

# Structural Analysis of ABS Plastic Framework of an Autonomous Mobile Robot Using ANSYS

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**ABSTRACT.** *The use of structural calculation software based on finite-element analysis is nowadays a common practice when designing products made from different materials. One of such software is ANSYS. In order to make adequate prediction of the service behavior of plastic components, it is necessary to carry out appropriate analysis when working with ANSYS. Structural analysis is a general term used to describe analyses where the results quantities include stresses and strains. It uses many methods to determine the stresses and strains in materials and structures subjected to forces. In this paper, a structural analysis is carried out for the frame members of the autonomous mobile robot BNRT-MOB-44. These frame members were originally made of aluminum. However, the design is to replace them with 3d printed Acrylonitrile Butadiene Styrene (ABS) plastic members. The approach in the analysis contains drawing the robot and each framework members using a 3d modeling software known as SolidWorks, determining the loading on each framework member, and analyzing each member on ANSYS. The output of this research is basically finding the stress and strain on each of the modified structural frames of the mobile robot. The results of each cases are weighed against the standards of safety.*

**KEYWORDS:** *ANSYS, structural analysis, FEM (finite element methods), ABS (Acrylonitrile Butadiene Styrene), autonomous mobile robot*

## 1. Introduction

Robots are now integrated into the daily management of society, services, and industrial production. It not only frees humans from complex and repetitive labor, but also changes human production and lifestyle with its intelligent, networked, and high-precision features. Mobile robots have the ability to autonomously move and judge the surroundings to suit different working environments [6]. The performance of it is measured not only on the precision and quality of desired work but also on the speed of completing these jobs. Generally, the weight of the robot will directly

affect its speed. Therefore, when designing the structure of a robot, it is a desire to make it as light as possible. One means of achieving this is to use lighter profile materials for building the structure of the robot. Nevertheless, every member should be able to withstand the stress created by the loading. A way of analyzing this is to use finite element methods (FEM). FEM is a mathematical method used to compute the approximation of a real physical system simulations such as geometry and load conditions. With this approach, simple interacting elements are applied. This means that a limited number of unknown variables can be used to approximate an infinite amount of unknown real system [9], [2]. During this research ANSYS software is used to perform this analysis.

ANSYS software is finite element analysis software used to simulate engineering problems. The software creates simulated computer models of structures, machine components to simulate strength, toughness, elasticity, and other attributes. ANSYS is used to determine how a product will function with different specifications, without building test products or conducting crash tests. Knowing precisely how product designs will perform during the manufacturing and assembly processes, and the subsequent product life cycle, before building physical prototypes, can save a tremendous amount of time and money. Traditionally, in a finite-element analysis, all input parameters such as material properties, geometric extensions of a component, external loads and boundary conditions are regarded as deterministic and fixed values. In reality, however, almost all of these input parameters are subjected to scatter and show variations from one component to another. With the new Probabilistic Design System (PDS) in ANSYS 5.7, these input variations can reportedly be taken into account and their effect on the analysis results can be quantified. This allows to address how products behave under real-life conditions. It also assists in quantifying as well as to optimizing the reliability and quality of a product in order to achieve a much more affordable design [3].

ABS is one of the most commonly used, and most versatile materials available in 3D printing today. ABS is a common thermoplastic formed by dissolving butadiene-styrene copolymer in a mixture of acrylonitrile and styrene monomers, and then polymerizing the monomers with free radical initiators. ABS offers the strength and rigidity of the acrylonitrile and styrene polymers together with the toughness of the polybutadiene rubber [8], [11].

## **2. Autonomous Mobile Robot BNRT-MOB-44**

The mobile robot of this project is named Autonomous Mobile Robot BNRT-MOB-44. The aim of its development is to make a prototype robot targeted at WorldSkills Competition. WorldSkills Competition is an international championship of vocational skills, and is held every two years in different parts of the world[7]. The overall structure of the mobile robot is shown below in Figure 1.

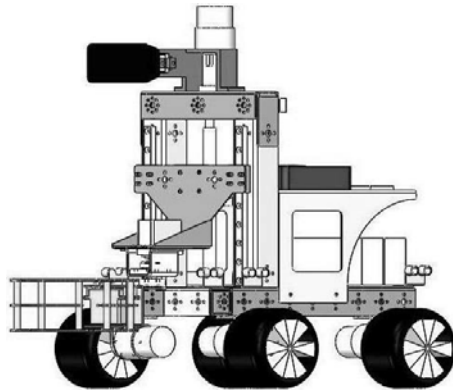


Figure. 1 Autonomous Mobile Robot BNRT-MOB-44

### 3. Statement of Problem

The framework members and battery carrier of the mobile robot are originally constructed from aluminum profiles. However, instead of aluminum, ABS plastic is suggested and analyzed in this paper. The frames have round holes in the profiles to facilitate the assembly of the chassis, reducing the processing steps and costs. Figure 2 and 3 below show the analyzed frame members and battery carrier respectively.

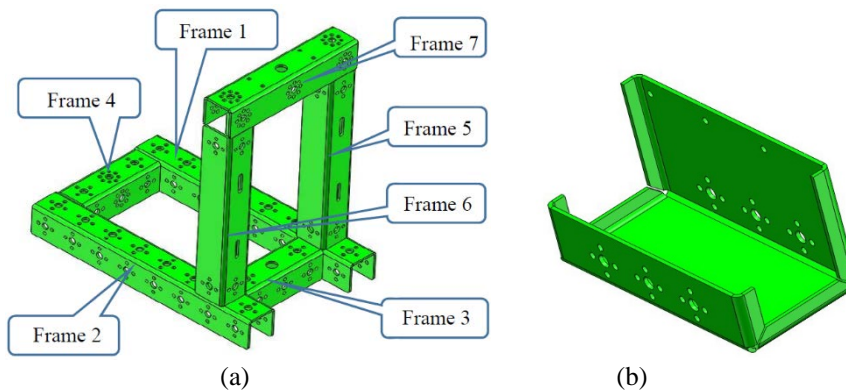


Figure. 2 (a) Frame members of the mobile robot, (b) Battery carrier of the mobile robot

The major reason for changing the profile material from aluminum to ABS plastic is reduction of weight. Weight is one of the most important factors affecting the mobility of a robot. A heavy robot requires larger motors and higher-capacity batteries, both of which add even more weight. However, using the same batteries

for different weights of a given mobile robot, the consumption of power from the batteries can differ drastically due to the ratio of power to weight. The ratio of power to weight is the ability of a robot with a given drive system to propel its own weight.

The minimum torque acting on the drive wheel of the mobile robot can be derived from the following formula:

- Static friction:

$$F_r = K \times m \times g \times \cos\theta \quad (1)$$

- Sliding friction:

$$F = m \times g \times \sin\theta \quad (2)$$

- Torque (drive shaft):

$$T_g = 1/N \times (F + F_r) \times r \quad (3)$$

- Torque (motor):

$$T_m = T_g / H_g \quad (4)$$

In the above formula,  $K$  is the static friction coefficient;  $m$  is the total mass;  $R$  is the radius of the wheel,  $H_g$  is the reduction ratio of the reduction gearbox;  $N$  is the number of wheels;  $\theta$  is the climbing slope of the robot.

Motor power consumption is calculated as:

$$P = V \times I \quad (5)$$

Where  $V$  is the rated voltage of the motor;  $I$  is the motor current,

$$I = T / K_t \quad (6)$$

The current can also be derived from the speed:

- Total motor torque:

$$T \approx T_m + T_r \quad (7)$$

- Internal friction torque:

$$T_r = I_0 \times K_t \quad (8)$$

$$I = T / K_t = (T_m + T_r) / K_t = T_m / K_t + T_r / K_t = T_m / K_t + I_0$$

In the above formula,  $T_m$  is the load torque;  $K_t$  is the torque constant for the motor;  $T_r$  the friction torque constant for the motor specifications;  $I_0$  is the motor no-load current. From this formula, it is clear that the mass of the robot directly affects the torque of the motor, which in turn affects its battery power consumption.

#### 4. Material Properties of ABS Plastic

The table below shows the material properties of ABS plastic[1].

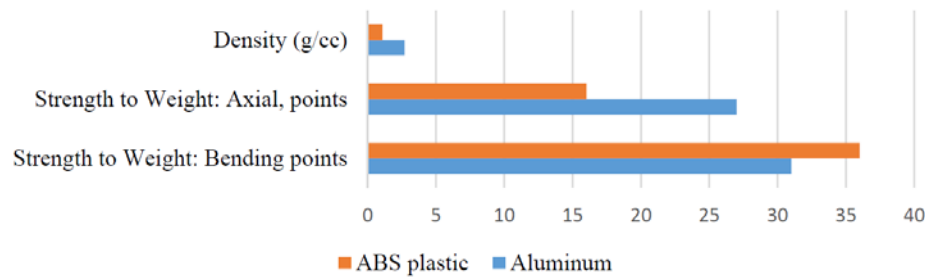
*Table 1 Physical properties of ABS plastic*

Physical Properties	Metric	English	Comments
Density	1.04 g/cc	0.0376 lb/in <sup>3</sup>	Grade Count = 3
Melt Flow	18 - 23 g/10 min	18-23g/10min	Average = 21.3 g/10 min; Grade Count = 3

*Table 2 Mechanical properties of ABS plastic*

Mechanical Properties	Metric	English	Comments
Hardness, Rockwell R	103 – 112	103 – 112	Average = 110; Grade Count = 3
Tensile Strength, ultimate	40.5 - 44.8 MPa	6160 - 6500 psi	Average = 44 MPa; Grade Count =3
Elongation at Break	23 - 25 %	23 - 25 %	Average = 24.3%; Grade Count = 3
Flexural Modulus	2.25 - 2.28 GPa	326 - 331 ksi	Average = 2.3 GPa; Grade Count =3
Flexural Yield Strength	60.6 - 73.1 MPa	8790 - 10600 psi	Average = 68.9 MPa; Grade Count =3
Izod Impact, Notched	2.46 - 2.94 J/cm	4.61 - 5.51 ft-lb/in	Average = 2.8 J/cm; Grade Count =3

The basic difference between aluminum and ABS plastic is briefly shown below in figure 2.



*Figure. 3 Material properties of Aluminum versus ABS plastic*

## 5. Modeling of Framework Using SolidWorks Software

ANSYS software requires three basic elements to perform FEM analysis. These are, a clear drawing with accurate dimensions, the correct loading, and the material property of the profile material. The preliminary step is to design the framework members or test specimens to be analyzed using SolidWorks software or relevant drawing software. Frame 1 and 2 are identical in all forms, as well as frame 5 and 6. Thus a single drawing is essentially sufficient to represent each pair. All frame member drawings, with the exception of the battery carrier, have a thickness of 2 millimeters.

➤**Battery Carrier:** The battery carrier is a separate structure made for carrying and protecting the two batteries of the robot and is not part of the chassis. Figure 3 shows the drawing of this structure. It has a width of 12.5 centimeters and length of 5.5 centimeters. At the front, it has a height of 3 centimeters, while at the rear end the panel has a height of 6.5 centimeters.

➤ **Frame 1 and 2:** These framework members are part of the chassis of the robot and have a typical u-shape. They are the sides of the chassis supporting the whole robot. They have length of 24 centimeters, height of 3 centimeters, and width of 3 centimeters. They are shown on figure 2.

➤ **Frame 3:** This framework member is also part of the chassis of the robot and has a typical u-shape. It's the front part of the chassis. It has a length of 9 centimeters, a height of 3 centimeters, and width of 3 centimeters. The drawing can be seen on figure 2.

➤ **Frame 4:** As can be seen on figure 2, this framework member is another part of the chassis and also has a typical u-shape. It's the back part of the chassis. It has a length of 9 centimeters, a height of 3 centimeters, and width of 3 centimeters. The holes on it, made for specific connections makes it different with frame3.

➤ **Frame 5 and 6:** These framework members stand straight and rest on the chassis members. They support the manipulator arm. Shown on figure 2, they also have a typical u-shape. They have height of 18 centimeters, length of 3 centimeters, and width of 3 centimeters.

➤ **Frame 7:** This framework member rest on frame 5 and 6. It gives support to the manipulator arm. It has a typical u-shape. They have height of 15 centimeters, height of 3 centimeters, and width of 3 centimeters. The drawing can be seen on figure 2.

## 6. Determining of Loadings

After obtaining the drawings for each specimen, the following step is to determine the exact load each is subjected to. Nevertheless, each pair of frame 1 and 2, frame 3 and 4, and frame 5 and 6 are subjected to the same loading. Therefore, computing the loading for one of the frames from the pair would be sufficient to represent both. The procedure can be divided to three sections, that is, the manipulator framework section, the chassis section, and the battery carrier section. They are discussed in detail below.

➤ **Manipulator framework section:** This section consists of frame 5, frame 6, and frame 7. This three group of frames are basically responsible for carrying the manipulator and sensors, and transfer the loads to the frames of the chassis. In the design, billiard balls placed on the ground are the targets to be picked up by the mobile robot. The mobile robot grabs the billiards that have been dropped on the ground and places them at the designated position. Therefore, the weight of the billiard ball is considered while calculating the loading.

For these frames, the weight of entire components of lifting and clamping mechanism are analyzed. The mobile robot uses ball screw mechanism as the actuator of the lifting mechanism. This mechanism has three basic components. These are the ball screw, the linear slider and the rail. In addition, there are four motors mounted. The first is a 37DB3530-10EN 12V DC motor, while the other three are MG996R metal gear torque digital servo motors. The tail of the DC motor is equipped with an encoder. Moreover, there are two rails mounted on the left and right symmetrical frames, and the slider is mounted on the guide rail. Other

components include a connecting plate, steering gear, metal plate, long arm, fixings, and the hand grasper. The weights of all the components are shown below.

- ✓ Weight of 37DB3530-10EN 12V DC motor= 204gm
- ✓ Weight of each three MG996R servo motor= 55.4gm
- ✓ Weight of the rest of components mentioned above= 761.3gm
- ✓ Weight of single billiard ball to be picked= 170gm
- ✓ Self-weight of frame 5, frame 6, and frame 7 made of ABS profile= 248.3gm
- ✓ Total weight of the above components= 1549.5gm

The weights of frames mentioned below are supposed to represent the ABS profile members. In order to find their weights, counterparts made of aluminum are measured, since the actual frames are made from aluminum. The total weight of the three members with aluminum profile is measured at 636.7gm. In order to convert one to another, their densities are considered. ABS plastic is 36%-39% as heavy as aluminum by weight on earth. For safety purpose, 39% is considered.

- ✓ Weight of frame members made with aluminum = 637.7g
- ✓ Weight of frame members made with ABS plastic = 39% \* Weight of frame members made with aluminum.
- ✓ Weight of frame members made with ABS plastic = 39% \* 637.7gm
- ✓ Weight of frame members made with ABS plastic = 248.3gm

In order to find the corresponding force exerted on the frame members, Newton's second law of motion is used;

$$F=m*a \tag{9}$$

Where F is force, m is mass, and a is acceleration: here a is acceleration due to gravity, which is  $9.81\text{m/s}^2$ .

Accordingly, the loading can be calculated as:

$$F= m*a$$

$$F= 1549.5\text{gm} * 9.81 \text{ m/s}^2$$

$$F= 15200.6\text{gm. m/s}^2$$

$$F=15.200\text{kg. m/s}^2 = 15.2\text{N}$$

This loading can be considered to be vertically applied at the other ends of frame 7, since the sliders are attached on the two symmetrical frames. Moreover, this loading should be divided into two because of the symmetry of the frames. Therefore, a point load of 7.6N will be exerted vertically on each ends of frame 7. Furthermore, the same loading will be exerted on longitudinally on each members of frame 5 and frame 6. However, by choosing the contact area on each member, ANSYS software can apply these loads on the exact areas of contact.

➤ **Chassis section:** This section consists of frame 1, frame 2, frame 3, and frame 4. These four groups of frames are responsible for carrying the whole robot and transfer the entire load to the wheels of the robot. All four frames of the chassis framework are subjected to distribute loading from the slab. The procedure requires

all the four frames acting like beams. The longer side of this slab is measured 18cm while the shorter is 15cm. Since the ratio of the lengths of long and short side is less than two, this member should be treated as two-way slab. Furthermore, because every loading is perfectly symmetrical, frame 1 and frame 2 will have the same loading, and frame 3 and 4 will also have the same loading. The dead weight on the slab is measured at 1.6kg or 1600gm. This can be converted to force as follows:

$$F = m \cdot a$$

$$F = 1.6\text{kg} \cdot 9.81 \text{ m/s}^2$$

$$F = 15.700\text{kg} \cdot \text{m/s}^2 = 15.7\text{N}$$

✓ Frame 1 and frame 2

These two frames are the longer beam members for the two-way slab load distribution procedure. The procedure is shown below.

$$Q_1 = (W \cdot L_x / 6) [3 - (L_x / L_y)^2]; \quad (10)$$

$$W = F / A \quad (11)$$

Where,  $Q_1$  is the distributed load exerted on longer beams,  $W$  is the distributed dead load on the slab,  $L_x$  is the length of the shorter side of the slab,  $L_y$  is the length of the longer side of the slab, and  $A$  is area of the slab.

$$W = F / A$$

$$W = 15.7\text{N} / (0.145\text{m} \cdot 0.18\text{m})$$

$$W = 15.7\text{N} / 0.0261\text{m}^2$$

$$W = 601.53\text{N} / \text{m}^2$$

$$\text{Accordingly, } Q_1 = (601.53\text{N} / \text{m}^2 \cdot 0.145\text{m} / 6) \cdot [3 - (0.145\text{m} / 0.18\text{m})^2]$$

$$Q_1 = (87.22\text{N/m} / 6) \cdot (3 - 0.65)$$

$$Q_1 = 14.54 \text{ N/m} \cdot 2.35$$

$$Q_1 = 34.17 \text{ N/m}$$

Self-weight of each frame of ABS plastic profile = 25.4N/m

Therefore, the load from the slab together with the self-weight of the beam would be:

$$(32.17 + 25.4) \text{ N/m} = 59.6\text{N/m}.$$

However, there is yet another load exerted on the beams from the manipulator framework section. As can be seen from figure 2, frame 5 transfers its load on frame 1, and frame 6 transfers its load on frame 2. Each of these loads are calculated above and resulted 7.6N. however, this load is to be exerted as a point load at 4.5 cm from the front end of beam.



✓ Frame 3 and frame 4

These two frames are the shorter beam members for the two-way slab load distribution procedure. The procedure is shown below.

$$Q = W * Lx / 3 \quad (12)$$

$$Q = 601.53 \text{ N/m}^2 * 0.145 \text{ m} / 3$$

$$Q = 601.53 \text{ N/m}^2 * 0.0483 \text{ m}$$

$$Q = 29.07 \text{ N/m}$$

Self-weight of each frame of ABS plastic profile = 10.8 N/m

Therefore, the total loading on each of these frames is:  $(10.8 + 29.07) \text{ N/m} = 39.87 \text{ N/m}$ .

However, there is an additional load from the battery and its carrier exerted on frame 3. Thus, this load is added when performing the analysis on ANSYS. The details of this load is discussed below.

➤ **Battery carrier:** This **component** of the robot is responsible for carrying and concealing the two batteries of the robot. Thus, the only load acting on it is its own self-weight and the weight of the batteries.

- ✓ The weights of each of the two batteries = 474 gm
- ✓ Self-weight of the ABS profile carrier = 113.1 gm
- ✓ Total weight of the above components = 1061.1 gm

Calculating for the force:  $F = m * a$

$$F = 1061.1 \text{ gm} * 9.81 \text{ m/s}^2$$

$$F = 10409.4 \text{ gm} \cdot \text{m/s}^2$$

$$F = 10.40 \text{ kg} \cdot \text{m/s}^2 = 10.4 \text{ N}$$

## 7. Results of FEM Analysis Using ANSYS Software

The force per unit area, measured in mega-Pascal (MPa), required to break a material is known as the ultimate tensile strength or tensile strength at break. The analogous test to measure tensile properties in the ISO system is ISO 527. On the other hand, deflection must be optimized with respect to the yield strength or strain of the material. The section geometry is examined to ensure that the desired deflection can be reached without exceeding the strength or strain limit of the material. Below are shown the allowable strain for ABS plastic without 30% glass fiber profile, as well as the ultimate tensile strength reported in the ASTM D638 and ISO 527 [4],[10].

Material	Ultimate Tensile Strength(MPa)	Unreinforced Allowable Strain
ABS plastic	40	6%-7%

➤ **Stability Condition:** In order for a structure or member to be stable, it needs to satisfy at least two safety conditions. These are the permissible stress/strength condition and strain/deformation condition.

✓ **Stress stability condition**

The allowable stress or allowable strength is the maximum stress that is allowed to be applied on a structural material. Factor of Safety, S (normal), of ABS material for bending and flexure is 1.5, and the corresponding allowable stress under room temperature is,  $\sigma_{allo}$  is 23MPa [5].

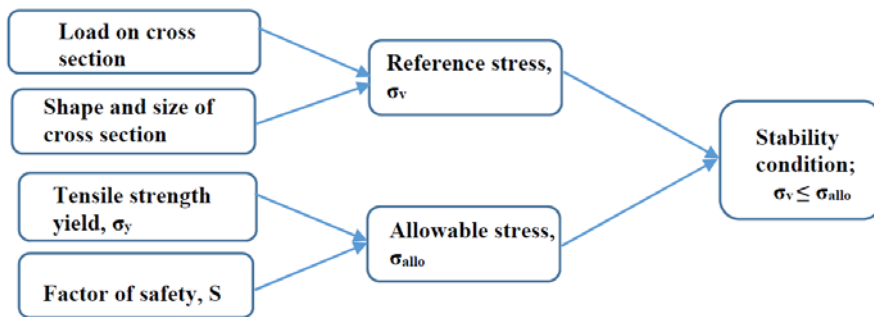


Figure. 4 Stress stability condition

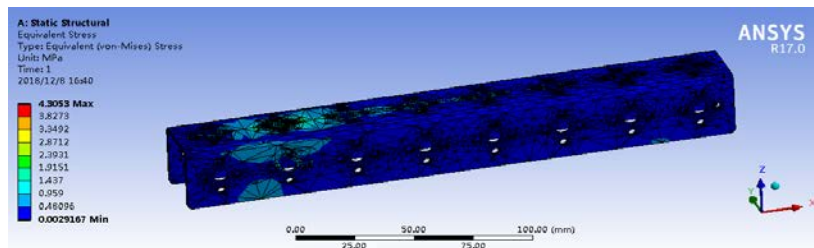
✓ **Deformation stability condition**

The maximum unreinforced allowable strain, E, for ABS material is 6%-7%.

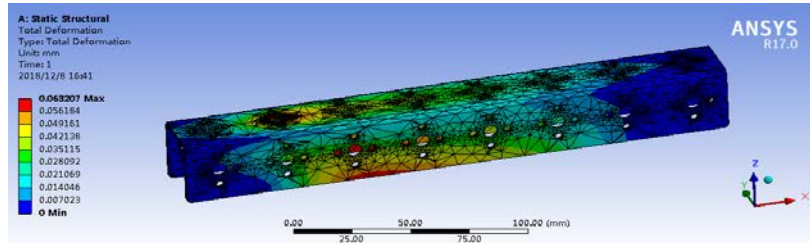
$$E = \frac{[(\text{Length of deformed section of the member } L_f) - (\text{Original length } L_o)] * 100}{\text{Original length } L_o} \quad (13)$$

**7.1 ANSYS Analysis Result**

✓ **Frame 1 and frame 2**



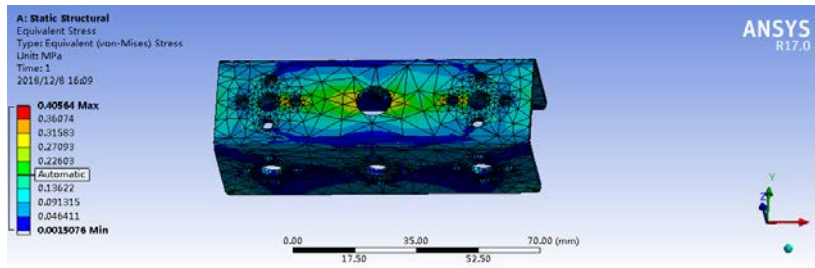
(a)



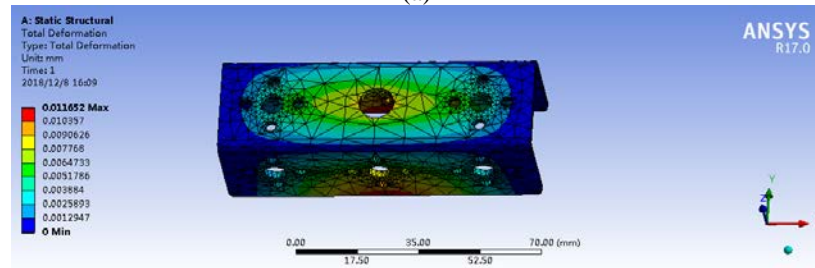
(b)

Figure 5 (a) ANSYS equivalent stress analysis result for frames 1 and 2,  
(b) ANSYS total deformation analysis result for frames 1 and 2.

✓ Frame 3 and frame 4



(a)



(b)

Figure 6 (a) ANSYS equivalent stress analysis result for frames 3 and 4,  
(b) ANSYS total deformation analysis result for frames 3 and 4.

✓ Frame 5 and frame 6

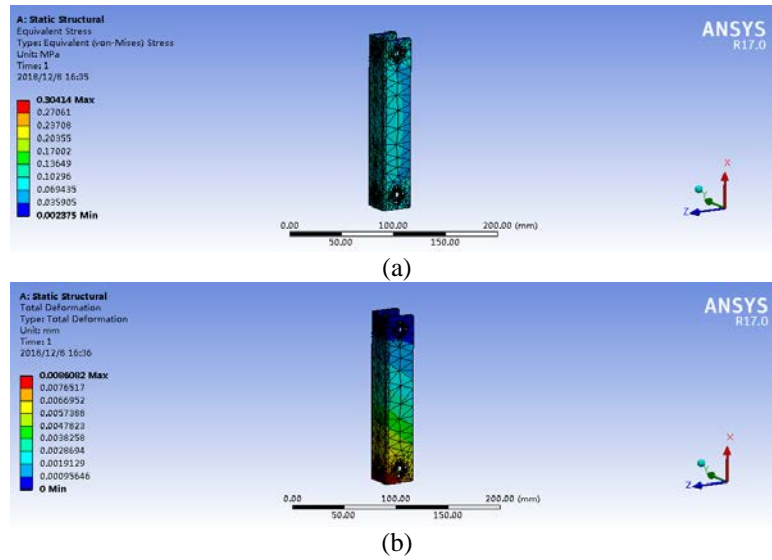


Figure. 7 (a) ANSYS equivalent stress analysis result for frames 5 and 6,  
(b) ANSYS total deformation analysis result for frames 5 and 6.

✓ Frame 7

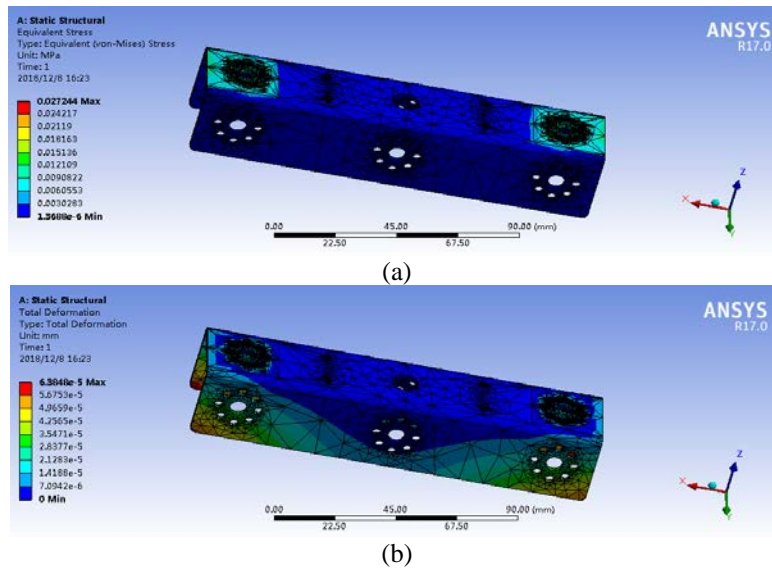
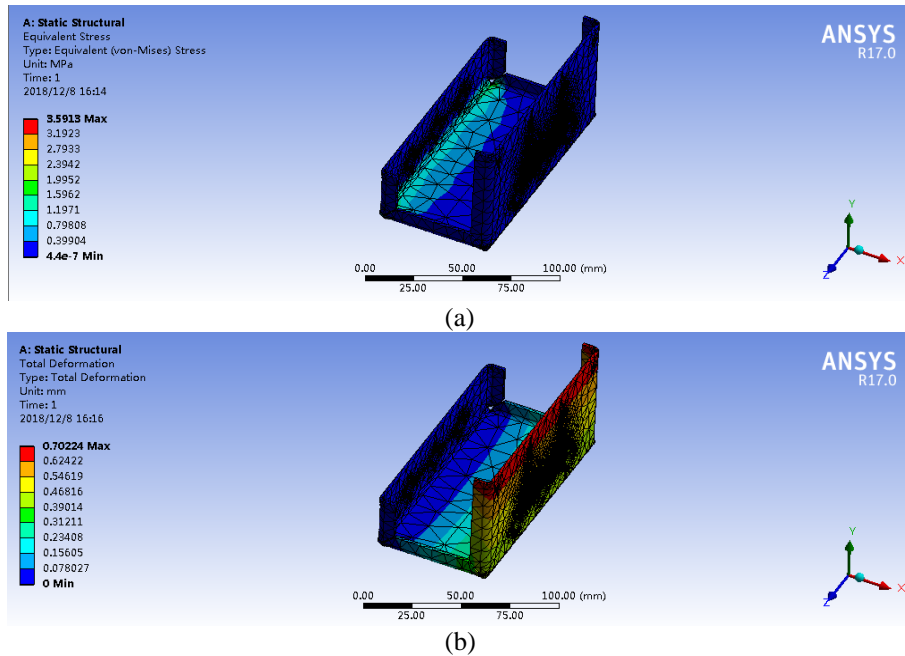


Figure. 8 (a) ANSYS equivalent stress analysis result for frame 7,  
(b) ANSYS total deformation analysis result for frame 7.

✓ Battery carrier



*Figure. 9 (a) ANSYS equivalent stress analysis result for battery carrier, (b) ANSYS total deformation analysis result for battery carrier.*

*Table 3 Result of analysis*

Member	Equivalent Stress (MPa)	Allowable Stress (MPa)	Total Deformation (mm)	Elongation (%)	Allowable Elongation, E(%)
Frame 1	4.3053	23	0.063207	0.026336	6-7
Frame 2					
Frame 3	0.40564	23	0.010357	0.011508	6-7
Frame 4					
Frame 5	0.3014	23	0.086082	0.047823	6-7
Frame 6					
Frame 7	0.027244	23	0.00006384	0.00004256	6-7
Battery Carrier	3.5913	23	0.70224	0.561792	6-7

## 8. Conclusion

The ability to resist yielding and ultimately breaking under stress is one of the most important and widely measured properties of materials used in structural applications. According to the analysis performed on this paper, all the framework members and battery carrier with ABS profile have shown to satisfy the stability conditions both for strength and deformation. This guarantees that the members

made of ABS plastic can substitute and be used for the structural framework of the mobile robot, thus delivering a cheaper production. Moreover, it will make sure the mobile robot will have a lighter weight making it faster during maneuver.

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