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DESIGN AND EVALUATION OF CARABINER USING FINITE ELEMENT ANALYSIS

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A carabiner is a fall protection safety tool that is used in various outdoor and indoor activities, most known usage is at climbing and high-risk work related to elevation. A standard carabiner is capable to withstand at least 7 kN of static load. In this study, we only observe how carabiners respond in certain static loads by using simulation software and comparing the result with the standard of carabiners. We use F1956-13 as a standard of the test procedure, and aluminum alloy 6061 as the material. After the study from simulation result, it shows that stress and deformation change linearly with loads. But the safety factor has different behavior, after the load applied increases over 1 kN the slope decreases significantly, and the safety factor is around 0,17 at 7 kN applied load. Besides that, we understand that design analysis by simulation is a good method to obtain the optimal geometry, or shape of the model, but computational simulation cannot replace physical mechanical tests.

Keywords: *Design, Evaluation, Geometry, FEA, Carabiner*

1. INTRODUCTION

Carabiner is a metal loop shaped (usually aluminum) with a spring-loaded gate on one side which used to connect various part of a climbing system [1]. First carabiner was used in 1868 by German soldier, to carry a rifle [2]. Climbing itself considered to be a high-risk sport since it may cause damage to health or life [3]. Therefore, safety of the tool has to be strong enough under certain load, either dynamic or static. It has been used as fall protection since mid-1980s [4]. Generally, carabiner used in various activity mostly as a fall protection system, beside climbing we can see it used in area such as navigation, civil engineering, mining, and rescue operation [5]. It is critical for the carabiner to serve as main safety equipment in those instances. To reduce risk and fatality improving standard become crucial [6]. Load, geometry, and resistance environment are important factor to establishing a carabiner design.

Higher the load carabiner can handle better for the user and lower the weight is better for the manufacturer. Well-designed model will increase efficiency by reduce time, electricity usage, and other source [7]. To Achieve lighter design manufacturer cut some materials that is unnecessary for the carabiner without sacrificing any of the strength. And the result is various kind of cross section, for a recent trend circular and “I-beam" style cross section are often seen in commercial carabiner [8]. And also, minimum failure loads of basic connector carabiner for major axis is 7k N for open gate and 20 kN for closed gate, and for minor axis at least it has 7kN of minimum failure load. These loads are obtained by tensile testing machine by hook and pull the carabiner with two pins that aligned with the axis on the test (pin diameter is vary depend on testing subject and relative axis) observe the loads applied and see necessary load to tear or break the carabiner [9]. Tensile stress applied on contact points between carabiner and pin may differ in every system tested depend on the carabiner dimension and pin size.

Most of carabiner nowadays are made from aluminum alloy since they are lightweight and offering adequate mechanical properties, ant yet relatively easy to manufacture and affordable in market. Al-Cu, Zn, Mg, Cr are used to increase mechanical properties of the aluminum. Popular materials used recently are 7075 or 6061 aluminum Bur [6, 7]. Although there is also carabiner from composites. Virgil Scott studied and

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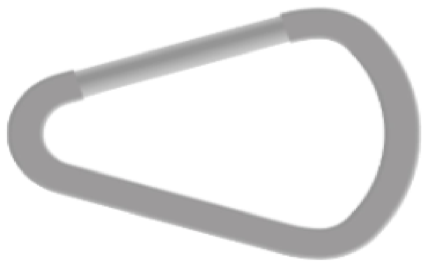
manufactured a composite carabiner design which are made from carbon fiber PEEK composite laminates and compared to the aluminum carabiner From properties of the material used in the comparison the composite has near to 20% more tensile strength and 40% lighter than aluminum. In the study, Scott FEA the CAD design and test the tensile strength of the manufactured carabiner. For the simulation in the study longitudinal or major axis closed gate are tested, with minimum restriction from EN12275 standard. In conclusion composite carabiner has less toughness compared to mainstream aluminum alloy yet manufacturing process and material demands higher costs [8]. One of method to reduce material cost is by using additive manufacturing method as the main manufacturing process, this method has been studied using Fused Filament Fabrication (FFF) types of 3D printer as a prototype of carabiner [10, 11]

Material selection in design and manufacturing process hold important roles. It can determine how the product success on market [12] Also, the geometrical design, to optimize stress distribution of the model. Which is material and geometrical shapes correlating. The product has to safe and lasts at minimum load required in Europe climbing carabiner standard from EN12275. How Ductile the material is also important factor too; ductility is range of plastic deformation before it fractures or failure [13]. Beside the load material has to withstand within certain environment, wear resistant and corrosion resistance of the material. Since most climbing activities are done in outside, thus the material will have a lot of contact with air, especially oxygen [14]. Which may cause corrosion, comparing 6000 series and 7000 series aluminum alloy from data sheet either of the alloy offers relatively high resistance for corrosion. Yet 7000 series have significantly higher tensile strength and better stress cracking resistance [15, 16].

In this study we are using single model, a regular carabiner that can found in store. There are some varieties of carabiner, every shape possesses different failure loads that has been stated taken from EN12275. The model used is D shape carabiner [17].

Table 1: Variation of climbing carabiner shape

Name	Scheme
Oval	
Offset D	
Pear	

Standard D	

This research will be conducted with computational test, using offset D shape basic connector carabiner used as a model. And then compare tensile stress, and safety factor of the model by simulating the CAD design on multiple loads, from 0 kN to 7 kN. By increasing the applied load gradually to understand how the subjected model changes its shape in every steps. Observe the changes of the carabiner then compare deformation, and form of failure. Simulation will be performed using Finite Element Analysis (FEA) with ANSYS software [18]. The CAD model made in CAD software by copying the physical model.

This study aimed to present correlation of loads, tensile stress, and safety factor. And understanding reliability of testing with simulation for development and optimization of geometry and shape of the Carabiner. Therefore, necessity of tensile testing with machine which require to break a material leads to cost effective development process [19]. This paper includes 1) Introduction, 2) Materials and Methods, 3) Results, 4) Discussion, and 5) Conclusion.

2. MATERIAL AND METHOD

2.1. MATERIAL

Material used in this study is aluminum, to be precise 6061 aluminum. Known as aluminum alloy for structure that require strength, weldability, and corrosion resistance. Properties of the material, obtained from aluminum 6061 datasheet [20]. The properties of the aluminum are shown in Table 2.

Table 2: Properties of Aluminum Alloy 6061 from ANSYS library

Properties	Value	Unit
Density	2713	kg/m³
Young Modulus	69040	MPa
Tensile Yield Strength	259	MPa
Tensile Ultimate Strength	313	MPa
Poisson's Ratio	0,33	

2.2. Method

The study conducted using Finite Element Analysis with Software ANSYS R2 2020 (student edition). The carabiner with similar geometry and dimension is modeled then simulated. D shape basic connector carabiner, that has 103 mm length, 62 mm height, with rectangular 9mm x 11mm rectangular cross section. As can see in Figure 1. The model was adapted from the carabiner that can be purchased in the market with the brand name "Eiger".

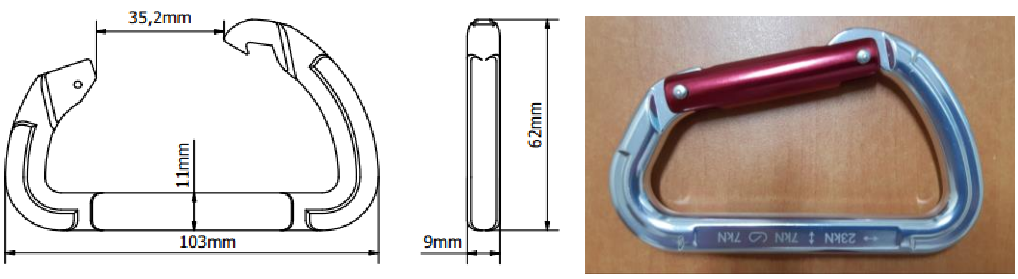


Figure 1: Dimension of the model

The simulation run by setting 10 mm diameter pins at both corners, instead of rope. Although normally in most activity ropes are used, to simplify and reducing the effect of other variable researched by Nikonov et al [21], Agnieszka et al [22], thus steel pin is used. One pin set as fixed pin and second pin that at other side to pull the model. Carabiner will be tested on open gate condition with applied forces at major axis.

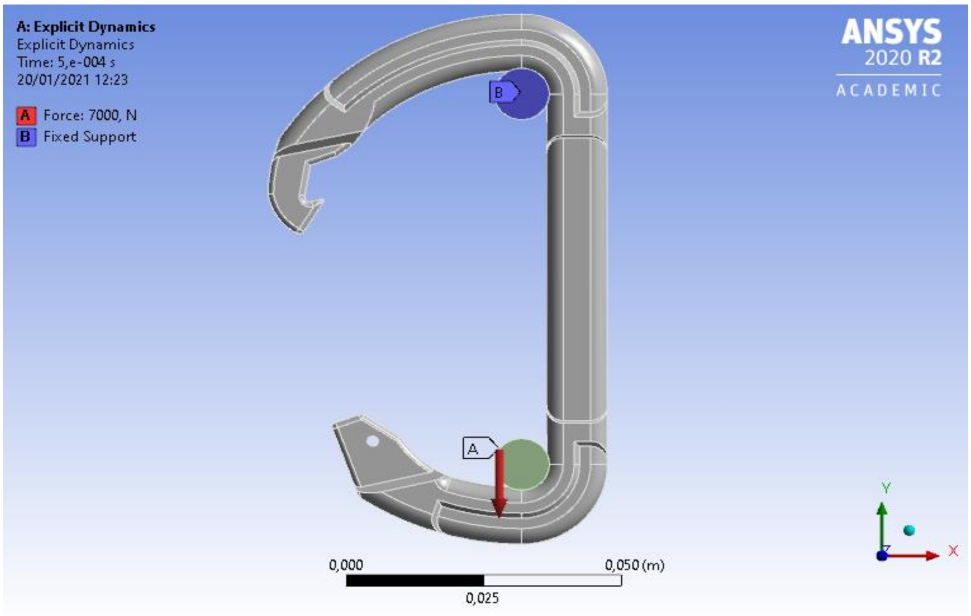


Figure 2: Analysis setting

Before run the simulation, first pin is constrained at any point then constrain the wide curve side of carabiner, after that constrain second pin at corner of other curvature. Each pin is aligned at Y axis of the absolute coordinate or aligned to major axis of the carabiner. This test setup is following F1956-13 rescue carabiner test for major axis gate open [23]. Material of carabiner used for the simulation is 6061 aluminum and pins material are set as structural steel (different from pin on F1956-3 testing set up, AIS SAE Type 01 Tool Steel but possess similar properties), and roughness of surface in tensile test result has studied by Daw-Kwei Leu [24] and neglected in this study to simplify the test. Normally, fixtures are made to avoid rotational movement from the test pins, since the test is done in major axis only, fixturing the model is most likely unnecessary. The contacts are suppressed and the body interaction type is frictionless, since friction doesn't affect the failure location [25]. Temperature set to environment since effect is not visible in small temperature differences [26].

Generated mesh for the simulation is 12848 elements, with medium quality smoothing, where load generated to negative Y direction by second pin. Applied loads vary, start from 1000, 3000, 5000, and 7000 N. After the simulation finished maximum principal stress, total deformation, and safety factor are observed.

In this simulation manufacturing method of carabiner is ignored. Only using solid 6061 series aluminum as material. Condition of carabiner in this simulation is closer to CNC manufactured carabiner without any hardening process. CNC milling machine is also an option for carabiner manufacture due to its higher accuracy and precision compared to traditional milling machine in mass production of a product. Open loop CNC with appropriate parameters ensure smooth and quick cutting process for industrial use [27].

3. RESULTS AND DISCUSSION

The FEA results from maximum principal stress, total deformation, and safety factor in end step shown in Figure below.

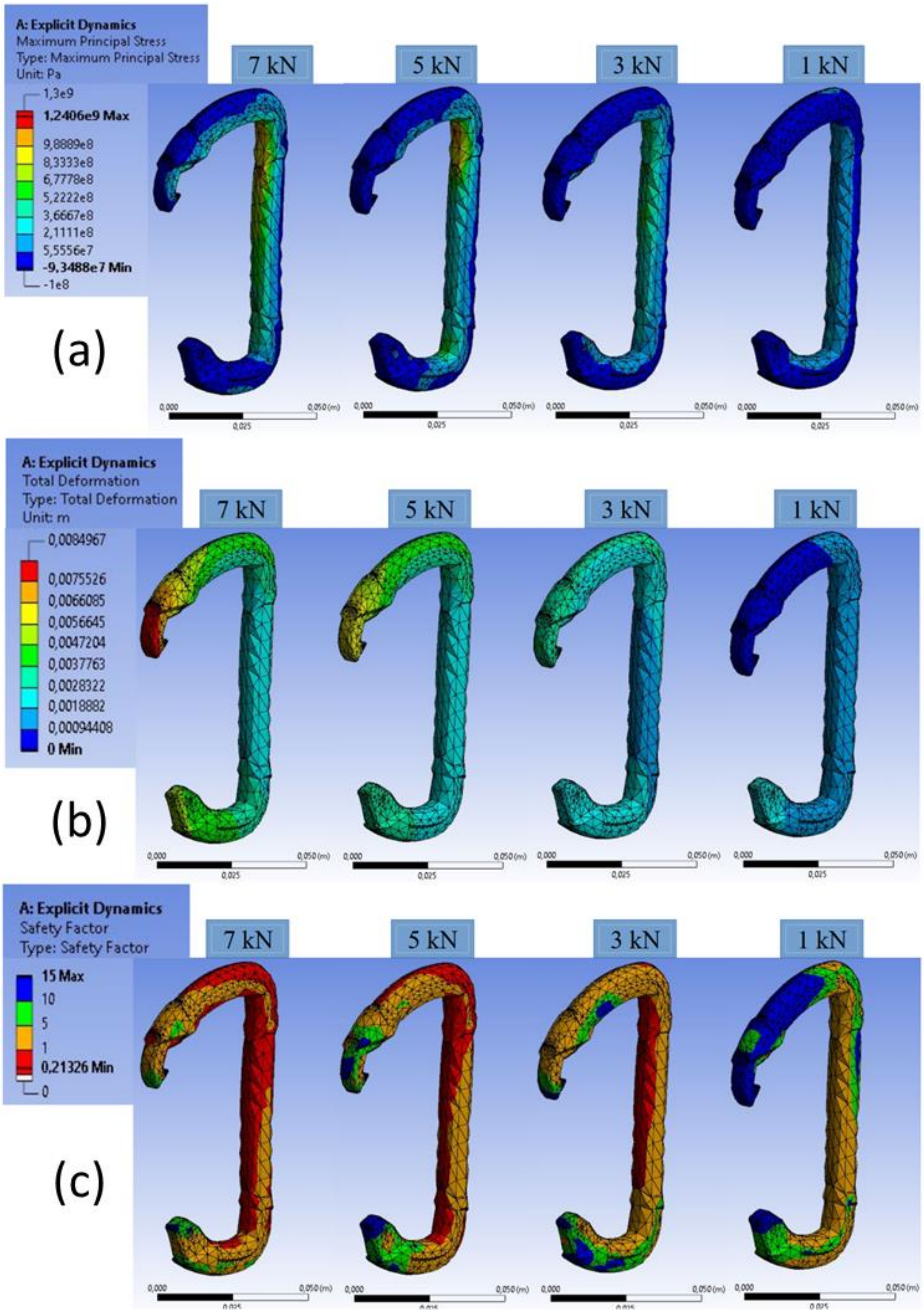


Figure 3: FEA simulation result by explicit dynamic module. (a) maximum principal stress of carabiner with various load, (b) total deformation of carabiner with various load, and (c) safety factor of carabiner with various load.

Simulation result presented in Figure 3, shows the distribution of the (a) maximum principal stress, (b) total deformation, and (c) safety factor, with 7 kN, 5 kN, 3 kN, 1 kN as applied respectively from left. Figure 3 (a) shows tensile stress occurring on carabiner under 3kN is relatively low and especially backside of carabiner has negative value of stress (blue area), which means compression is happening in there. And also, the highest tensile stress in Figure 3 (a) at 7 kN load is yellowish with 1182 MPa. And at 5 kN load the highest tensile stress is 1240 MPa.

In Figure 3 (b) we can see the deformation of carabiner is quite significant, at 7 kN load about 8 mm of deformation occurs. It happens because as we can see from Figure 3 (a) back side of carabiner has compression thus the tips of the carabiner get pulled by. The main cause of deformation is arcing back, the both tips of the carabiner don't experience significant deformation.

On the other hand, Figure 3 (c) shows safety factor, or ratio of yield stress of the material (aluminum alloy 6061) and von mises stress. In this study von mises stress simulation is not conducted. From the result we can assume below 1 kN load has no red area, which means relatively safe to use. In this explicit dynamic simulation, the model may fracture, but at 7 kN load it has not, although considerable amount of red is that has safety factor value less than 1. Most likely the failure would occur on that area. At 3 kN the safety factor value under 1 is already covered about 40% near the top curve, it may undesirable to use open gate carabiner at load higher than 3 kN. Also, the lowest safety factor value stays close to the highest principal stress. With these illustrations we can understand which place require modification to decrease stress, which will lead to higher load capacity.

As you can see in Figure 4 for some reason the stress with 5 kN load is higher. Since the simulation is done with explicit dynamic, it is possible. Unlike static stress the stress result is not increasing linearly.

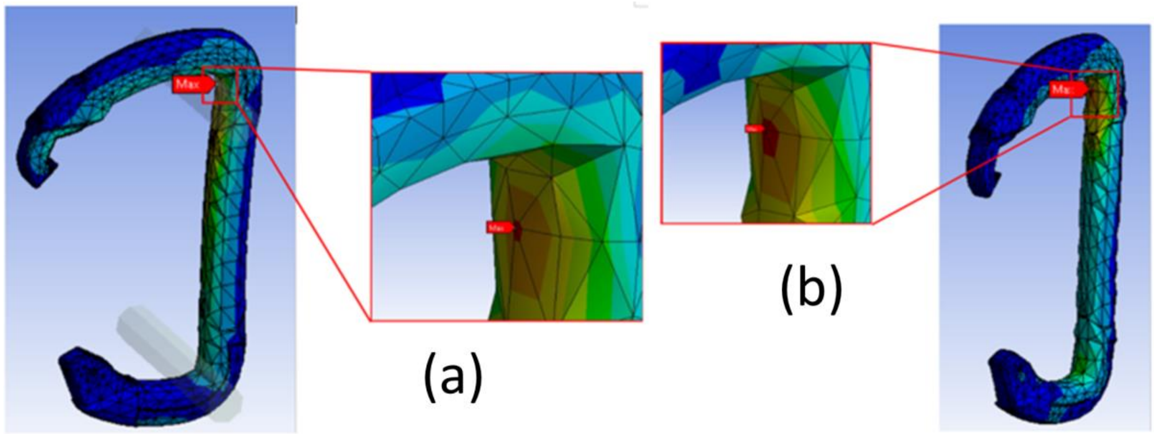


Figure 4: enlarged view of maximum probe of maximum principal stress (a) at 7kN load, (b) at 5kN load.

In Figure 4 at same location at 5 kN load has thicker color, since it has larger stress. Explicit dynamics has different characteristic than static structural module, explicit dynamic is time-based analysis, which means the result is relatively close to real world phenomena. The analysis is done within certain time duration only, for every steps or fraction of the duration the solutions are not linear. In certain time the at 7kN load stress is higher than maximum stress happened in 5 kN load analysis, but at end step the 5kN has higher stress due to fluctuation of the stress to the time.

The stress during the tensile load concentrate on the major axis and the top curve of the carabiner, the create various angle for each element, increasing the shear stress on that area. Therefore smaller radius at top curve creates ton of shear stress with steep angles, these axial and shear stress leads to the rise of principal stress. The maximum principal stress of carabiner is located on top curve of the model, for the bottom curve recieve significantly lower stress compared to its counterpart. Even though both curve are pulled by same pin, the simulation result for the maximum principal stress difference is too significant. Similar visual result can be seen in Figure 3 (c). In this simulation top pin is constrained while bottom pin are pulled downward. This constraining setting is the most possible answer in this case.

4. CONCLUSION

Goal of this study is to understand how the load affects tensile stress, deformation, and safety factor. Correlation between those three parameters. Also, to determine if the computational simulation is a reliable method for the further development and research of geometry and design. From this research can concluded that:

1). Value of the principal tensile stress and deformation are linear with the load applied on the carabiner. The value of the stress in this study used principal stress point of view to determine the real stress that acting onto the plane that we avoided the shear stress (zero shear stress). Moreover, this study also used failure theory based on the maximum principal stress. It is well known that by using principal stress, it is applicable for the brittle materials. Principal stress also suitable when it described by using Mohr circle principal to determine the maximum stress and minimum stress.

2). Safety factor shows negative exponential curve, the value changes drop significantly after reach certain load.

3). This simulation method as main way to simplify the development of geometry and design is quite promising, but only for some extent. We can understand how the load is distributed in the model by this simulation, so to optimize the design this is quite reliable. But for further research, simulation cannot achieve true value durability or safety factor.

4). Physical mechanical properties tests cannot be replaced by computational simulation.

This carabiner tensile test was done by ignoring the changes in properties by manufacturing process. To obtain more reliable simulation more configurations are required for more precise simulation result on specified manufacturing process.

5. ACKNOWLEDGMENT

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