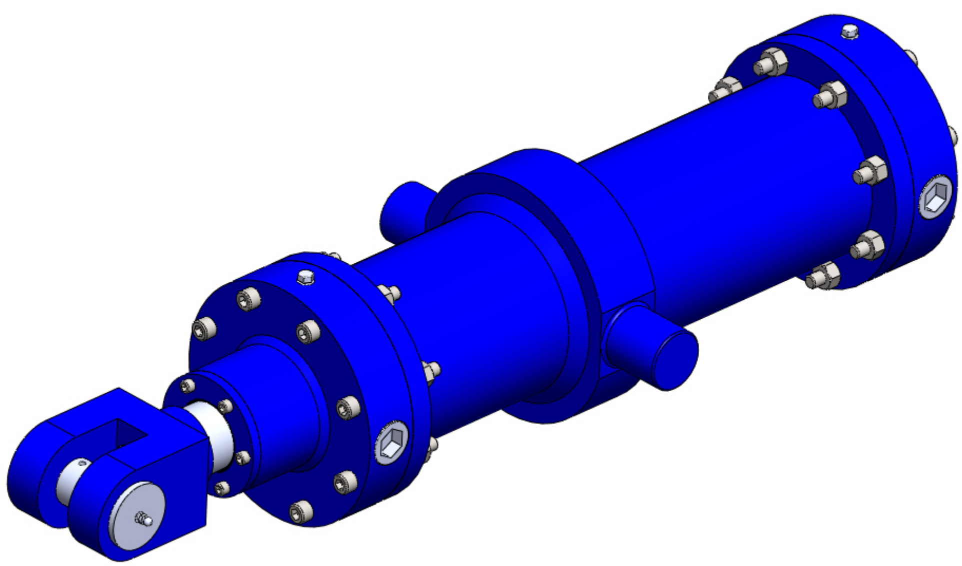
Steering Roll Cylinder Piston Rod Thread Failure - Finite Element Analysis Report



Prepared for Trident Fluid Power and AK Steel Corporation

By

Michael P. Woods

9/1/11

Introduction

The following is intended to provide a quick reference of the results obtained from the Finite Element Analysis (FEA) studies completed on the Steering Roll Cylinder Piston Rod Threads. More detailed results and information can be found throughout the body of this report. All Figures and Tables have been labeled and are listed below the table of contents for easy reference.

Completion of the FEA studies using SolidWorks Simulation Professional provided a quantitative value that can be used to confirm the potential cause of the failure of the current thread design. In addition through the analysis of an alternative design, a potential solution was found using a different thread pitch. A brief synopsis of the results can be seen below in the table.

	MAXIMUM STRESS	
	FULL ENGAGEMENT	PARTIAL ENGAGEMENT
C1045 YIELD STRENGTH	76870 PSI	76870 PSI
C1045 ULTIMATE STRENGTH	90648 PSI	90648 PSI
CURRENT DESIGN (12 TPI)	70018 PSI	81960 PSI
ALTERNATIVE DESIGN (8 TPI)	45163 PSI	48762 PSI

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1 - Description

The following report is a failure analysis of the piston rod clevis threads on the six inch bore Steering Roll Cylinder. A Finite Element Analysis (FEA) study was completed using SolidWorks Simulation Professional and the supplied operating conditions. The current design of the Steering Roll Cylinder piston rod is 2-1/2 inches in diameter and has 2-1/2 inches of 1-7/8-12 threads which are used to secure the rod end clevis component. Both the rod end clevis and the piston rod are made from C1045 steel and have an ultimate strength of 90,648 psi and yield strength of 76,870 psi. A general assembly of the components can be seen below in figure 1.1.

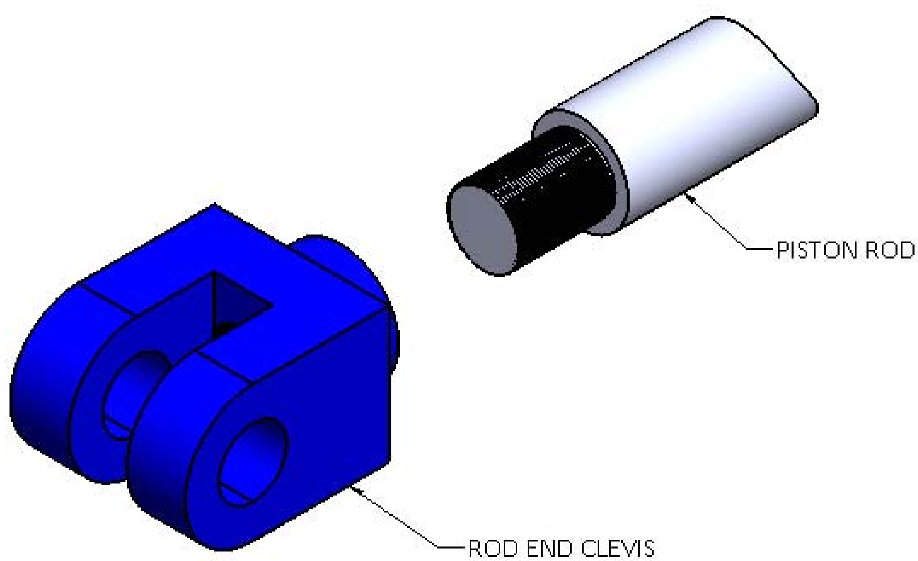

Figure 1.1 – Piston Rod Assembly

The piston rod was modeled with thread details on the rod clevis end only, and later a quarter symmetric section (see figure 1.2 and 1.3) of the threaded end was analyzed. Symmetry is often used for more complex models (i.e. detailed threads) where higher numbers of elements are required to create a smooth and accurate mesh. This in turn allowed for creation of a finer mesh and more accurate post processing results while reducing calculation time.

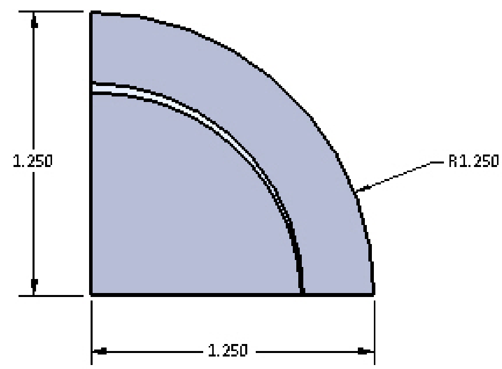

Figure 1.2 – End View of Quarter Symmetric Section

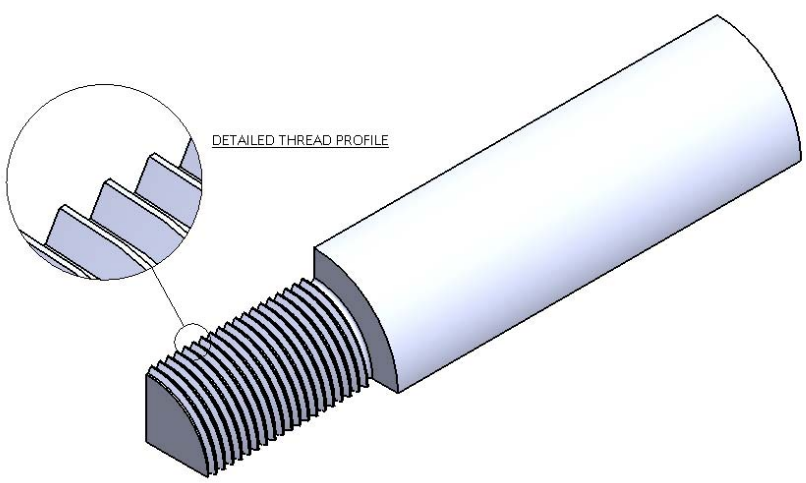

Figure 1.3 – Isometric View with Thread Profile Detail

2 - Thread Failure of Current Piston Rod

The following images (figures 2.1 and 2.2) show the thread failure of the current Steering Roll Piston Rod, along with temporary repair efforts by means of welding. After looking at the images it appears that the clevis component was threaded onto the piston rod a distance of about 1.50 inches from the base of the clevis. While this engagement held for some time, it eventually released allowing the clevis to pull away

Figure 2.1 – Image of Failed Threads with Scale

from the piston rod during the retracting stroke, thus requiring the necessary temporary fix. In the images it appears that the clevis was welded to the piston rod at a distance of about 1.50 inches from the base of the clevis. In addition it appears that the first weld was either repositioned or failed thus requiring the second weld shown at the base of the clevis. With an overall thread length of 2.50 inches on the piston rod end, figure 2.2 shows approximately only ¼ inch of threads engaged into the clevis at the time of the second weld.

Figure 2.2 – Image of Failed Threads Showing ¼" Engagement

3 - Analysis Procedure

Detail models of the current piston rod and an alternative design were created for analysis. After modeling of the current piston rod design and the alternative piston rod design, two quarter symmetric models were created for the studies. The current design includes 2.50 inches of 1-7/8 - 12 threads and the alternative design has a set of coarser threads at 1-7/8 – 8 TPI. Using the two models, four studies were completed for each model including partial engagement of the threads, full engagement of the threads, partial engagement fatigue, and full engagement fatigue.

The approximate mass of each symmetric model was 2.55 lbs and each consumed a volume of about 8.99 in^3. A static analysis using a direct sparse solver was ran for both symmetric models with the mesh properties outlined in table 3.2.

Past research on thread loading has revealed that each thread does not carry equal portions of the total load applied. It has been shown that the load carried by each thread is based on a percentage calculated over the first engaged threads. The remaining threads in the connection carry very small portions of the total load. The general rule of thumb for thread loading begins with thread #1 carrying about 34% of the load, and the remaining five threads carrying 23%, 16%, 11%, 9%, and 7% respectively. Figure 3.1 shows the thread locations for both the full engagement and partial engagement models for the current design along with numeric labels for each of the threads. Figure 3.2 shows the thread locations for the alternative design.

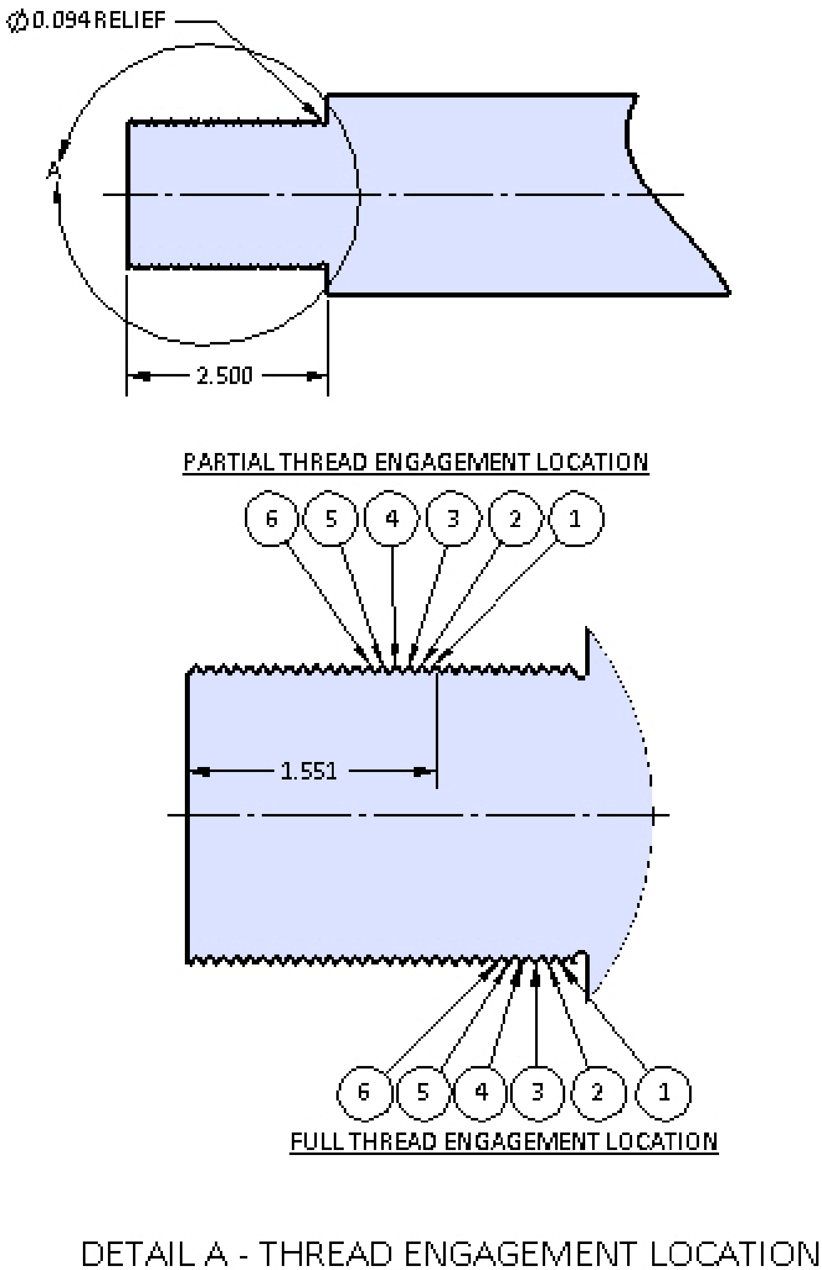

Figure 3.1 – Thread Location for Current Design (Full and Partial Engagement 1-7/8-12 TPI)

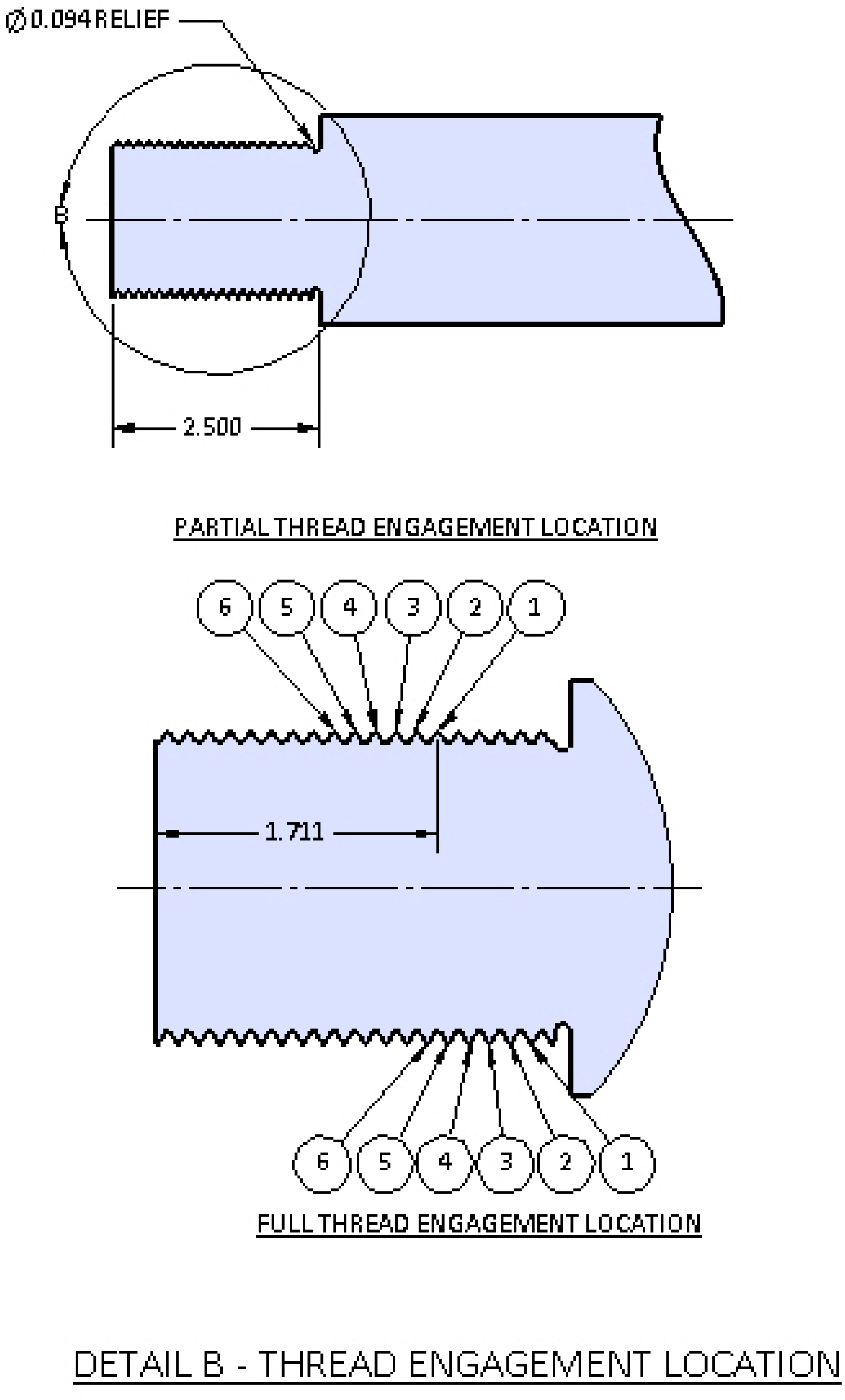

Figure 3.2 – Thread Location for Alternative Design (Full and Partial Engagement 1-7/8-8 TPI)

The total load on the piston rod threads during the retracting stroke was 28,038 lbs. By using a quarter symmetric model the total load had to be reduced by 75% to a value of 7009 lbs. Each model was then restrained using the fixed geometry (see figure 3.3) option on the piston rod diameter toward the piston end. Additionally symmetrical restraints were then applied to the two sectioned faces of the piston rod along their entire length. The appropriate loads were then applied to each of the first six engaged threads for each study.

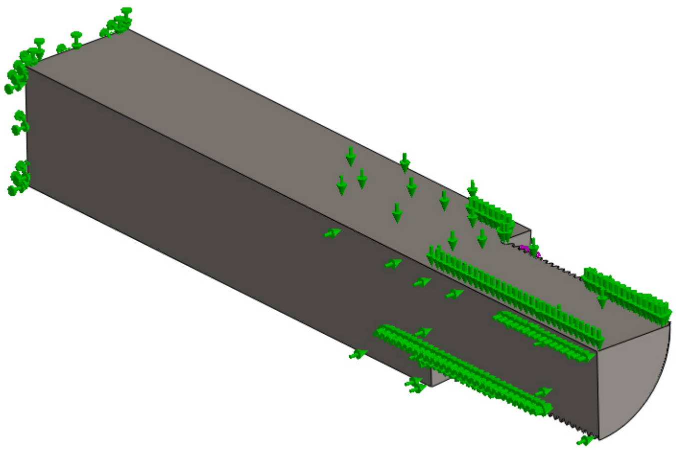

Figure 3.3 – Fixture Locations

Table 3.1 below shows the calculated loads that were applied to each thread. A curvature based mesh was then applied to each model with a refined mesh applied to the threaded section to allow for more accurate

% OF LOAD APPLIED	LOAD APPLIED LBS	THREAD #
34.00	2383.23	1
23.00	1612.19	2
16.00	1121.52	3
11.00	771.05	4
9.00	630.86	5
7.00	490.67	6

Table 3.1 – Thread Loading (lbs)

results. The maximum element size used was 0.208 inches which was placed on the 2.50 inch piston rod diameter and the smallest element size created was 0.041 along the threaded section. Figure 3.4 shows the mesh used for the current design model and a similar mesh was also used for the alternative design. The rest

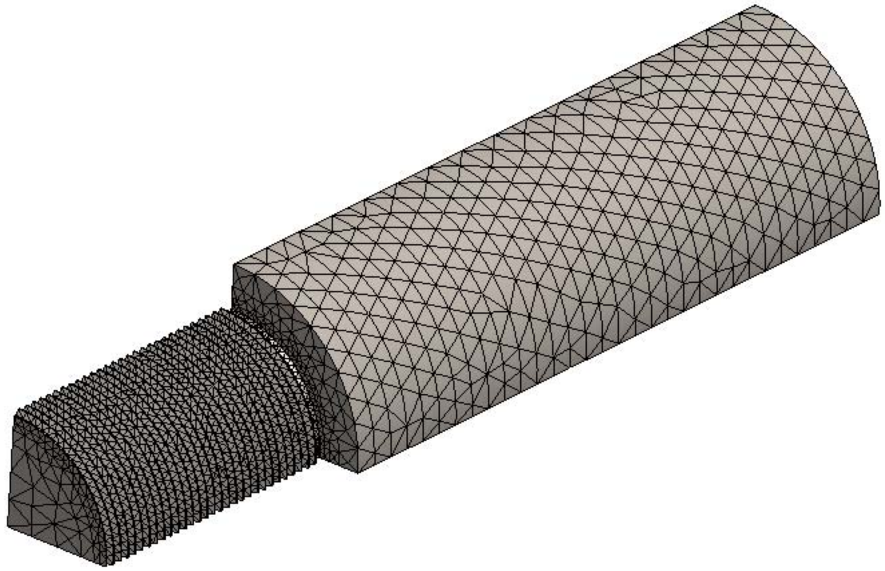

Figure 3.4 – Meshed Model

of the mesh details can be seen in table 3.2. After creation of the mesh the models were then processed and the results were tabulated and plotted for review.

MESH DETAILS	
MESH TYPE	SOLID MESH
MESHER USED	CURVATURE BASED
JACOBIAN POINTS	4 POINTS
MAX. ELEMENT SIZE	0.208 IN
MIN. ELEMENT SIZE	0.041 IN
MESH QUALITY	HIGH
TOTAL NODES	52459
TOTAL ELEMENTS	32983
MAX. ASPECT RATIO	75.29

Table 3.2 – Mesh Details

4 - Mechanical Properties of C1045 Steel and Cylinder Operating Parameters

The following section contains information on the mechanical properties of the material and the current operating conditions of the cylinder.

C1045 STEEL	
MASS DENSITY	0.283 lbs/in^2
POISSON'S RATIO	0.29
ULTIMATE STRENGTH	90648 psi
YIELD STRENGTH	76870 psi
MODULUS OF ELASTICITY	2.97e+007 psi

Table 4.1 – C1045 Mechanical Properties

STEERING ROLL CYLINDER	
OPERATING PRESSURE	1200 psi
PISTON BORE	6.00 in
ROD DIAMETER	2.50 in
PISTON AREA	28.27 in^2
ANNULUS AREA	23.36 in^2
FORCE - EXTENDING	33929 lbs
FORCE - RETRACTING	28038 lbs

Table 4.2 – Cylinder Operating Parameters

5 – Results

After completion of the four stress and fatigue studies for both the current and alternative designs, several stress and fatigue plots were created. Those plots along with several graphs comparing the results will be presented in this section.

A) Current Design Results – Full Engagement

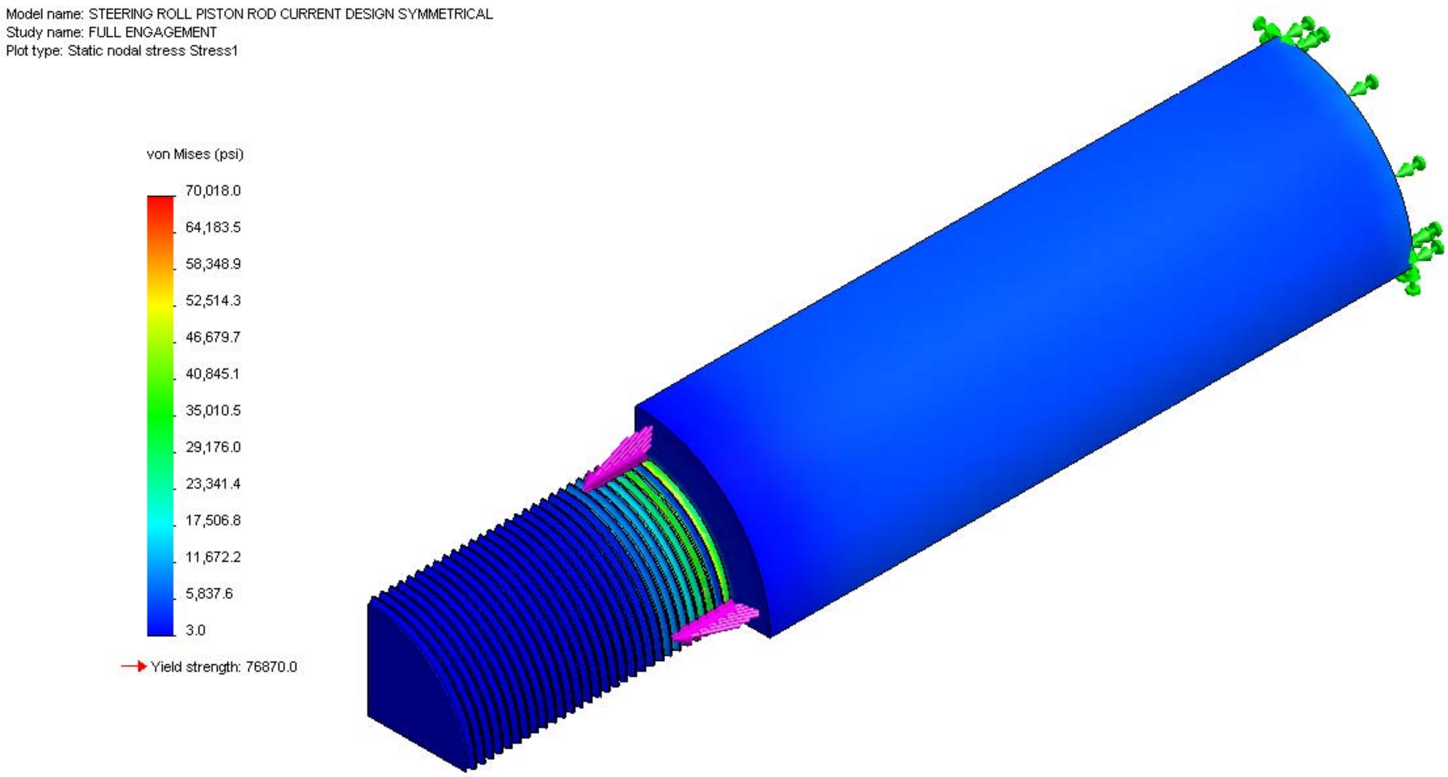

Figure 5.1 – VonMises Stress in Current Design – Full Engagement - View 1

Figures 5.1, 5.2, 5.3, and 5.4 are stress plots for the current design with full thread engagement. The purple arrows on the threads are force loads indicating the positioning of the different loads for each thread as discussed in section 3 (ref. table 3.1). The color chart to the left of the plot shows the color indicated stress values which correspond to the colors on the actual model with blue highlighting areas of low stress and red indicating the maximum stress. The yield strength for C1045 steel is labeled at the bottom of the color chart for reference. It can be seen from the four figures that the area of higher stress lies around the first thread loaded with a localized area of red, best seen in figure 5.4. The value of maximum stress calculated in the part was found to be 70,018 psi. This value approached the yield value of 76,670 psi which would seem to indicate the potential for some localized yielding of the steel and subsequent failure of the threads. Figure 5.4 offers the best view of the stress in the threads and shows the results range from 20,000 psi to the maximum of around 70,000 psi over the first six threads. Tabulated results can be referenced in table A.1 in the appendix. With the calculation completed values for minimum, average, and maximum stress were picked from

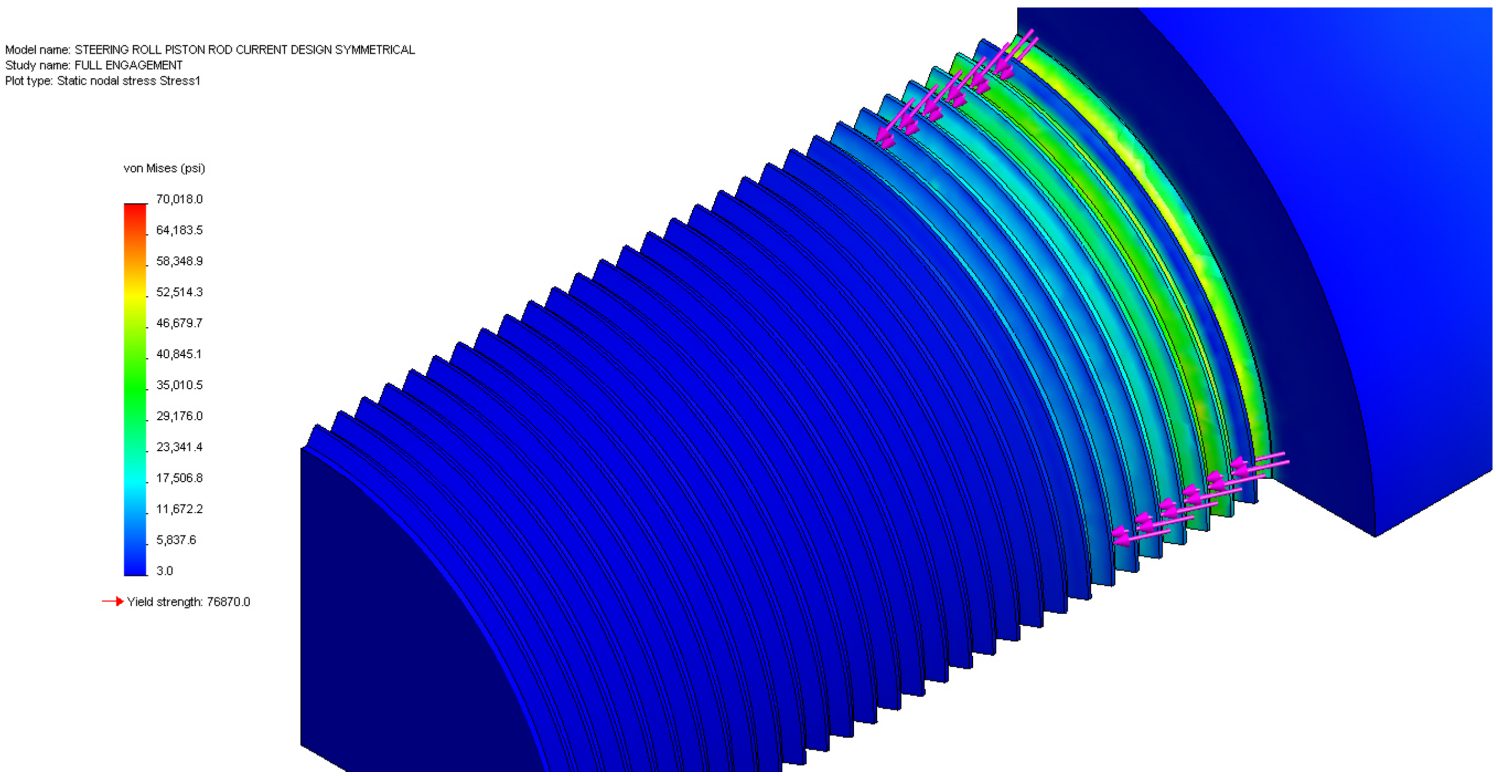

Figure 5.2 – VonMises Stress in Current Design – Full Engagement – View 2

the VonMises diagram. These values were obtained from the surface area in between each thread and were tabulated and plotted to create figure 5.5. This graph shows the minimum, average, and maximum stress developed in each thread and it can be seen that the stress drops off substantially at around thread number 8. This was predictable due to the initial loading conditions of the model. The remaining threads do carry a very small amount of the load and therefore a reduced amount of stress, however there is still some stress transfer from the first 6 or so threads into the remaining threads.

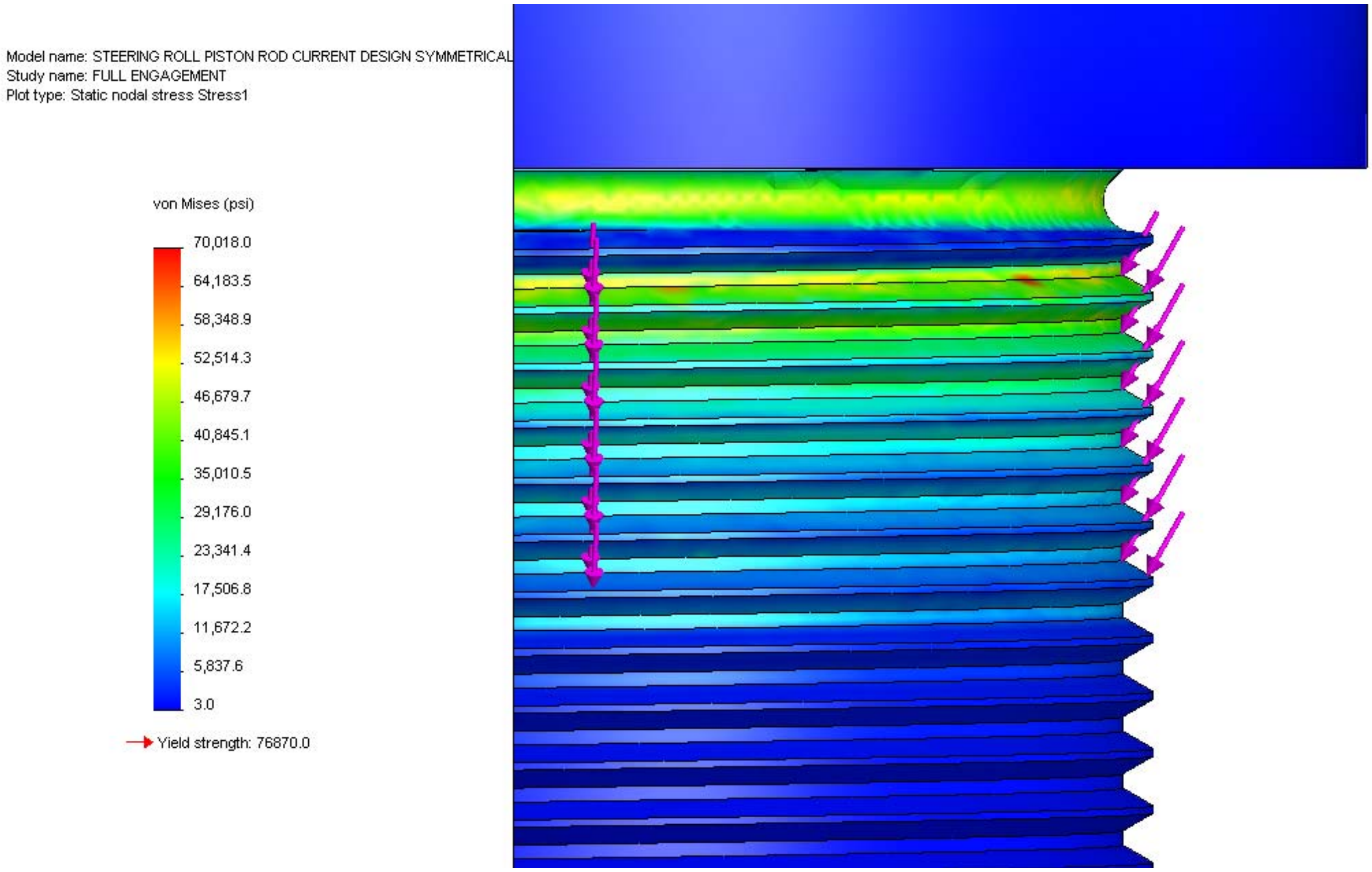

Figure 5.3 – VonMises Stress in Current Design – Full Engagement - View 3

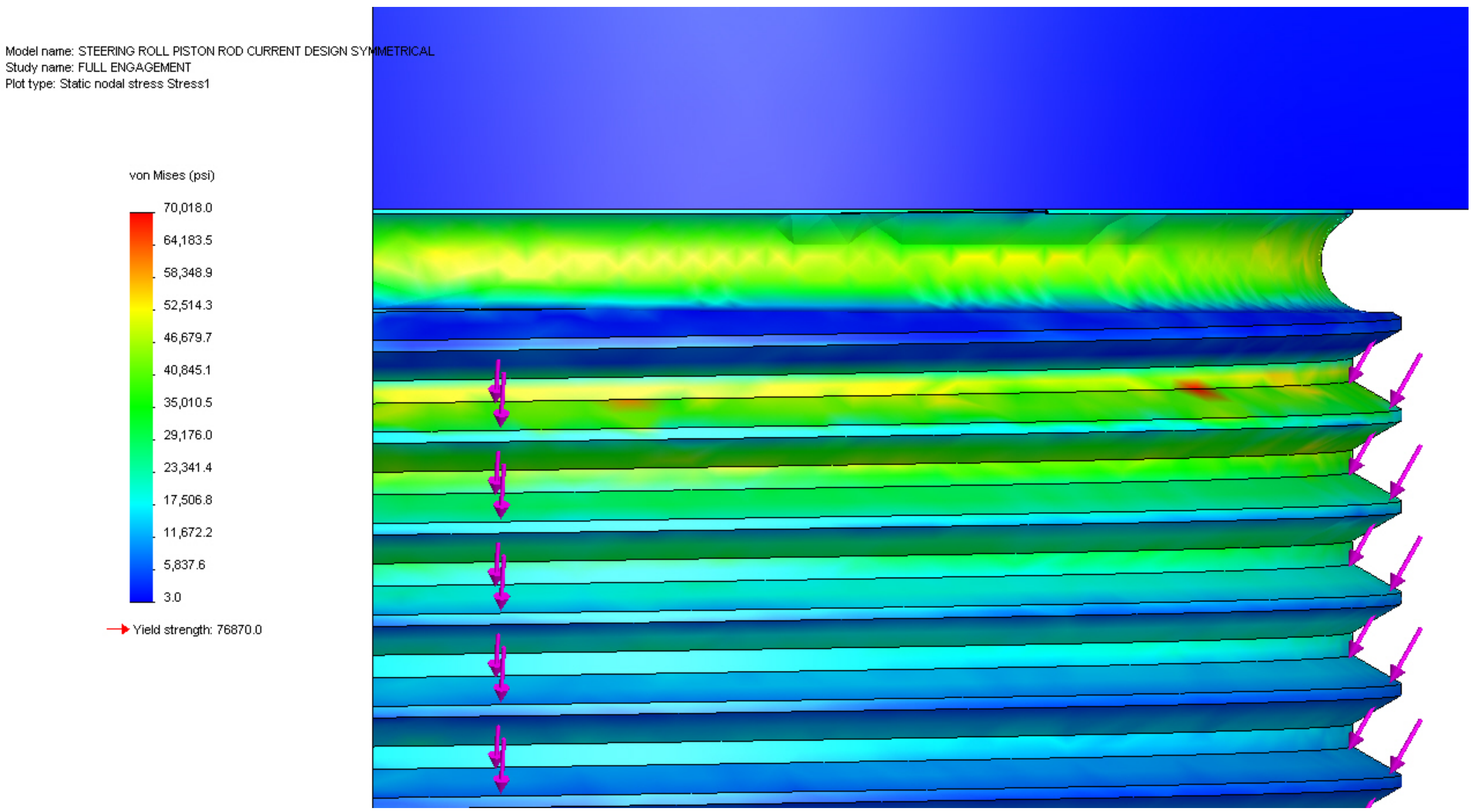

Figure 5.4 – VonMises Stress in Current Design – Full Engagement – View 4

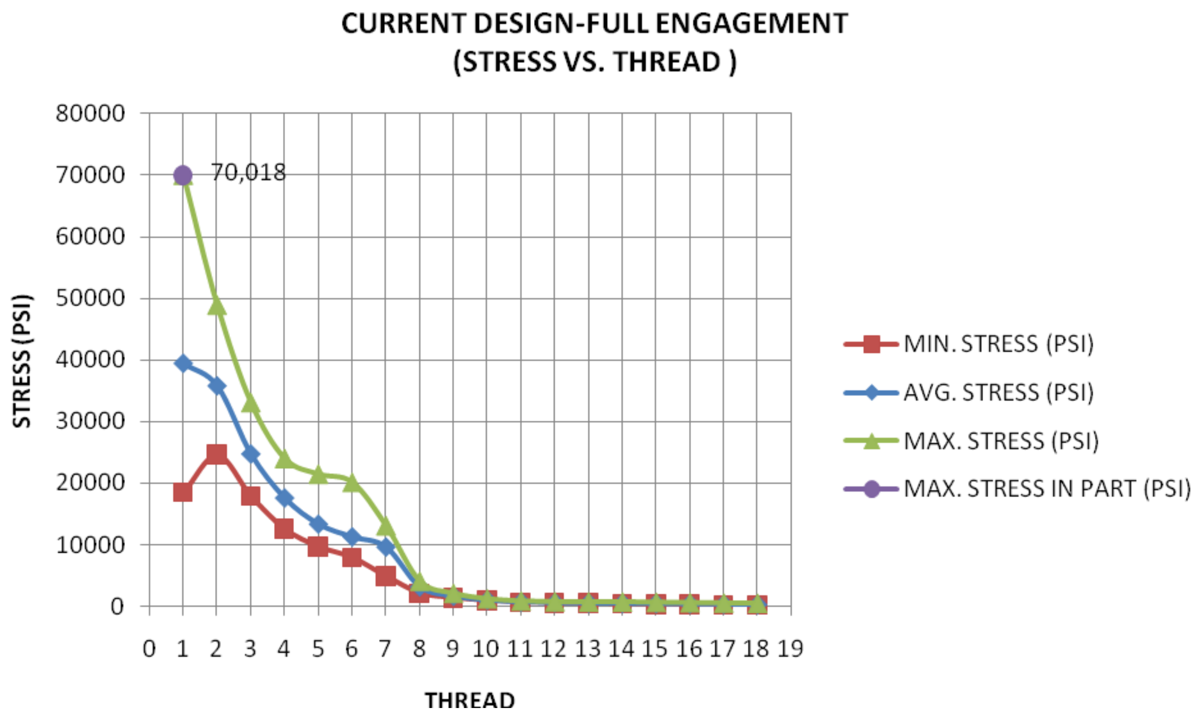

Figure 5.5 – VonMises Stress in Current Design – Full Engagement – Minimum, Average, and Maximum Stress vs. Thread

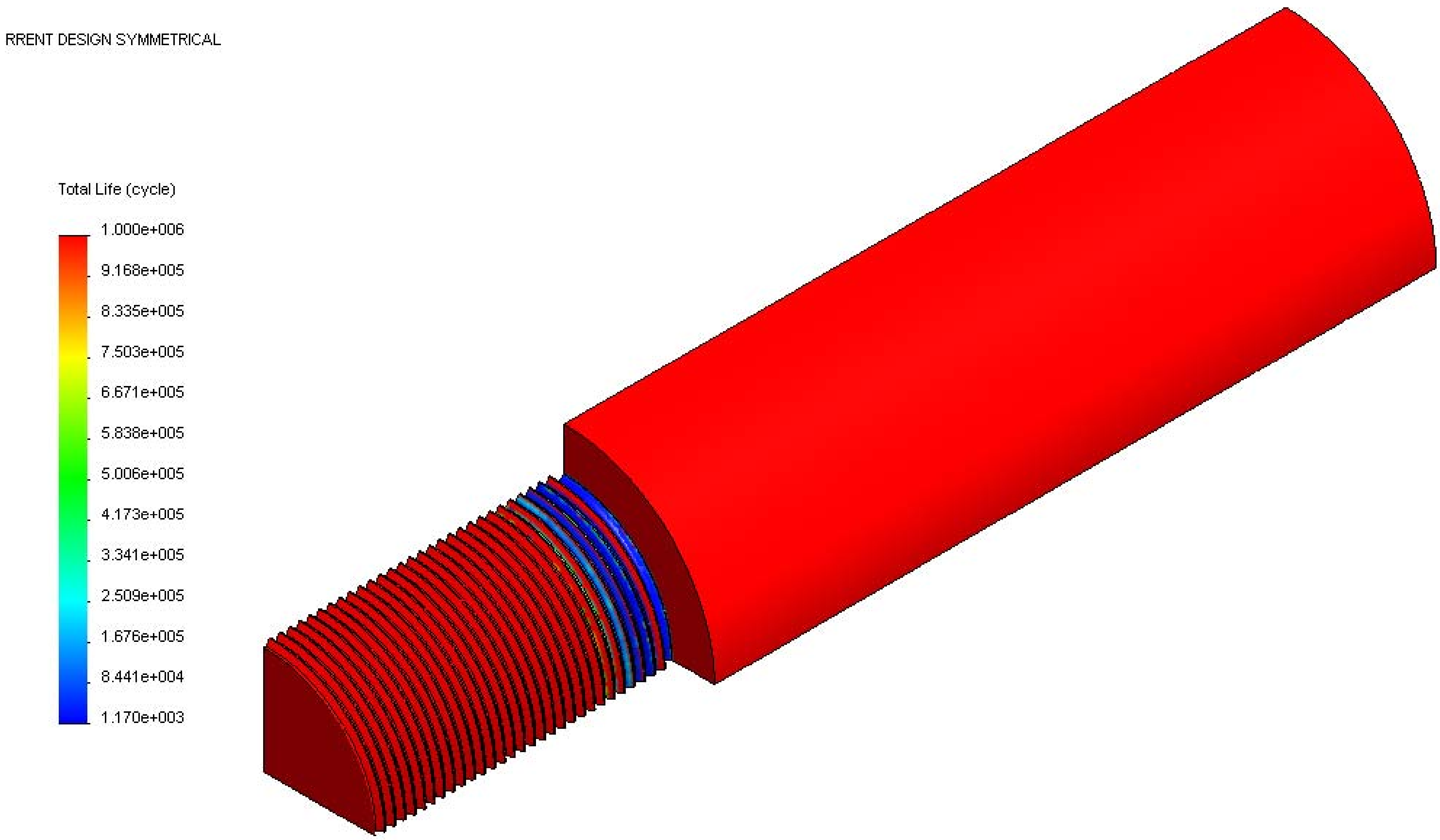

Figure 5.6 – Fatigue Life in Current Design – Full Engagement - View 1

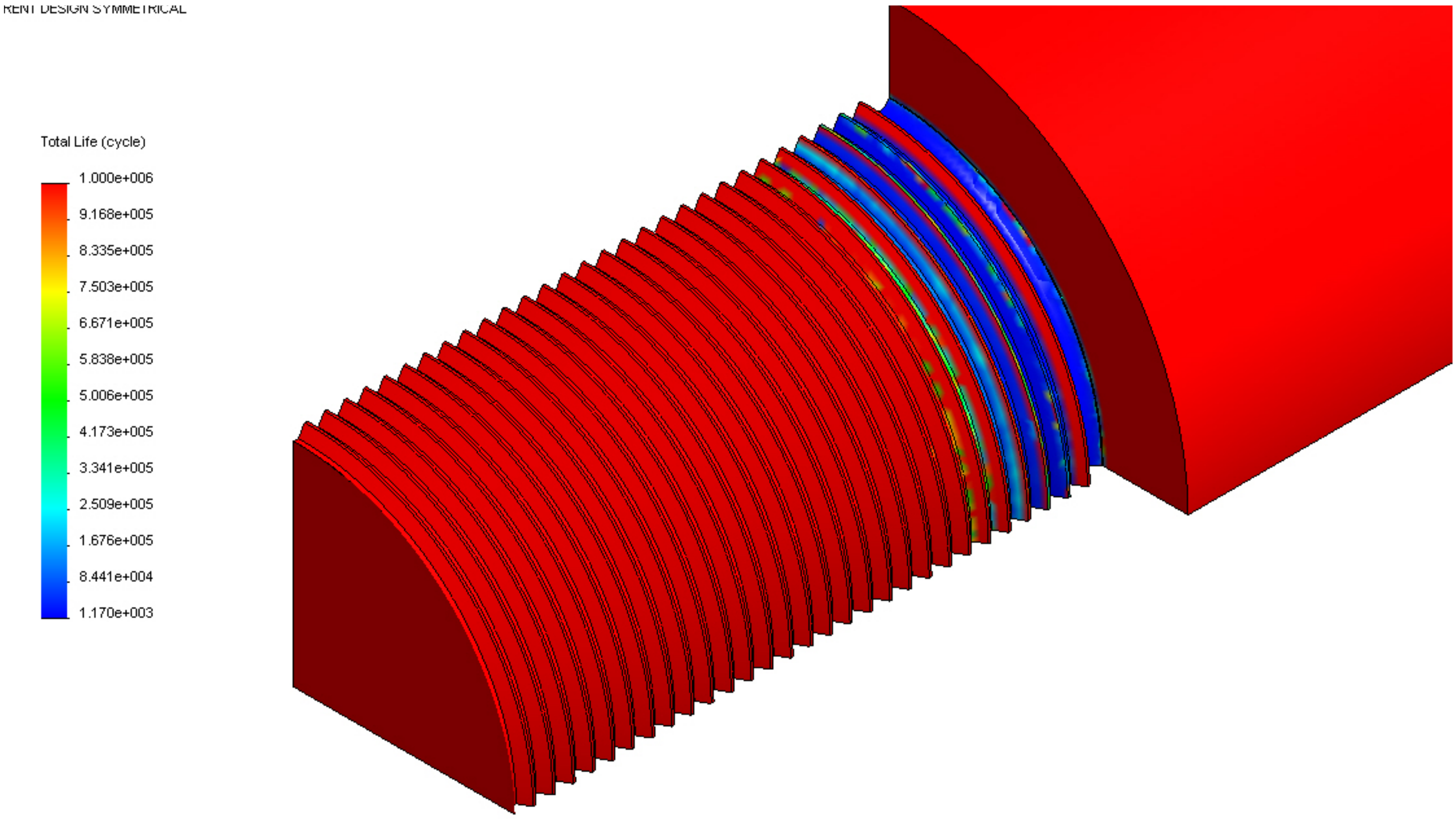

Figure 5.7 – Fatigue Life in Current Design – Full Engagement – View 2

B) Current Design Results – Partial Engagement

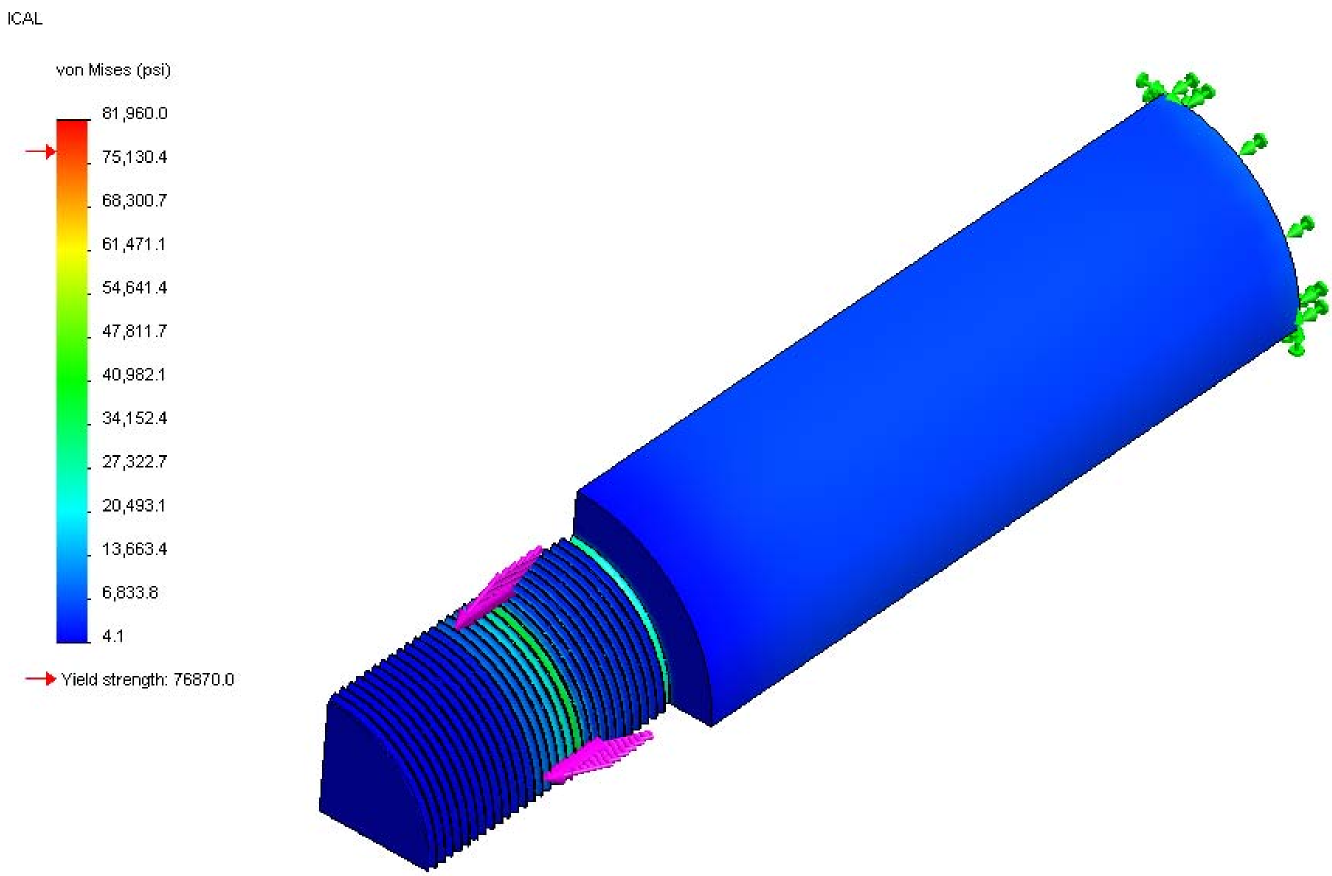

Figure 5.8 – VonMises Stress in Current Design – Partial Engagement - View 1

Partial engagement of the model revealed very similar stress plot results to that of the fully engaged model with the one noticeable difference in the maximum stress seen in the part. The partially engaged model shows a maximum stress of 81,960 psi compared to the maximum of 70,018 psi found in the fully engaged model. This small region of peak stress can be observed best in figure 5.11, but in general both the fully and partially engaged models seem to follow closely on the graphs (see figures 5.15, 5.16, & 5.17). The increased stress in the partially engaged model seems to indicate that there was less stress transferred through the remaining threads (there were fewer threads engaged), therefore this made the first six or so threads carry additional stress.

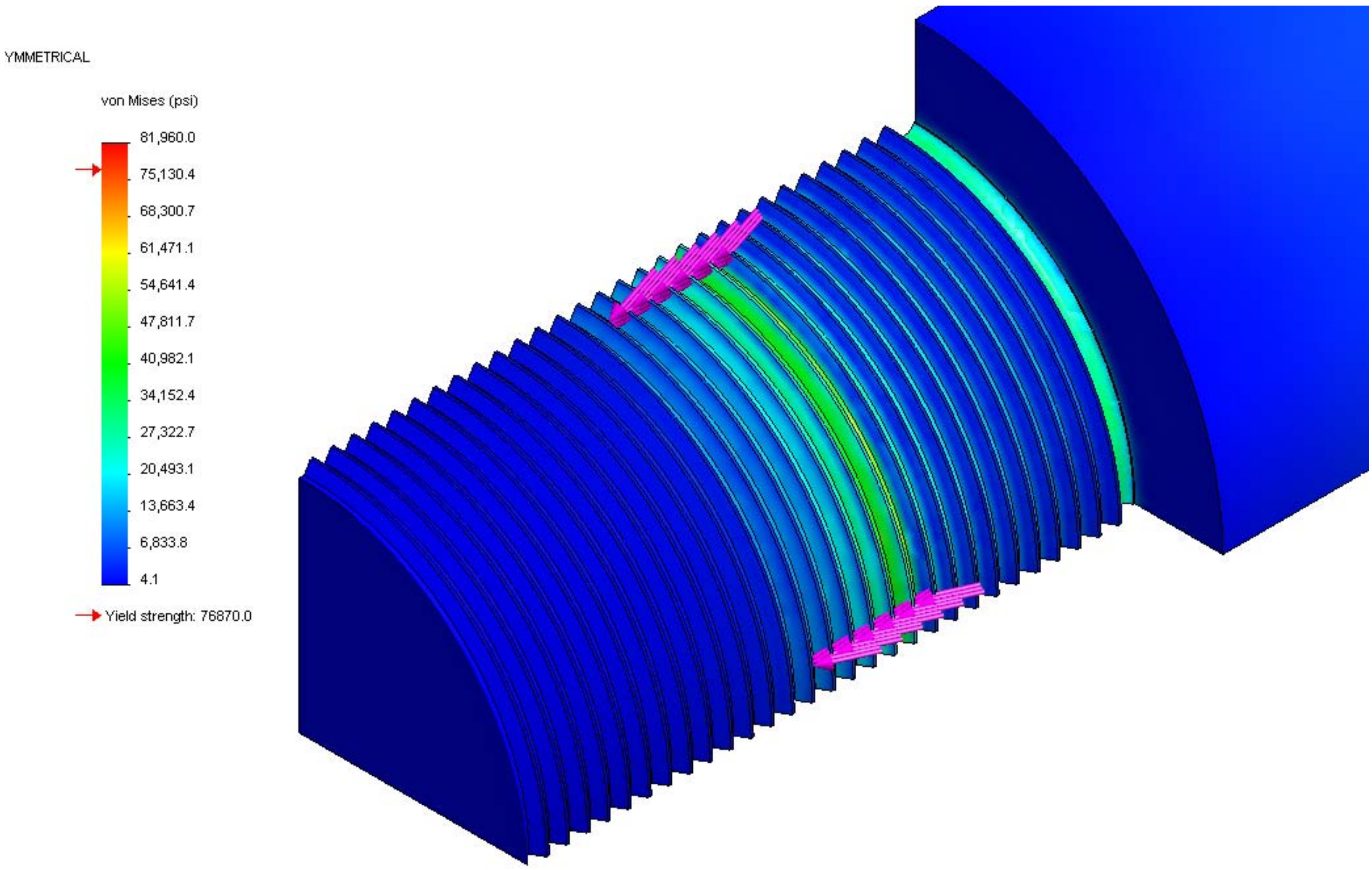

Figure 5.9 – VonMises Stress in Current Design – Partial Engagement - View 2

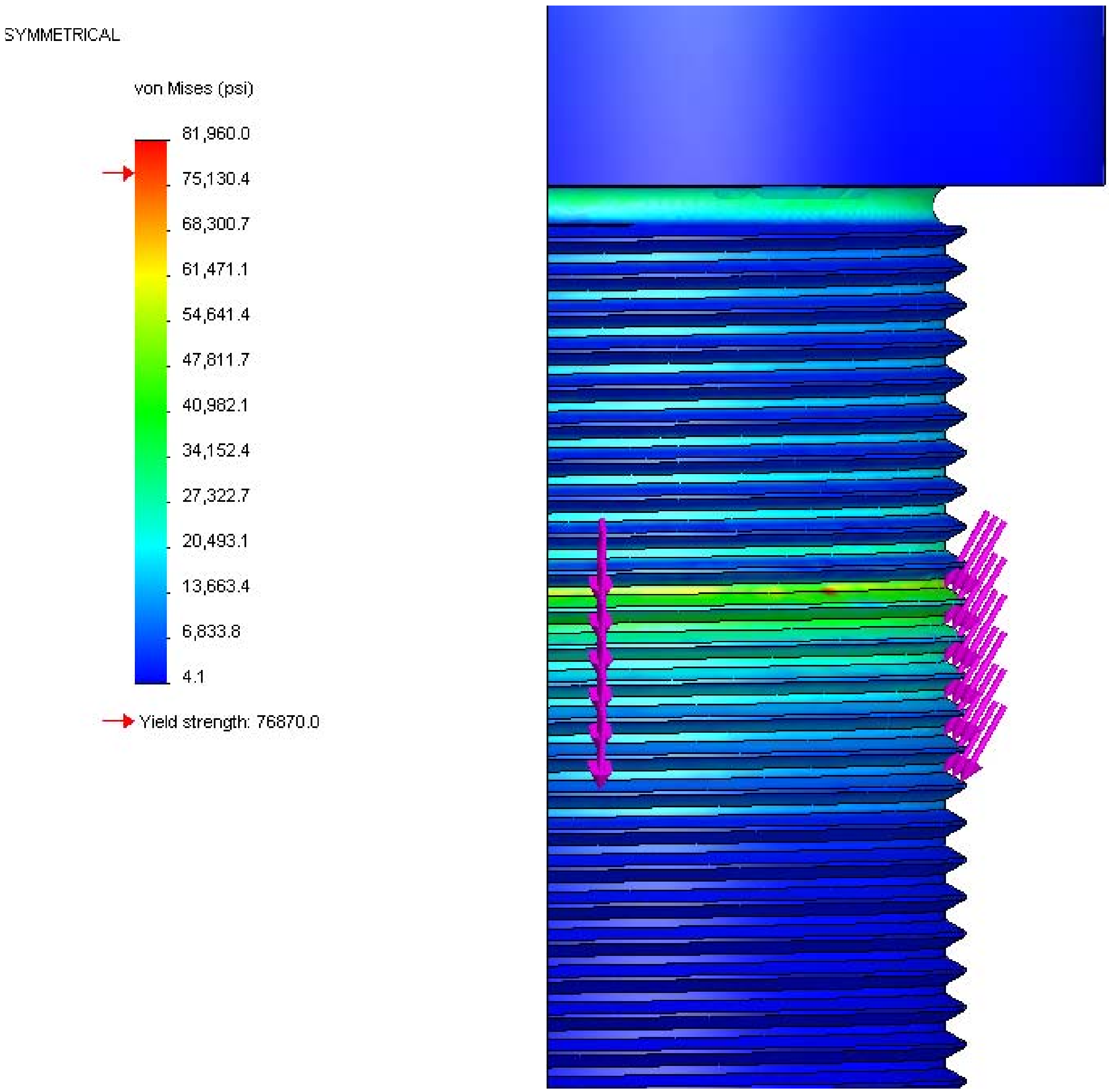

Figure 5.10 – VonMises Stress in Current Design – Partial Engagement - View 3

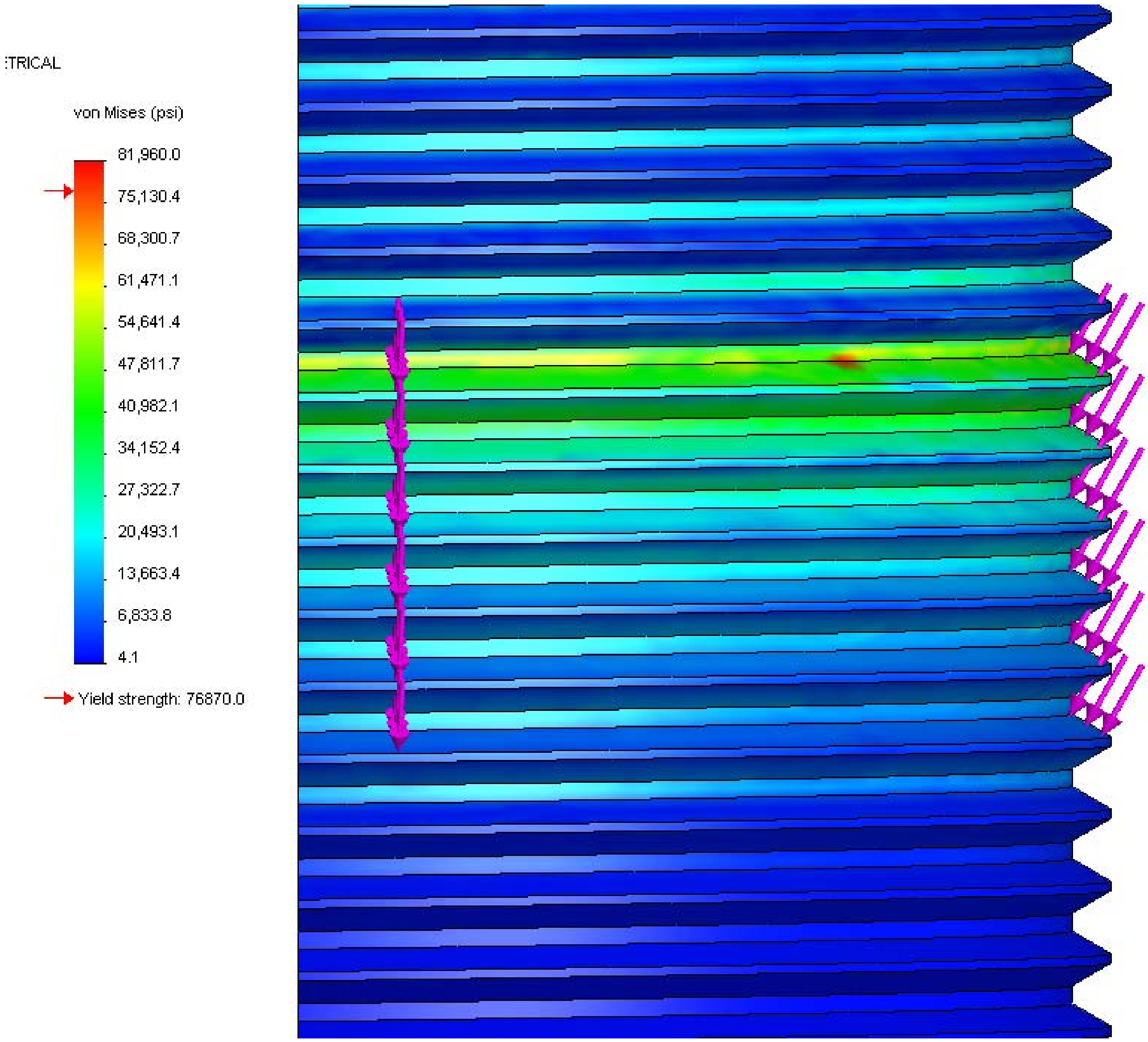

Figure 5.11 – VonMises Stress in Current Design – Partial Engagement - View 4

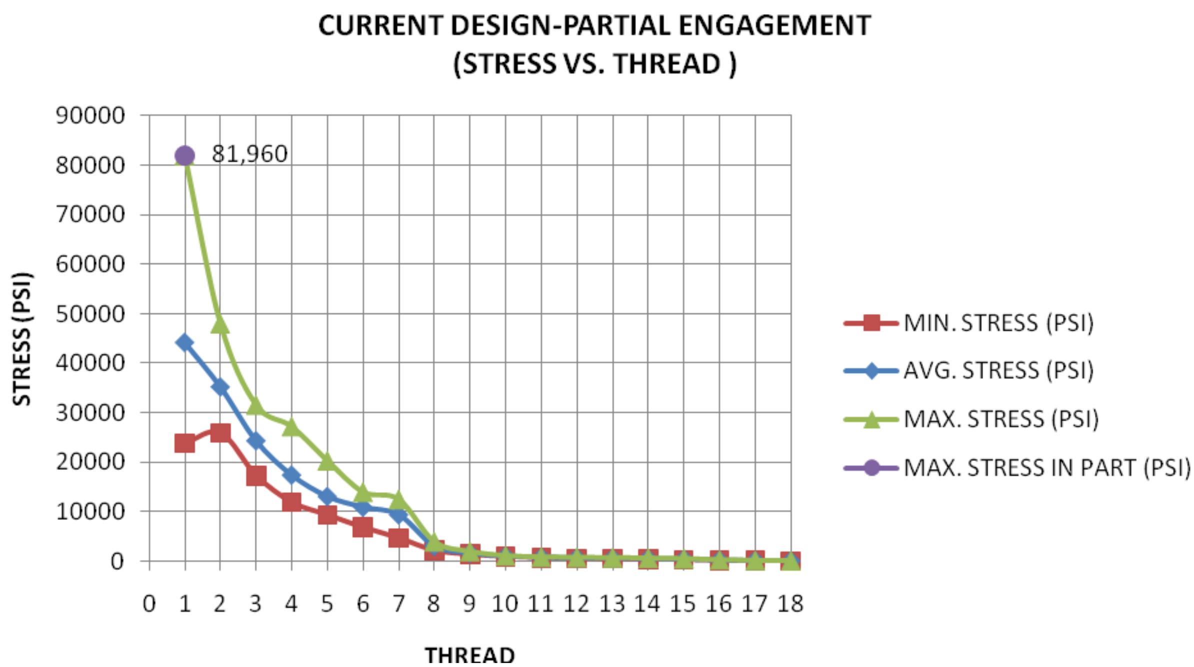

Figure 5.12 – VonMises Stress in Current Design – Partial Engagement – Minimum, Average, and Maximum Stress vs. Thread

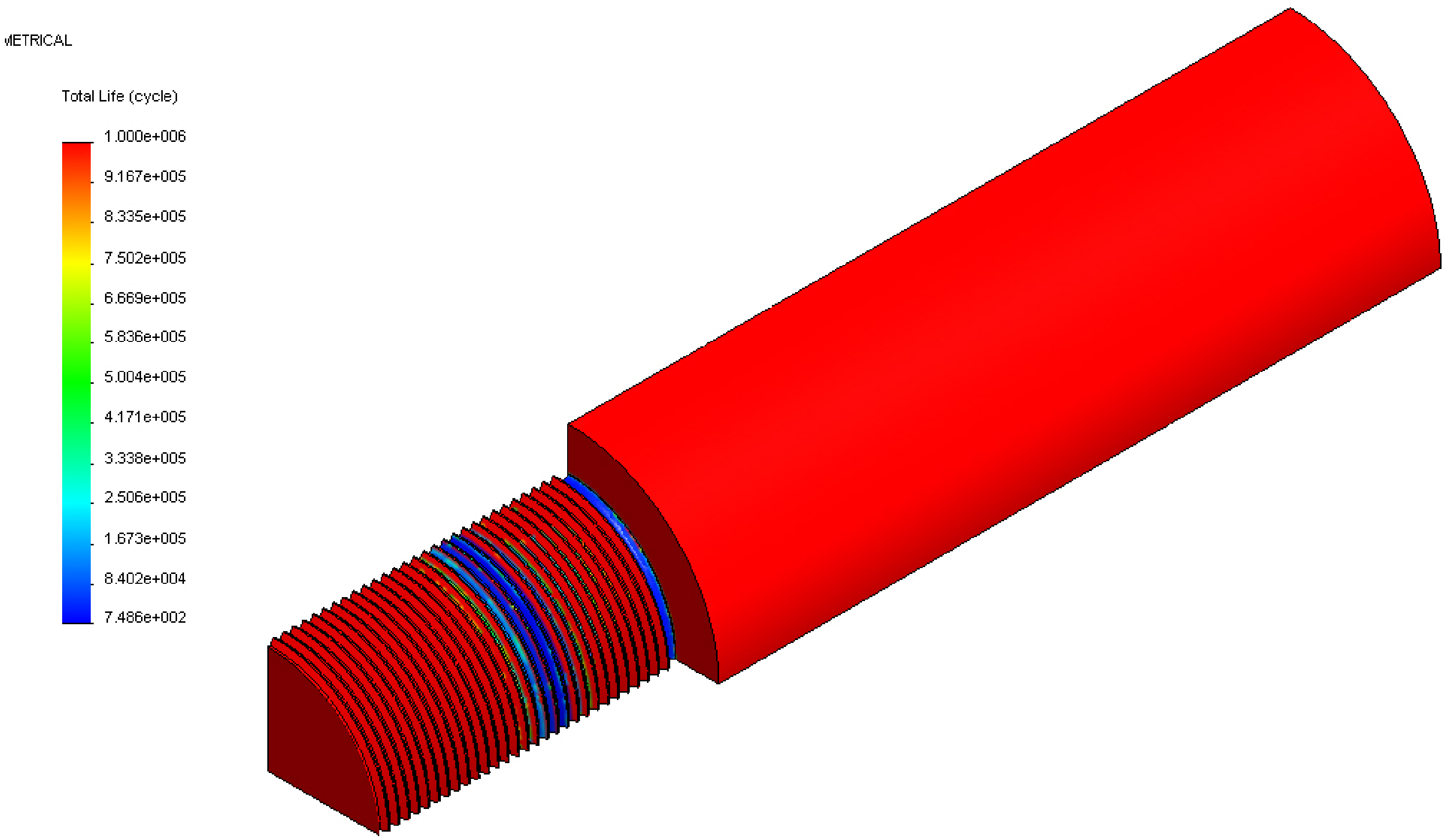

Figure 5.13 – Fatigue Life in Current Design – Partial Engagement – View 1

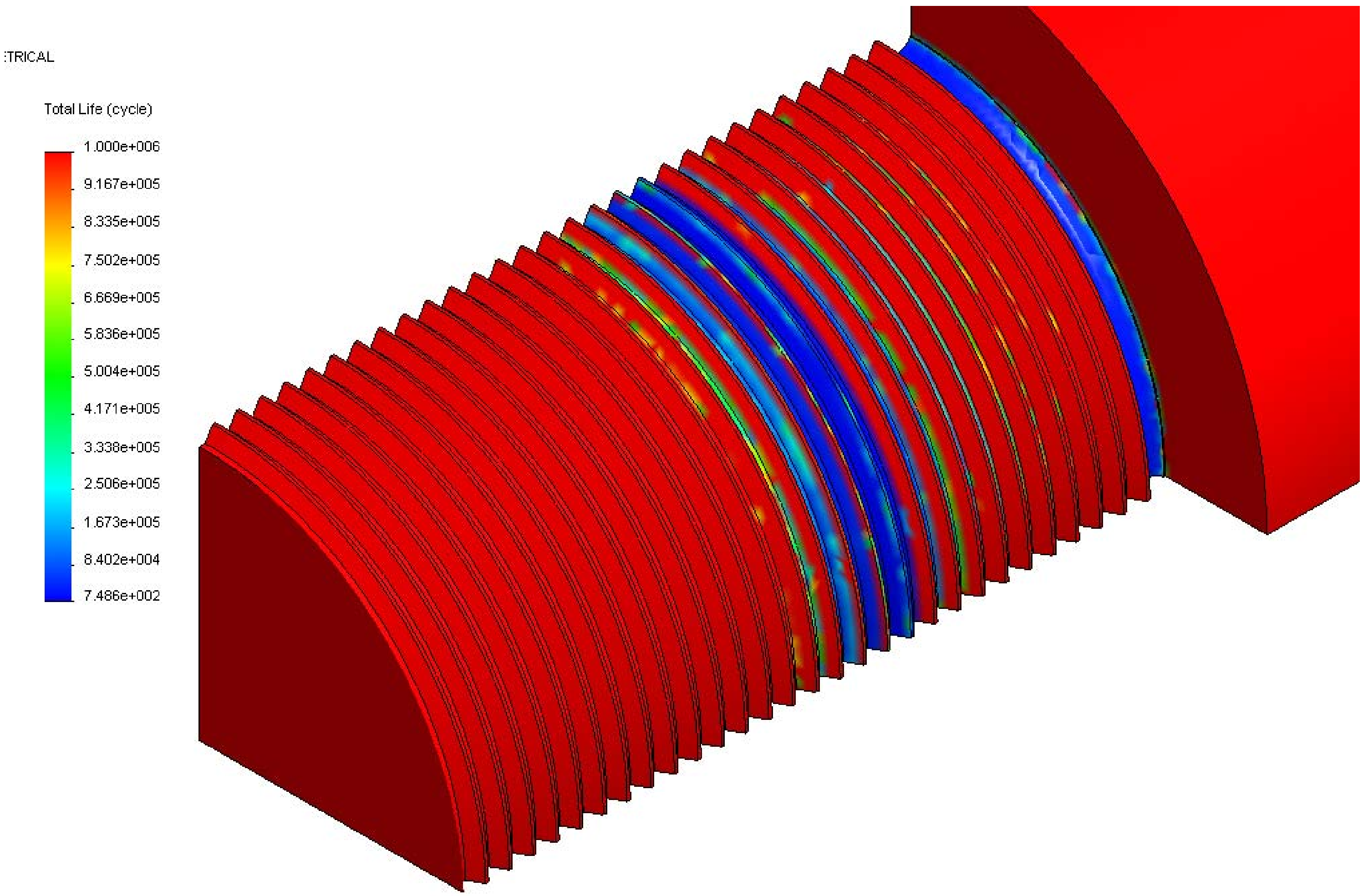

Figure 5.14 – Fatigue Life in Current Design – Partial Engagement – View 2

The following three graphs (figures 5.15, 5.16, & 5.17) compare the minimum, average, and maximum stress values obtained for the corresponding threads for both the current design partial and full engagement models. Both lines seem to track fairly close together and can be compared to the two horizontal lines that represent the yield and ultimate allowable stress for C1045 steel.

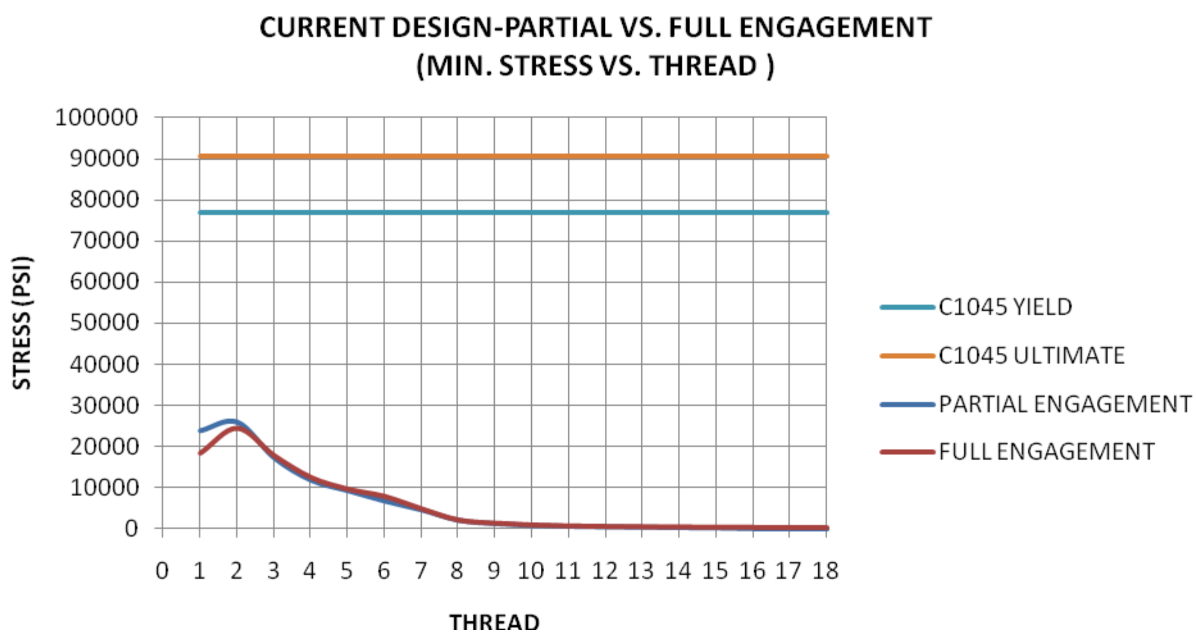

Figure 5.15 – VonMises Stress in Current Design – Partial and Full Engagement – Minimum Stress vs. Thread

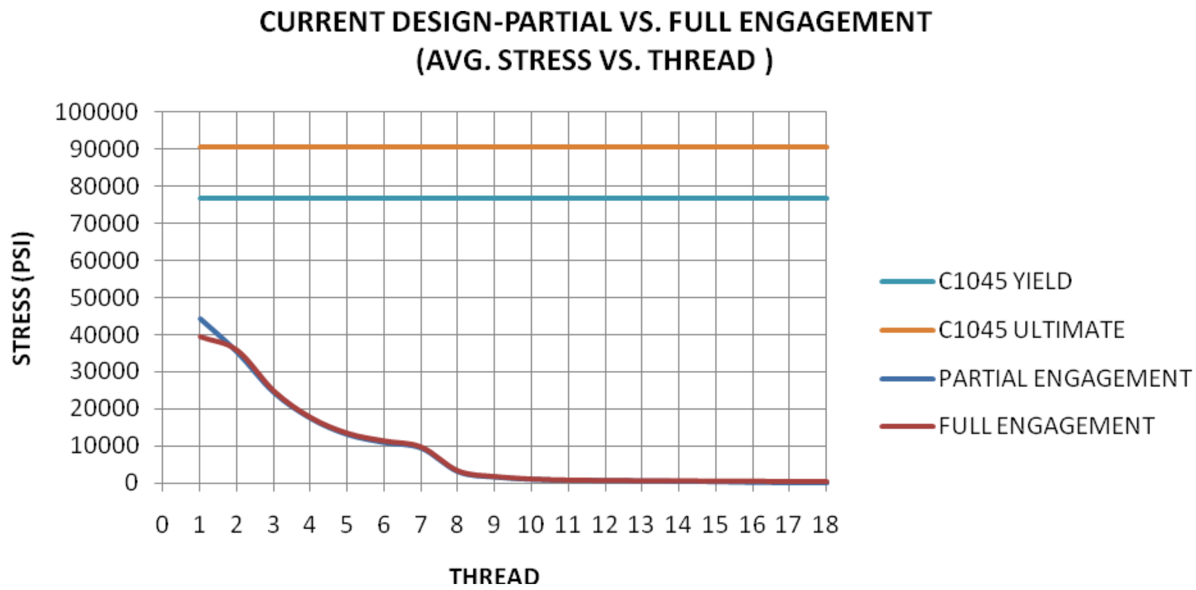

Figure 5.16 – VonMises Stress in Current Design – Partial and Full Engagement – Average Stress vs. Thread

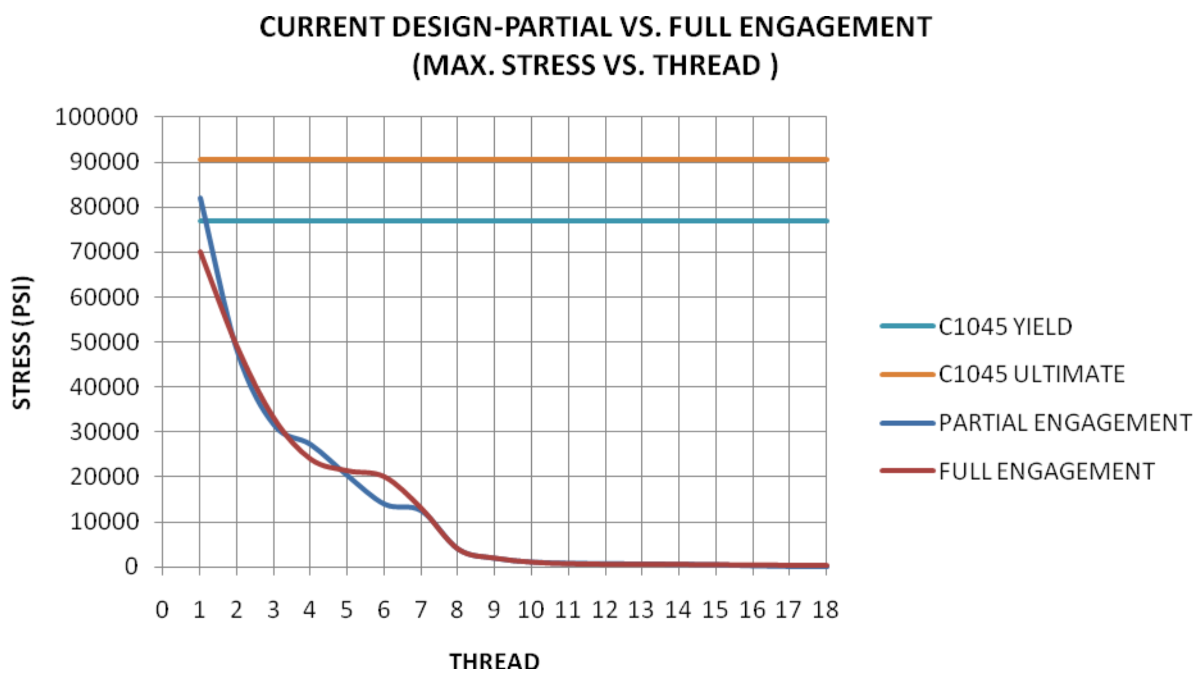

Figure 5.17 – VonMises Stress in Current Design – Partial and Full Engagement – Maximum Stress vs. Thread

C) Alternative Design Results – Full Engagement

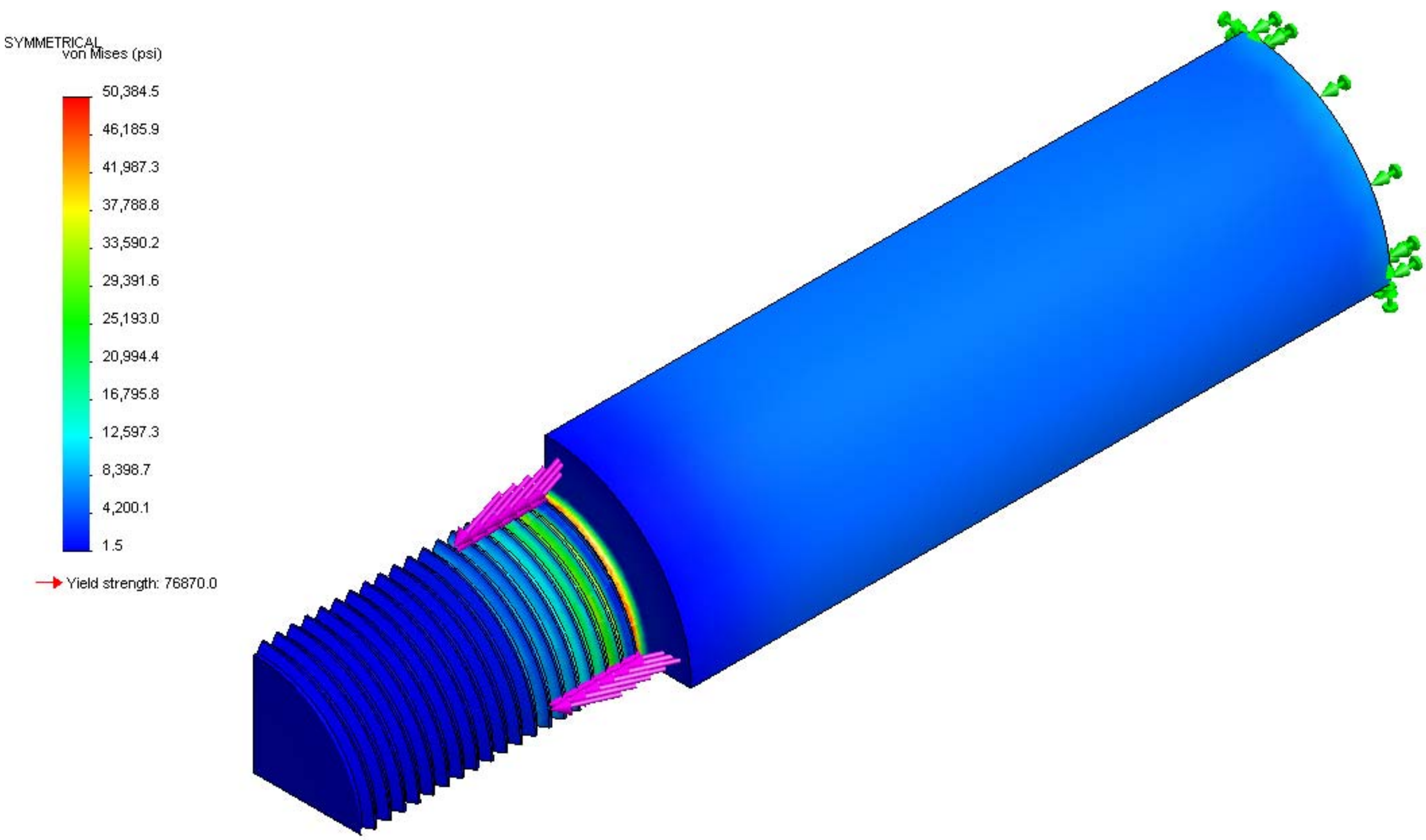

Figure 5.18 – VonMises Stress in Alternative Design – Full Engagement - View 1

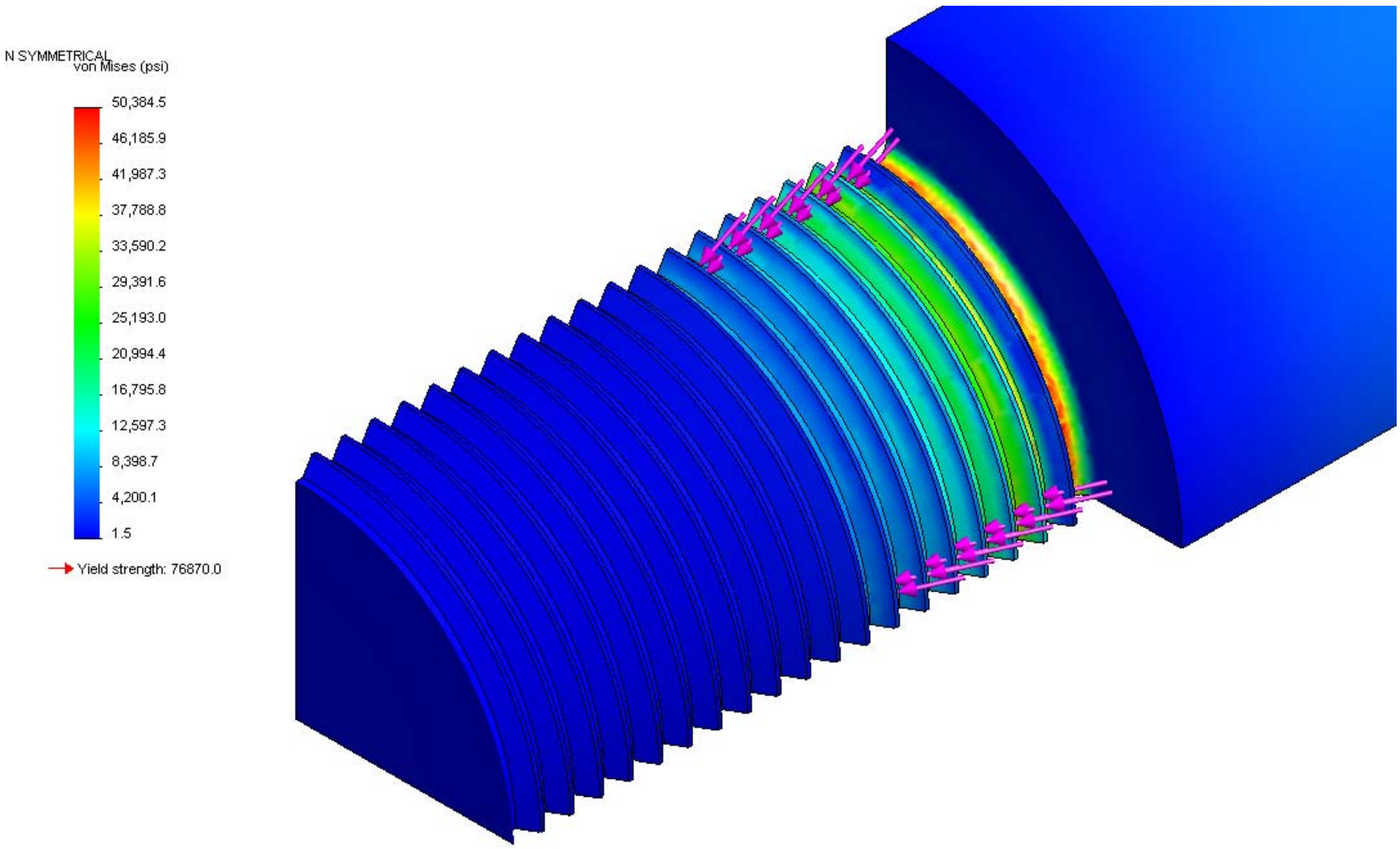

Figure 5.19 – VonMises Stress in Alternative Design – Full Engagement - View 2

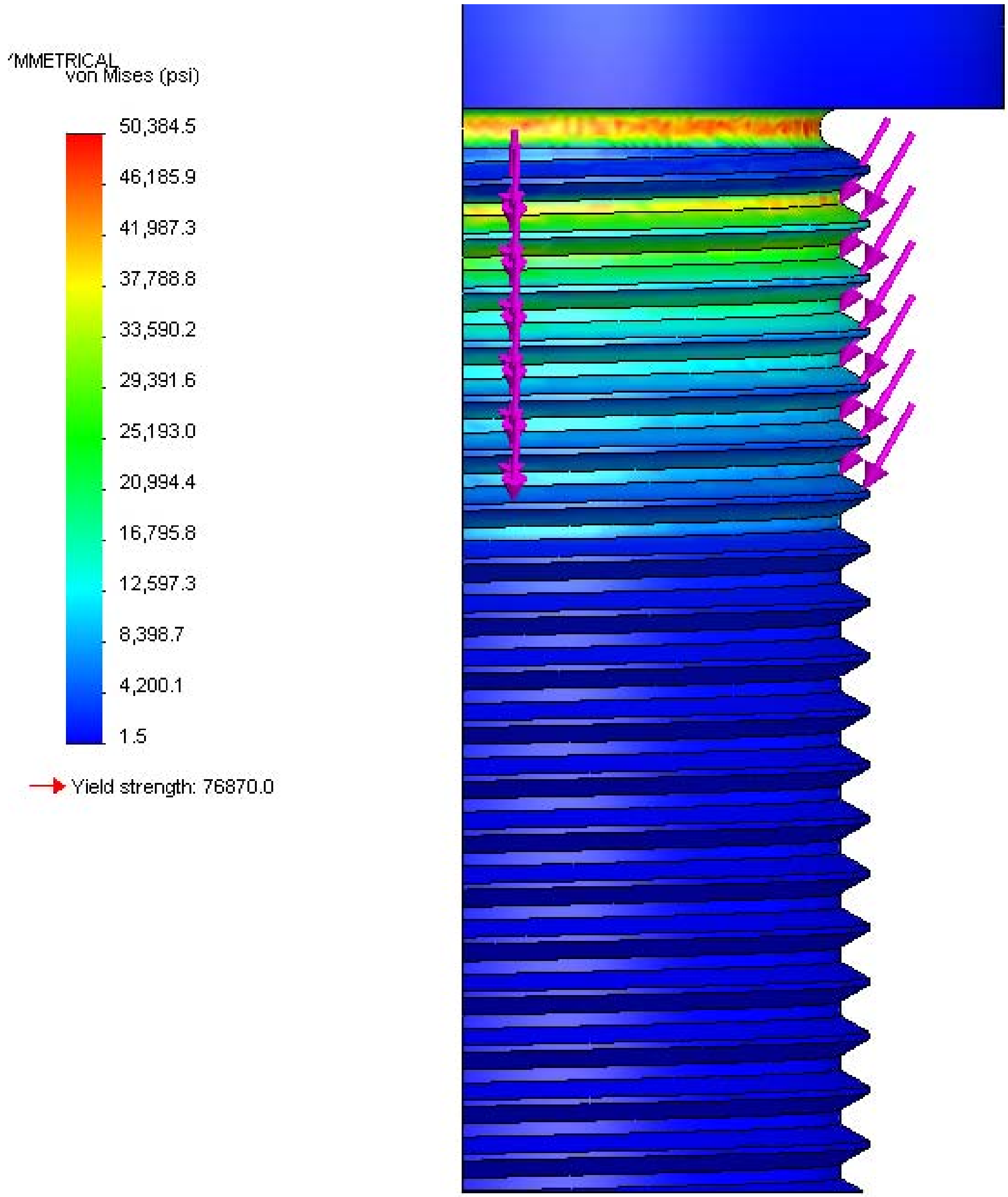

Figure 5.20 – VonMises Stress in Alternative Design – Full Engagement - View 3

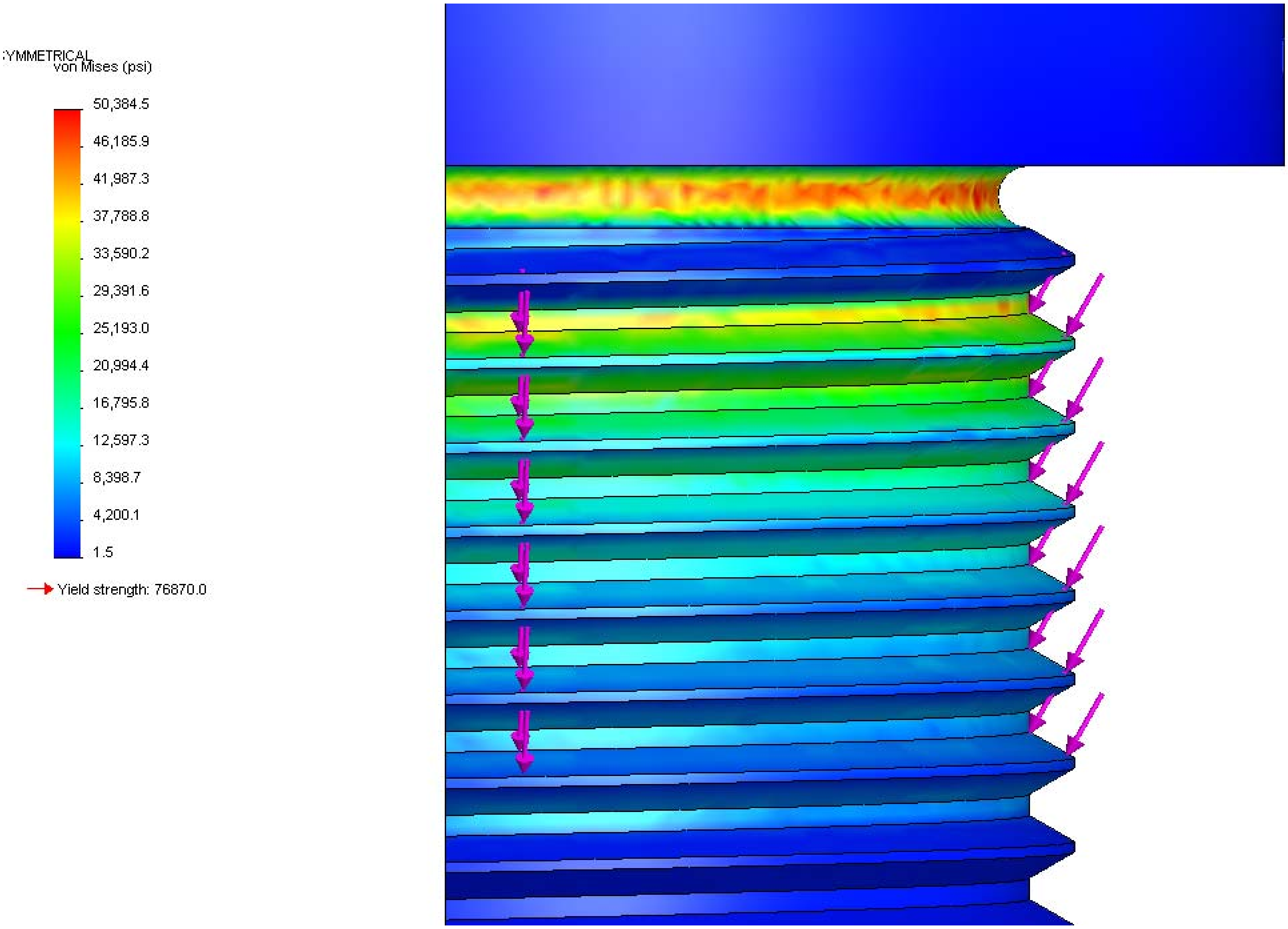

Figure 5.21 – VonMises Stress in Alternative Design – Full Engagement - View 4

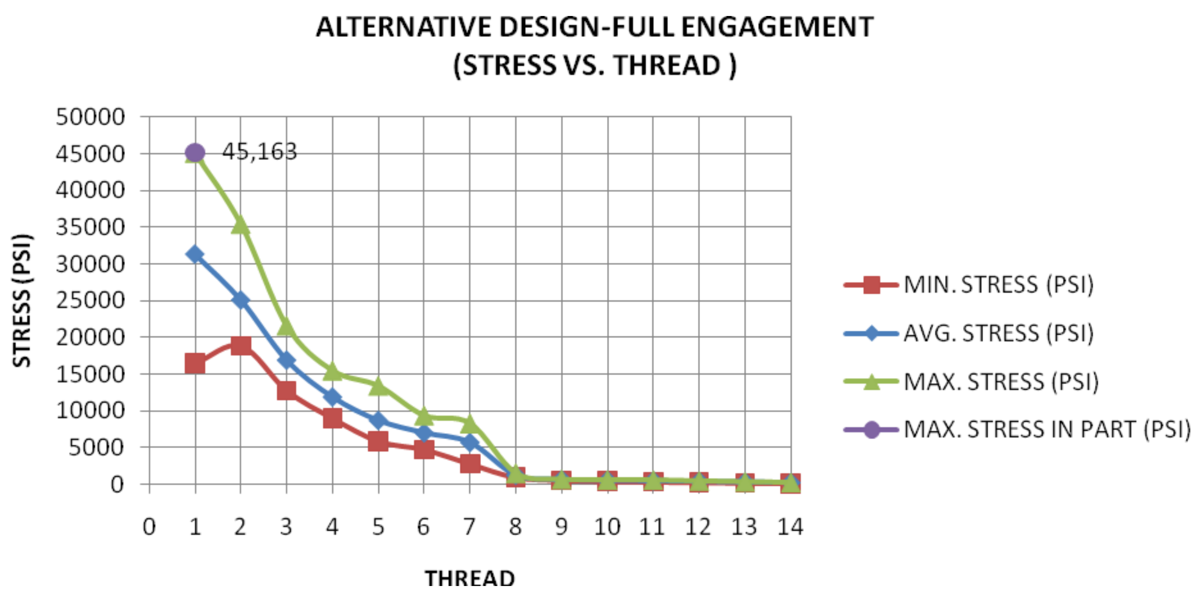

Figure 5.22 – VonMises Stress in Alternative Design – Full Engagement – Minimum, Average, and Maximum Stress vs. Thread

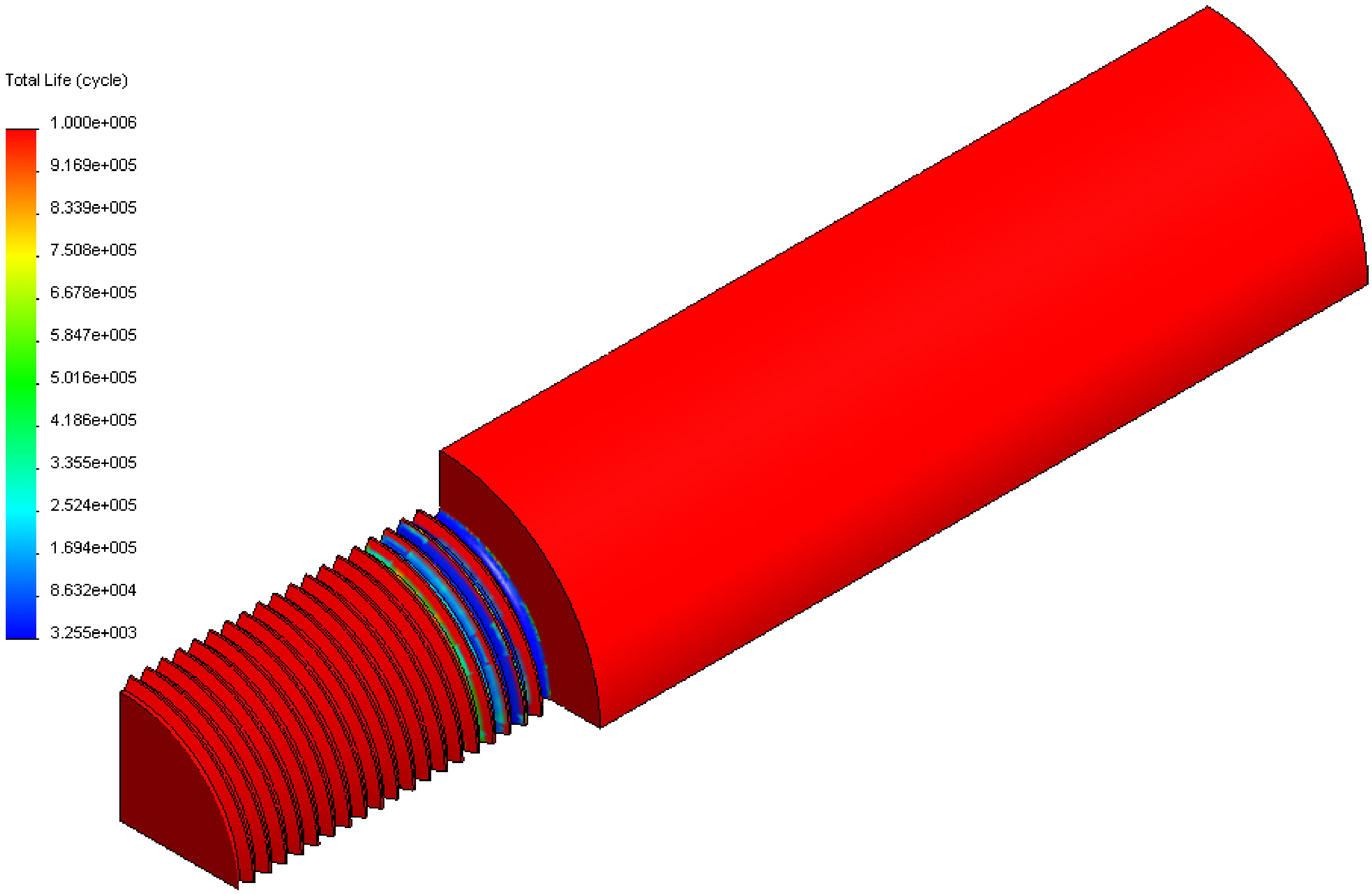

Figure 5.23 – Fatigue Life in Alternative Design – Full Engagement - View 1

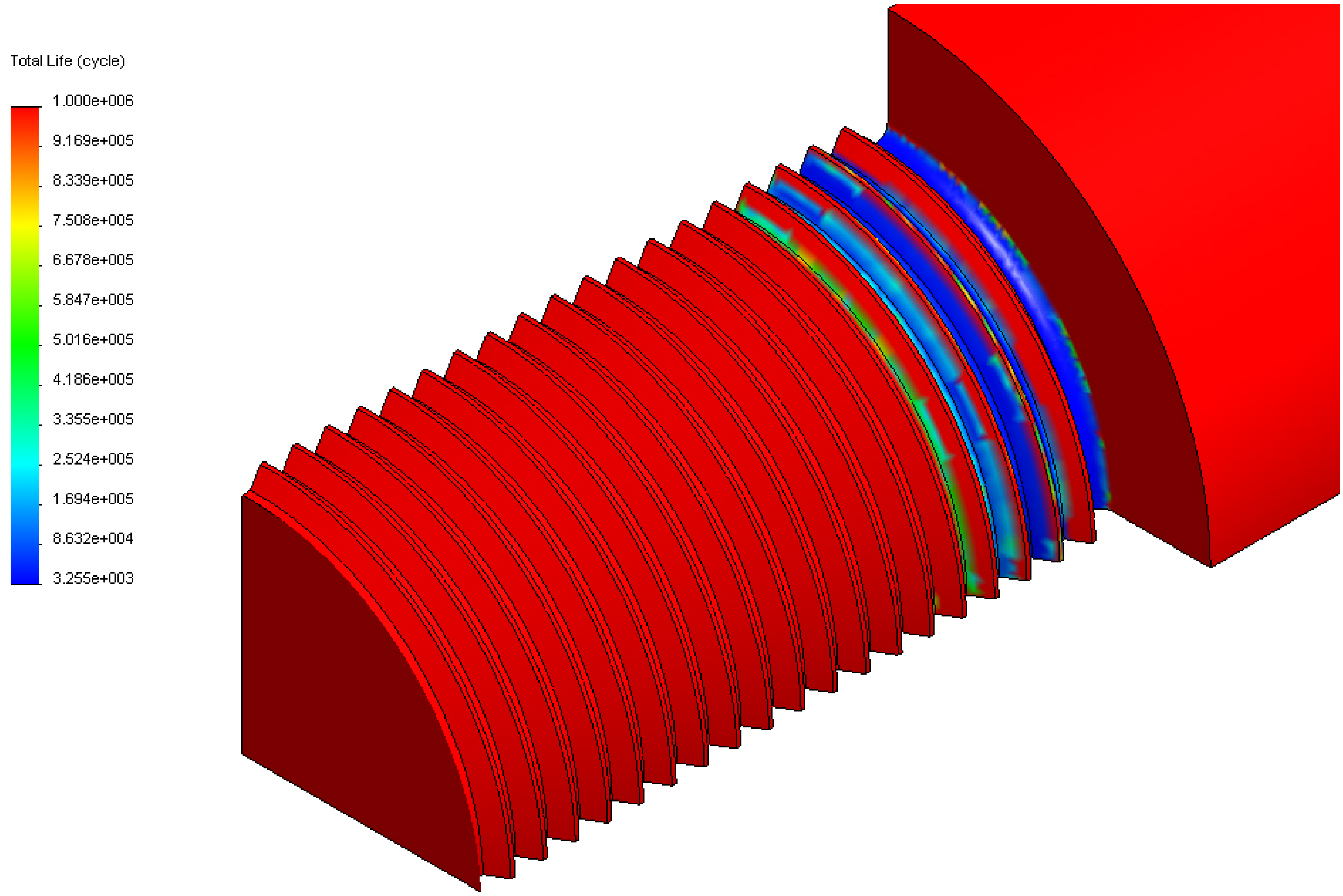

Figure 5.24 – Fatigue Life in Alternative Design – Full Engagement - View 2

D) Alternative Design Results – Partial Engagement

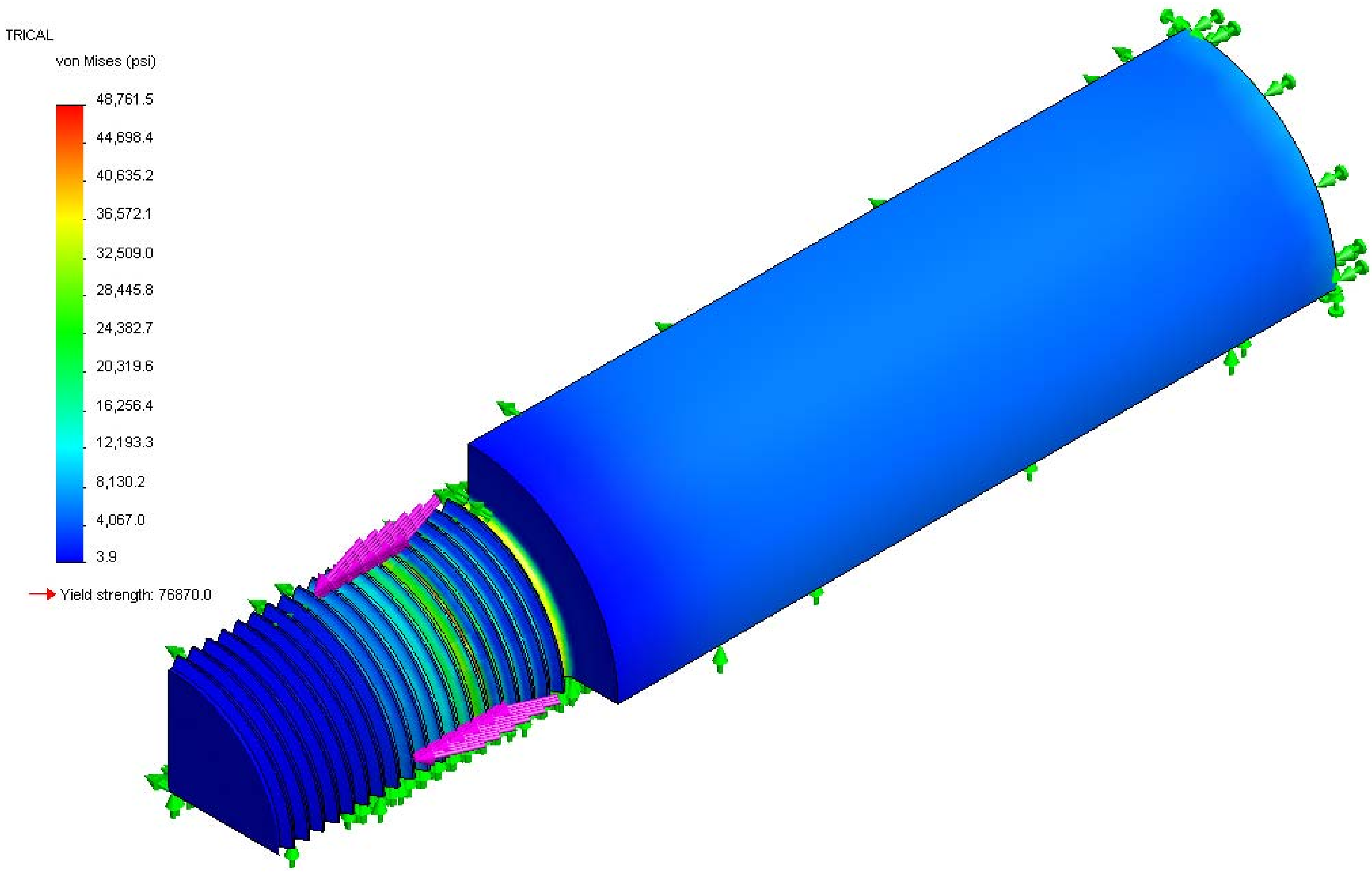

Figure 5.25 – VonMises Stress in Alternative Design – Partial Engagement - View 1

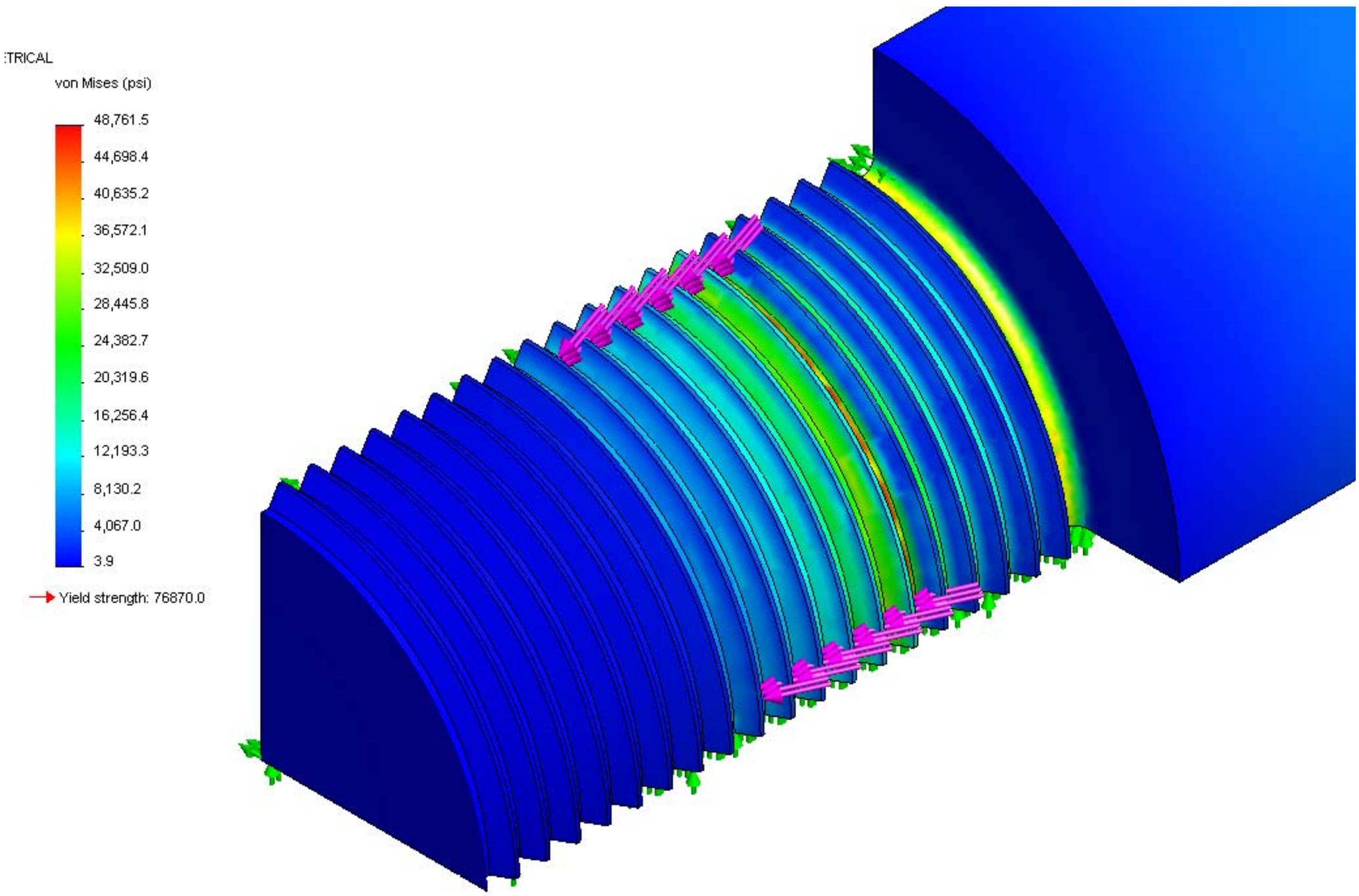

Figure 5.26 – VonMises Stress in Alternative Design – Partial Engagement - View 2

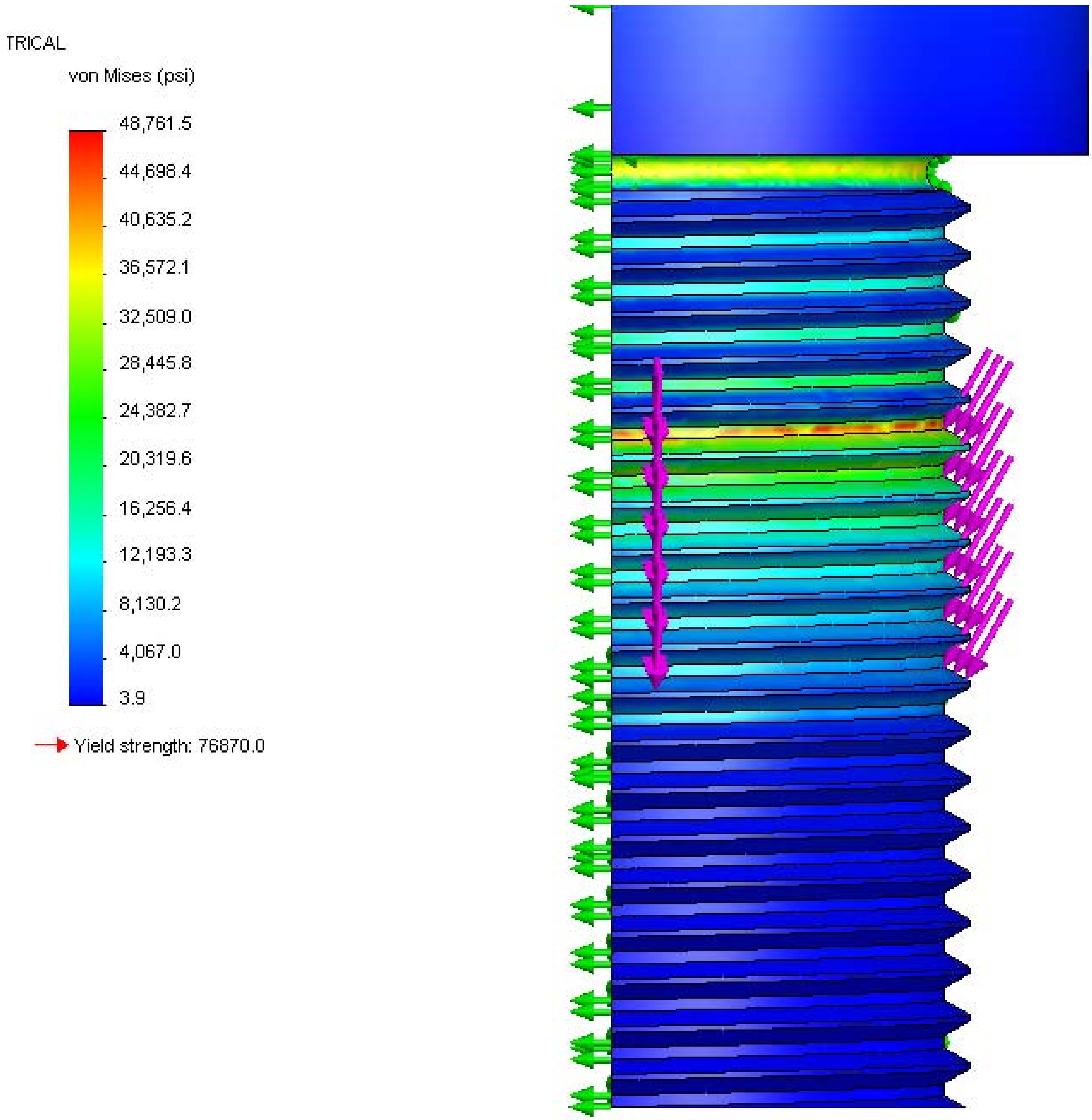

Figure 5.27 – VonMises Stress in Alternative Design – Partial Engagement - View 3

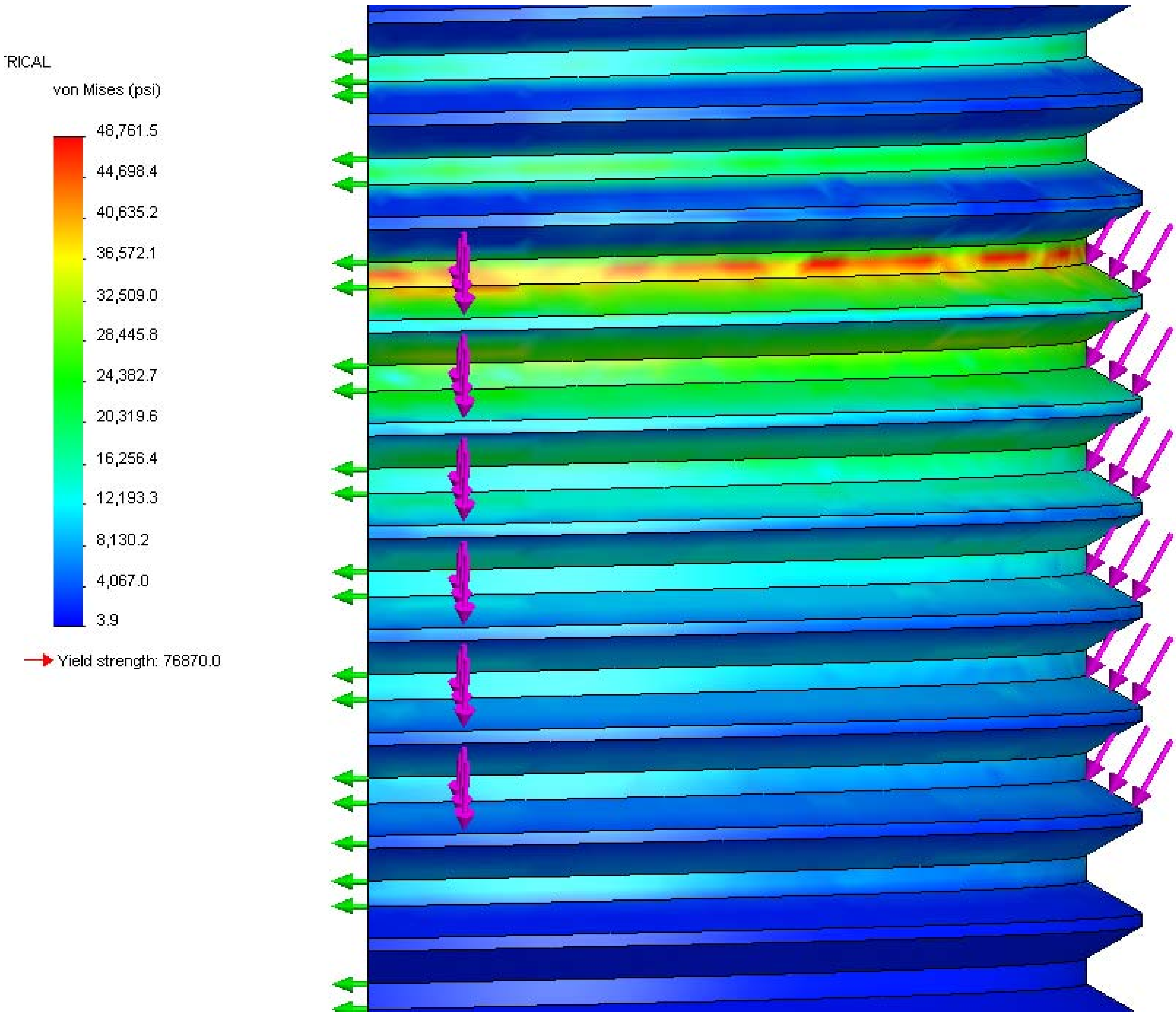

Figure 5.28 – VonMises Stress in Alternative Design – Partial Engagement - View 4

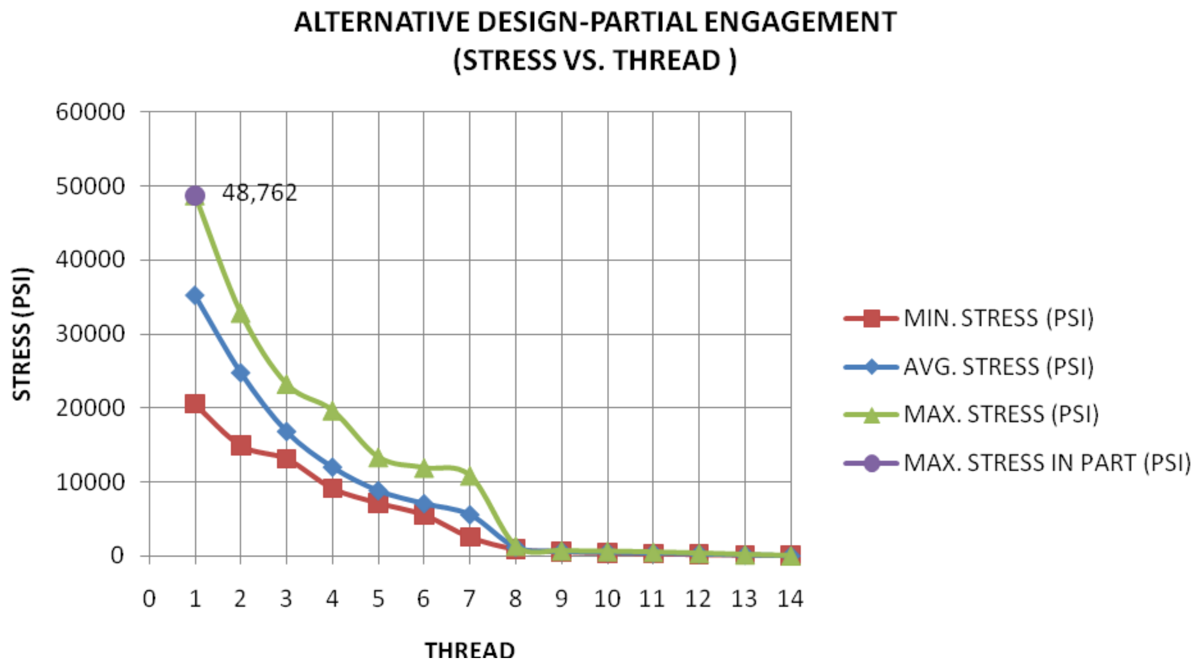

Figure 5.29 – VonMises Stress in Alternative Design – Partial Engagement – Minimum, Average, and Maximum Stress vs. Thread

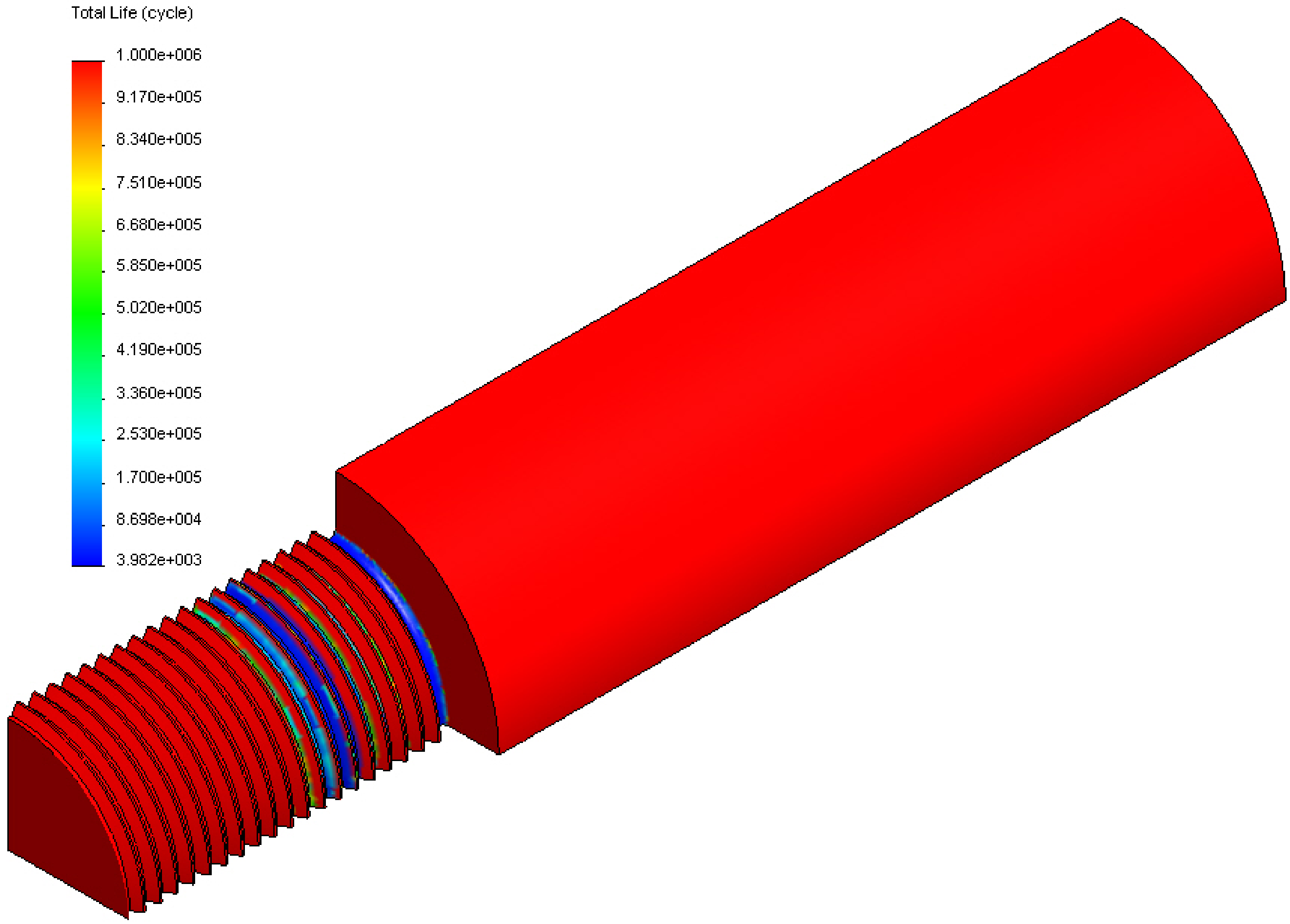

Figure 5.30 – Fatigue Life in Alternative Design – Partial Engagement - View 1

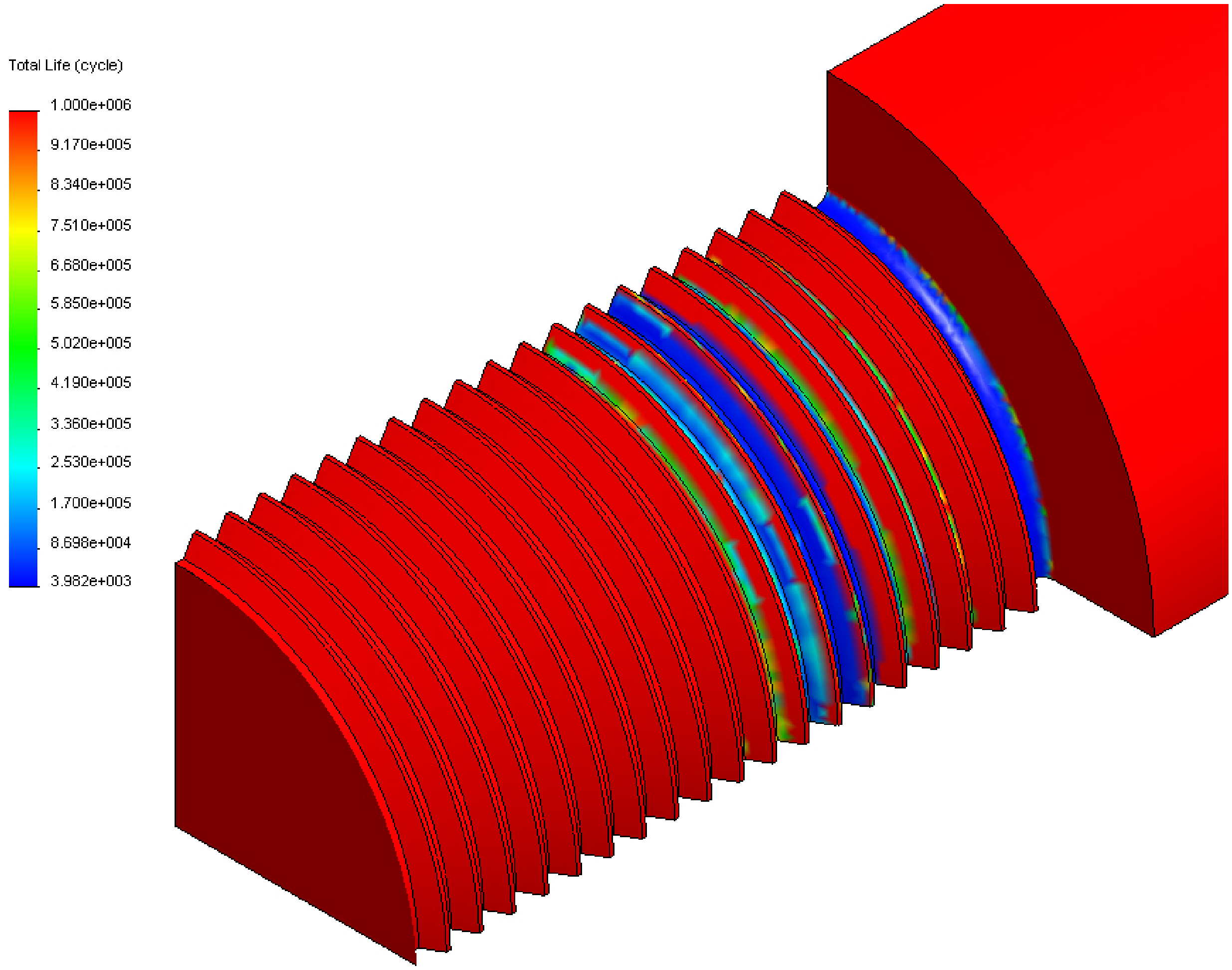

Figure 5.31 – Fatigue Life in Alternative Design – Partial Engagement - View 2

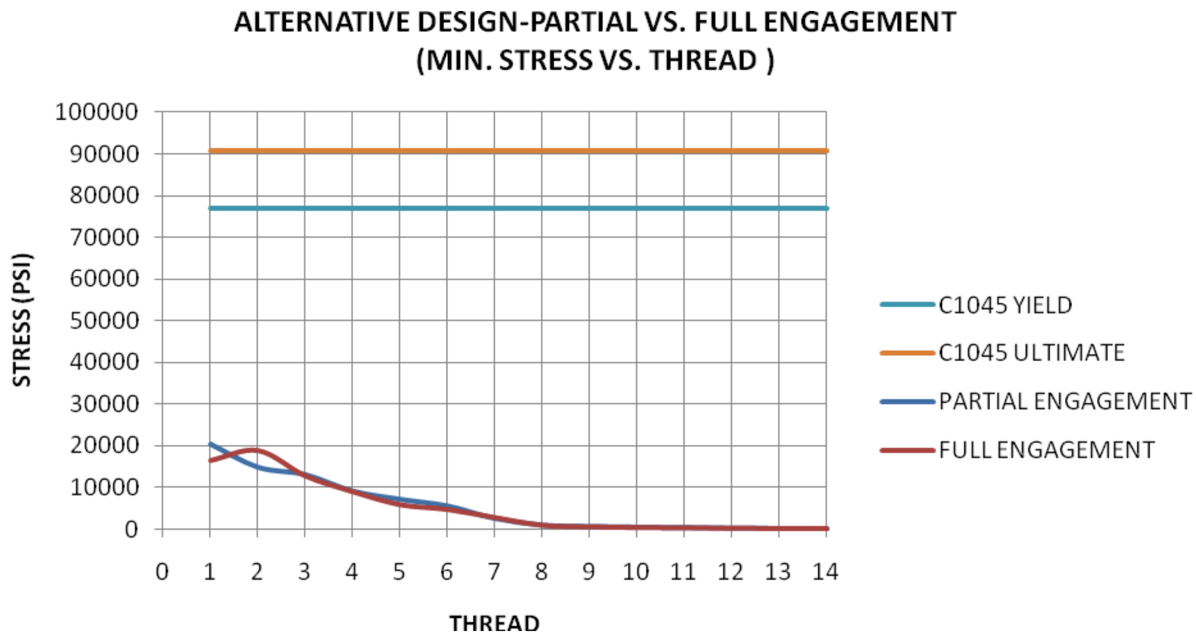

Figure 5.32 – VonMises Stress in Alternative Design – Partial and Full Engagement – Minimum Stress vs. Thread

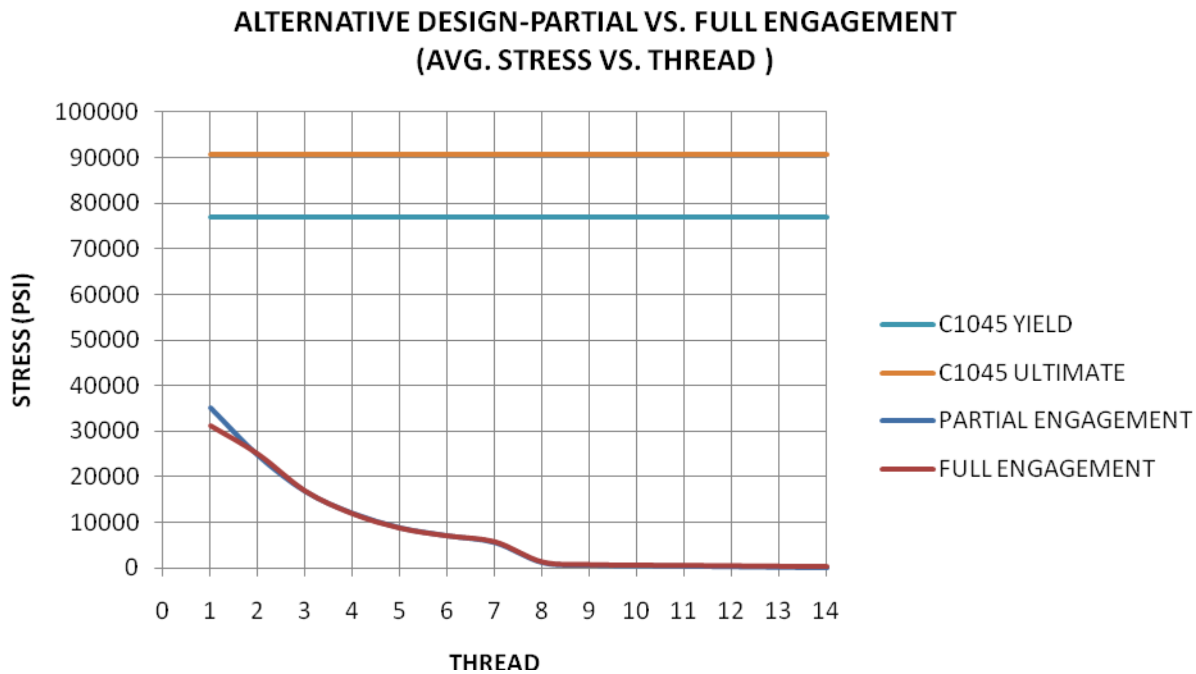

Figure 5.33 – VonMises Stress in Alternative Design – Partial and Full Engagement – Average Stress vs. Thread

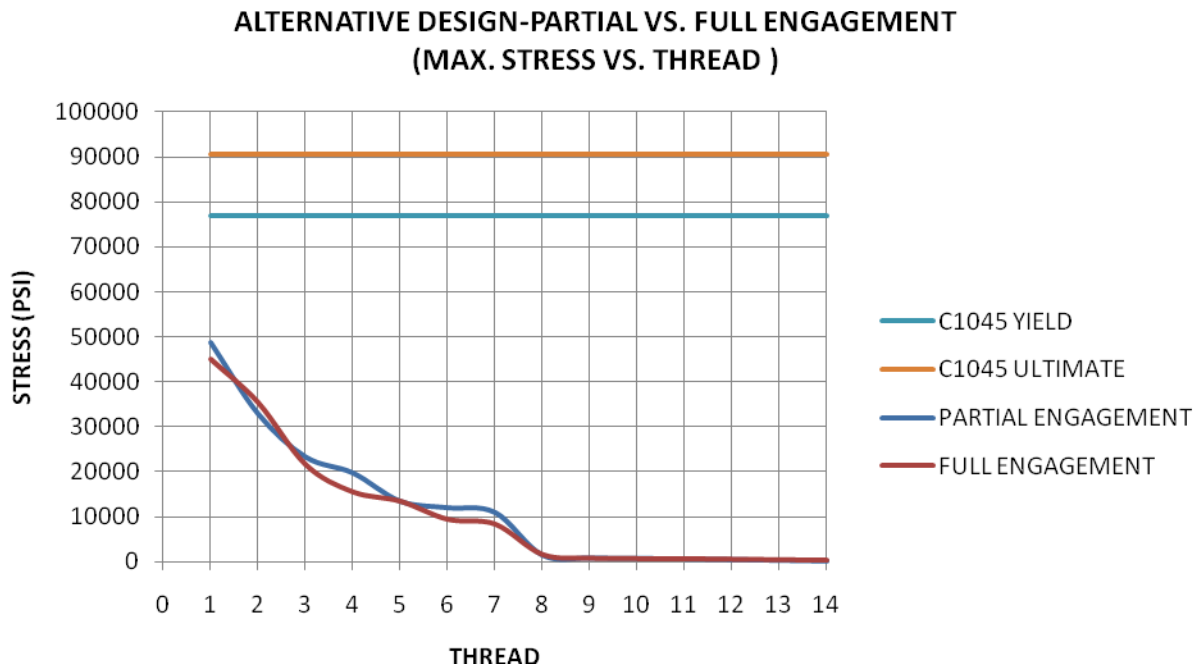

Figure 5.34 – VonMises Stress in Alternative Design – Partial and Full Engagement – Maximum Stress vs. Thread

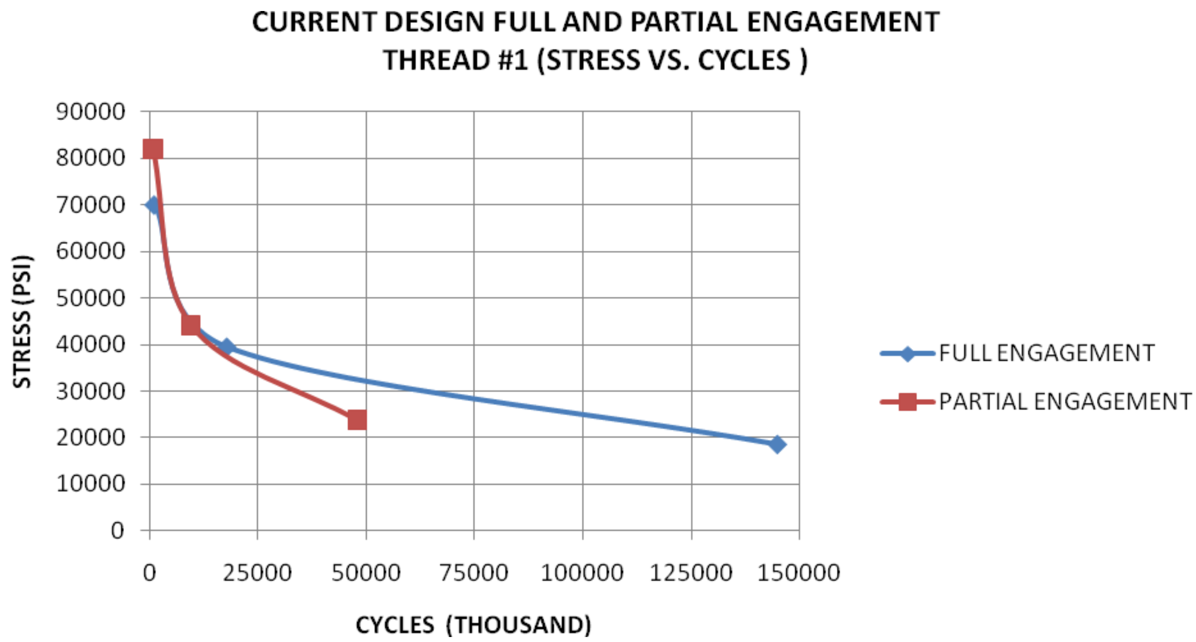

Figure 5.35 – Fatigue Plot for Current Design (Full and Partial Engagement)

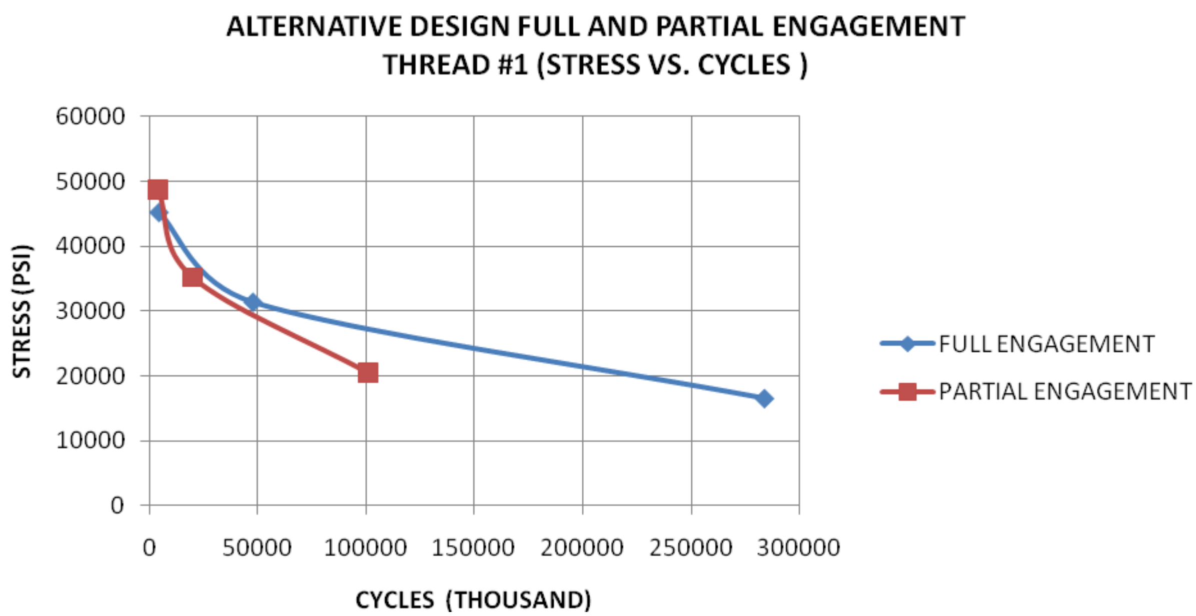

Figure 5.36 – Fatigue Plot for Alternative Design (Full and Partial Engagement)

After completion of the stress plots, fatigue studies were completed for both the current design and alternative design models. These were ran for both models in both the full and partial engagement load positions and the results can be seen in figures 5.6, 5.7, 5.13, 5.14, 5.23, 5.24, 5.30, and 5.31. Graphs for each model were also generated using the minimum, average, and maximum cycles allowed for the corresponding stress on thread #1 (See figures 5.35 and 5.36). By referencing figure 5.7 it can be seen that the surfaces shaded in red can easily accept loading cycles of 1 million whereas the blue region shows fatigue occurring around 1,170 cycles. In comparison figure 5.14 shows a minimum of 748 cycles near thread #1 and 1 million cycles throughout the rest of the model. This represents a minimal difference between the full and partial engagement models.

Review of the alternative design fatigue results show a definite improvement in cycle life. The full engagement model indicated a minimum fatigue value of 3,255 cycles, while the partial engagement model showed 3982 cycles. Both models peaked at over 1 million cycles throughout the remaining geometry of the part. After further investigation it was found that the minimum cycle condition (3,255 cycles) for the partial engagement model was found at thread #1 and the minimum cycle condition (3,982 cycles) for the full engagement model was found on the surface of the thread relief. The minimum number of allowable cycles on thread #1 for the full engagement model was found to be 4,653 cycles.

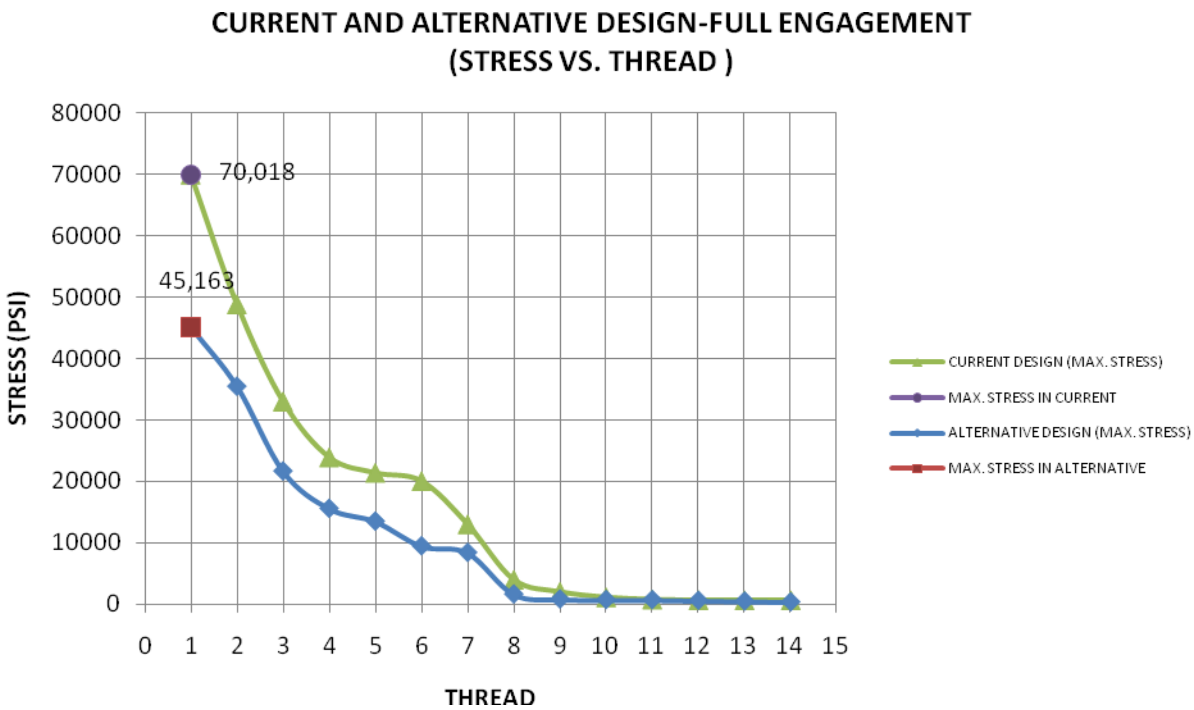

Figure 5.37 – Maximum Stress Plot for Current and Alternative Design (Full Engagement)

6 - Conclusion

After review of the stress plots, fatigue plots, and supporting data it can be concluded that a redesign of the threads on the Steering Roll Cylinder would help reduce failure and increase service life. Figure 5.37 above compares the full engagement models of the current design and the alternative design. Full engagement would be optimal in reducing the maximum stress in thread #1 as indicated by the greater maximum stress in thread #1 of the partially engaged model. A hand calculation for minimum thread engagement was also completed and verified that a minimum of 1.768 inches of threads should be engaged to prevent stripping (see calculation C.5).

The current design has a maximum stress in thread #1 of 70,018 psi which is about 25,000 psi greater than the maximum stress value in the alternative design. The two curves begin to merge together around the 9th or 10th thread confirming the minimal load carrying contribution of the additional threads. Although the maximum stress value in the current design is about 7,000 psi below the yield stress of 76,870 psi for C1045 steel and well below its ultimate stress of 90,648 psi, there are still potential avenues for localized yielding of the component. This in turn can lead to failure of thread #1, which will then transfer the majority of the load to thread #2, and so on. This will eventually lead to complete thread stripping and cylinder failure. Other potential factors involved with thread failure can include excessive working loads, fluid pressure spikes, impact loading, material quality, manufacturing defects, and environmental conditions.

By choosing the alternative design the stress in the threads can be reduced significantly, however there are some disadvantages with moving to a coarser thread. They include the forfeiting of finer adjustments in components, increased resistance to vibrations, and a reduced tensile stress area. Besides selection of a different material there are additional mechanical methods which may be employed to increase the life of the components such as pinning of the clevis, using a clamp collar, etc.

Appendix

% OF LOAD APPLIED	LOAD APPLIED LBS	THREAD #	MIN STRESS PSI	AVG STRESS PSI	MAX STRESS PSI	THREAD AREA	MIN LBS	AVG LBS	MAX LBS	MEASURED % OF LOAD (MIN)	MEASURED % OF LOAD (AVG)	MEASURED % OF LOAD (MAX)
34.00	2383.23	1	18489.00	39422.00	70018.00	0.029	536.18	1143.24	2030.52	17.90	24.43	28.89
23.00	1612.185	2	24603.00	35780.00	48881.00	0.029	713.49	1037.62	1417.55	23.82	22.17	20.17
16.00	1121.52	3	17909.00	24731.00	33036.00	0.029	519.36	717.20	958.04	17.34	15.32	13.63
11.00	771.045	4	12542.00	17584.00	23956.00	0.029	363.72	509.94	694.72	12.14	10.90	9.88
9.00	630.855	5	9671.00	13345.00	21420.00	0.029	280.46	387.01	621.18	9.36	8.27	8.84
7.00	490.665	6	7884.00	11272.00	20081.00	0.029	228.64	326.89	582.35	7.63	6.98	8.29
N/A	N/A	7	4840.00	9628.00	13041.00	0.029	140.36	279.21	378.19	4.69	5.97	5.38
N/A	N/A	8	2098.00	3170.00	4002.00	0.029	60.84	91.93	116.06	2.03	1.96	1.65
N/A	N/A	9	1331.00	1661.00	2029.00	0.029	38.60	48.17	58.84	1.29	1.03	0.84
N/A	N/A	10	898.00	1002.00	1143.00	0.029	26.04	29.06	33.15	0.87	0.62	0.47
N/A	N/A	11	644.00	710.00	791.00	0.029	18.68	20.59	22.94	0.62	0.44	0.33
N/A	N/A	12	523.00	595.00	680.00	0.029	15.17	17.26	19.72	0.51	0.37	0.28
N/A	N/A	13	450.00	537.00	656.00	0.029	13.05	15.57	19.02	0.44	0.33	0.27
N/A	N/A	14	381.00	495.00	649.00	0.029	11.05	14.36	18.82	0.37	0.31	0.27
N/A	N/A	15	326.00	445.00	582.00	0.029	9.45	12.91	16.88	0.32	0.28	0.24
N/A	N/A	16	292.00	393.00	525.00	0.029	8.47	11.40	15.23	0.28	0.24	0.22
N/A	N/A	17	231.00	334.00	463.00	0.029	6.70	9.69	13.43	0.22	0.21	0.19
N/A	N/A	18	196.00	282.00	407.00	0.029	5.68	8.18	11.80	0.19	0.17	0.17

Table A.1 – Calculated Data for Current Design – Full Engagement

% OF LOAD APPLIED	LOAD APPLIED LBS	THREAD #	MIN STRESS PSI	AVG STRESS PSI	MAX STRESS PSI	THREAD AREA	MIN LBS	AVG LBS	MAX LBS	MEASURED % OF LOAD (MIN)	MEASURED % OF LOAD (AVG)	MEASURED % OF LOAD (MAX)
34.00	2383.23	1	23790.00	44165.00	81960.00	0.029	689.91	1280.79	2376.84	22.35	27.10	33.32
23.00	1612.19	2	25879.00	35190.00	47961.00	0.029	750.49	1020.51	1390.87	24.31	21.59	19.50
16.00	1121.52	3	17269.00	24304.00	31540.00	0.029	500.80	704.82	914.66	16.22	14.91	12.82
11.00	771.05	4	11849.00	17368.00	27168.00	0.029	343.62	503.67	787.87	11.13	10.66	11.05
9.00	630.86	5	9313.00	13039.00	20258.00	0.029	270.08	378.13	587.48	8.75	8.00	8.24
7.00	490.67	6	6792.00	10882.00	13943.00	0.029	196.97	315.58	404.35	6.38	6.68	5.67
N/A	N/A	7	4655.00	9368.00	12467.00	0.029	135.00	271.67	361.54	4.37	5.75	5.07
N/A	N/A	8	2139.00	3027.00	3913.00	0.029	62.03	87.78	113.48	2.01	1.86	1.59
N/A	N/A	9	1342.00	1595.00	1928.00	0.029	38.92	46.26	55.91	1.26	0.98	0.78
N/A	N/A	10	893.00	994.00	1080.00	0.029	25.90	28.83	31.32	0.84	0.61	0.44
N/A	N/A	11	672.00	742.00	825.00	0.029	19.49	21.52	23.93	0.63	0.46	0.34
N/A	N/A	12	545.00	627.00	723.00	0.029	15.81	18.18	20.97	0.51	0.38	0.29
N/A	N/A	13	457.00	545.00	684.00	0.029	13.25	15.81	19.84	0.43	0.33	0.28
N/A	N/A	14	375.00	469.00	587.00	0.029	10.88	13.60	17.02	0.35	0.29	0.24
N/A	N/A	15	283.00	372.00	493.00	0.029	8.21	10.79	14.30	0.27	0.23	0.20
N/A	N/A	16	109.00	174.00	244.00	0.029	3.16	5.05	7.08	0.10	0.11	0.10
N/A	N/A	17	46.00	82.00	119.00	0.029	1.33	2.38	3.45	0.04	0.05	0.05
N/A	N/A	18	28.00	39.00	49.00	0.029	0.81	1.13	1.42	0.03	0.02	0.02

Table A.2 – Calculated Data for Current Design – Partial Engagement

% OF LOAD APPLIED	LOAD APPLIED LBS	THREAD #	MIN STRESS PSI	AVG STRESS PSI	MAX STRESS PSI	THREAD AREA	MIN LBS	AVG LBS	MAX LBS	MEASURED % OF LOAD (MIN)	MEASURED % OF LOAD (AVG)	MEASURED % OF LOAD (MAX)
34.00	2383.23	1	16452.00	31321.00	45163.00	0.043	707.44	1346.80	1942.01	22.44	28.39	29.31
23.00	1612.185	2	18836.00	25079.00	35506.00	0.043	809.95	1078.40	1526.76	25.69	22.73	23.04
16.00	1121.52	3	12771.00	16894.00	21666.00	0.043	549.15	726.44	931.64	17.42	15.31	14.06
11.00	771.045	4	9002.00	11876.00	15555.00	0.043	387.09	510.67	668.87	12.28	10.76	10.09
9.00	630.855	5	5870.00	8688.00	13471.00	0.043	252.41	373.58	579.25	8.01	7.87	8.74
7.00	490.665	6	4743.00	6993.00	9437.00	0.043	203.95	300.70	405.79	6.47	6.34	6.12
N/A	N/A	7	2790.00	5684.00	8366.00	0.043	119.97	244.41	359.74	3.81	5.15	5.43
N/A	N/A	8	951.00	1243.00	1587.00	0.043	40.89	53.45	68.24	1.30	1.13	1.03
N/A	N/A	9	559.00	645.00	766.00	0.043	24.04	27.74	32.94	0.76	0.58	0.50
N/A	N/A	10	416.00	530.00	667.00	0.043	17.89	22.79	28.68	0.57	0.48	0.43
N/A	N/A	11	339.00	468.00	660.00	0.043	14.58	20.12	28.38	0.46	0.42	0.43
N/A	N/A	12	268.00	389.00	537.00	0.043	11.52	16.73	23.09	0.37	0.35	0.35
N/A	N/A	13	191.00	300.00	421.00	0.043	8.21	12.90	18.10	0.26	0.27	0.27
N/A	N/A	14	135.00	221.00	309.00	0.043	5.81	9.50	13.29	0.18	0.20	0.20

Table A.3 – Calculated Data for Alternative Design – Full Engagement

% OF LOAD APPLIED	LOAD APPLIED LBS	THREAD #	MIN STRESS PSI	AVG STRESS PSI	MAX STRESS PSI	THREAD AREA	MIN LBS	AVG LBS	MAX LBS	MEASURED % OF LOAD (MIN)	MEASURED % OF LOAD (AVG)	MEASURED % OF LOAD (MAX)
34.00	2383.23	1	20539.00	35197.00	48762.00	0.043	883.18	1513.47	2096.77	27.20	31.00	29.56
23.00	1612.185	2	14941.00	24745.00	32889.00	0.043	642.46	1064.04	1414.23	19.79	21.79	19.94
16.00	1121.52	3	13152.00	16818.00	23277.00	0.043	565.54	723.17	1000.91	17.42	14.81	14.11
11.00	771.045	4	9148.00	12012.00	19707.00	0.043	393.36	516.52	847.40	12.12	10.58	11.95
9.00	630.855	5	7163.00	8833.00	13394.00	0.043	308.01	379.82	575.94	9.49	7.78	8.12
7.00	490.665	6	5536.00	7086.00	11969.00	0.043	238.05	304.70	514.67	7.33	6.24	7.26
N/A	N/A	7	2530.00	5584.00	10901.00	0.043	108.79	240.11	468.74	3.35	4.92	6.61
N/A	N/A	8	920.00	1204.00	1381.00	0.043	39.56	51.77	59.38	1.22	1.06	0.84
N/A	N/A	9	562.00	646.00	758.00	0.043	24.17	27.78	32.59	0.74	0.57	0.46
N/A	N/A	10	413.00	519.00	667.00	0.043	17.76	22.32	28.68	0.55	0.46	0.40
N/A	N/A	11	291.00	414.00	550.00	0.043	12.51	17.80	23.65	0.39	0.36	0.33
N/A	N/A	12	178.00	291.00	397.00	0.043	7.65	12.51	17.07	0.24	0.26	0.24
N/A	N/A	13	98.00	160.00	232.00	0.043	4.21	6.88	9.98	0.13	0.14	0.14
N/A	N/A	14	31.00	48.00	74.00	0.043	1.33	2.06	3.18	0.04	0.04	0.04

Table A.4 – Calculated Data for Alternative Design – Partial Engagement

Calculations

C.1) Piston Rod Annulus Area (Retracting)

Annulus Area = A1 (Piston) – A2 (Piston Rod)

$A1 = \pi r^2 = \pi 3^2 = 28.274\ in^2$
$A2 = \pi r^2 = \pi 1.25^2 = 4.908\ in^2$

Annulus Area = $28.274\ in^2 - 4.908\ in^2 = \underline{23.365\ in^2}$

C.2) Piston Rod Force Calculation

Pressure = Force / Area

Force = Pressure x Area

Force = 1200 psi x $23.365\ in^2$

Force = <u>28,038 lbs</u>

C.3) Load Applied to Thread #1

Load = 34% x 28,038 lbs = 0.34 x 28,038 lbs = <u>9,532 lbs</u>

C.4) Load Applied to ¼ Symmetric Thread #1

Load = 0.25 x 34% x 28,038 lbs = 0.25 x 0.34 x 28,038 lbs = <u>2,383 lbs</u>

C.5) Current Design Length of Thread Engagement Required

$$Le = \frac{2 \times At}{(0.5\pi)\,(D - 0.64952\, p)}$$

$$Le = \frac{2 \times 2.53\ in^2}{(0.5\pi)\,[1.875 - (0.64952)(0.083)]}$$

<u>*Le* = 1.768 in</u>