Basketball Hoop Design Testing

ME 55100 Finite Element Analysis

Dr. Khosrow Nemotollahi

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Carson Snyder, Nathan Watterson, & Luc Rulinda

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Summary

The objective of this project is to analyze and simulate a homeowner's style basketball rim. The first simulation to be performed is a dunk from an averaged sized NBA player. This will be done through static structural analysis, transient analysis and fatigue analysis. The second simulation will simulate the fatigue analysis of a basketball being shot and hitting the front of the rim. This was achieved by applying a load on the front of the rim at a 45 degree angle to find the lifecycle of the rim.

The model that was obtained from Grabcad needed adjustment such that our analysis would be accurate. Instead of fixing all the errors that existed within the rim and backboard, we obtained a different rim and backboard model to analyze and attached the new models to the existing support structure. The mesh method was chosen to be hex-dominant except for the support structure since there was much less accuracy that was needed for that section. The mesh sizing was then refined such that all sections of the model converged to a solution and gave consistent results for all testing scenarios.

The results from this testing shows that this rim is suitable for the regular use of a homeowner, but should not be used for high intensity play where dunking and hanging from the rim is involved.

Introduction

The aim of this finite element analysis is to simulate different loading scenarios on a homeowner's style basketball hoop. The first loading scenario involves an average sized NBA player dunking on the rim. This load will be considered for a static structural, transient, and fatigue analysis. The purpose is to determine the total deformation and stresses of the basketball hoop when it is pushed to its limit. The second loading condition is the force of someone shooting a basketball that hits the front edge of the rim at a 45 degree angle. This scenario will also be used to perform a fatigue analysis and determine the life cycle of the rim under normal loading conditions. Two different materials, structural steel and high tensile carbon steel- will be compared for the static analysis.

The idea of this project was new for all of our group members. The idea of the different loading conditions and tests formed as the project progressed. The basketball hoop model for this analysis was obtained from Grabcad. This assembly required a significant amount of modification in order to create a well refined mesh and obtain accurate results. Specifically, the hoop and backboard on the initial file had to be remodeled due to significant flaws in the design.

Theoretical Background

The hex-dominant method is desired for the critical parts of the model meshes because of the characteristics of the naturally occurring mesh. When hex-dominant is used a 90 degree grid is most produced when geometry allows such a grid to exist. This produces the least amount of error due to the number of faces that experience forces that are normal to the element.

The results of the ANSYS analysis were determined to be accurate by reducing the meshing size until the results changed by less than 1%. This was done by experimentally reducing the mesh size of each major component of the basketball hoop assembly one at a time. Since the hoop was determined to be the component with the most significant deflection, it required the most mesh refinement. Since most of the deflection was determined to be occurring at the front of the basketball hoop assembly, the backboard required the second most mesh refinement. The least important component in our analysis was the back structure of the model due to very little deformation. Thus, this component had the coarsest mesh.

The following assumptions were made for the analysis and testing performed.

- Average weight of an NBA player (Curcic, 2021). W = 961.2 N
- Angle of approach of basketball (Noah, 2017). θ = 45°
- Mass of a basketball (Basketball, 2021). M = 0.625 kg
- Impact Velocity of a basketball (estimated) Vi = 4.5 m/s
- Bounce Velocity of a basketball (estimated) Vf = 4.3 m/s
- Contact time (estimated) Δt = 0.1 s

Estimated calculation of applied force by basketball

The following equation represents the conservation of momentum at the level of the basketball rim when in contact with a basketball. Using the estimated velocity of a basketball before contact *Vi*, the mass *M* of the basketball, the estimated time of contact *Δt* and final basketball velocity *Vf* we deduced the value of the force exerted on the rim.

$M*Vi + \Delta t*F = M*Vf$
$F= [(M*Vf)- (M*Vi)]/ \Delta t$
$F = 0.625*(4.5+4.3)/0.1$
$F = 55\ N$

Model Details

The basketball hoop assembly obtained from Grabcad required a significant amount of modification and refinement due to flaws in the original design. The most significant change was that the backboard and rim had to be replaced. A new rim from Grabcad and a newly modeled backboard were used to replace the components on the original assembly. The hooks for the net on the new rim were removed due to their small geometry and negligible impact on the rim's structure. Other modifications involved using SpaceClaim to repair and prepare the model for ANSYS meshing. The downloaded model had many duplicate and inexact edges which had to be removed.

The following images show the mesh that was used for all tests that were performed. The size of mesh that was used for the supporting structure that is located behind the backboard had an automatic meshing method and a mesh sizing of 45mm, the backboard itself had a hex-dominant method of mesh size 25 mm, and the rim had also had a hex-dominant method that had a mesh sizing of 1.5mm. The total number of elements within the mesh was a little over 250 thousand elements and the total number of nodes was just over 1 million nodes.

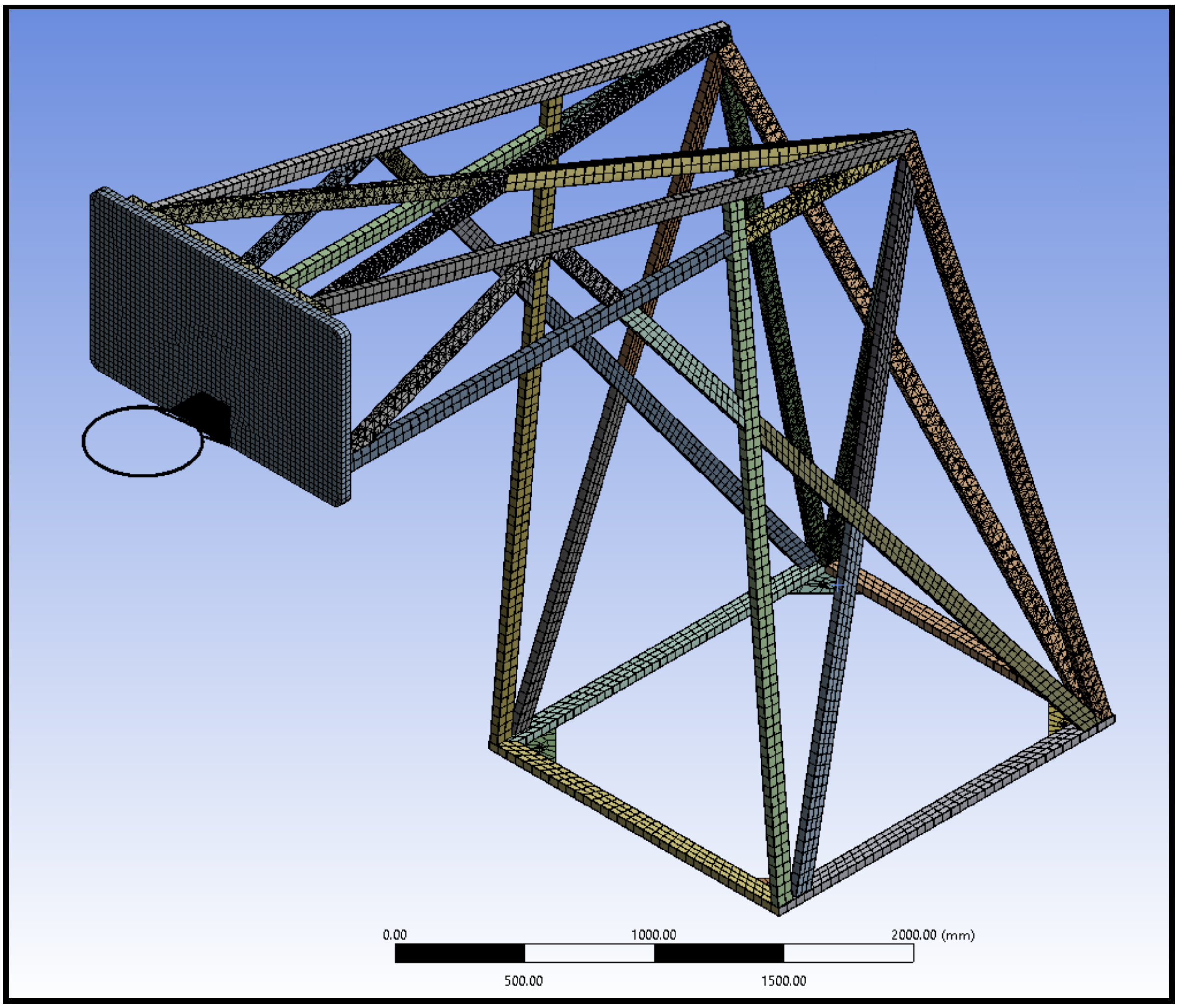

Figure 1: Total Mesh View

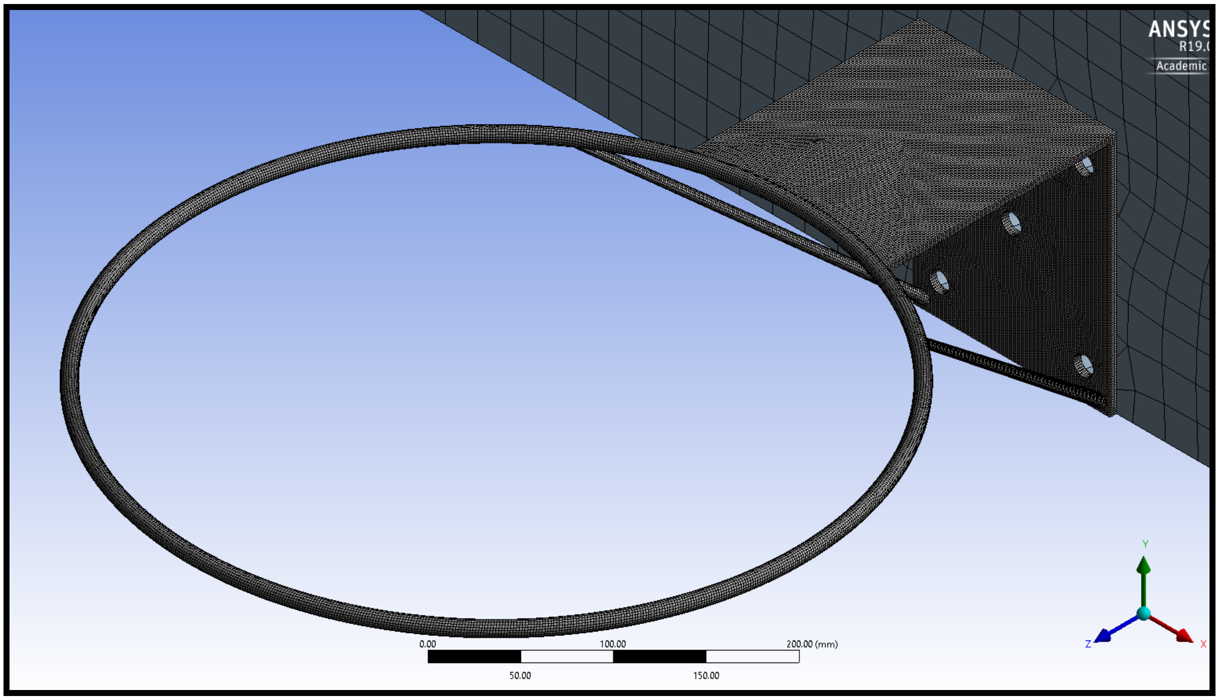

Figure 2: Rim Mesh View

Static Structural

The static structural analysis studied the effect of having an averaged sized NBA player hanging from the rim itself. The weight of the NBA player was applied as a force on the top of the rim that acted in the negative y direction.

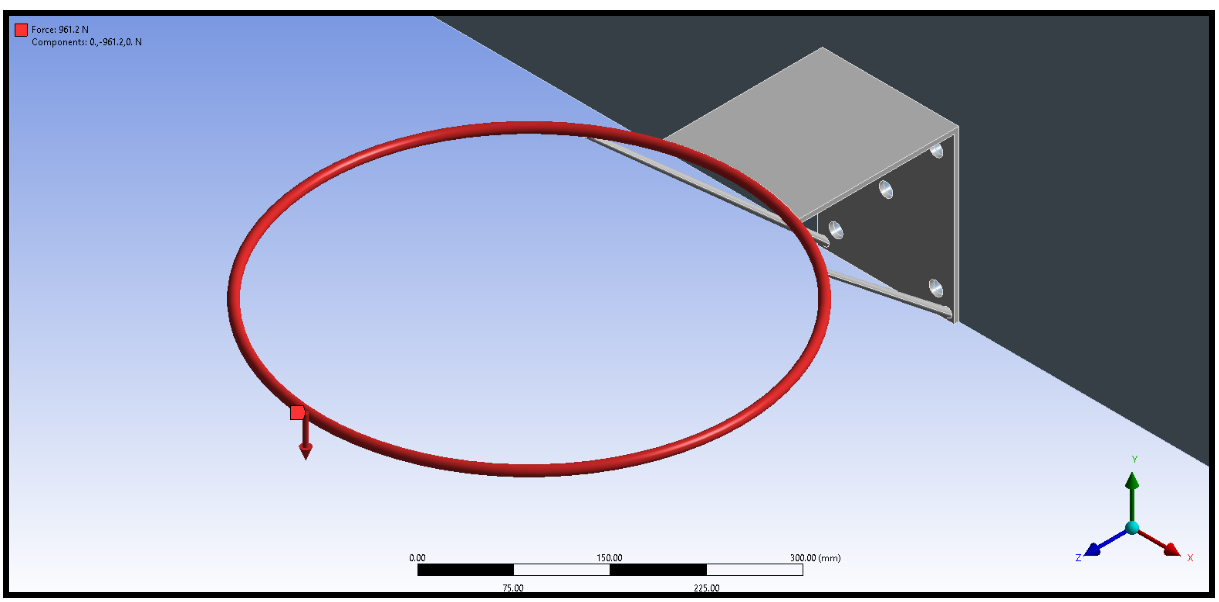

Figure 3: Force Condition

The fixed support acted at the base of support structure. The fixed supports were specifically placed on the plates that have the required holes for anchoring the structure.

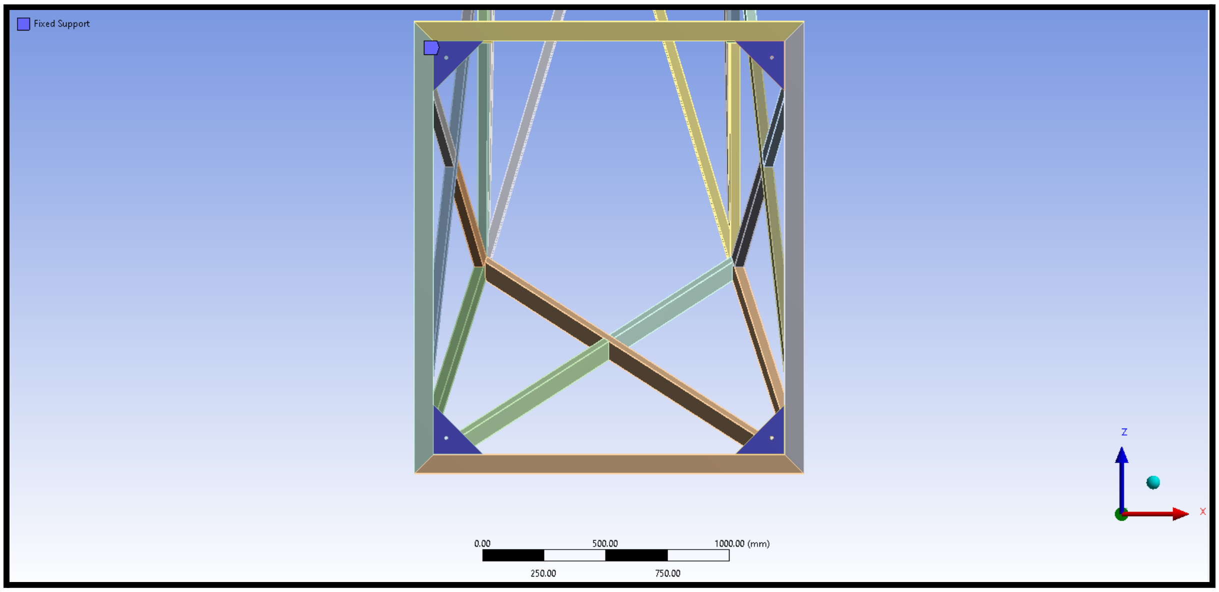

Figure 4: Fixed Support Condition

Transient Analysis

The Mode-Superposition method was used for performing a transient analysis of the basketball hoop. This method consists of doing a preliminary modal analysis in order to determine the response characteristics of the structure. For this analysis, the model was fixed at the same four mounting points as in the static structural analysis. These results were then passed to the transient analysis where they were used to determine the transient response of the system to an applied load of 961.2 Newtons on the rim. This load was applied in the same manner as shown in figure 3. The overall setup of the analysis with the Mode-Superposition method is shown below.

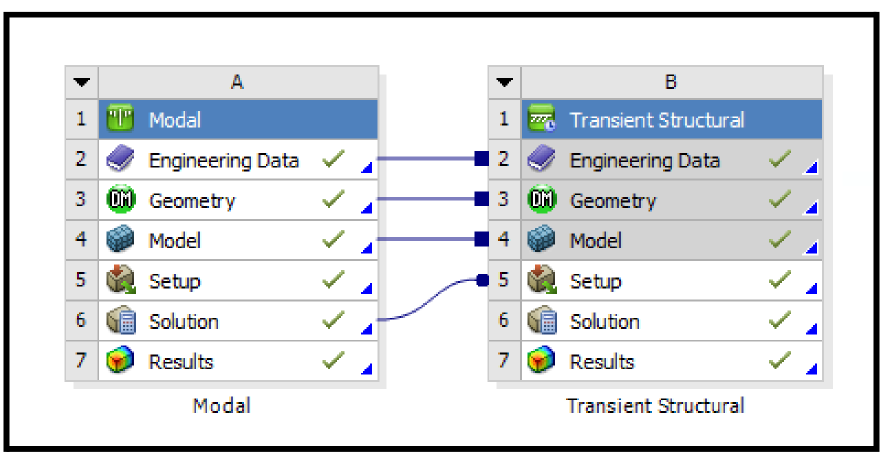

Figure 5: Transient Analysis Setup in Workbench

The only other analysis settings that had to be specified for the transient analysis were the number of substeps and the end time. At first, an end time of 1 second was used along with 500 substeps. From the results of this initial analysis, it was determined that a shorter run time would be sufficient in representing the data. A run time of 150 milliseconds was selected. Next, the simulation was run multiple times as the number of substeps was gradually reduced to ensure the results remained consistent. A final substep number of 50 was chosen. The step controls can be seen in the following figure.

Step Controls	
Number Of Steps	1.
Current Step Number	1.
Step End Time	0.15 s
Auto Time Stepping	Off
Define By	Substeps
Number Of Substeps	50.
Time Integration	On
Options	
Include Residual Vector	No
Output Controls	
Damping Controls	
Analysis Data Management	
Visibility	

Figure 5: Transient Analysis Step Control Settings

Fatigue Analysis

A fatigue analysis was done on the basketball hoop model, and its goal was to determine how long we should expect it to fail under applied loadings. The results of this analysis were obtained thanks to the alternating mean stress data available in the Ansys library for structural steel shown in Figure 1. (1998 ASME BPV code).

Table of Properties Row 13: Alternating Stress Mean Stress

	A
1	Mean Stress (Pa)
2	0
*	

	B	C
1	Cycles	Alternating Stress (Pa)
2	10	3.999E+09
3	20	2.827E+09
4	50	1.896E+09
5	100	1.413E+09
6	200	1.069E+09
7	2000	4.41E+08
8	10000	2.62E+08
9	20000	2.14E+08
10	1E+05	1.38E+08
11	2E+05	1.14E+08
12	1E+06	8.62E+07
*		

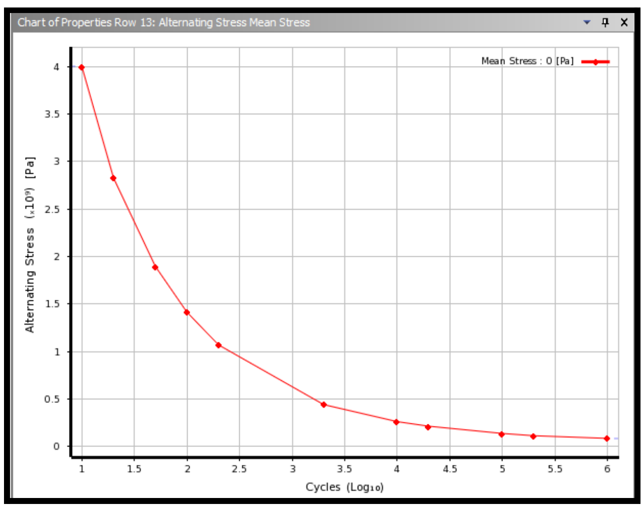

Figure 6: Alternating Stress Mean Stress Data

The design life was set to one million cycles (1*10E6.) The type of analysis is a stress life , with a mean stress theory set to the Goodman method, and Von-Mises stress as the stress component of the analysis.

The fatigue analysis results we were specifically looking for are the minimum fatigue life cycle, the safety factor across our model parts, the damage, biaxiality indication and fatigue sensitivity of our overall model.

Results and Discussions

Static Structural

The static structural results that were analyzed was the total deformation and the equivalent stress solution outputs. The maximum deflection that was observed from the test that was performed was approximately 98.8mm. The maximum stress that was experienced through the static analysis was approximately 1679MPa. That value of stress is above the yield stress of the material and this rim would suffer permanent damage if an NBA player were to hang from the rim.

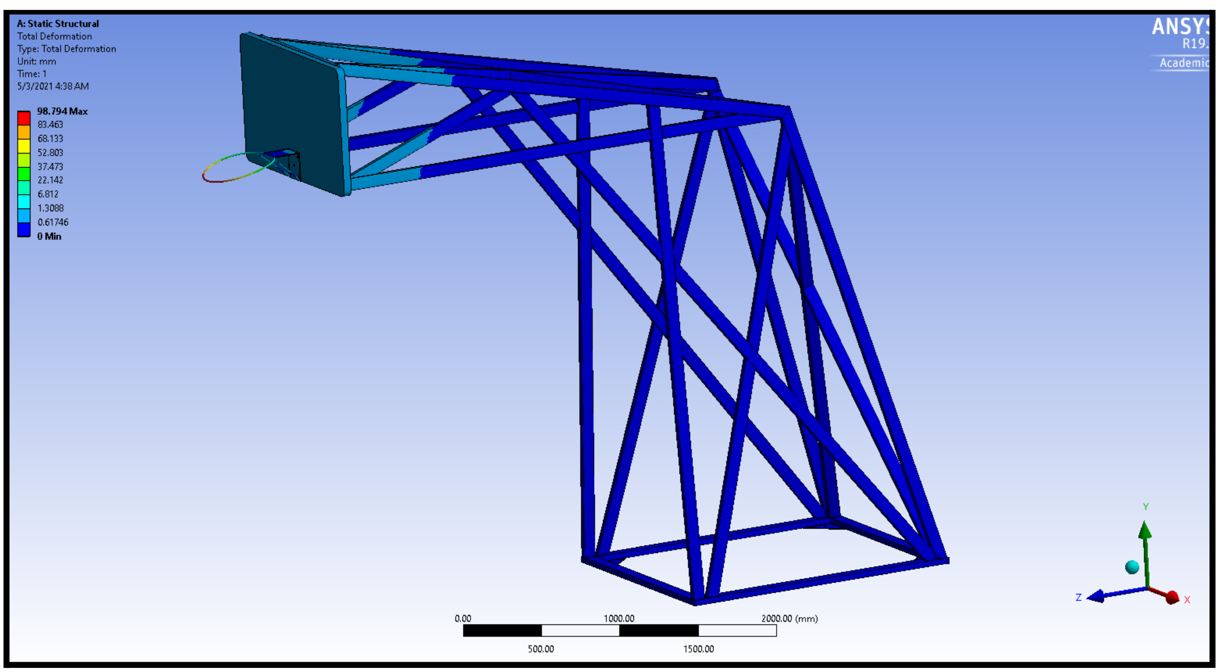

Figure 7: Total Displacement

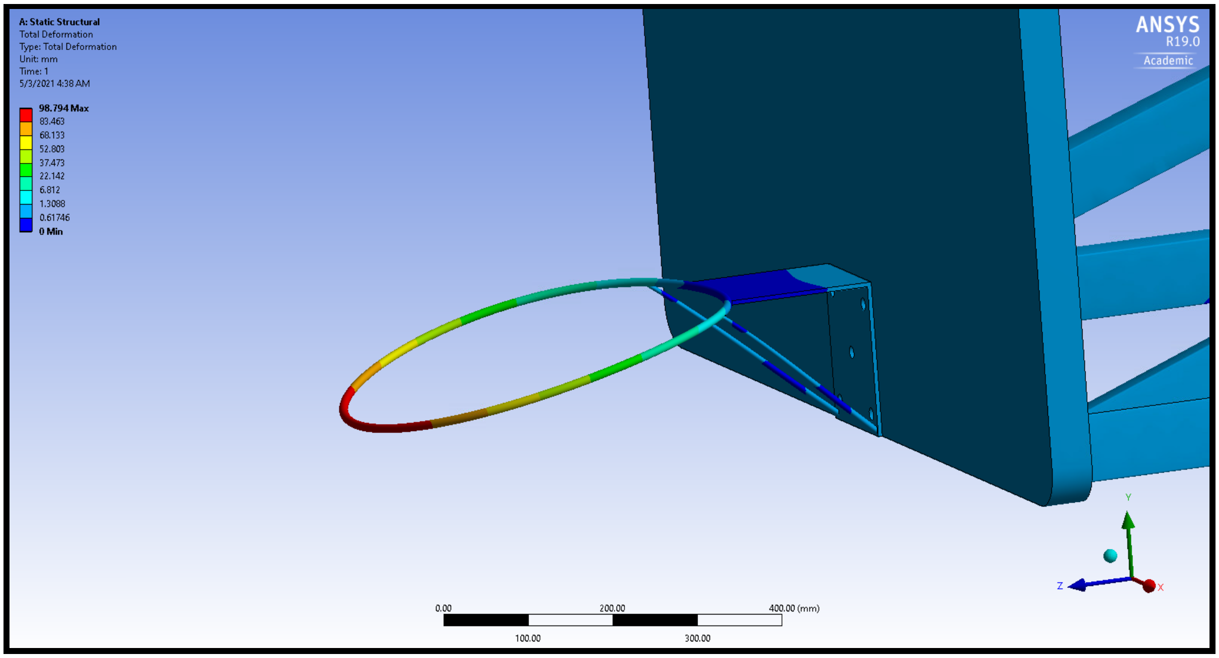

Figure 8: Rim Total Displacement

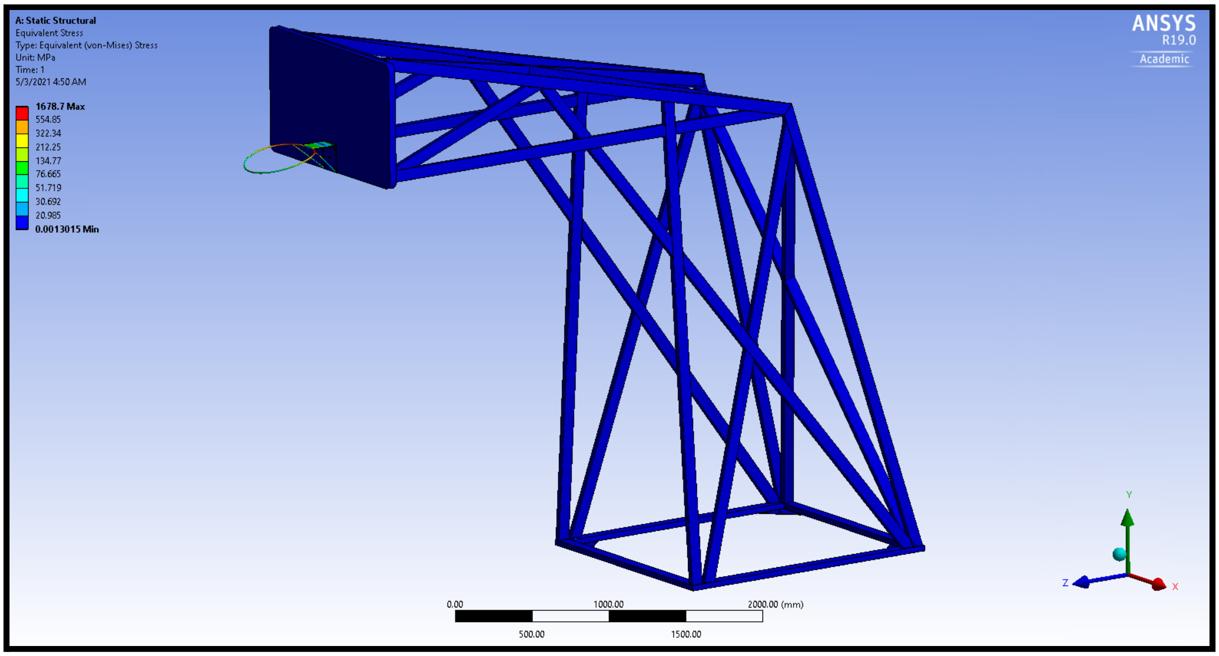

Figure 9: Equivalent Stress

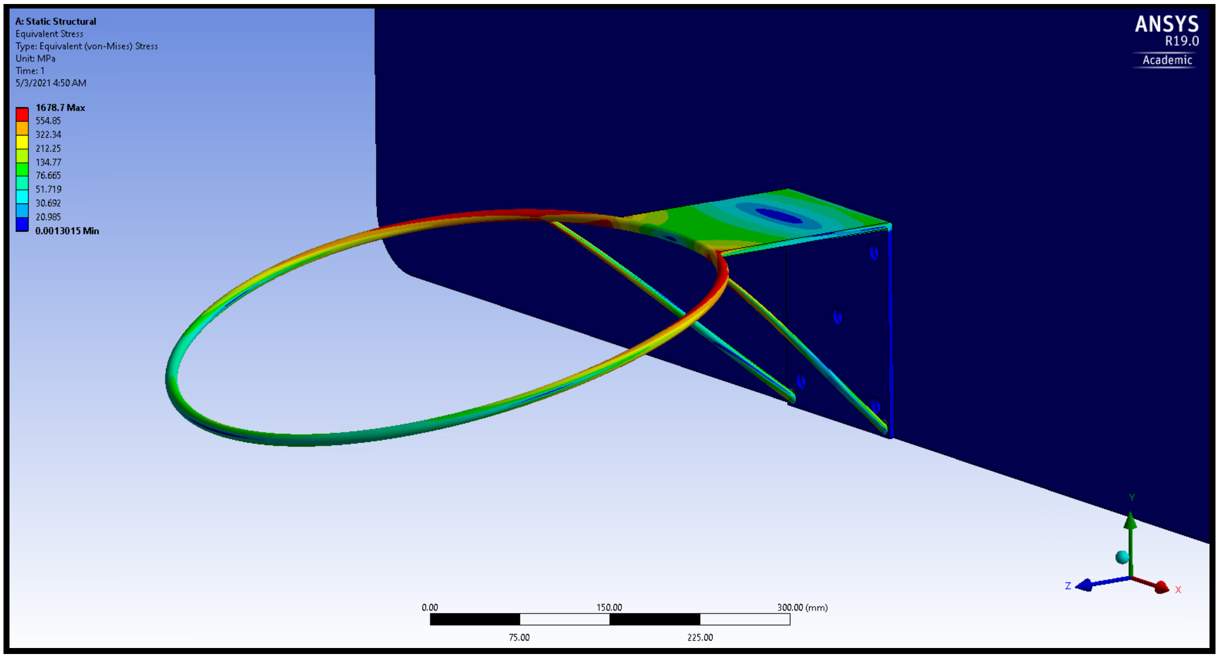

Figure 10: Rim Equivalent Stress

Transient Analysis

The results of the transient analysis are presented next. The total deformation of the basketball hoop for the force of an average sized NBA player dunking is considered first. Figure 10 shows the response of the whole structure to this applied load of 961.2 Newtons. This figure shows that the deformation oscillations are uniform in magnitude with a peak value of 196.21 mm and minimum very close to 0 mm.

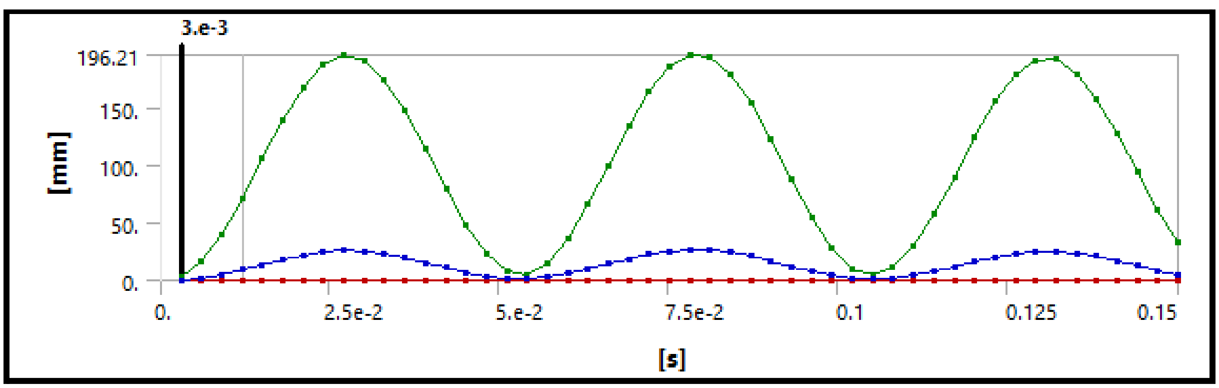

Figure 11: Transient Response Plot of Total Deformation

The next figure shows the total deformation distribution across the whole structure. The deformation of the whole rear support structure has a deflection of very close to zero. This means the rear structure will oscillate hardy at all when the player dunks. The previously discussed maximum deflection of the whole basketball hoop occurs on the rim.

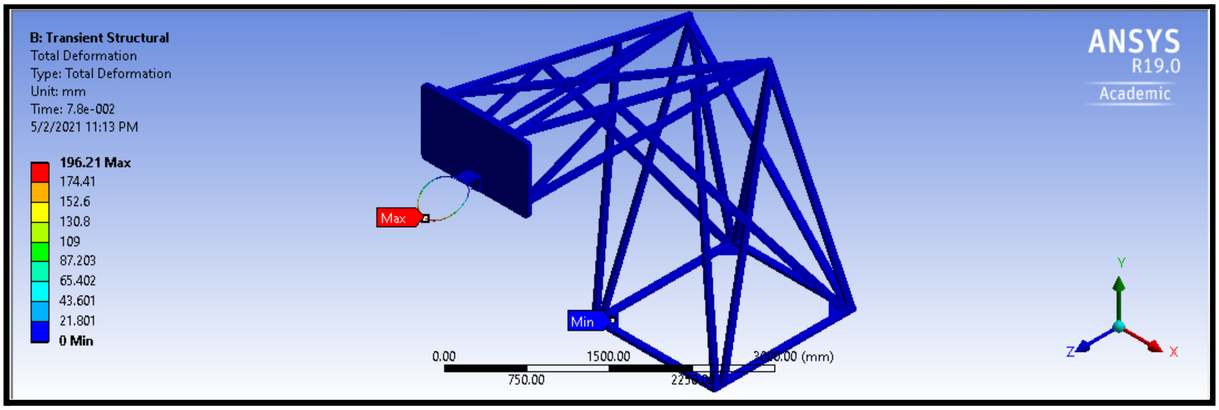

Figure 12: Transient Analysis Total Deformation

In the following figure, the deformation of the rim can be seen in greater detail. The rim was the part of most interest during this analysis due to it being the location of the most significant deformation. The deformation distribution shows that the maximum deformation of 196.21 mm occurs on the tip of the rim. The deformation of the rim decreases gradually to approximately zero as the rear mounting bracket is approached.It should be noted that this maximum deformation value is nearly double the maximum deformation found in the static analysis.

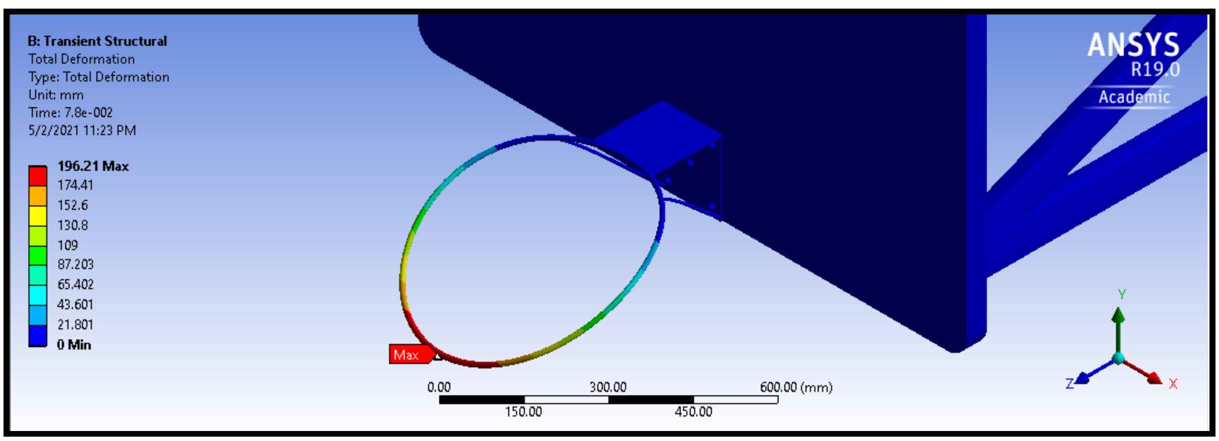

Figure 13: Transient Analysis Total Deformation on the Rim

Next, the transient response of the equivalent stress is considered. The following figure shows the stress oscillations for the first 150 milliseconds of the system's response. The oscillations are once again uniform in magnitude with a maximum stress value of 3080.4 MPa and a minimum very close to 0 MPa.

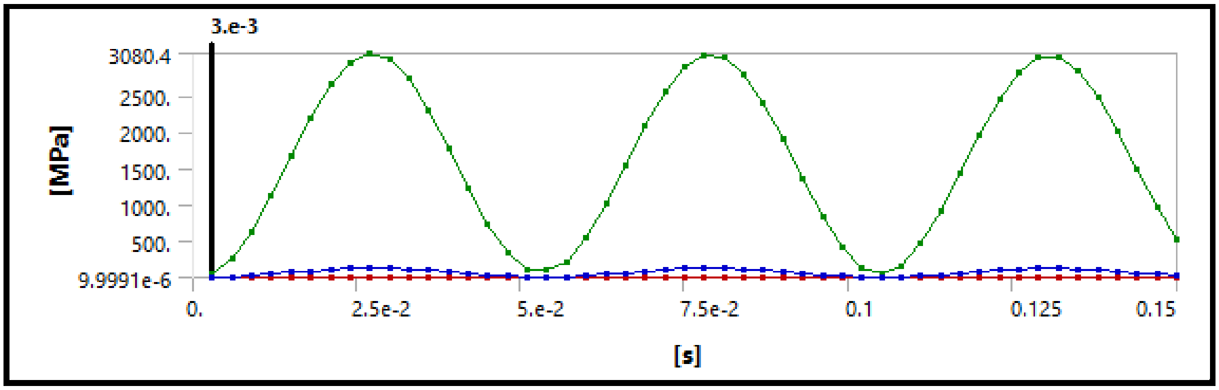

Figure 14: Transient Response Plot of Equivalent Stress

The next figure shows the equivalent stress distribution over the whole basketball hoop structure. Similar to the deformation, the stresses on the back supporting structure are very close to 0 MPa. Once again, the rim is the part of interest due it containing the highest stresses.

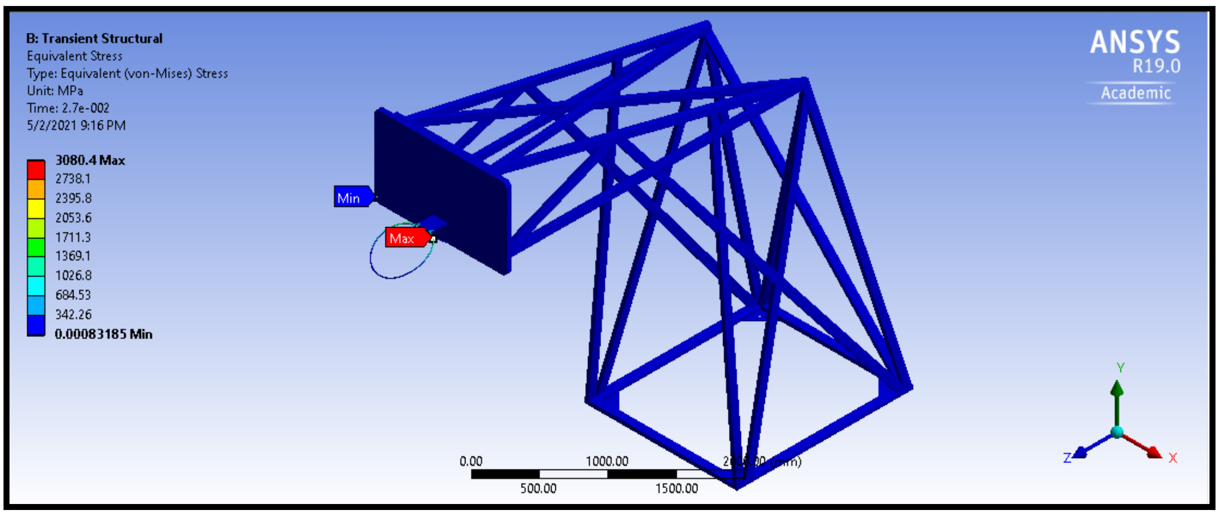

Figure 15: Transient Analysis Equivalent Stress

The following figure shows the stress distribution on the rim in greater detail. The highest stresses on the rim occur where the ring of the rim connects to the mounting bracket. This is as expected since the largest moment on the rim created by the load of the basketball player will occur at the mounting bracket. Since the hoop has the smallest cross-sectional area, the maximum stress expected to occur at this location on the rim. It should be noted that the maximum stress is more than ten times greater than the yield stress of the structural steel that the rim is made of. This means that the rim will fail under the 961.2 Newton load of a dunking NBA player.

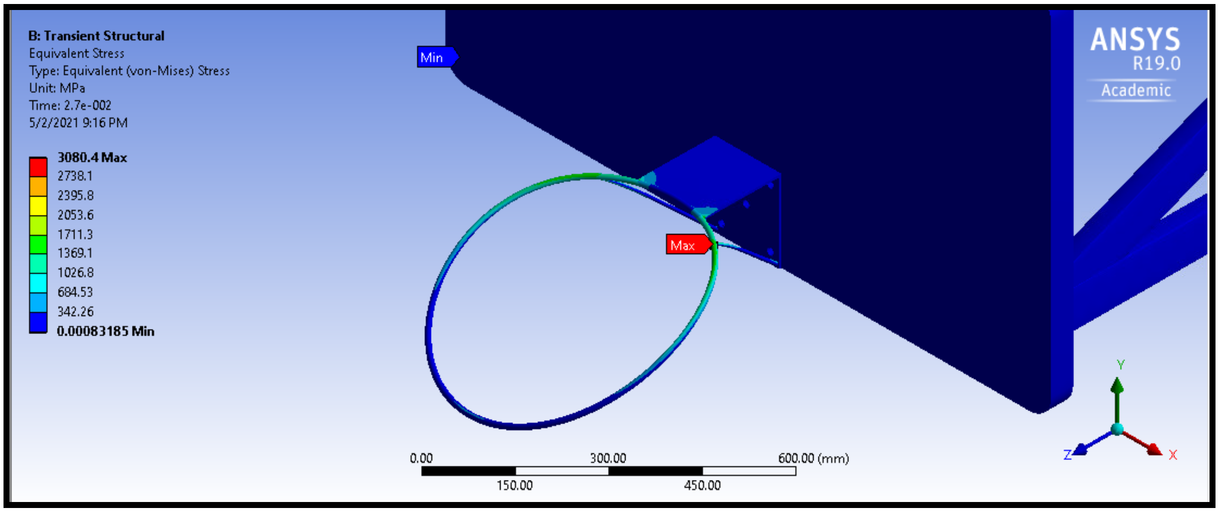

Figure 16: Transient Analysis Equivalent Stress on the Hoop

The next figure shows a zoomed-in view of the underside of the rim where the maximum stress is located. The precise location of the maximum stress is where the rim supports connect to the ring. This will be the location where the rim first yields.

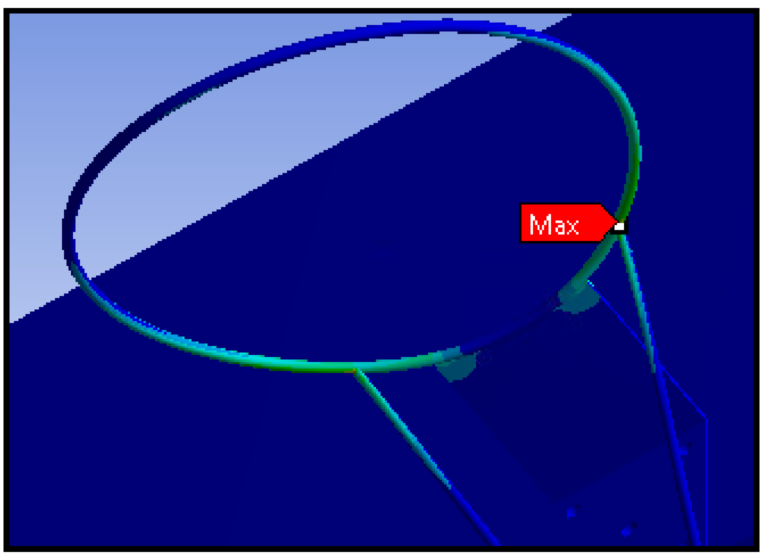

Figure 17: Underside View of the Maximum Equivalent Stresses on the Rim

Fatigue Analysis

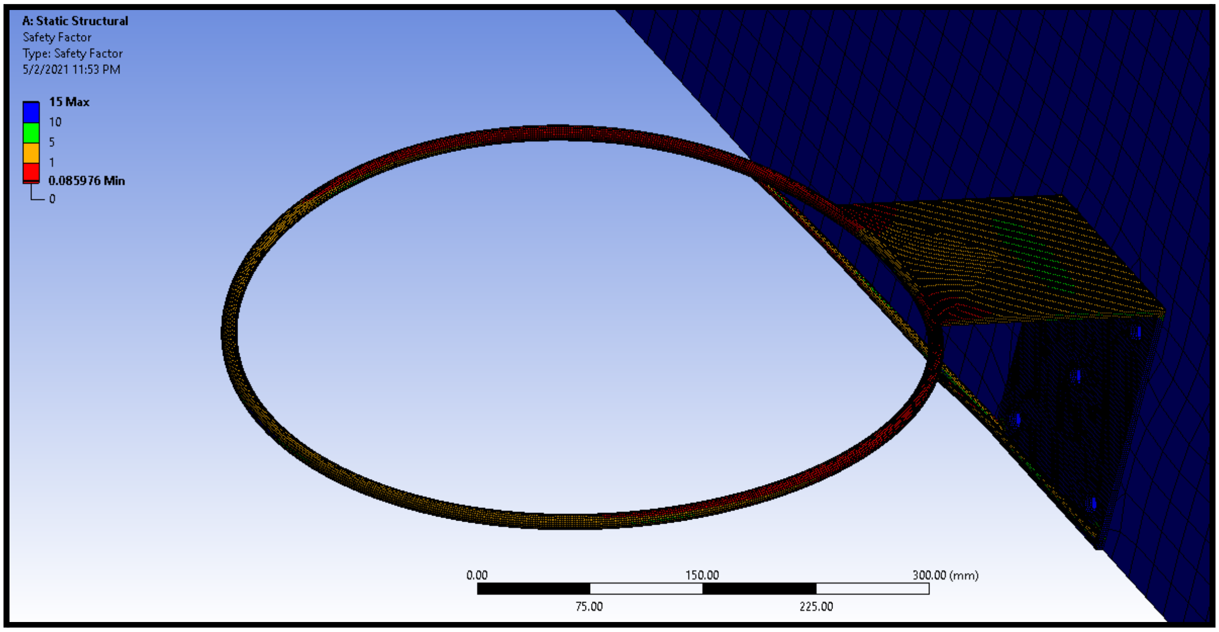

Figure 18: Safety factor result case 1 (dunk)

The rim has the lowest safety factor in the entire model so one can also expect to find there most of the fatigue in the basketball hoop. The following are the results of the fatigue analysis for a dunk (action of hanging on the rim) and a basketball shot.

Table 1: Results from the Fatigue Analysis for Both Cases

	Case 1 (dunk)	Case 2 (basketball shot)
Minimum life cycle	67.3	1E6
Maximum damage	1.486 *10E7	1
Minimum safety factor	5.104* 10E-2	2.03
Avg. Biaxiality indication	-0.14818	-0.209
Avg. Equivalent alternating stress (Mpa)	63.071 MPa	1.307 Mpa

Both the minimum life cycle and maximum damage were found on the basketball rim, which makes it the least reliable part of the entire model. A life cycle of 67.3 found in the first case means that the average basketball player can dunk on this rim 67 times before it fails. It is important to note that failure alludes to the breaking point and not the yielding point, given that the stress in the rim exceeds the yielding point the basketball player would break this rim after it had already been deformed- It only takes one dunk for this rim to get deformed. In the second case our model has an infinite life cycle since the minimum life cycle obtained on the entire model is one million cycles (1e6 cycles) .

Since for fatigue damage, values greater than 1 indicate failure before the design life is reached, this rim cannot sustain the loading imposed by a dunk before it reaches one million cycles. In the case of the basketball shot however, it can sustain an infinite number of shots.

It is also clear that the rim in the case of the first case would not reach the desired life cycle because values less than one indicate failure before the design life is reached. In the second case the entire model is robust enough to sustain as many basketball shots as possible.

From this fatigue analysis we can conclude that the boundary conditions in the first case (a dunk) cannot be sustained by our basketball rim. If however, the basketball player intends to only shoot on this basketball hoop then this model is robust enough to endure an infinite number of basketball shots (case 2).

Material comparison

Properties of Outline Row 3: AISI 1095

	A	B	C
1	Property	Value	Unit
2	Material Field Variables	Table	
3	Density	7.85	g cm^-3
4	Isotropic Secant Coefficient of Thermal Expansion		
6	Isotropic Elasticity		
7	Derive from	Young's Modulus and Pois...	
8	Young's Modulus	2.05E+05	MPa
9	Poisson's Ratio	0.29	
10	Bulk Modulus	1.627E+11	Pa
11	Shear Modulus	7.9457E+10	Pa
12	Alternating Stress Mean Stress	Tabular	
13	Interpolation	Semi-Log	
14	Scale	1	
15	Offset	0	Pa
16	Tensile Yield Strength	570	MPa
17	Compressive Yield Strength	425	MPa
18	Tensile Ultimate Strength	965	MPa
19	Compressive Ultimate Strength	0	MPa

Figure 19: AISI 1095 material properties

The table below is a comparison between two materials: structural steel whose material properties are already available in the ANSYS library, and high tensile structural steel- AISI 1095- whose material properties had to be defined as seen in Figure 19 (Matweb, 2021). AISI 1095 is a high-carbon steel that offers maximum surface hardness with high strength and wear resistance (Matweb). Data pertaining to fatigue analysis could not be found hence the lack of a comparison in that department.

Table 2: Structural steel and high tensile carbon steel results comparison

	Case 1 (Dunk)		Case 2 (Basketball shot)	
	Structural steel	**High tensile carbon steel**	**Structural steel**	**High tensile carbon steel**
Max. equivalent stress (MPa)	1688.7	1687.9	71.469	71.446
Avg.equivalent stress (MPa)	63.071	63.068	2.582	2.582
Min. equivalent stress (MPa)	1.70E-03	1.71E-03	4.01E-05	4.01E-05
Max. deformation (mm)	98.841	96.192	3.911	3.805
Avg. deformation (mm)	13.562	13.215	0.524	0.51
Min. deformation (mm)	0	0	0	0

One can observe from Table 2 that the difference between the stress and deformation data of the two materials is not significant. However, the stresses in the structure of the high tensile carbon steel is always lower than in structural steel. The deformation in the basketball rim is also lower when it is made of high tensile carbon steel.

Since the lowest stress and deformation in our basketball rim is observed in high tensile carbon steel in both cases there is no doubt that it would be the preferred material for production.

Conclusions

This project consisted of testing a basketball rim model found on Grabcad in order to determine its safety of use for the average basketball player. Two different scenarios were explored in this project: an average NBA player hanging on this rim (as in the case of a dunk) and a 45° angle basketball shot relative to the rim. These two scenarios required different loading conditions that were used to perform structural, transient and fatigue analyses. Both the structural analyses confirmed that the first case of a dunk will cause a permanent deformation in our basketball rim due to the equivalent stresses in the rim that exceed the material yield stress. This immediately makes our basketball rim inadequate for the purpose of performing a dunk. In the case of the second case, an average basketball shot, the fatigue analysis concluded that our basketball

hoop model is robust enough for an infinite amount of basketball shots. We also compared the use of two different materials, structural steel and high tensile carbon steel. The latter proved to be the more favorable material although the differences in results were minimal.
This basketball hoop model then is only suitable for basketball players that will never hang on the rim. In order to make it adequate for all basketball purposes the rim in this model would need to be modified.

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