Stress and Safety Analysis of Steel Ladder: Taking Second Men's Dorm Ladder as an Example

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Abstract

This article analyzes the stress distribution of ladder by modeling a person climbing up and down using the ladder. This is done by using Computational Aided Engineering (CAE) software to use Finite Element Method in the ladder. The modelling of the ladder is created in Inventor software and is analyzed in Finite Element Analysis feature in Inventor software. The material we assign to the ladder is 6063-T831 Aluminum. Two cases which is the original design case and a redesign case are modelled and analyzed by assuming an average-weight person using the ladder. From the analysis, the breakage of the ladder might be caused by the stress distribution in ladder or exceeding the endurance strength of the ladder.

Key words: Ladder, Stress Analysis, Finite Element Analysis

1. Introduction

As an international student came from Malaysia, it is inevitable for us to stay and live in the hostel in our school for about four years at least. Other than us, Taiwanese that came from other cities would feel the same as we feel. In Men 1st, 2nd Dorm, Men 1st Graduate Dorm, Freshman Women Dorm, Women 3rd, 6th Dorm, they are using the same ladder design that connects the ground floor and bed area.

Therefore, the safety of ladder and the upper limit to safely support an individual going up and down using the ladder has to be analysed. Taking us as an example, we are living in Men 2nd and 3rd Dorm, the ladder design in Men 3rd Dorm is similar to stairs Therefore it is safer comparing to design in Figure 1.

Figure 1 Ladder Design in Men 2nd Dorm. [1]

Figure 2 Ladder Design in Men 3rd Dorm. [1]

Moreover, there is breakage of ladder happened in Men 2nd Dorm, thus we are using this incident as an example, we will be analysing the design of the ladder in order to make sure that it can sustain different situations like different weight of dormmates, to prevent the breakage of ladder happening in the future again.

Figure 3 The Breakage of ladder in Men 2nd Dorm.

2. Design and Modeling

We try to obtain the engineering drawings of the ladder from the Student Housing Service Division in Office of Student Affairs, they are not able to provide us because of some privacy issues, therefore the real dimensions of the ladder are measured on our own in the Men 2nd Dorm using the Vernier Calipers and Tape Measure. The modelling of the ladder is then created in Inventor Software with the dimensions obtained.

Figure 4 The modelling of ladder using Inventor.

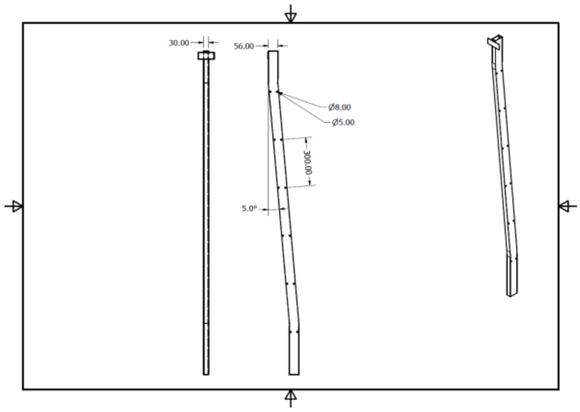

Figure 5 The left and right component of ladder

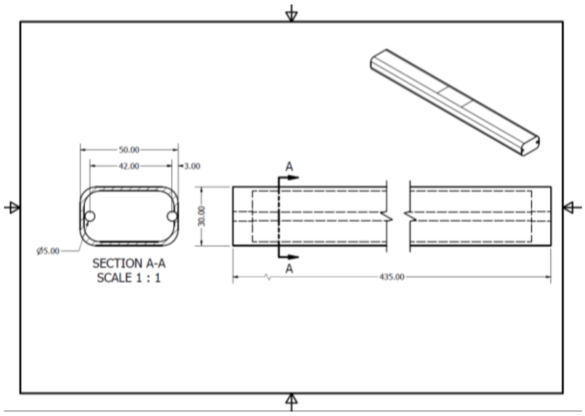

Figure 6 The middle part of the component, named Ladder_C

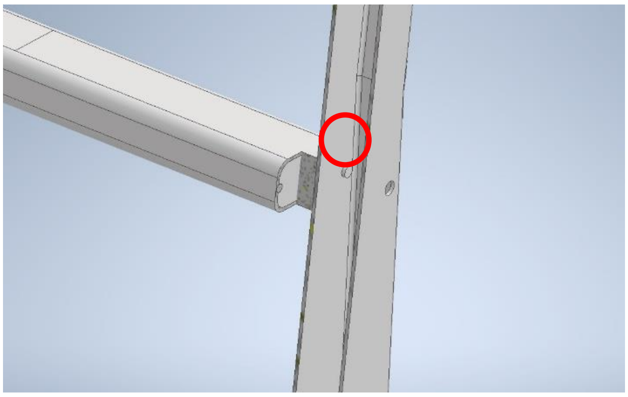

Figure 7 The showing of connections between components with screw using section view

From Figure 6, it is surprised to see the design of the Ladder_C has flaws in it. The right hole of Ladder_C is only distanced by 3mm from the edge, it has high possibilities to cause stress concentration in that particular area and lead to breakage of the ladder. Thus, with the speculations above, a new redesign Ladder_C is created in order to avoid stress concentrations and to compare the result of two different cases.

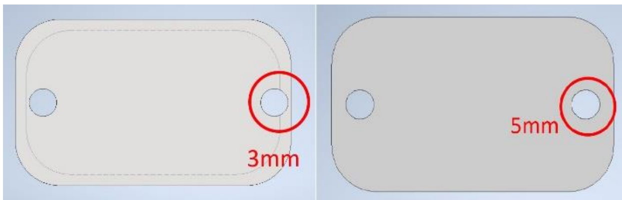

Figure 8 The before and after designing the Ladder_C.

3. Materials

Same goes for determining the material of the ladder, the Student Housing Service Division in Office of Student Affairs does not provide any information of ladder as well, by just looking and touching the ladder, we speculate the material of the ladder is made of steel. In order to get more detailed data, it is needed for us to look for more information on the Internet.

But by doing more research on the Internet, ladder is mostly made of aluminum alloy. For ALACO ladder company[2], they use 6000 series of aluminum alloy for their fire ladders, platform ladders etc. Furthermore, Aluminum 6063-T831 has applications include furniture[3], thus we assign this material for our ladder. As for the screw, we simply assign stainless steel for it as it is not the main part to analyze.

Density (kg/m^3)	2700
Young's Modulus (GPa)	68
Poisson's Ratio	0.33
Ultimate Tensile Strength (MPa)	210
Yield Strength (MPa)	190
Fatigue Strength (MPa)	64

Table 1 Mechanical Properties of Aluminum 6063-T831[4]

4. Setup

4.1 Real life scenario

In real life situation, the ladder is fixed on the top part (rectangular part) of the ladder by screwing the part into the bed area. When a person is climbing up or down the stairs, the highest stress happened when there is only one leg standing on the Ladder_C, and the whole weight of an individual's body is exerted onto the ladder. In this situation, it is the most likely for Ladder_C to undergo breakage, hence it is going to be analyzed.

Figure 9 A person climbing a ladder in real life while ejecting the highest force on ladder [5]

4.2 Load and Constraint

To analyze the situation above, we will use the Finite Element Analysis in Inventor software to setup and to calculate the highest Von Mises Stress in the situation. The upper parts of the ladder (rectangular part) is fixed using the fixed feature in FEA. Next, we will apply loads onto the ladder, in order to setup just like the real-life situation, we will instead apply a force in a small area on Ladder_C. The area will be showing in the figure below. (Figure 10)

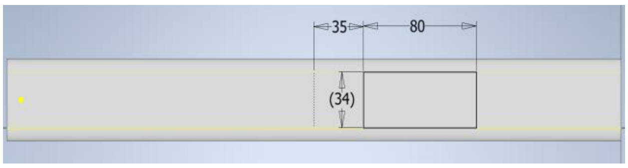

Figure 10 The location of force onto Ladder_C

In real life, we will not be stepping in the middle of ladder, thus the area is 35mm away from the midline of Ladder_C. The 80mm is a rough width of soles of human foot. As for the force, it is set to be 700N (71.3 kg) which is around the average weight of a male. Therefore, the pressure exerted on Ladder_C can be calculated by

$$P = \frac{F}{A} = \frac{700\text{N}}{80\text{mm} \times 34\text{mm}} = 0.2574 \text{ MPa}$$

This pressure will be exerted onto two different steps in ladder, which is the first and the third. Choosing the third step because the ladder that went broken in Men 2nd Dorm is exactly on the third step, analyzing it should be very straight forward. Choosing the first step in ladder because it is the highest on the ladder, if that step is broken, the severity of the injuries caused will be the highest. Lastly, all the steps above will be repeated for original design and a redesign case (Figure 8).

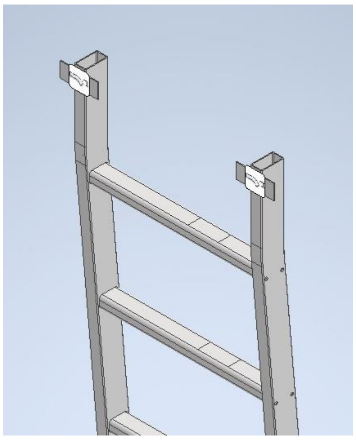

Figure 11 The upper part of ladder is fixed.

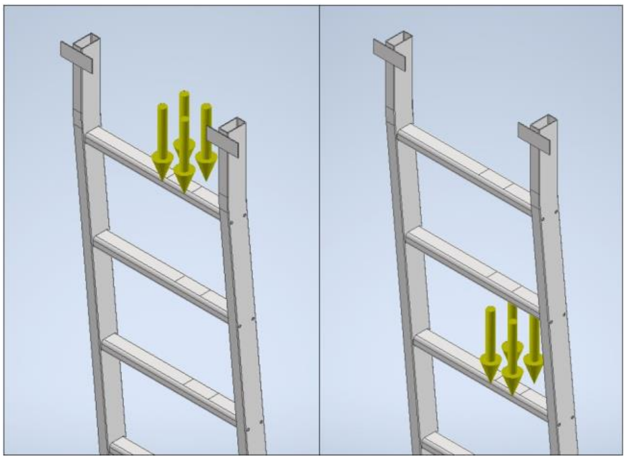

Figure 12 Pressure exerted on first and third step.

The conditions that will be analyzed are:
1. First ladder step with original design.
2. Third ladder step with original design.
3. First ladder step with redesign.
4. Third ladder step with redesign.

4.3 Interaction (Bonded)

As for the contact of the ladder model, Inventor can automatic setting up the contact part of all the contact area to be bonded. It is not require to set up one by one, but double checking with the correct automatic setting is required as some contact area are not supposed to be bonded.

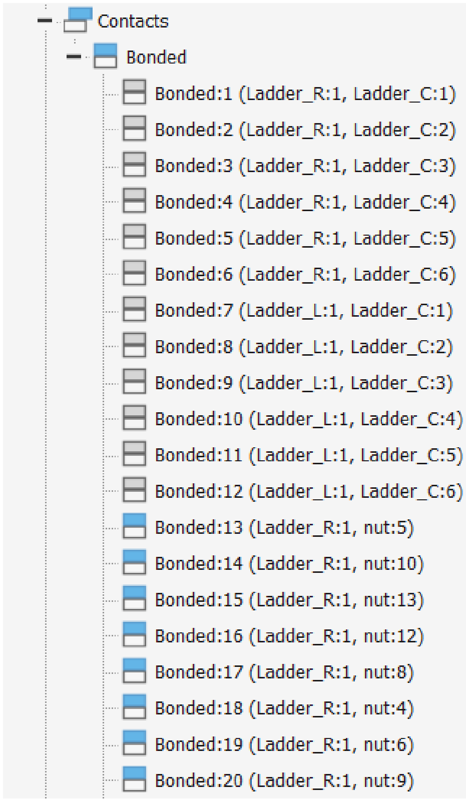

Figure 13 A portion of bonded setting of the model in ladder. Grey symbol stands for setting that is switched off because of false automatic setting by Inventor.

4.4 Meshing

Next step is to mesh the model of ladder. In the mesh settings, average element size are set 0.100, grading factor of 1.5 and maximum turn angle of 60°. Furthermore, applying Local Mesh Control to the Ladder_C that is focused on to increase the element number in order to increase the accuracy of analyzation. Overall, there are 112150 notes and 56958 elements generated.

Figure 14 Meshing of the ladder

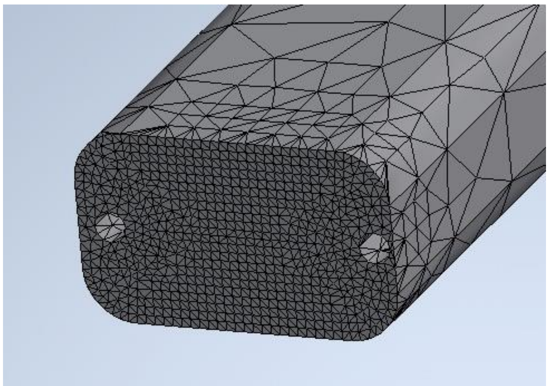

Figure 15 Locus Mesh Control on part that is interested.

5. Result

From Figure 3, the breakage happened at Ladder_C, therefore we are only interested in analyzing the highest Von Mises Stress in Ladder_C. After running through the four conditions stated above, stepping on the first or stepping on the third gives the same result. Thus, the result will compare the stress analysis on original design and redesign conditions.

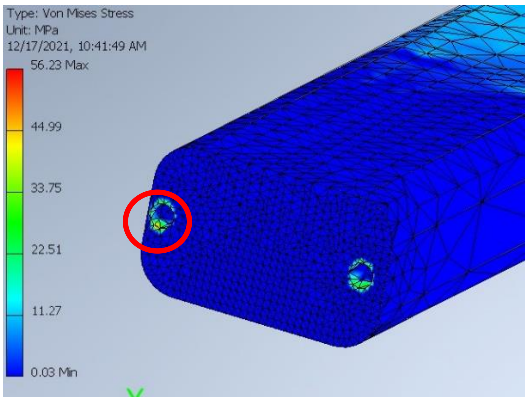

Figure 16 Stress Distribution on Original Design of Ladder_C (First step and Third Step of ladder)

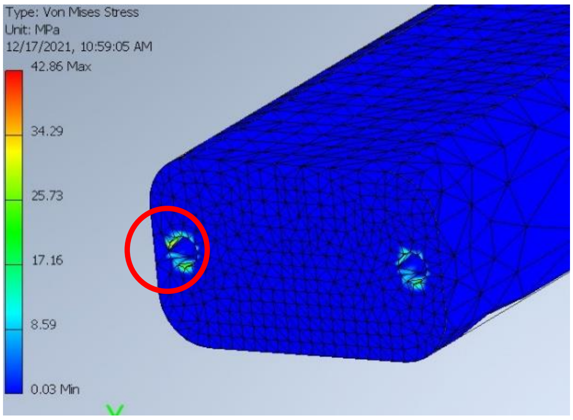

Figure 17 Stress Distribution on Redesign of Ladder_C (First Step and Third Step of ladder)

Conditions	Highest Von Mises Stress (MPa)
1	56.23
2	56.42
3	42.86
4	42.34

Table 2 Result of Conditions 1 and 3.

If we are not focusing on the Ladder_C, the highest Von Mises Stress is actually on the screw that is connecting the ladder. From the analysis, the highest stress is 113.7 MPa, a much higher number compared to the stress in Ladder_C. As the screws are made of steel, which has higher ultimate tensile strength, yield strength or even fatigue strength compared to aluminum. Thus, Ladder_C that made with aluminum will break before screws if breakage really happen.

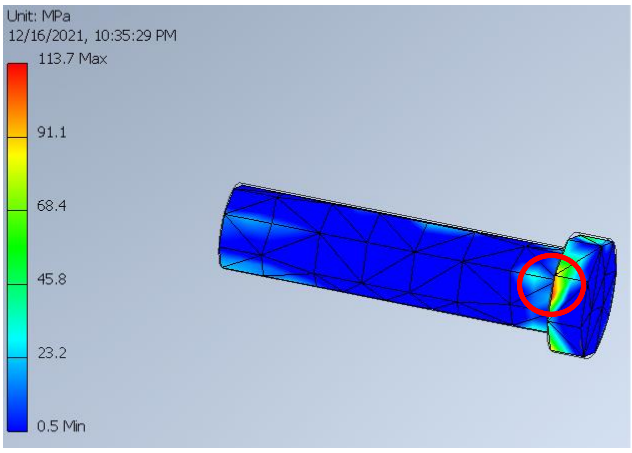

Figure 18 The stress distribution on the screw.

6. Discussion

From Table 2, there is 14 MPa difference for original design and redesign of Ladder_C. The only difference between original design and redesign is just the distance of the center of the hole and the edge, from 3mm to 5mm. The highest Von Mises Stress can be decreased significantly by just moving a small distance of hole away from the edge. Thus, showing that a proper design of a hole is important to avoid stress concentration and leads to breakage.

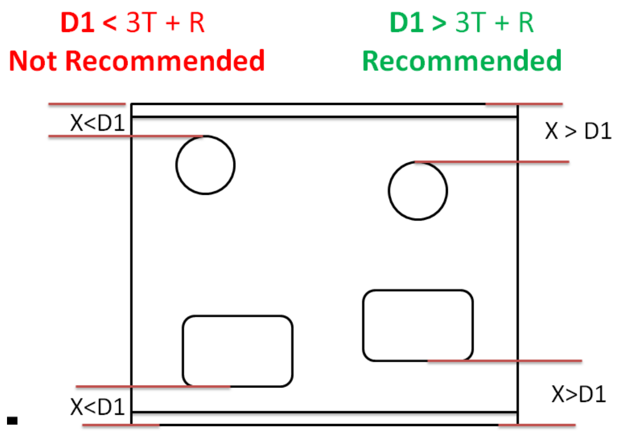

Figure 19 Criteria for design hole for sheet metal. [6]

For sheet metal, the hole and the edge must be distanced by $3T + R$ where T is the thickness of the sheet metal and R is bend radius. In our case, the distance of the hole and the edge does not larger than $3T + R$, thus there is high chance for Ladder_C to undergo permanent deformation or even breakage.

Other than that, we can compare the result obtained in Table 2 with Table 1. The highest Von Mises Stress are actually way lower than the ultimate tensile strength and the yielding strength. Theoretically, Ladder_C would not break or undergo plastic deformation. However, the result values are close to the fatigue strength of Aluminum 6063-T831. We speculate that the ladder will break because of high amount of stress cycles acted on the ladder.

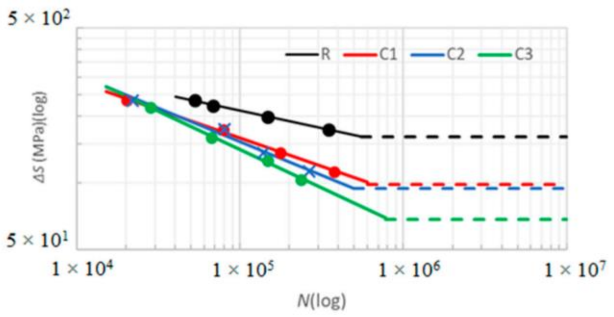

Figure 20 Stress vs. average number of cycles at Failure of Aluminum 6082. [7]

The accuracy of the result is low, but it does helps us to make an approach to further understand the reason that causes the ladder to break. There are several reasons that might affect the accuracy of the result:

1) The unknown material of the ladder. In order for our analyzation to continue, we are forced to find a metal that suits the situation. Different material will have different mechanical properties that includes fatigue strength, tensile strength etcetera which will heavily affect the calculation for safety factor.

2) The force on the ladder. When we are climbing up a ladder, it is not just a static analysis. A moving up or down of the ladder surely will increase the force acted on the ladder, therefore increasing the stress and leads to breakage. The force we set in our simulation is an average weight of a male, while in real life, the weight might be higher than that, causing an error in calculating the result.

3) Weight of ladder is neglected. For the analysis, we realized we forget to setting up weight which is our mistake. The weight of the ladder might increase the highest stress acted on the ladder as well.

4) Simplification of scenario. Simulation of a real-life scenario is not easy as there is much more factor to think and to setup. A simple

setup like this has already took 10 to 15 seconds to calculate the result, if a more detail simulation is done, it might take up to days. However, a detailed simulation might give back a more promising result.

7. Conclusion

(1) Good design for Hole is important to avoid stress concentration and plastic deformation or even worse, breakage of metal. By the comparing the result of original design and redesign, a significant decrease in highest Von Mises Stress are observed when the distance of the hole and the edge are increasing. In order to achieve the best result, the distance of the hole and the edge must follow the criteria, $3T + R$.

(2) For any material, other than ultimate tensile strength and yielding strength, endurance strength (fatigue strength) is an also important mechanical property to focus on in order to avoid failure at some stress cycles. We should assume ladder will undergoes much more cycles as an individual might climb up and down the ladder for 3 to 4 times at least per day. Choosing an material that has high endurance strength in order to achieve infinite life cycle theoretically.

8. Reference

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