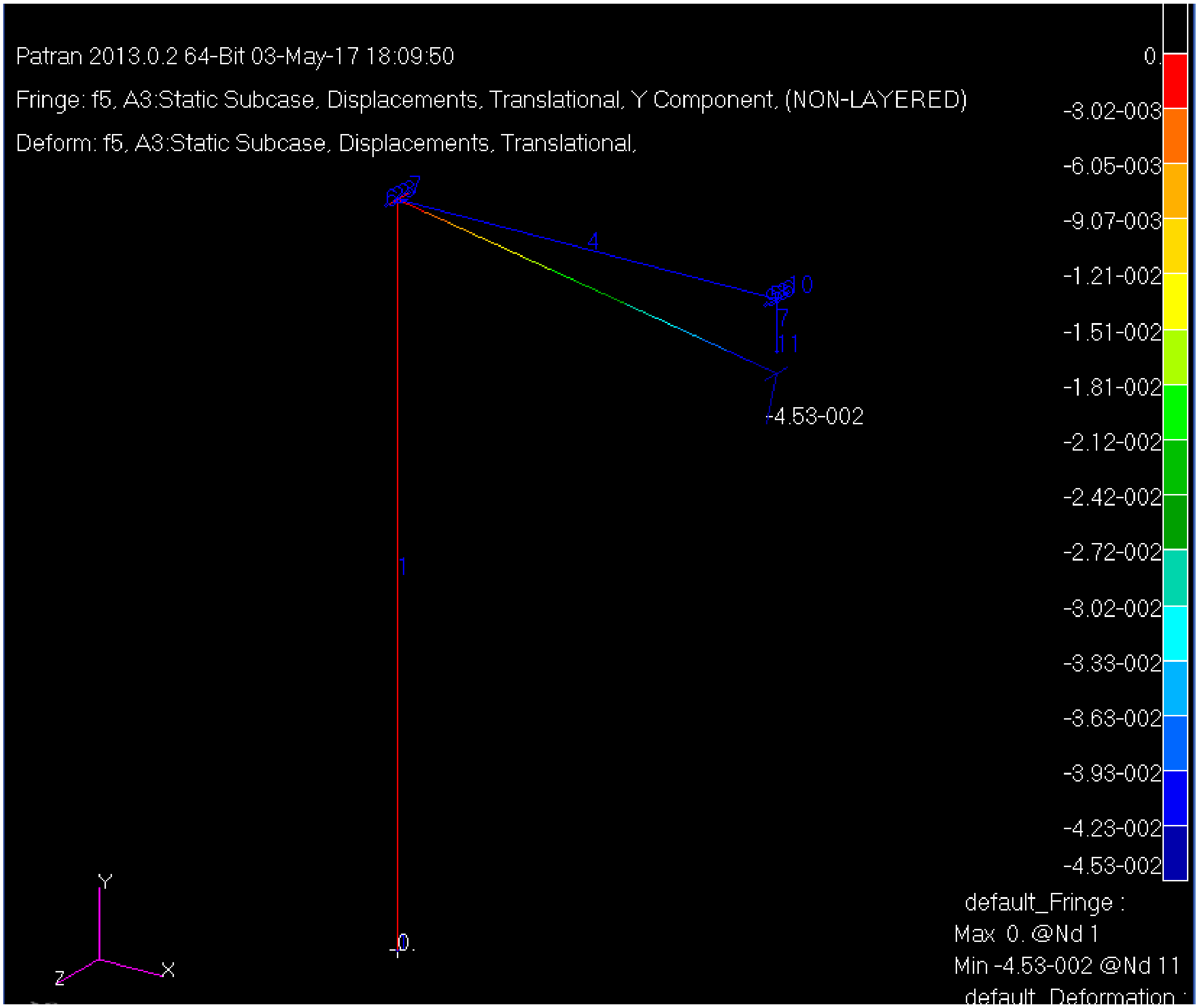

Figure 9: Vertical Deflection for 2.23lb Load

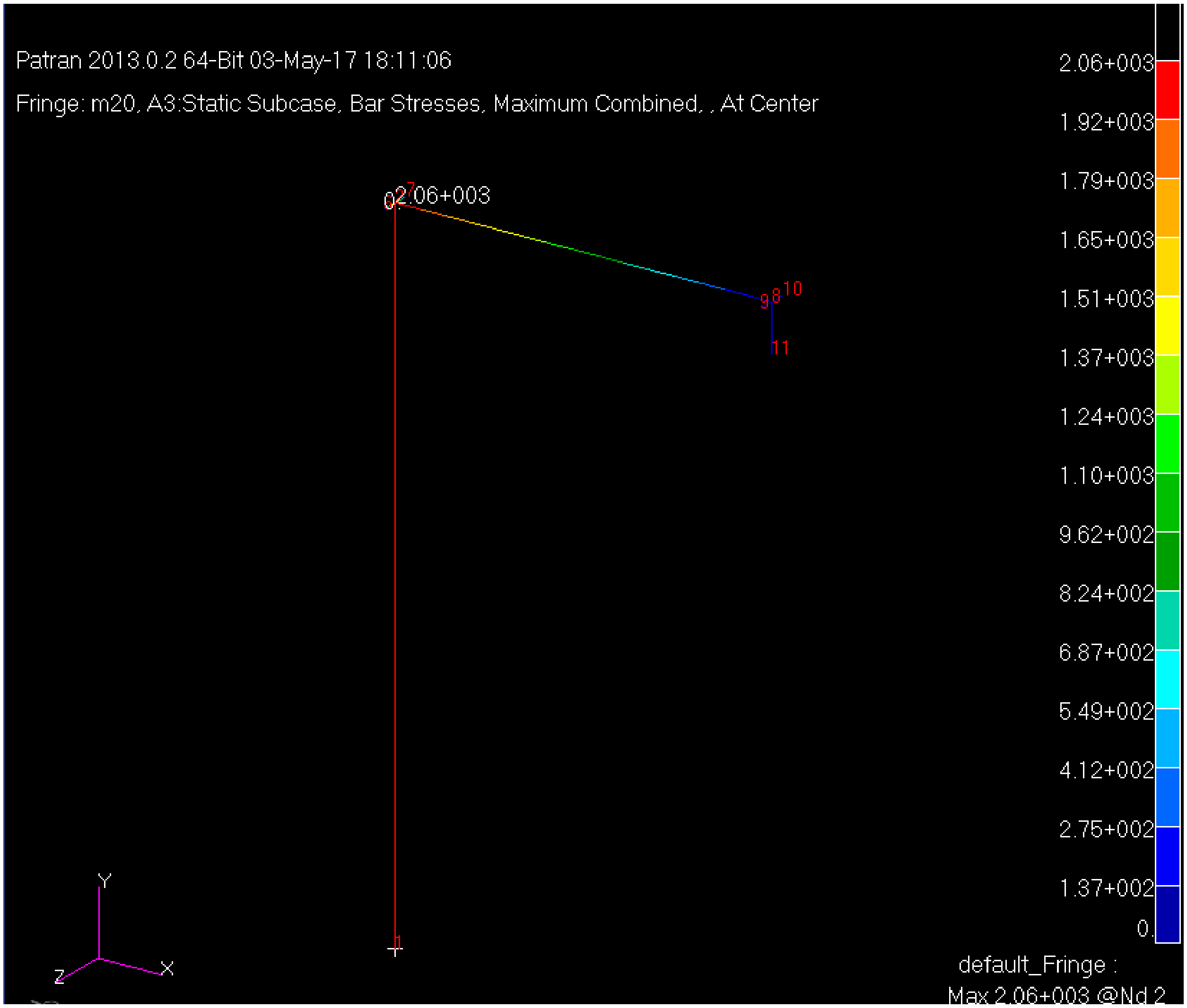

Figure 10: Stress for 10lb Load

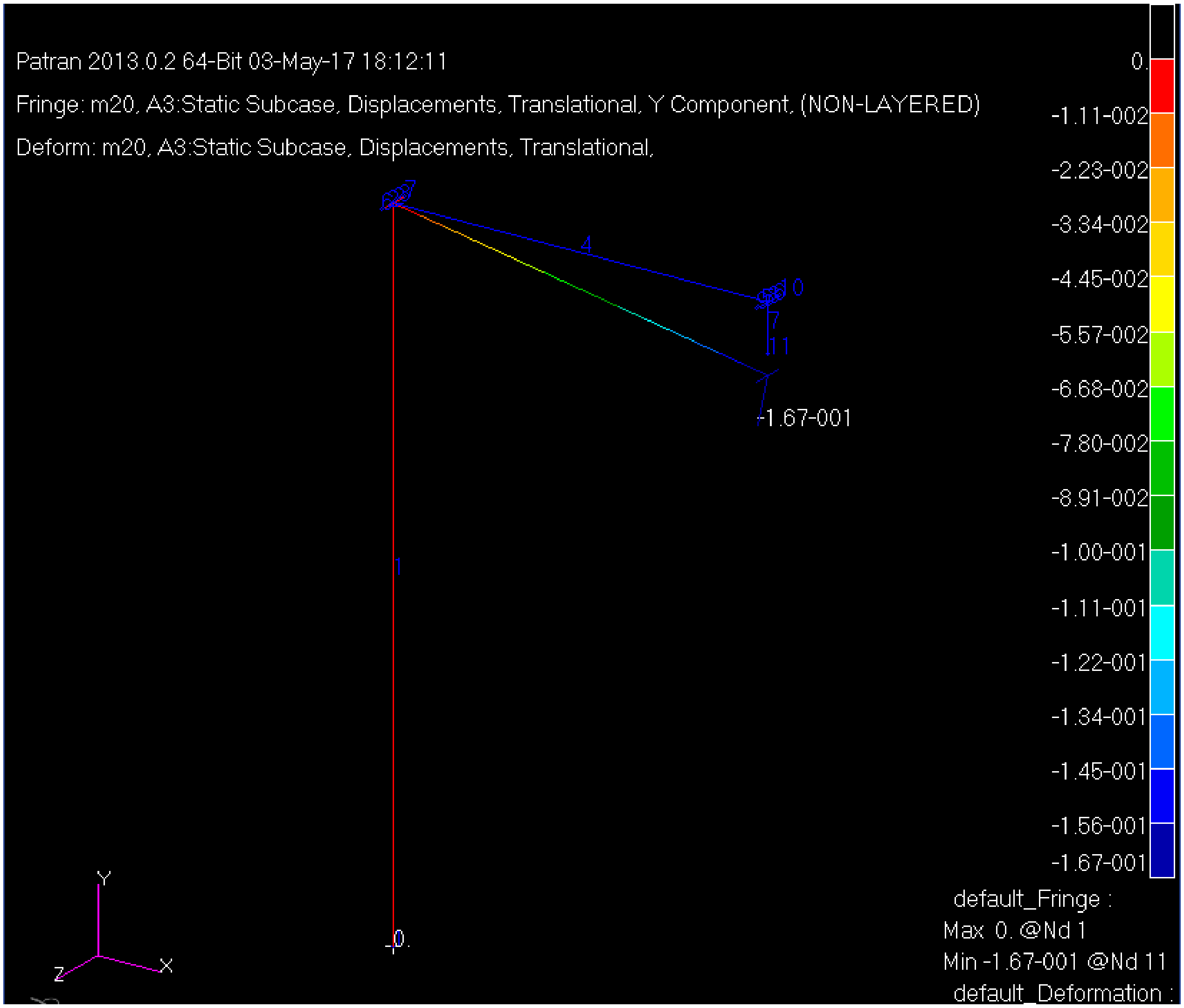

Figure 11: Vertical Displacement for 10lb load