University of Wisconsin-Platteville

Department of Mechanical Engineering

ME 3330 Design of Machine Elements

Truck Bed Ramp Design

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Introduction and Problem Statement

Trucks are very useful tools that can be used to move many different types of loads, but they sometimes can be challenging and unsafe to get a load into the bed of the truck. The purpose of this project was to design a tailgate or tailgate attachment that better allows for many different types of loads to be placed and hauled in the bed of a truck safely and ergonomically. The tailgate was to follow several requirements as created by our design group. The ramp system was to follow the following requirements: hold a load requirement of 1500 lbs., allow loading on varying terrains, be easy to deploy, not affect truck performance/cargo capacity, be structurally affixed to the vehicle, be safe to use, have good surface traction, and be visually pleasing. These overarching tasks were done by first splitting our class into several expert groups that explored varying aspects before product design could be started. The tasks of these groups are detailed below as well as what from each group was taken for our design. The proposed design as well as the calculations required to get there are detailed as well.

Background

Expert Group 1: Expert Group 1 researched past and present patents for designs of truck bed ramps for loading an ATV, motorcycle, UTV, etc. in the back of the owner's truck bed. The challenge that was shown while researching the patents was that the design of the truck bed ramp either took up the entire space in the bed of the truck, so the truck was restricted from doing other work, or was detachable from the tailgate but took up space elsewhere in the truck. Another observation was that all the designs of the ramps were two separate ramps with an empty space in the middle. This design is great for loading vehicles with four wheels; however, it could be dangerous for vehicles with two wheels or for people who want to load other heavy cargo, i.e. furniture, appliances. Based off of those problems with the other ramps, a ramp that folded into an aftermarket tailgate and had options for a full tailgate width ramp or two individual ramps was designed.

Expert Group 2: Expert group 2 worked to research current products on the market relating to ramp designs for consumer vehicles. What was found was that most products today consist of a set of ramps that don't fold or a set of ramps that are of a single fold design. These products had a load rating ranging from 1000 to 2000 pounds. For the designs rated for 2000 pounds, zero turn lawn mowers were their main loading item. For the design considered for our concept, an ATV was considered the max load so the 1500 pound range was considered as the maximum load rating for our ramp setup. Most of the ramp setups consisted of ramps that needed to be stored via space in either the cab of the truck or the truck bed. The design that we most closely resemble would be Ford's design for ramps that are telescoping ramps that have dedicated mounting areas within the bed of the truck as not to sacrifice storage space. This design also had the best mounting point setup with a rail that was mounted on the tailgate with ramps that slid onto it from either side allowing very secure mount points of the ramp. What was taken from this research was as follows. The mounting point setup of Ford's design was investigated more closely and somewhat adapted to our design. The folding ramp setup of other designs was used as the basis for out design as well. A single folding ramp instead of two was picked so that walking up the ramp would be easy as opposed to two ramps.

Expert Group 3: Expert group 3 discussed codes, rules, regulations and any other restrictions that could affect the design of the tailgate. The major ideas used from this research was the dimensions of an average truck along with dimensions and other properties of different types of loads. We researched and found a tailgate is normally 36.2 inches from the ground, 62.2 inches long (wheel to wheel direction) and 21.1 inches wide. After looking at different four wheelers and snow mobiles, we decided a load of 1000 lbs. with a safety factor of 1.5 (to make the load 1500 lbs.) was reasonable for different types of possible loads. To do calculations we used a four-wheeler as the typical load with a distance of 54 inches between the front wheels and back wheels.

Expert Group 4: Expert group 4 researched safety considerations as well as ergonomics of lifting and general human motion. Some key take-a-ways from this include data from OSHA that states that lifting heavier than 50 lbs increases the risk of injury, reduced lift heights decrease chance of injury, and any unneeded extension of the body increase unnecessary strain. Several guidelines on safe lifting practices were found via New Jersey's Science and Technology University.

Proposed Concept

The Initial design process involved every group member brainstorming and drawing up what they believed would be the best design for truck bed ramps. This allowed us to get the best ideas from each person and to bring all of the best ideas into one design. The first design involved using a replaceable tailgate with folding ramps to minimize the storage impact of the ramps. This tailgate storage option was a good idea but had some concerns. One of the main ones was that when an ATV was loaded into the back it would be hard/impossible to store the ramps. The second design focused on ramps that were telescoping and had a rail that would be mounted onto the truck's existing tailgate. The concerns with this involved having to drill into the consumer's truck tailgate to mount the product as well as having to find space to store the ramps. Other design options involved telescoping ramps that telescope within the tailgate, expanded metal ramp surfaces, U-Haul inspired ramps, and a ramp system that sits within the truck bed.

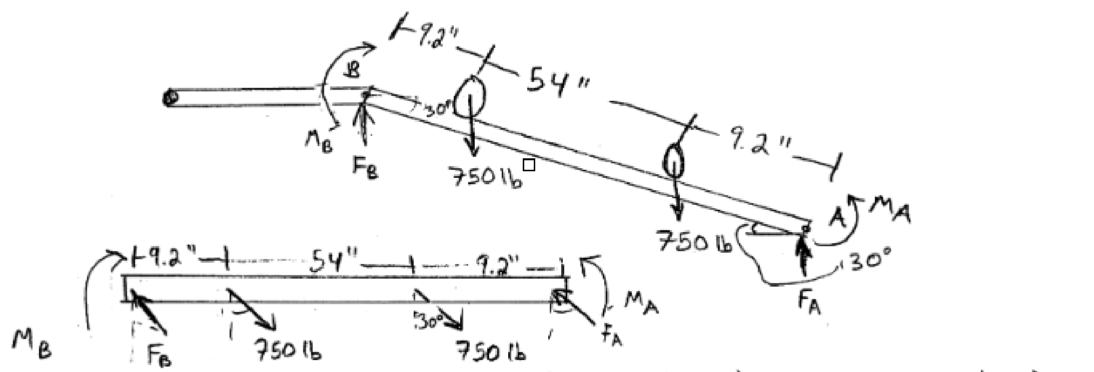
After looking at all design considerations, our group decided a tailgate replacement was the best option. This would allow for the easiest transition of the tailgate from one vehicle to another while keeping the ramps from taking up truck bed storage space when not in use. Our design included a ramp that is attached by a single mounting rod to the tailgate. This ramp would be foldable into the tailgate which would keep it from taking up any valuable space within the truck bed. It would also be able to be held in an unfolded position from the tailgate if a load is longer than the truck bed. A load such as a four-wheeler may prevent the ramps from being completely folded into the truck bed. The rod in which the tailgate attaches would be able to detach and rotate on one end so the ramp could be moved, removed or replaced. This would also allow for the option of one large ramp or two smaller ones to be interchanged as the load type varies. A CAD image of the proposed ramp concept is shown in figure 20 which helps to illustrate what this ramp setup looks like.

Calculations

The calculations portion of the ramp setup was based on some key assumptions which are outlined as they become relevant. To begin doing force calculations, dimensions needed to be finalized. A Chevy Silverado was used as the base platform in which this design would be used on. After getting the relevant tailgate dimensions, a load needed to be decided upon. For the load, research was done on the maximum weight ATV that wasn't a side-by-side that would be loaded into a pickup truck. The ATV that was found was the Polaris Sportsman XP1000 which came in around 1000 pounds. With attributing a weight safety factor of 1.5, the maximum load that the ramp would have to be designed to would be 1500 lbs. The wheelbase of the ATV came in at 54 inches. Measuring the distance from the ground to the truck bed gave a dimension of 36.2 inches. Assuming a ramp angle of 30 degrees, the ramp length came to be 72.4 inches. This requires 4 folds of the ramp for it to fit into a 21.1 inch tailgate. For the calculations, a single non-folded ramp was assumed which allowed for much more simplified calculations. The load was assumed to be in the direct center of the ramp as well. For fatigue analysis, the ATV ramp setup was assumed to be used twice a day for a product life of around 10 years giving a cycle number of 7300. Initial material to be used to minimize weight would be 6061-T6 aluminum. This would also prevent as much corrosion as possible.

Resultant Force Analysis of Ramp:

The calculations were split into three different component sets. These three sets were the tailgate, the mounting point of the ramp to the tailgate, and the ramp itself. What had to first be done was find the force at the connection point between the tailgate and the ramp so that the stresses at each component could be analyzed. This is shown in figure 1.



① $\circlearrowleft$ $\Sigma M_B = 0: -M_B - 750\cos 30\,(9.2'') - 750(63.2)\cos 30° + F_A \cos 30° (72.4) + M_A = 0$

② $\circlearrowleft$ $\Sigma M_A = 0: M_A + 750\cos 30°\,(9.2'') + 63.2''(750)(\cos 30) - F_B \cos 30° (72.4) - M_B = 0$

$(+\uparrow)\ \Sigma F = 0: F_B \cos 90 - 750\cos 30 - 750\cos 30 + F_A \cos 30 = 0$

$\boxed{F_A = F_B} = \boxed{750\text{ lb}}$

① $-M_B + M_A - 38{,}395.89 + F_A\, 51.1945 = 0$

② $-M_B + M_A + 38{,}395.89 - F_B\, 51.1945 = 0$

$F_A = 750\text{ lb}$

$-M_B + M_A - 38{,}395.89 + 38395.875 = 0$

$M_B = M_A = 0$

Figure 1: Ramp Force Calculations

Tailgate Calculations:

From this point, calculations of the stresses at each component were done. Starting from the tailgate and working towards the ramp, the following calculations were performed. The tailgate consists of three main components: the tailgate, the tailgate to truck mounting pins, and the cable for holding the tailgate up. This tailgate component breakdown is shown in figure 2 below which has these components listed as component 1, 2, and 3. Bending stresses were calculated at the tailgate, component 1, at points A, B, and C. Point A is where the tailgate mounts to the truck. Point B is where the cable that attaches the tailgate to the upper part of the truck bed is mounted. Point C is where the tailgate mounts to the ramp. Bending analysis was done assuming the tailgate is one piece of 2"x 62.2"x 19.69" aluminum. Figure 3 shows the bending stress analysis of the tailgate and its comparison to the yield strength of 6061-T6 aluminum. Fatigue failure analysis is also shown which resulted in no expected failure due to fatigue.

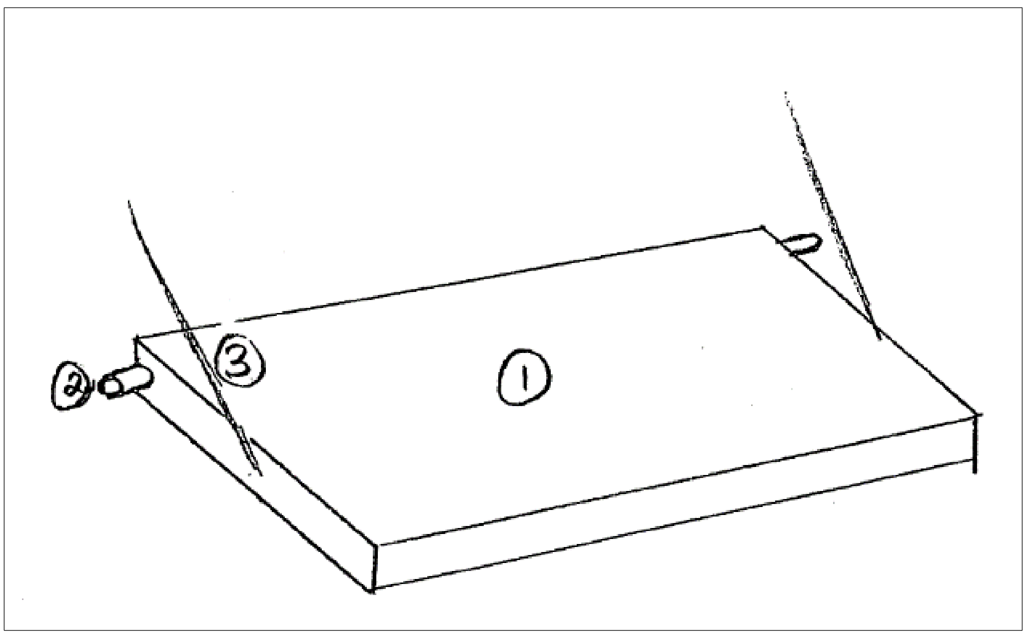
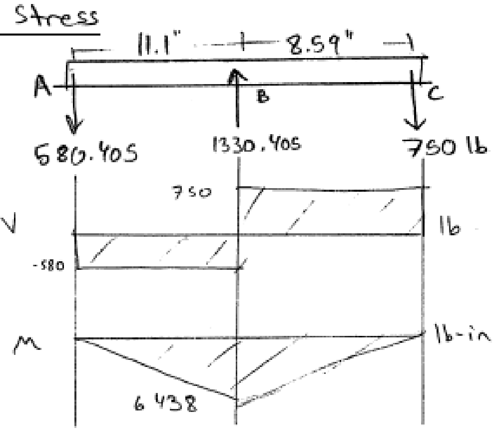


Figure 2: Tailgate Diagram

Bending Stress



Point B is most severe loading, so check bending stress at this location.

$\sigma = \frac{My}{I}$ ← 1" $\frac{(6438\ \text{lb in})(1\ \text{in})}{41.46\ \text{in}^4}$ $I = \frac{bh^3}{12} = \frac{(62.2")(2^3)}{12} = 41.46\ \text{in}^4$

$\sigma = 155.257$ psi

$\sigma_{y\,6061\text{-}T6} = 40$ ksi

$\boxed{\text{Therefore, bending will not be an issue on this component at the force induced}}$

Fatigue Failure for 10 years with use 2x a day

$N = 7300$ Cycles

$S_{u\,6061\text{-}T6} = 45$ ksi

$S_{1000} = 0.9\,S_u = 40{,}500$ psi

$\sigma_{max} = 155.257$ psi

$\sigma_{min} = 0$ psi

$\sigma_m = \sigma_a = 77.629$ psi

Based on fig 8.9 from book,
$S_n' = 17$ ksi at 5×10^8 cycles

$S_n = S_n'\,C_{load}\,C_{size}\,C_{surf}$

$C_{load} = 1.0$, $C_{size} = 0.869\,d^{-0.097}$

where $d = \sqrt{\frac{0.05hb}{0.0766}} = 9.01116"$

C_{surf}: fig 8.13, 0.8 for cold drawn (approx. for all.)

$S_n = (17\text{ksi})(1.0)(0.702)(0.8)$

$S_n = 9548.715$ psi

$S = 10^c N^b$ $c = \log \frac{S_{1000}^2}{S_n}$ $b = -\frac{1}{3}\log\left(\frac{S_{1000}}{S_n}\right)$

$c = 5.2349$ $b = -0.2092$

$S = 26{,}711.1667$

$\frac{\sigma_m}{S_u} + \frac{\sigma_a}{S} = \frac{1}{SF}$

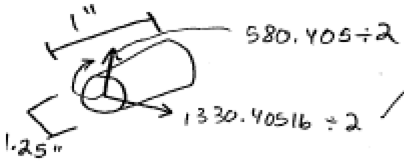
$\frac{77.629}{45\text{ksi}} + \frac{77.629}{26711.166} = \frac{1}{S.F.}$

$\boxed{\text{S.F.} = 215.92\text{, so don't expect failure due to fatigue with tailgate}}$

Figure 3: Bending Stress and Fatigue Analysis of Tailgate

What was seen from figure 3 was that the main stress at point B would be way less than the yield strength of 6061-T6 aluminum due to bending and that the safety factor due to fatigue would be very large which suggested no failure due to fatigue. A simplified model of the tailgate plate was created on SolidWorks to verify the findings done by the hand, shown in figure 22. Component two, the pin where the tailgate connects to the truck, was then analyzed to see if its' size would be effective at handling the forces required in figure 4 below.

Pin at A — The pin will experience 1/2 of the load on Figure 3



$$F_R = \sqrt{665.2^2 + 290.203^2}$$
$$F_R = 725.747 \text{ lb}$$

Assuming a bending failure at end? $\sigma = \frac{My}{I}$ $\quad I = \frac{\pi d^4}{64}$

$$\sigma = \frac{(725.747\text{ lb})\left(\frac{1.25}{2}\right)}{0.1198 \text{ in}^4} \qquad I = 0.1198 \text{ in}^4$$

$\boxed{\sigma = 3{,}782.35 \text{ psi and } \sigma_y \text{ for 6061-T6 is } 40{,}000 \text{ psi}}$ which gives a S.F. of 10.58 which proves that the pin connection at the bottom of the tailgate will hold.

Fatigue at tailgate Pin

$N = 7300$ cycles

S_u 6061-T6 $= 45$ ksi

$S_{1000} = 0.9 S_u = 40{,}500$ psi

$\sigma_{max} = 3{,}782.35$ psi

$\sigma_{min} = 0$ psi

$\sigma_m = \sigma_a = 1891.175$ psi

fig 8.9 from book

$S_n' = 17$ ksi @ 5×10^8 cycles

$S_n = S_n' \, C_{load} \, C_{size} \, C_{surf}$

$C_{load} = 1.0$

$C_{size} = 0.869\, d^{-0.097} = 0.85$

C_{surf}: fig 8.13 (approx.) 0.8

$S_n = 17\text{ksi}(1.0)(0.85)(0.8)$

$S_n = 11.56$ ksi

$$\frac{\sigma_m}{S_u} + \frac{\sigma_a}{S_n} = \frac{1}{SF} \rightarrow \frac{1891.175\text{ psi}}{45{,}000 \text{ psi}} + \frac{1891.175\text{ psi}}{11{,}560 \text{ psi}} = \frac{1}{SF}$$

$\boxed{SF = 4.86}$, so failure due to fatigue for tailgate pin isn't expected.

Figure 4: Tailgate Pin Analysis

Figure 4 proved that the pin on either side of the tailgate would in fact be able to handle the stresses involved with holding the tailgate to the truck with a safety factor of 10.58 due to bending and a safety factor of 4.86 due to fatigue. The final component analyzed on the tailgate itself was the cable, component 3, which holds the tailgate upright. This is the main component that holds the whole ramp assembly up so it is a crucial component.

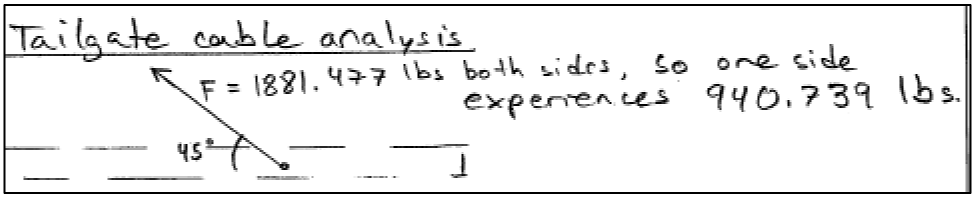


Figure 5: Tailgate Cable Analysis

Figure 5 shows that the force that the cable would need to withstand would be about 1000 pounds. When researching minimum diameter of steel cable based on safe load ratings, it was found that a rope diameter of 0.25 inches has a safe load rating of 1100 lbf. At minimum, a 0.25 inch cable on either side of the tailgate would need to be used.

Ramp Mounting Rod:

The second main component of the ramp assembly was the attachment rod that holds the ramp to the tailgate which is pointed out in figure 6.

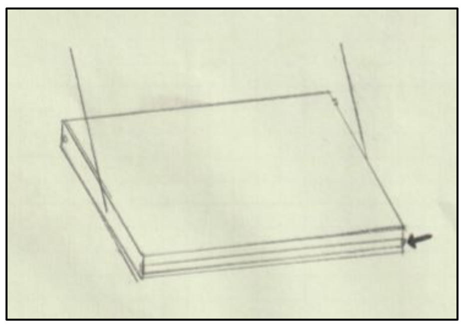


Figure 6: A drawing to show the location of the rod that is being analyzed.

To ensure the rod would hold the load with supports only on the end, it was decided that the rod would be made of AISI 1030 cold drawn steel with a tensile strength of 76.1 ksi, yield strength of 63.8 ksi, and a modulus of elasticity of 29900 ksi.

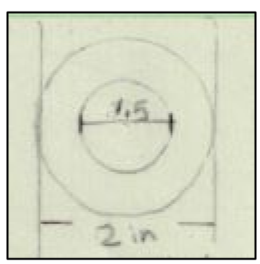


Figure 7: The cross-section of the rod.

Figure 7 is the cross section of the rod which shows it is a hollow rod with an outer diameter of 2 inches and an inner diameter of 1.5 inches.

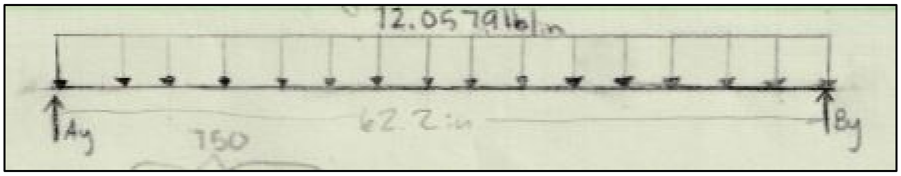


Figure 8: forces acting on the rod during loading

Figure 8 shows the force diagram of the rod and where the reaction forces are. The first step to analyzing the rod was to determine what the reaction forces were, and this can be seen in figure 9. For our calculations, we chose to make it one solid ramp so there is a distributed load of 12.0579 lb/in applied to the rod to result in a total load of 750 lbs.

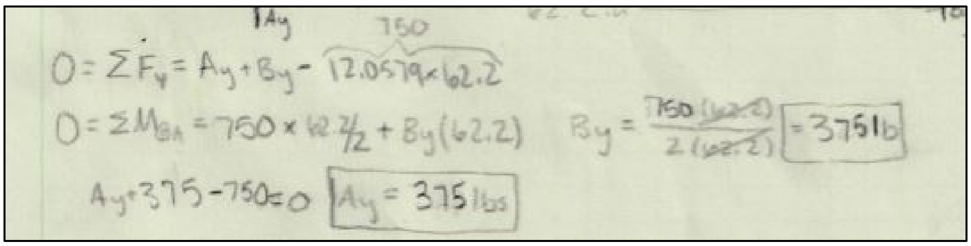


Figure 9: Calculations for solving the reaction forces on each end of the rod that were labeled in figure 8.

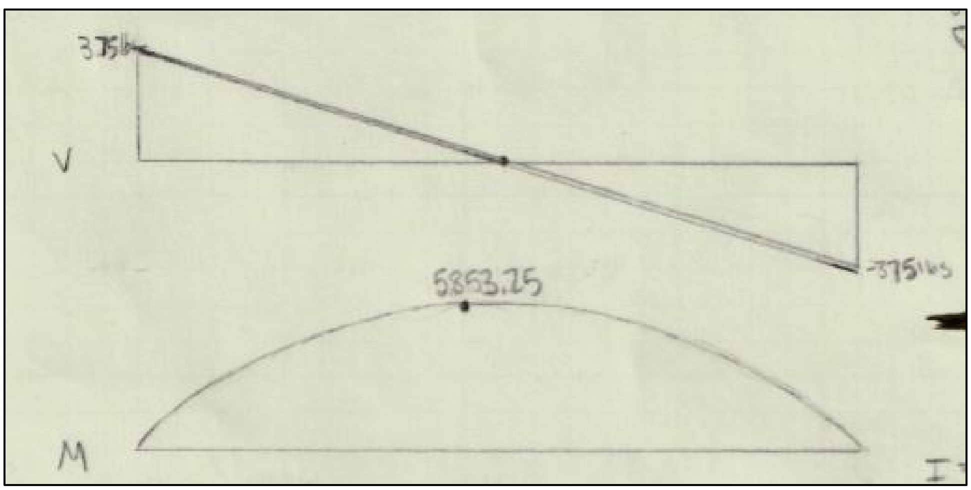


Figure 10: Shear and moment diagram for the rod.

Figure 10 shows the shear and moment diagrams for the rod, so it was easier to visualize when determining the bending stress at the critical point which was where the moment was the largest. In order to determine the bending stress and to later determine the deflection in the rod, the moment of inertia needed to be determined and that is shown in figure 11.

$$I = \frac{\pi}{64}\left(2^4 - 1.5^4\right)$$
$$= .5369 \, in^4$$

Figure 11: Calculations for moment of Inertia

$$\sigma_b = \frac{Mc}{I} = \frac{5853.25 \cdot 1}{.5369} = 10,861 \text{ psi}$$

Figure 12: Calculations for bending stress.

Comparing the max bending stress (figure 12) of 10.861 ksi to the yield strength of 63.8 ksi shows that the bending stress will not cause the rod to yield. The next calculations done were to determine the max amount of deflection (figure 13) there will be when the load is applied.

$$\delta = \frac{5wL^4}{384EI} = \frac{5(12.0579)(62.2)^4}{384(29\times10^6)(.5369)} = .146 \text{ in}$$

The max deflection in the rod will be .146in

Figure 13: Calculations for deflection.

The next calculations done were to calculate data to create a S-N curve (figure 14) and to do fatigue analysis (figure 17). The first steps to creating a SN curve is to calculate S1000 and Sn which had other calculations within itself. To calculate Sn, C_{load}, C_{size} and $C_{surface}$ had to be calculated so they could be multiplied by ½ of the tensile strength. Next, S1000 and Sn were plotted (figure 15) and used for calculating a strength at a certain fatigue life (figure 16).

$$\sigma_m = \sigma_a = \sigma_b/2 = 5430.48 \text{ psi} \qquad C_{Lo} = 1$$
$$S_{1000} = .9 S_u = (.9)(76.1) = 68.49 \text{ ksi} \qquad C_{si} = .869(2)^{-0.097} = .8125$$
$$C_{su} = 2.70(76.1)^{-.265} = .8566$$
$$S_n' = .5 S_u = (.5)(76.1) = 38.05 \text{ ksi} \qquad S_n = S_n' \cdot C_{Lo} \cdot C_{si} \cdot C_{su} = 38.05(1)(.8125)(.8666) = 26.48 \text{ ksi}$$

Figure 14: Calculations for data used in SN curve.

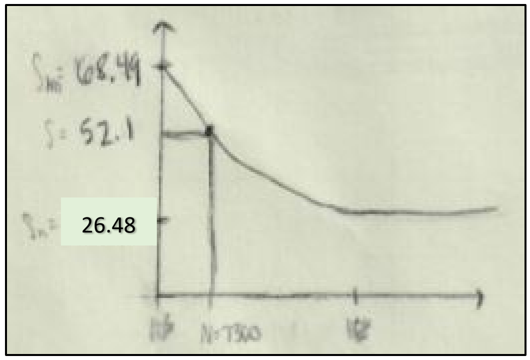


Figure 15: The SN curve for the connecting rod.

$$C = \log\left(\frac{S_{1000}^2}{S_n}\right) = 2.24834$$

$$b = -\frac{1}{3}\log\left(\frac{S_{1000}}{S_n}\right) = -.13757$$

$$S = 10^C N^b = 52.103$$

Figure 16: Calculations for strength after a certain fatigue life.

A fatigue life of 7300 cycles was decided which was used to calculate the strength after that many cycles. This strength was used in the Goodman Equation in replacement of the Sn value that is normally in the denominator of one of the fractions. The safety factor was determined using both strength values.

$$\frac{\sigma_m}{S_u} + \frac{\sigma_a}{S_n} = \frac{5.4305}{76.1} + \frac{5.4305}{26.48} = \frac{1}{S.F.}$$

S.F = 3.62 so the tailgate will not fail due to fatigue

$$\frac{\sigma_m}{S_u} + \frac{\sigma_a}{S} = \frac{5.4305}{76.1} + \frac{5.4305}{52.1} = \frac{1}{S.F.}$$

S.F = 5.70 so the tailgate will not fail due to fatigue over expected time of use.

Figure 17: Calculations for the factor of safety.

Figure 17 shows that the rod has a good safety factor for both situations so fatigue failure in the rod is not expected to occur. A simplified model of the rod was created in SolidWorks to verify the findings done by the hand, shown in figure 23.

Ramp Calculations:

The final part that was analyzed was the ramp itself. The ramp was simplified to be a single flat plate instead of several sections for easier calculations. The thickness of the ramp was made to be 0.5 inches so that four folds could fit into the tailgate for storage. The ramp was calculated using 6061-T6 aluminum for the material. What was found was that the tailgate won't fail due to either bending or fatigue under these conditions. Calculations of the flat ramp used two forces at half the weight of the ATV, assuming the ATV had a 50-50 weight distribution, and angled the forces at 30° to simulate the ramp angle. The normal force and the force of the ATV on the end connected to the tailgate were determined to both be 750 lbs as shown in figure 18. The safety factor of the ramp with 0.5 inch thick plate was determine to be 21.66, also shown in figure 18.

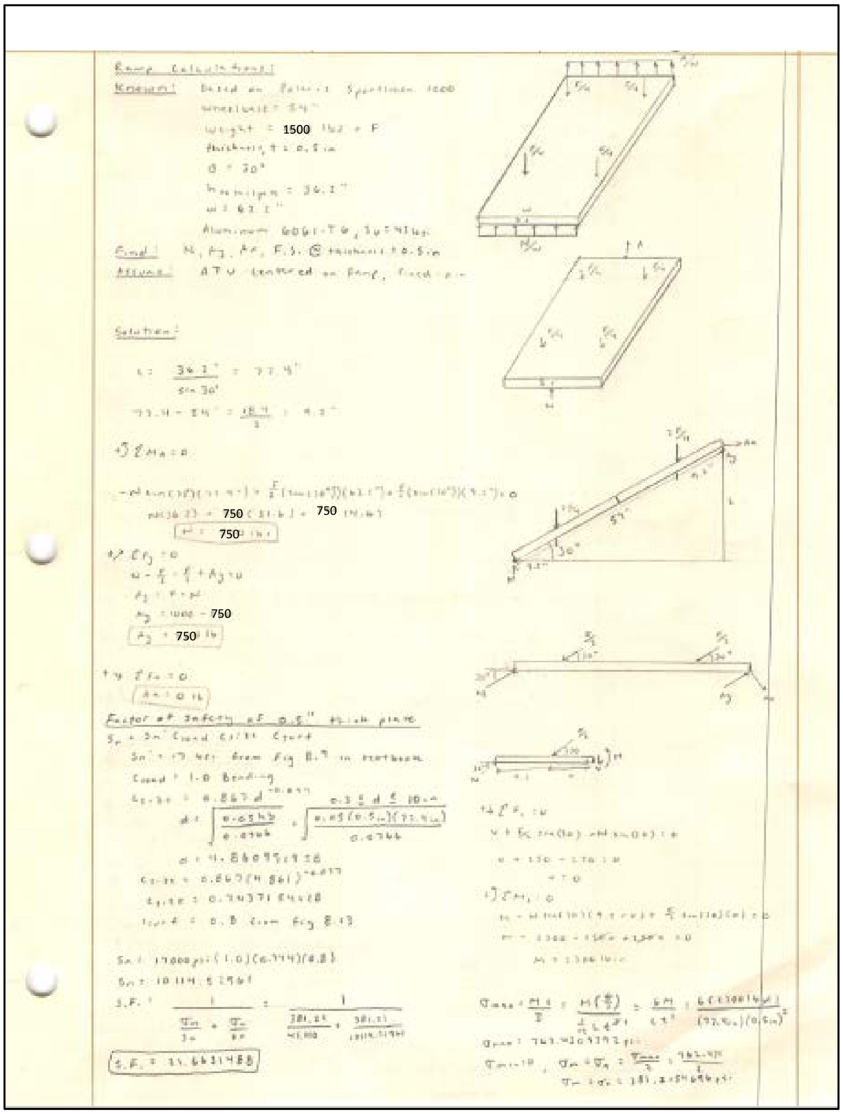


Figure 18: Ramp Calculations of Forces and Safety Factor

To determine if the ramp would survive an ATV loading the ramp two times per day for 10 years an S-N curve was used as shown in figure 19. The results of the S-N curve help show that the ramp will survive more than the 7300 cycle that the ramp is expected to experience. A simplified model of the ramp was created in SolidWorks to verify the findings done by the hand, shown in figure 21.

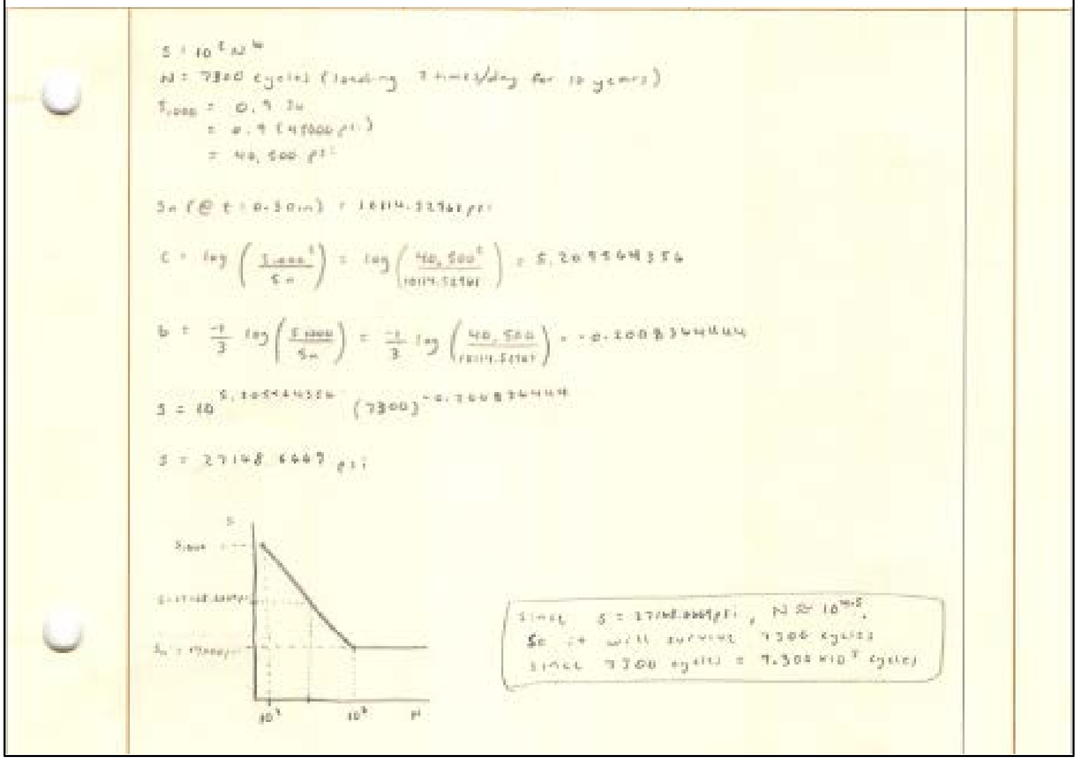


Figure 19: Life Cycle of Ramp

S*<u>olidWorks Model:</u>*

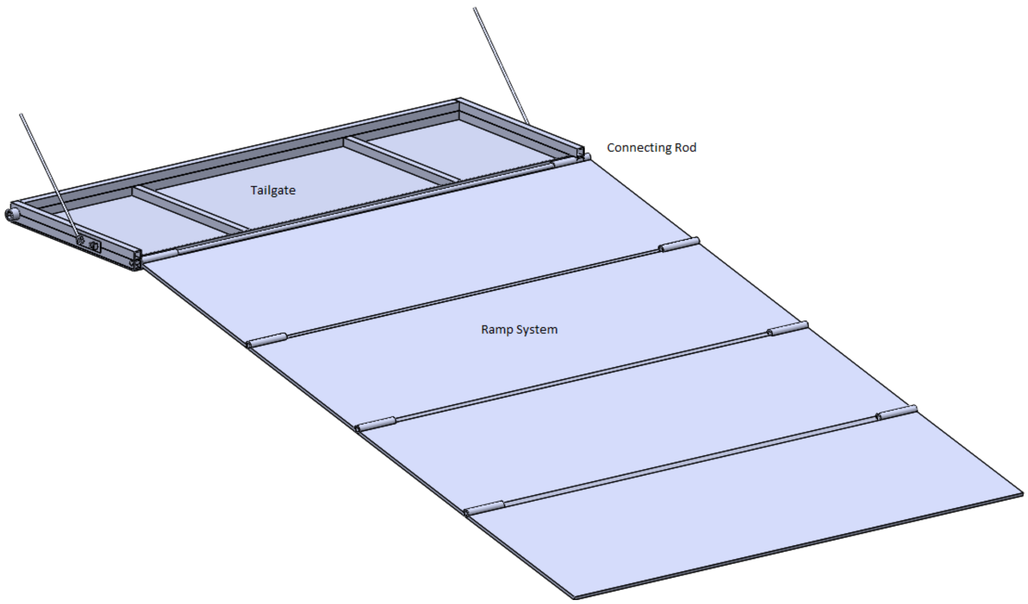


Figure 20: SolidWorks Ramp Setup

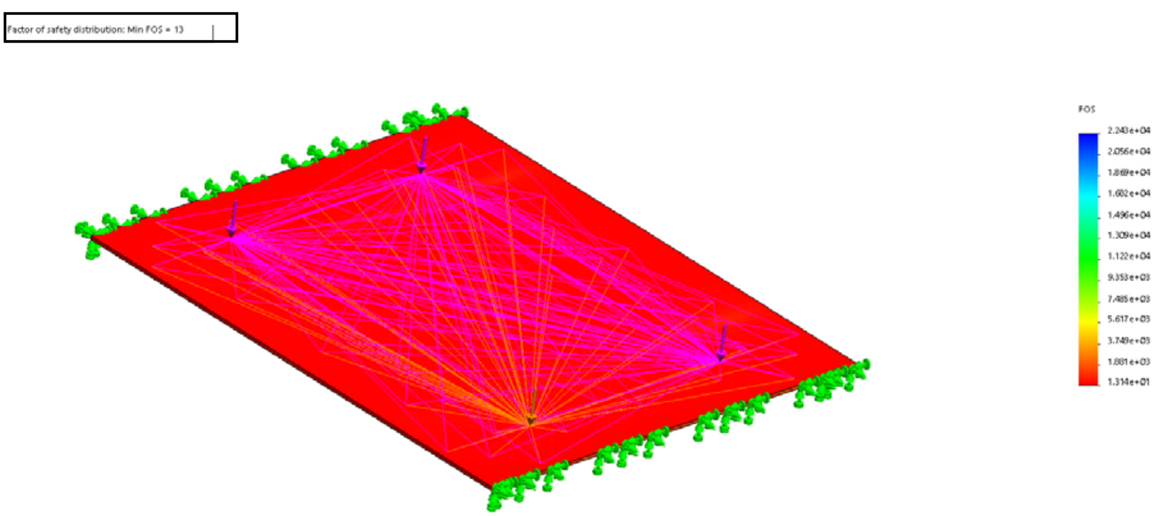


Figure 21: Ramp SolidWorks FEA

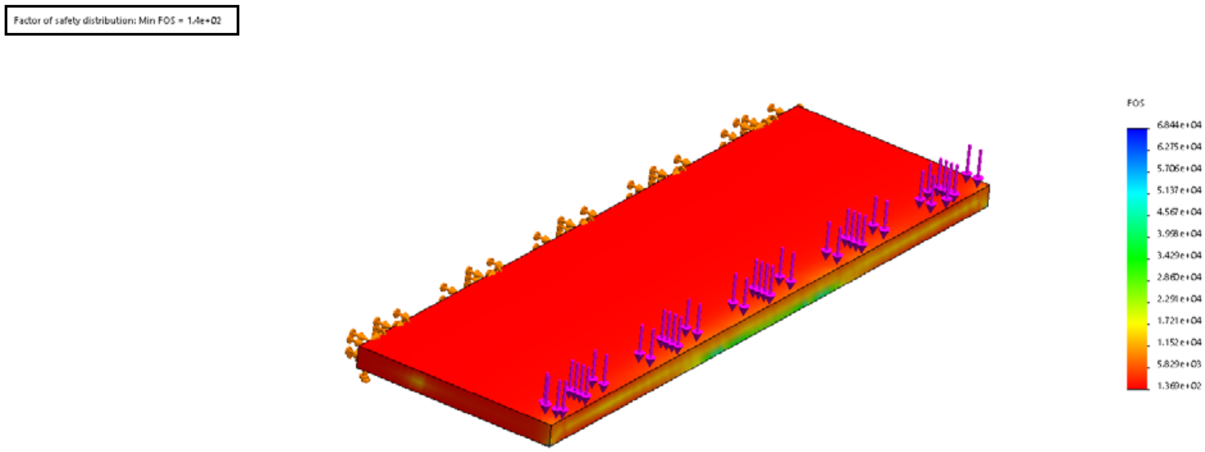


Figure 22: Tailgate SolidWorks FEA

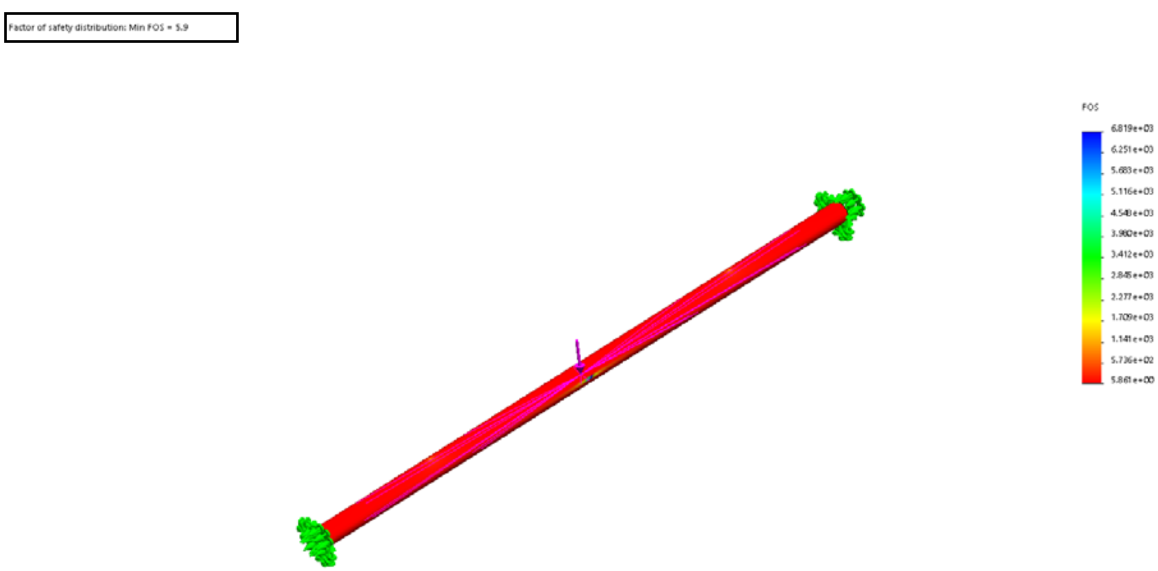


Figure 23: Connecting Rod SolidWorks FEA

Results and discussion

The final design is shown of the SolidWorks model, figure 20. This model shows a ramp that has four folding sections. These sections fold upwards into the tailgate itself for storage. The ramp and tailgate were designed using 6061-T6 aluminum and the mounting rod was designed with AISI 1030 cold drawn steel. The minimum safety factor for the tailgate came out to be 4.86 at the pin connection to the vehicle. The tailgate was simplified as a 2 inch thick plate of 6061-T6 aluminum. The mounting rod ended up having a safety factor of 3.62. The final component, the ramp, was simplified as a single plate of ½" thick 6061-T6 aluminum and ended up having a safety factor of 21.66. This analysis proves that the ramp will not fail due to the bending stress/fatigue induced by loading an ATV. Each component's calculations were verified with the use of FEA (Finite Element Analysis) on SolidWorks. Even though our design is calculated not to fail, additional factors should be considered.

If the design were to continue on this ramp setup, additional calculations should be done on each individual folding ramp piece to ensure that both the connections, and the ramp segments can withstand the forces required. After a complete calculation analysis of the actual parts are considered, a working prototype should be created to both test loads and verify manufacturability. Additional ramp designs are recommended to be created with respect to having two folding ramps as well as the single large ramp. Ramp surface materials should be researched so that a surface material that has good traction is used. User ergonomics should be verified by use of the prototype. If the design isn't ergonomically sound, it should be altered to meet the needs of the average user.

This design definitely has potential as no other company has this standalone tailgate design where the ramps actually fold into the tailgate. The mechanism of folding the ramps into the tailgate would be a novel idea to try and patent. If the design would be universal to most truck brands, it would enhance manufacturability and become a much cheaper product; research should go into the feasibility of this. If it were an easy swap from the customer's original tailgate, it would be a very useful product. Research into an exterior design of the tailgate should be done which analyzes curves/body lines that match up to most truck's bed designs. The aesthetics of this tailgate would be a deciding factor in whether or not people would actually buy it. It should be a major design criteria for future design work of the tailgate ramp. One big issue that is foreseen with this tailgate is cost. No cost analysis was done but with the current design, it may be rather expensive for the average consumer.

Conclusions

The engineering analysis done for the truck ramp tailgate system proved that the ramp would withstand loads in excess of 1000 pounds. 1500 pounds was used as the max load rating which gave us safety factors in excess of two proving that the system would survive. Fatigue analysis was done on each component with an assumed use of two times per day for ten years. A SolidWorks model was created that shows the concept design of the ramp system. SolidWorks FEA was done for each component after they had stress analysis done by hand to verify that the numbers were relatively close to the hand calculations. Weight of the ramp was reduced by making the components out of aluminum. This also reduces the chance of the components corroding. The design met the requirement of not taking up storage space within the bed of the truck and being a self-contained unit. With further design analysis and prototyping, this design could be a viable and marketable product in the future.