CAE Final Project

Structural analysis of rear part of self-made electric car and its development

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▣ Introduction

In the self-made electric car introduced here, the rear wheels move according to the driving of the motor. As the motor drives, the chain sprocket rotates, transmitting power to the large sprocket and driving the rear wheel. We aim to observe problems that occur depending on the maximum operation of the motor and analyze the exact cause using ANSYS software. And, the final goal is to make development for the original model later and analyze to what extent the problem areas can be improved. The figure below shows the case portion of the electric vehicle being analyzed and the motor that runs inside.

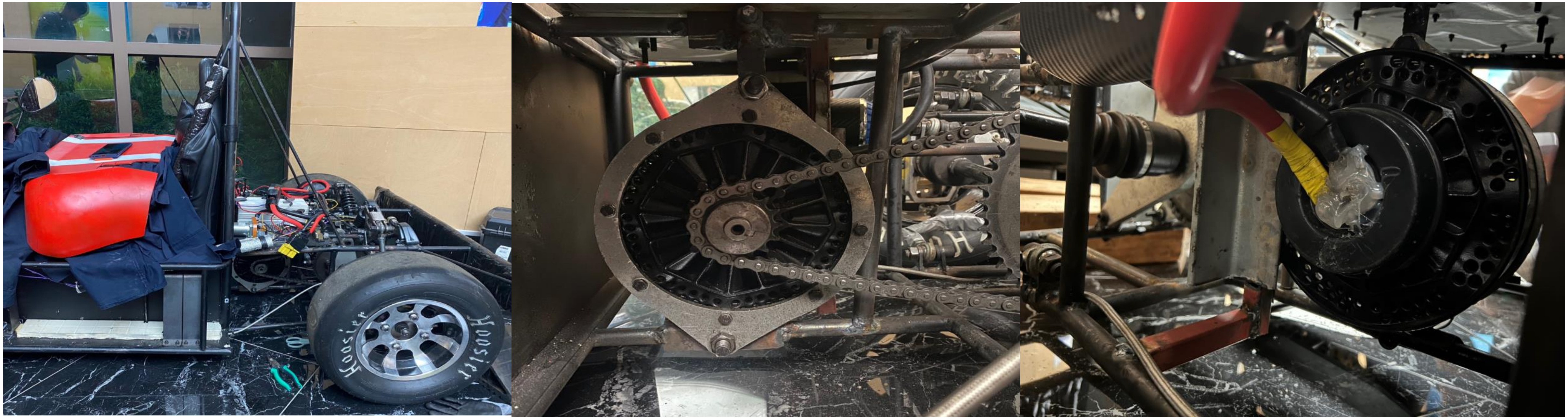


Figure #. Self-made electric car and its motor & chain components

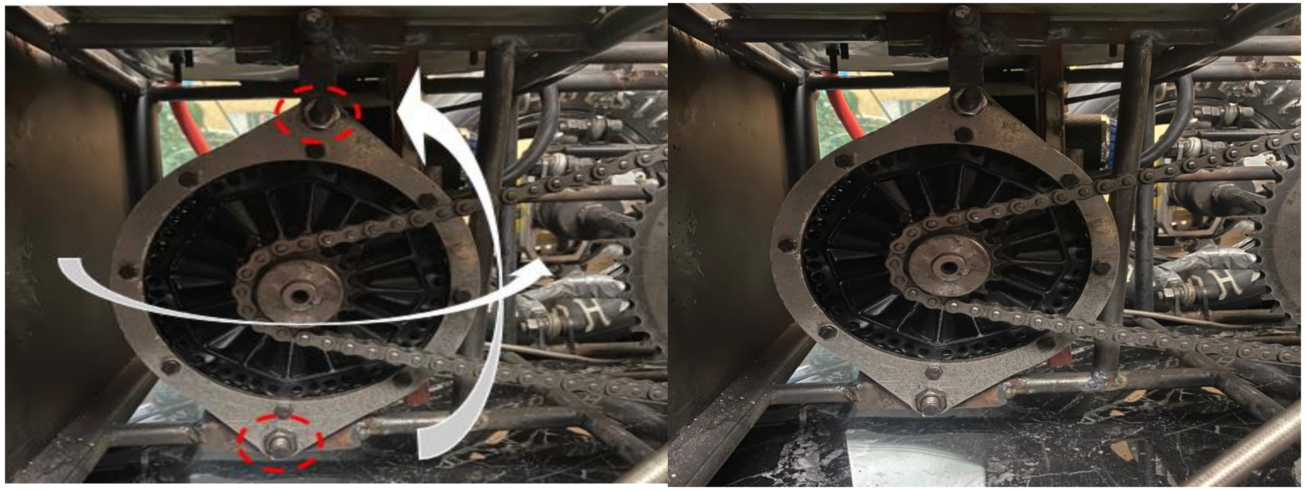
▣ Problem analysis

Problem statement

Under the maximum operating conditions of the motor, the force exerted by the chain on the sprocket cannot be ignored. When the motor is driven at maximum spec, chain tension occurs, which actually causes the following two main problems.

- Chain loosening problem due to horizontal rotation of motor
- Observation of material yield behavior due to strong stress acting on a specific frames

Since motor part of original model has only two point contacts with the frame, tension caused by motor driving with maximum spec causes horizontal rotation of the motor part. And it is connected with chain loosening problem. And some frame parts are exposed to the high stress, they are observed with yield behavior.



: point contact condition of motor case

: Frame in yield condition

Figure #. Contact condition of motor & Frame with yield

▣ 3D model generation

3D model

To proceed with the structural analysis in ANSYS software, a three-dimensional model of the rear part of the vehicle was created with SOLIDWORKS software. The rear frame and the motor case are modeled as right figure. And many components were eliminated to reduce the complexity of the model. And those were considered with force or boundary condition with eliminating.

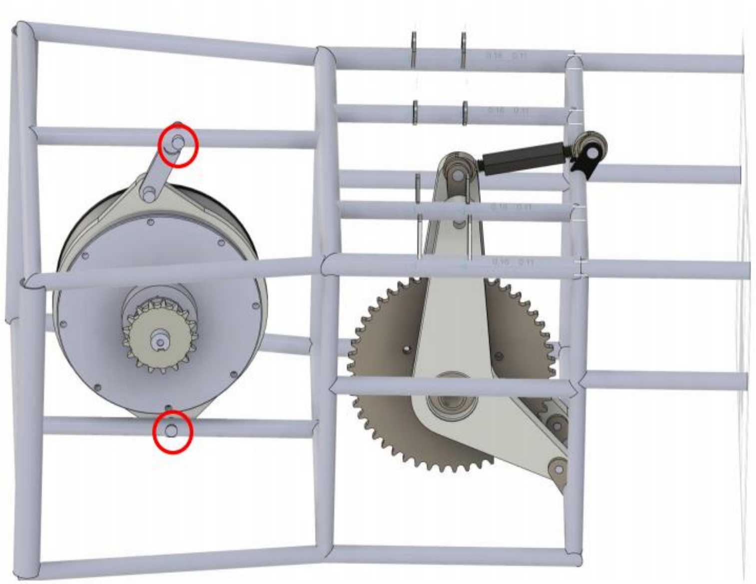


Figure #. Rear part of the car (left), Generated 3D model (right)

Table #. Eliminated components

Eliminated components	Considered factor
Chain	Chain tension
Motor	Weight
Upper & Lower arm	Remote displacement
Suspension	Suspension force

▣ Mesh generation

Tetrahedron mesh

To implement the actual model, various parts such as frame, LSD, turnbuckle, etc. are assembled. Therefore, the assembled shape is very complex, and it is difficult to create a good mesh and proceed with the analysis. Therefore, the analysis was conducted using a tetrahedron mesh rather than other methods. The default size was used in areas that were not of great interest in the analysis. Additionally, a size of $10\ [mm]$ was applied to frames that showed problems such as material yielding. Tetrahedron mesh was applied to all parts of the model.

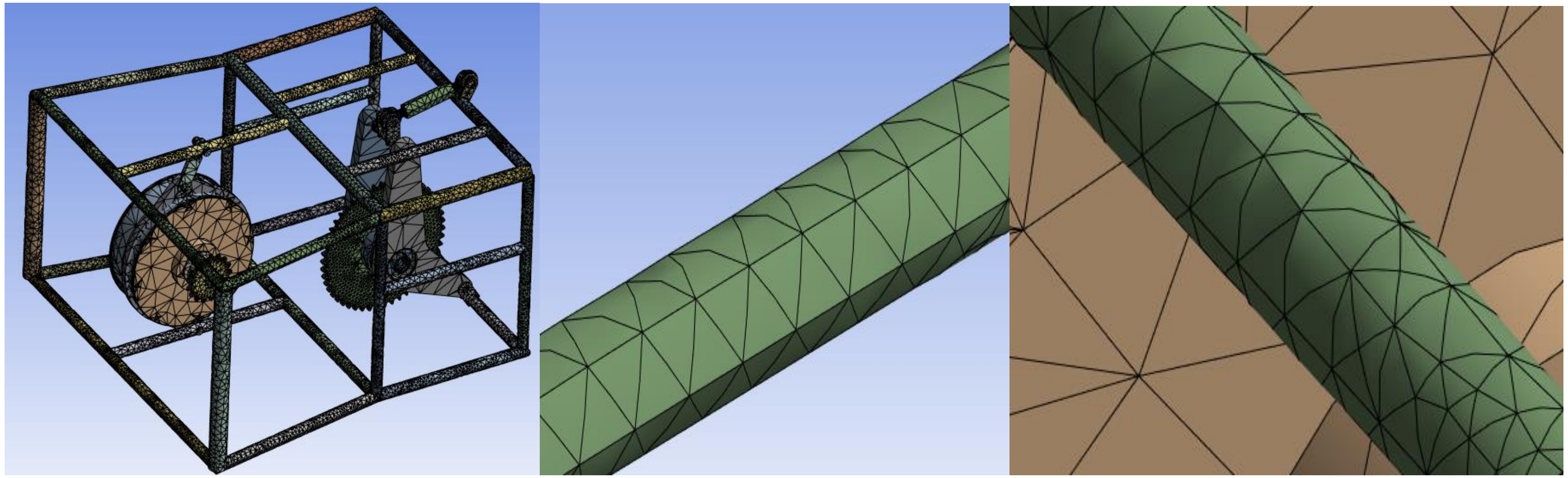


Figure #. Generated mesh, default sizing (2nd), $10\ [mm]$ sizing (3rd)

Table #. Mesh information

Type	Tetrahedron
Body sizing	$10\ [mm]$ & default
Nodes	285128
Elements	144715

▣ Material

Used material

SM45C material was used for the frame. Additionally, because the chain sprocket must withstand the strong tension generated while the motor is running, SM45C with induction heat treatment and iron oxide coating was used. And, the LSD and motor case were made of aluminum 6061-T6 material. In addition, there are several parts including coupling bolts, etc., but since they are not actually important elements in the analysis, we set them to structural steel and proceeded with the analysis.

Table #. Material information

Component	Material	Main properties
Main body (frame)	SM45C	$E = 205\ [GPa]$ $S_y = 320\ [MPa]$ $S_{ut} = 540\ [MPa]$
Chain sprocket	SM45C Induction hardening Anodized	Much higher than frame
LSD, motor case	AL6061-T6	$E = 70\ [GPa]$ $S_y = 276\ [MPa]$ $S_{ut} = 310\ [MPa]$
Bracket (case – frame)	SM45C	$E = 205\ [GPa]$ $S_y = 320\ [MPa]$ $S_{ut} = 540\ [MPa]$
Other components	Structural steel	$E = 200\ [GPa]$ $S_y = 250\ [MPa]$ $S_{ut} = 400\ [MPa]$

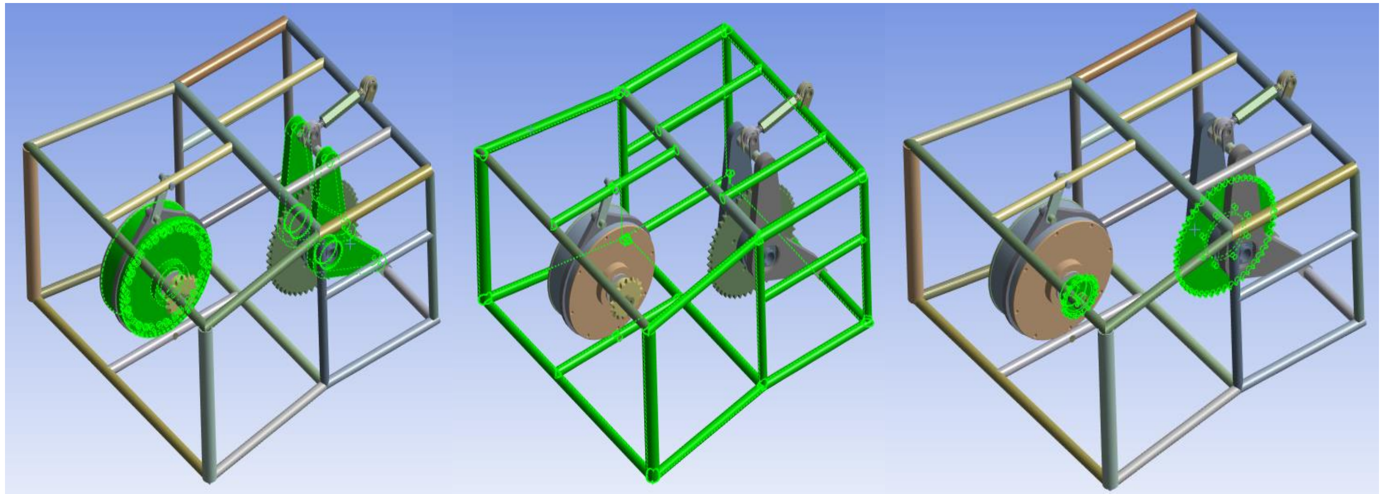


Figure #. AL 6061-T6 / SM45C / Strengthened SM45C

▣ Connection condition

Bolt fastening part

In analysis, appropriately setting the contact conditions between parts is an essential element in conducting accurate analysis. First, the conditions for the bolt fasteners were set as follows. The joint between the bolt and the part was set to bonded, and a frictionless connection condition of 0.5 friction coefficient was given to the parts that are fastened and in contact, considering friction. In addition, the bonded condition was given to all parts that are actually welded, such as frames.

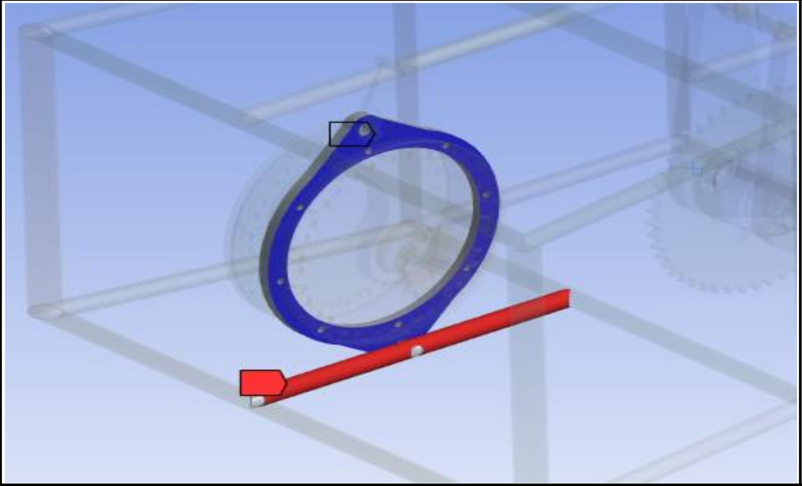
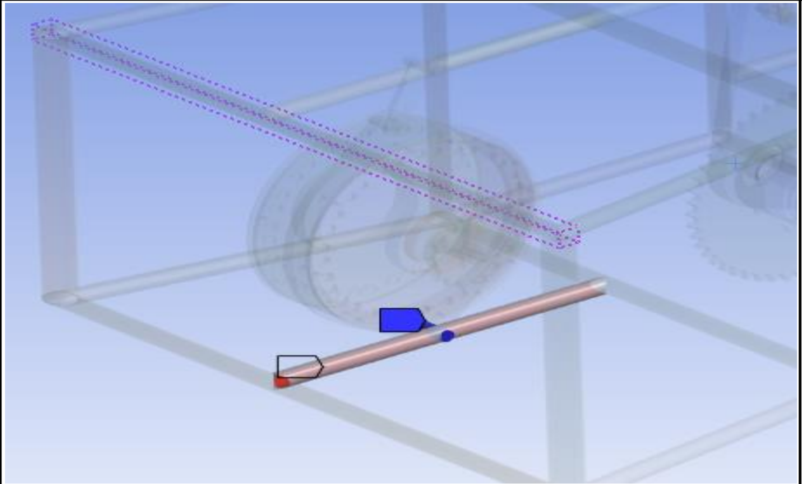
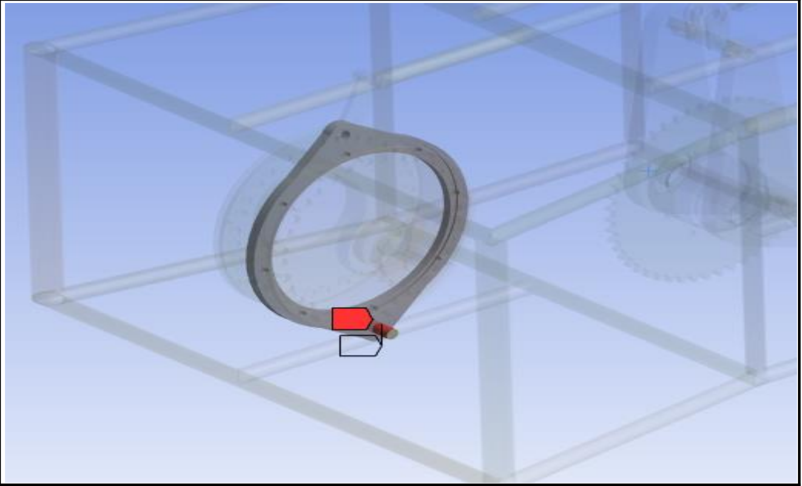
Frictionless support $(coef = 0.5)$	**Bonded connection (Bolt – component)**	**Bonded connection (Bolt – component)**
		

Figure #. Connection condition of bolt fastening part

▣ Connection condition

Revolute joint

A revolute joint condition was given to the joint of the rear turnbuckle and rod end bearing. The reason for giving this condition is that it has the degree of freedom to rotate around the x-axis. The process for granting the connection is as follows. Both sides of the rod end bearing were set as scope faces, and the bearing part was set as mobile faces. A two revolute joint conditions were granted for a total of two connected parts.

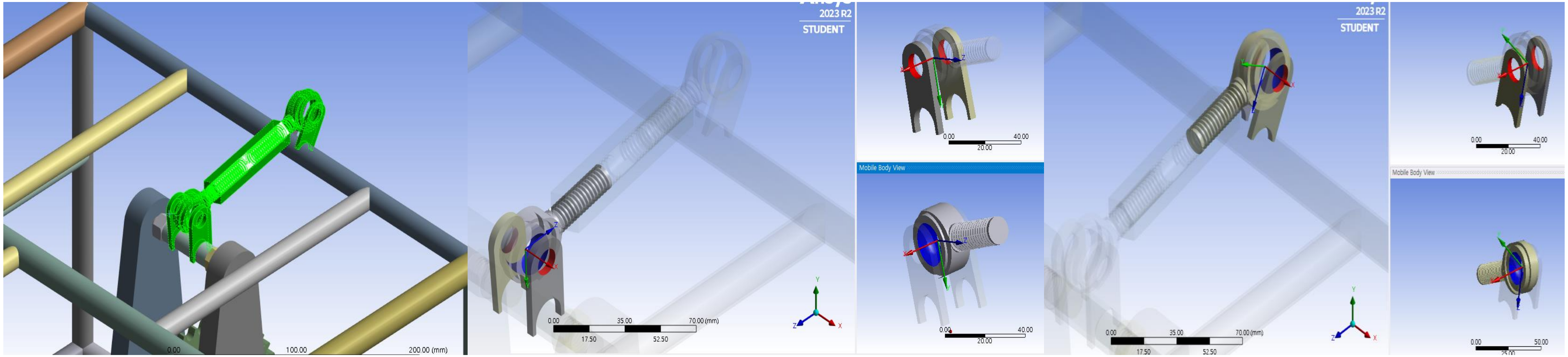


Figure #. Revolute joint connection setting

▣ Force analysis

Chain tension

After that, the most important thing is to consider the tension of the chain. The tension generated according to the maximum driving specifications of the motor was considered. Also, considering conditions such as impact coefficient, usage coefficient, etc., a force of about 3.5 times was considered. In addition, since the chain is designed with a safety factor of 10 in mind, the maximum force that occurs during sudden stops or acceleration was multiplied by about 7 times.

Table #. Detailed specifications

Specifications	Values
Maximum rpm	$2600\ [rpm]$
Rated power	$7\ [kW]$
Mass of motor	$11\ [kg]$
Diameter of small sprocket	$69.12\ [mm]$
Horizontal angle of chain	$14.8263\ [deg]$

$$\omega = 2600[rpm] = 272.27[rad/s], \qquad power = 7[kw]$$

$$\phi = 69.12[mm], \qquad \theta = 14.82°$$

$$\tau = \frac{power}{\omega} = 25.71\ [N \cdot m], \qquad T = \frac{\tau}{\phi/2} = 743.91[N]$$

$$coef_{use} = 1.2, \qquad coef_{vel} = 1.6, \qquad coef_{impact} = 2.0$$

$$T_{max} = 2 \cdot coef_{use} \cdot coef_{vel} \cdot coef_{impact} \cdot T = 5.714\ [kN]$$

$$T_{\max hori} = T_{max} \times \cos\theta = 5.524\ [kN]$$

$$T_{\max vert} = T_{max} \times \sin\theta = 1.462\ [kN]$$

▣ Force analysis

Bell crank part

In the referenced paper, the force of the pushrod transmitted to the bell crank attached to the frame above the rear of the car is first calculated. Then, the suspension force(F_s) and bell crank support force(F_{main}) are obtained through static analysis. All relevant values were taken from the referenced papers and used.

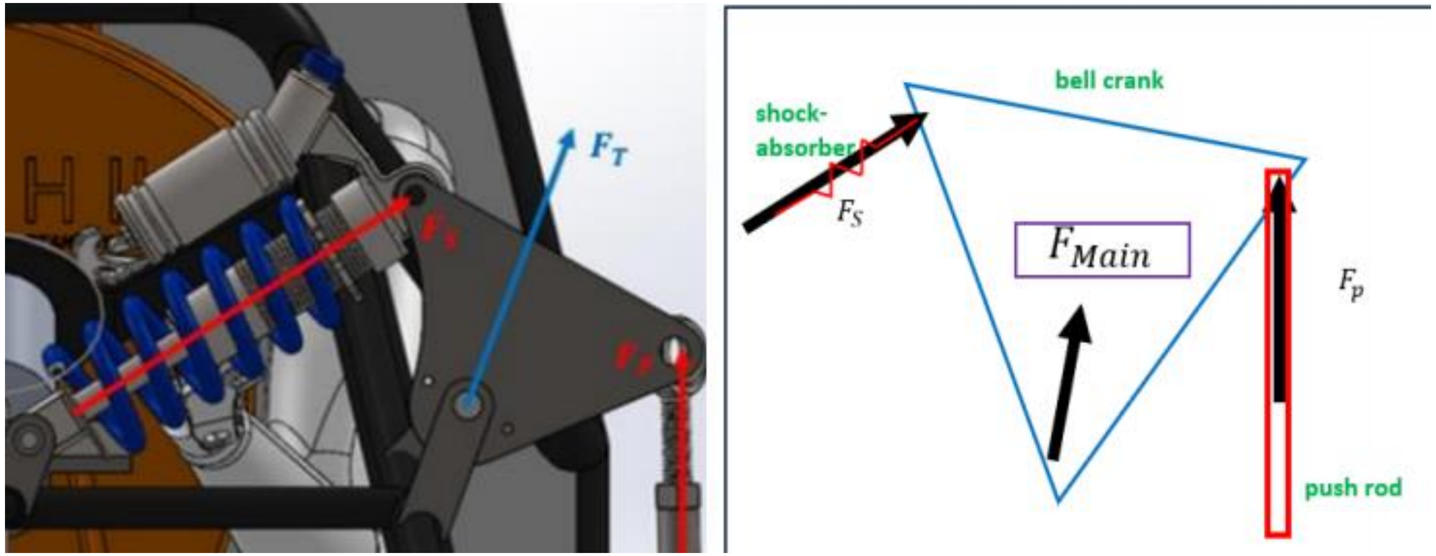


Figure #. Forces related to bell crank part

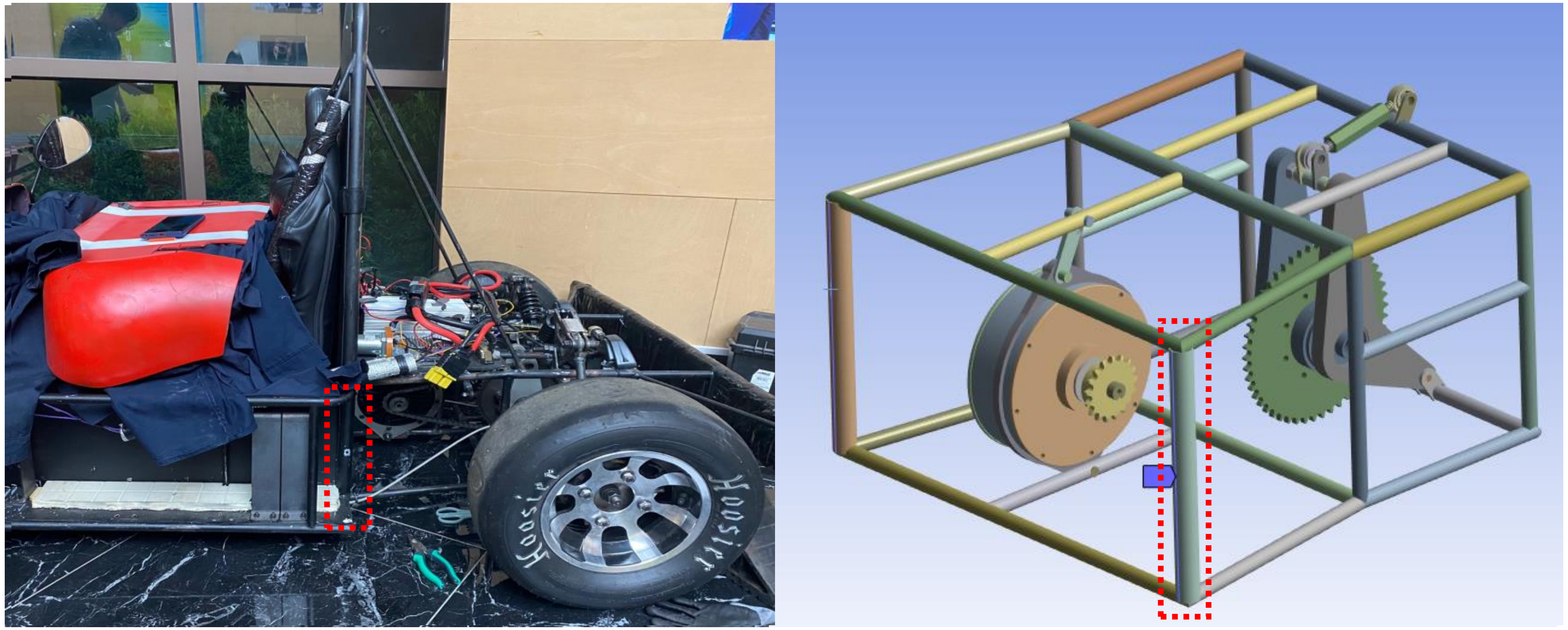
$$F_s = 732\ [N]$$
$$F_{tx} = 682.1\ [N]$$
$$F_{ty} = 1214.2\ [N]$$

$$F_{sx} = 577.1554\ [N]$$
$$F_{sy} = 450.2396\ [N]$$

▣ Boundary condition

Fixed support

To obtain an accurate solution, it is also essential to provide appropriate fixed support conditions. In order to obtain an accurate solution, it is correct to model and analyze the entire vehicle, but since this is not possible, appropriate fixed support must be provided. As can be seen in the square box in the figure of the actual vehicle below, the vertical frames are line welded. Therefore, when conducting ANSYS analysis, an edge fixed support condition was given to vertical frames.



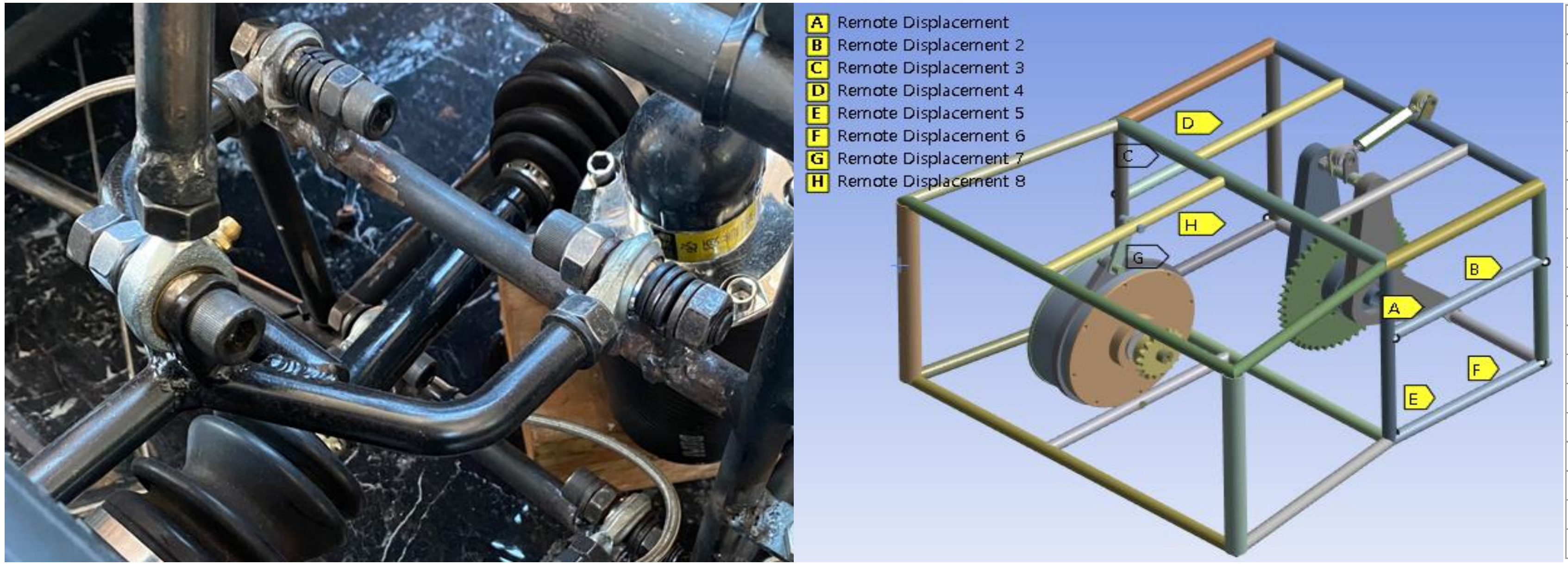
: Frame in edge welded condition

Figure #. Fixed boundary condition (edge part)

▣ Boundary condition

Remote displacement

Another important element is the arm connected part of the frame. Two lower arms and two upper arms are connected, and each is connected with two brackets welded to the frame as can be seen in the figure below. Therefore, a remote displacement boundary condition must be applied while removing the arm part. An offset was given considering the size of the welded bracket, and free conditions were given for the translational y element and rotation z element. A total of 8 conditions were granted. Because vertices could be selected at the junction between frames, condition assignment was relatively simple.



Scope	
Scoping Method	Geometry Selection
Geometry	1 Vertex
Coordinate System	Global Coordinate System
X Coordinate	249.44 mm
Y Coordinate	200. mm
Z Coordinate	-1205. mm
Location	Click to Change
Definition	
ID (Beta)	820
Type	Remote Displacement
X Component	0. mm (ramped)
Y Component	Free
Z Component	0. mm (ramped)
Rotation X	0. ° (ramped)
Rotation Y	0. ° (ramped)
Rotation Z	Free
Suppressed	No
Advanced	

Figure #. Remote displacement boundary condition

▣ Static analysis condition

Whole condition

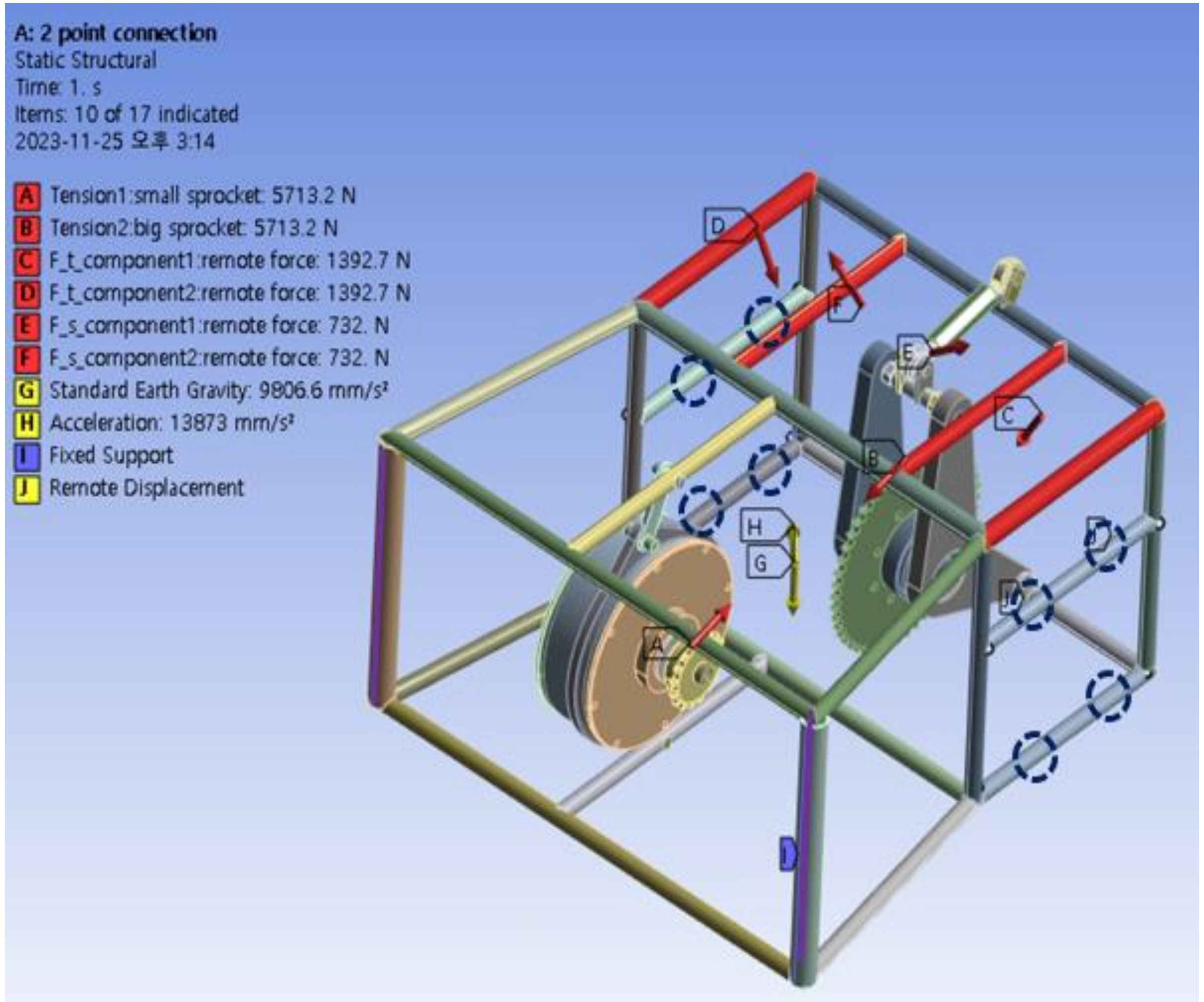


Figure #. Static analysis condition

<u>Considered force</u>

- Tension on the chain sprockets
- Influence of gravity & acceleration
- Suspension & main force of upper frame

<u>Boundary condition</u>

- Line fixed support (point welding)
- Remote displacement (8 point)

  (connecting part : arm – frame)

▣ Analysis result : problem model

Equivalent stress

As can be seen from the simulation results, when the maximum tension considered occurs, the stress on the frame, which was a problem during actual operation, appears as shown in the figure below. These stresses were observed to be higher than the yield stress of the material. The parts observed with the probe in the figure below are all frames that were problematic in actual operation.

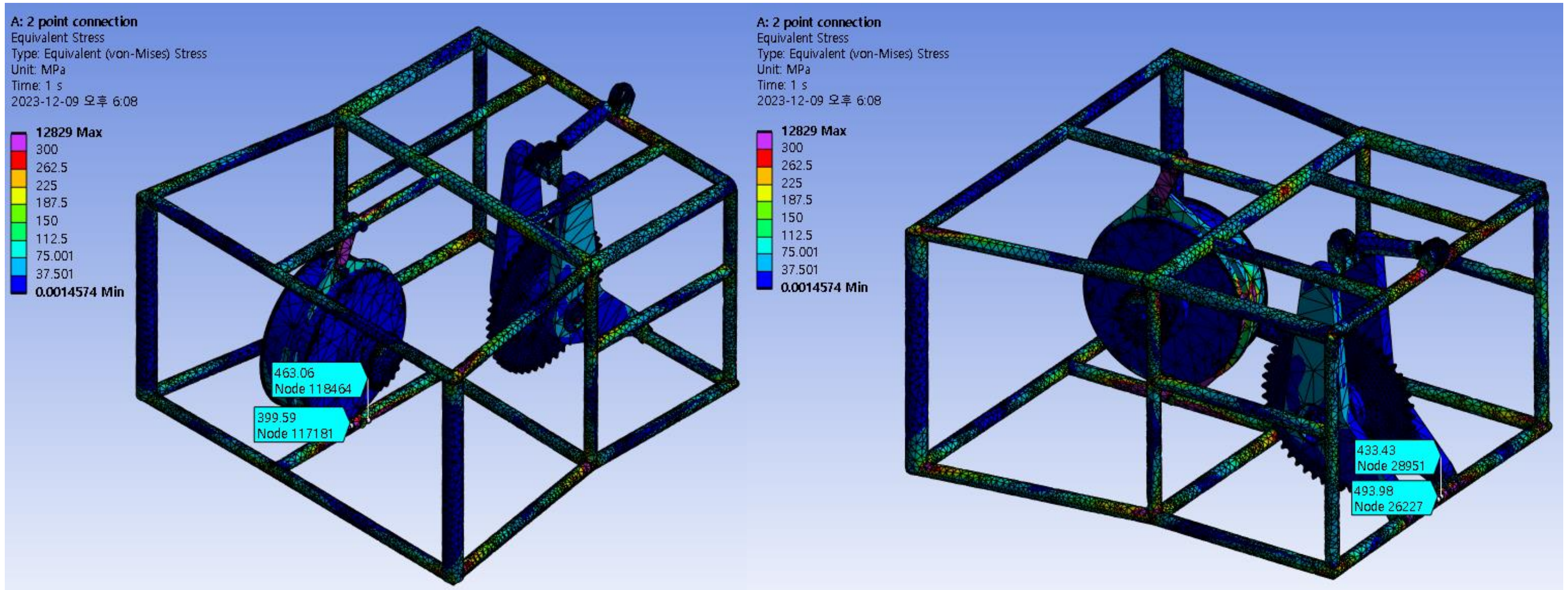


Figure #. Equivalent stress values

Table #. Equivalent stress

Part	Stress value
Front frame	$390 \sim 480\ [MPa]$
Rear frame	$433 \sim 490\ [MPa]$

$$\sigma_{equivalent} > S_Y$$

▣ Analysis result : problem model

Directional deformation

In addition to frame yielding, rotation due to tension in the motor case actually became a problem. This problem caused chain loosening problem. Therefore, it is necessary to observe the deformation values in each direction. The figures below show deformation values in the x, y, and z directions. Through the corresponding figures, it is possible to check the problem of the fixing conditions of the motor case, which is fixed through two point contact.

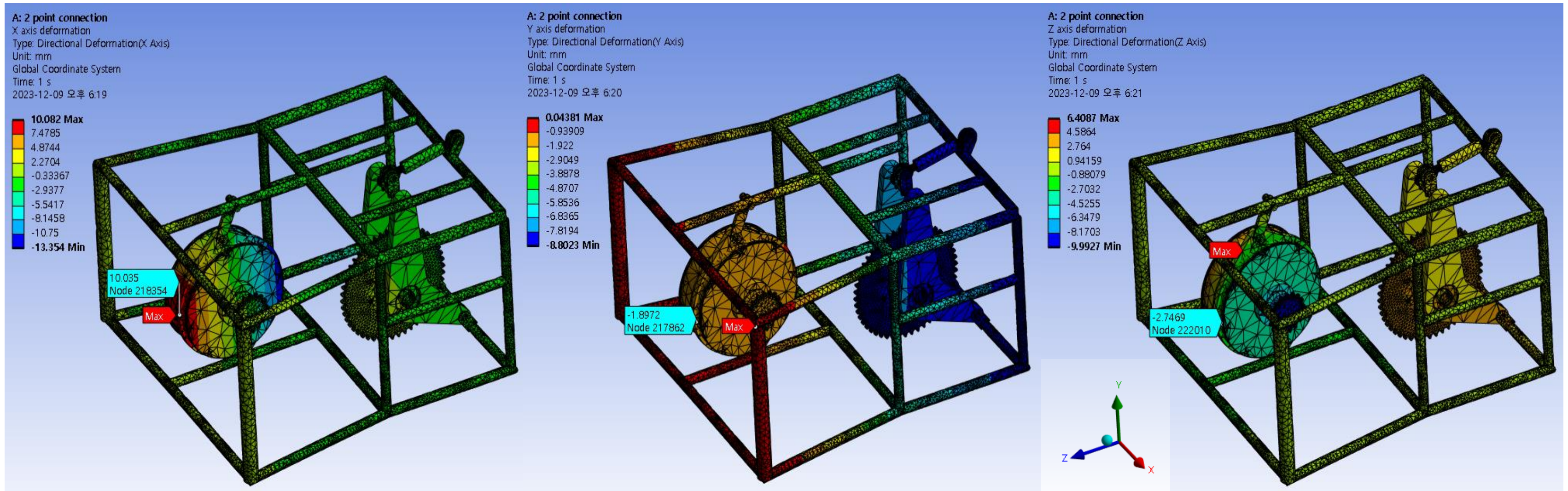


Figure #. Directional deformation values (x,y,z respectively)

Table #. Directional deformation

Direction	Values $[mm]$
X	10.082
Y	1.8972
Z	2.7469

▣ Fatigue analysis

Analysis condition

First, in order to proceed with fatigue analysis, it is necessary to define the SN diagram of the material and the repetitive load. When performing the structural analysis, the maximum force was considered, and the repeated load was multiplied by 3.5, considering only repetition, use, speed coefficient, etc. In other words, the force factor was kept the same and the fatigue strength scale factor was set to 0.5. And all the forces except chain tension are suppressed for getting the proper fatigue analysis result.

	A	B
1	Cycles	Alternating Stress (MPa)
2	10	370
3	20	360
4	50	350
5	100	340
6	200	320
7	2000	300
8	10000	285
9	20000	280
10	1E+05	275
11	1E+06	270 $: 0.5 \cdot \sigma_{ut}$

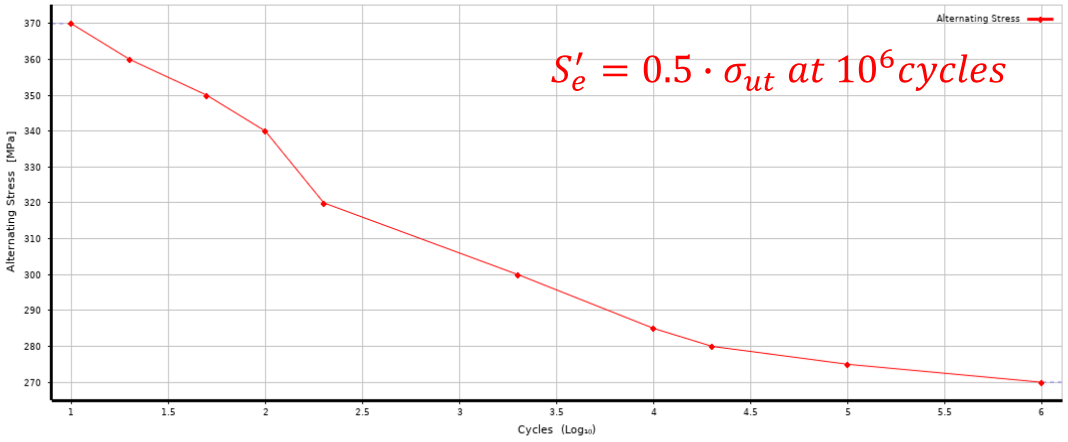


Figure #. SN curve definition

Table #. Fatigue analysis condition

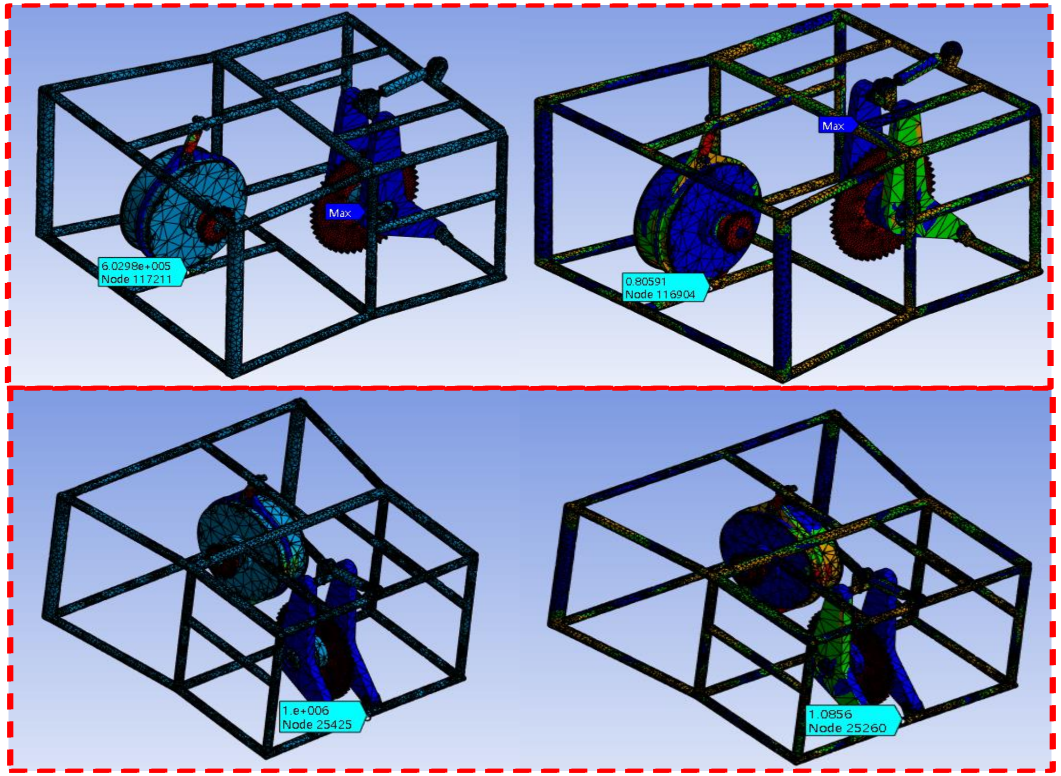
Parameter	Values
Stress type	Zero-based
Stress theory	Goodman
Scale factor	0.5
Fatigue strength factor	0.5

$$\frac{\sigma_a}{\sigma_e} + \frac{\sigma_m}{\sigma_{ut}} = \frac{1}{N}$$

▣ Fatigue analysis

Fatigue analysis result

The figures below show safety factor values according to the fatigue design life of 100,000 cycles. As you can see from the results, you can see that the frame in question has a safety factor around 1.0. In other words, it is essential to consider damage based on 100,000 zero-based cycles.



Front frame
(life / SF)

Rear frame
(life / SF)

Figure #. Life, safety factor

Table #. Life & Safety factor values

Type		Values
Front frame	Life	$6.0298e + 05$
	SF	0.81
Rear frame	Life	$1e + 06$
	SF	1.09

▣ Developing process

3D model

As can be seen from the previous structural analysis and fatigue analysis results, improvements are needed. First, in order to prevent horizontal rotation of the motor case, the existing two point contact conditions need to be improved. In this case, the existing 2 point contact conditions were improved to 3 point contact conditions. Additionally, a frame was added to the bottom right to consider the load distribution effect. Through this, it will be possible to prevent a specific frame from showing yield behavior due to distributed load.

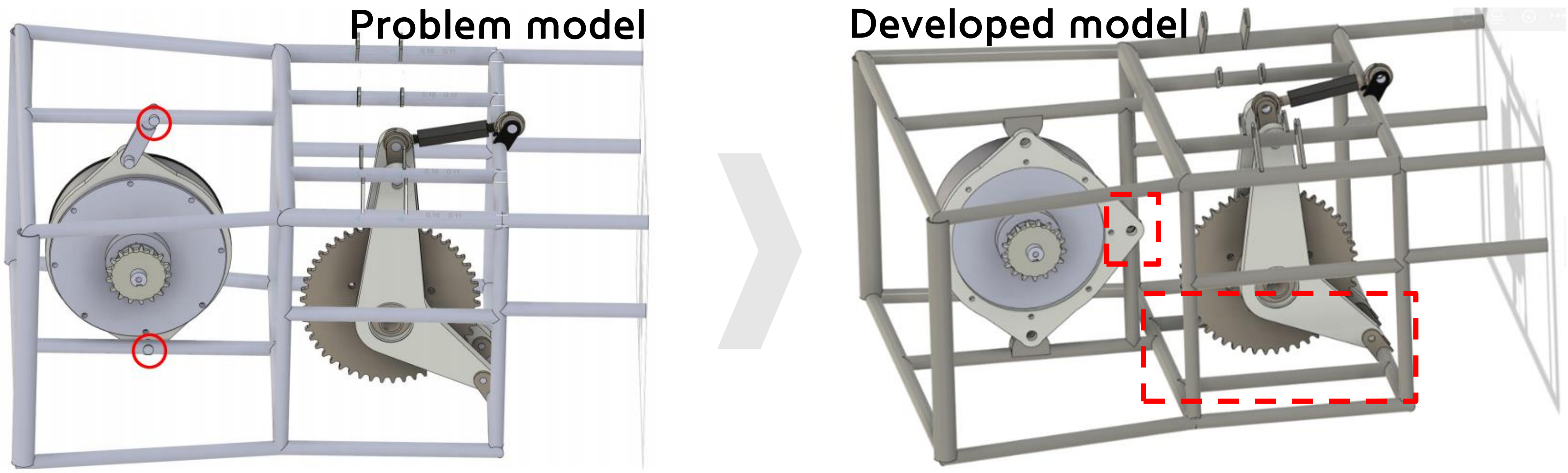


Figure #. Problem model (left) and developed model(right)

▣ Analysis result : developed model

Equivalent stress

As can be seen from the simulation results, when the maximum tension considered occurs, the stress on the frame, which was a problem during actual operation, appears as shown in the figure below. These stresses were observed to be lower than the yield stress of the material. n other words, the load distribution effect was obtained through the addition of a frame and the motor case contact condition, and as a result, a maximum stress value lower than the material's yield stress was obtained.

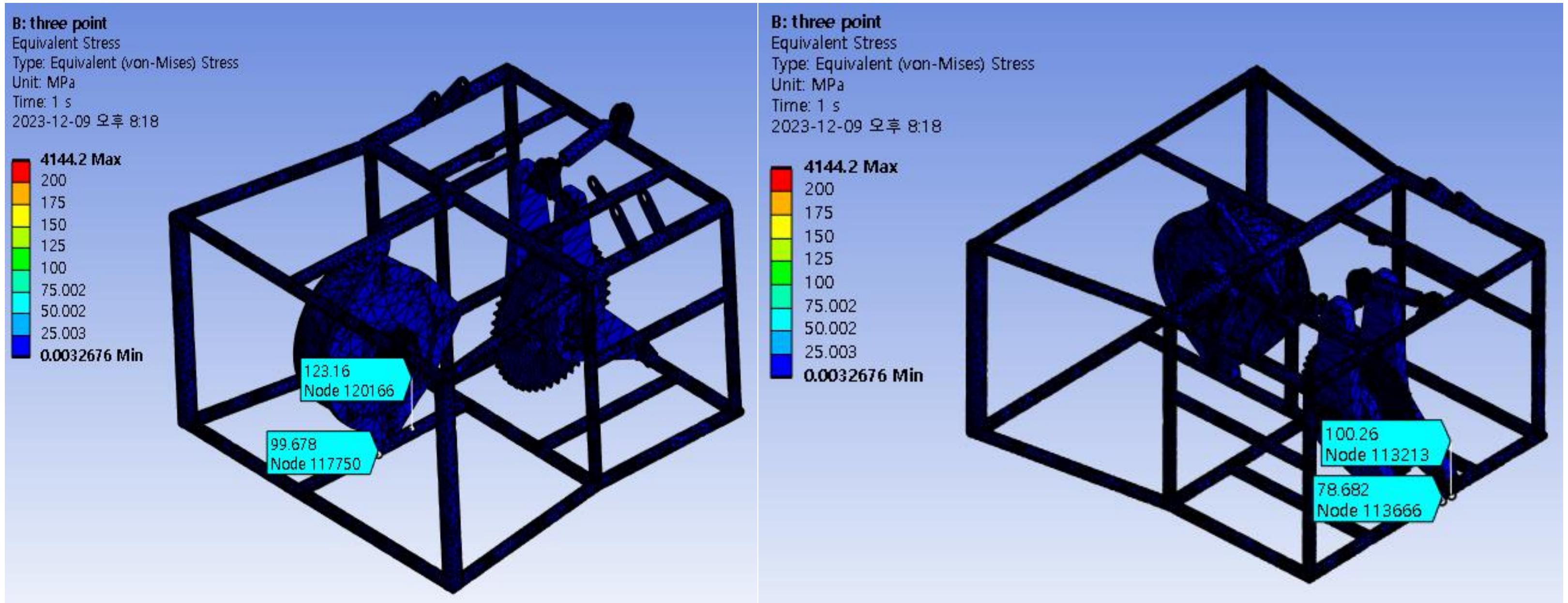


Figure #. Equivalent stress values

Table #. Equivalent stress

Part	Stress value
Front frame	$99 \sim 123.16[MPa]$
Rear frame	$78 \sim 100.26\ [MPa]$

$$\sigma_{equivalent} < S_Y$$

▣ Analysis result : developed model

Directional deformation

In addition to frame yielding, rotation due to tension in the motor case actually became a problem. This problem caused chain loosening problem. Therefore, it is necessary to observe the deformation values in each direction in the developed model. The figures below show deformation values in the x, y, and z directions of the developed model. Through the corresponding figures, it is possible to check the positive effect of adding one more point contact of the motor case.

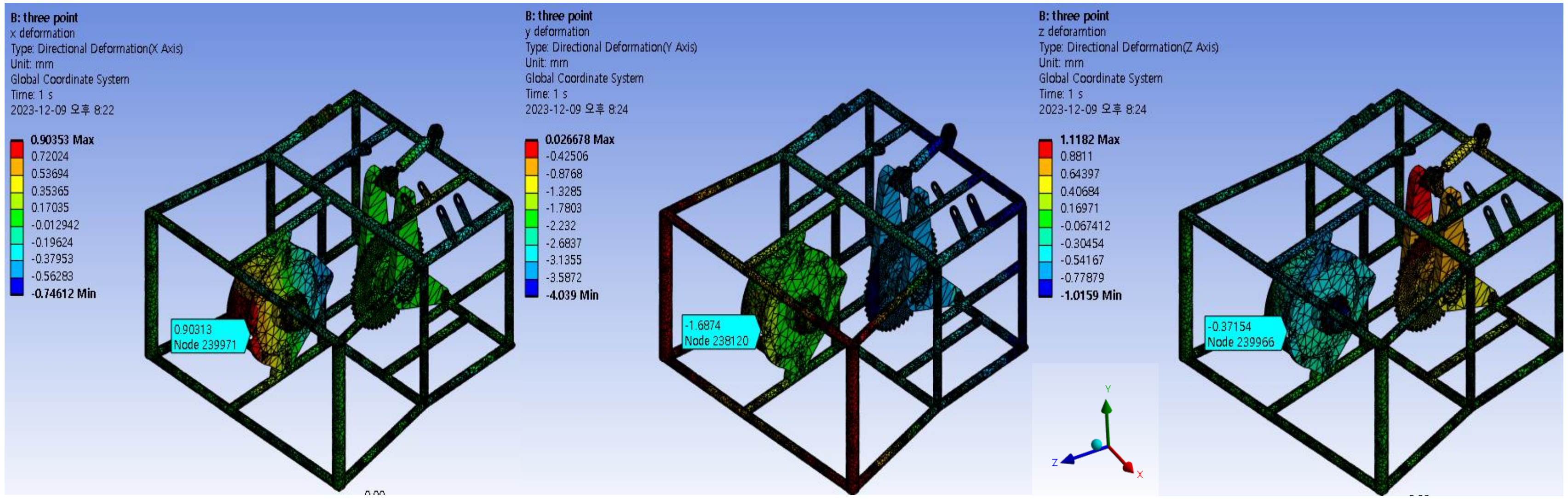


Figure #. Directional deformation values (x,y,z respectively)

Table #. Directional deformation

Direction	Values $[mm]$
X	0.903
Y	1.6874
Z	0.3715

▣ Fatigue analysis

Fatigue analysis result

The improved model that added 3 points and a frame also utilized the same fatigue analysis conditions as the previous problem model. The following figures show the fatigue analysis results for the improved model. Since high stress concentrated values are unreliable, the values around the interested part are averaged to use.

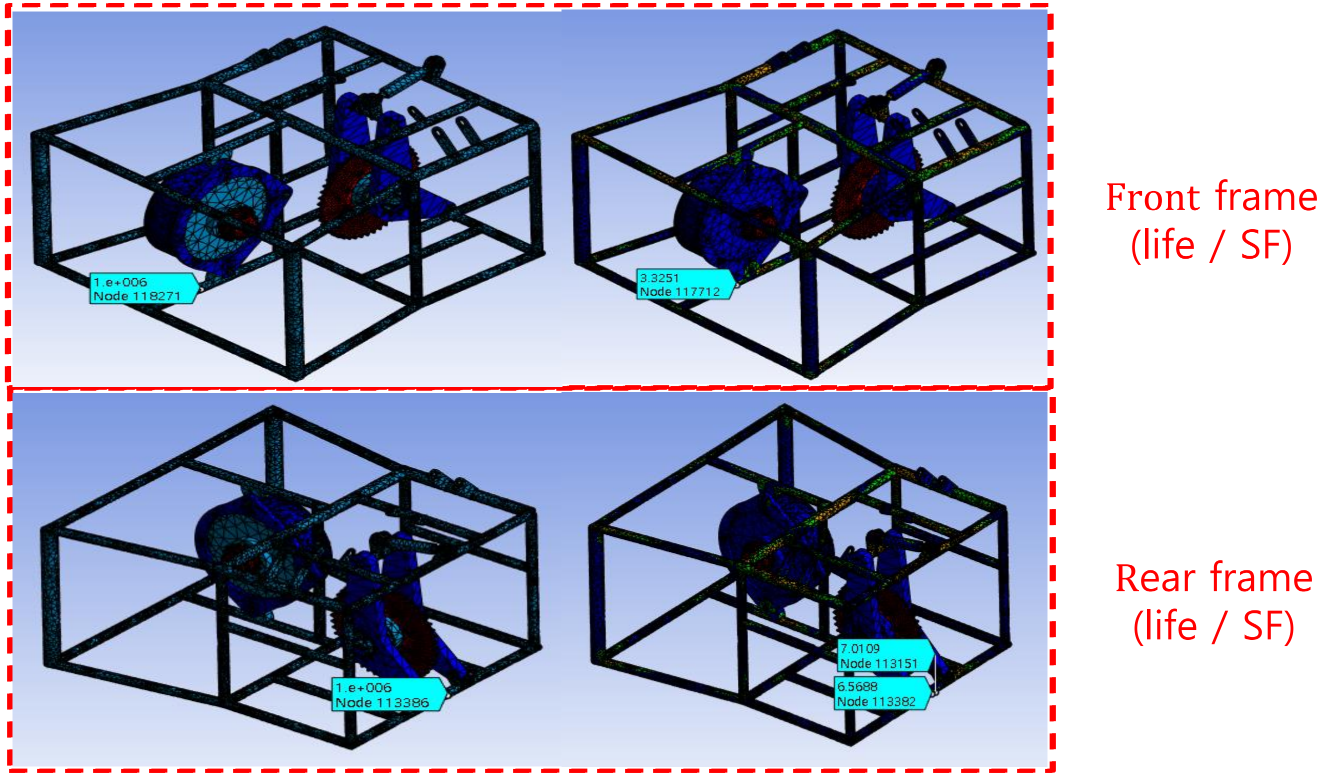


Figure #. Life, safety factor

Table #. Life & Safety factor values

Type		Values
Front frame	Life	$1e+06$
	SF	3.3251
Rear frame	Life	$1e+06$
	SF	6.75

▣ Simulation result comparison

Deformation

The comparison of simulation results for deformation between the problem model and the improved model is as follows.

Table #. Comparison of deformation value

Problem model		**Developed model**	
Direction	Values $[mm]$	Direction	Values $[mm]$
X	10.082	X	0.903
Y	1.8972	Y	1.6874
Z	2.7469	Z	0.3715
Total deformation	10.408	Total deformation	1.9449

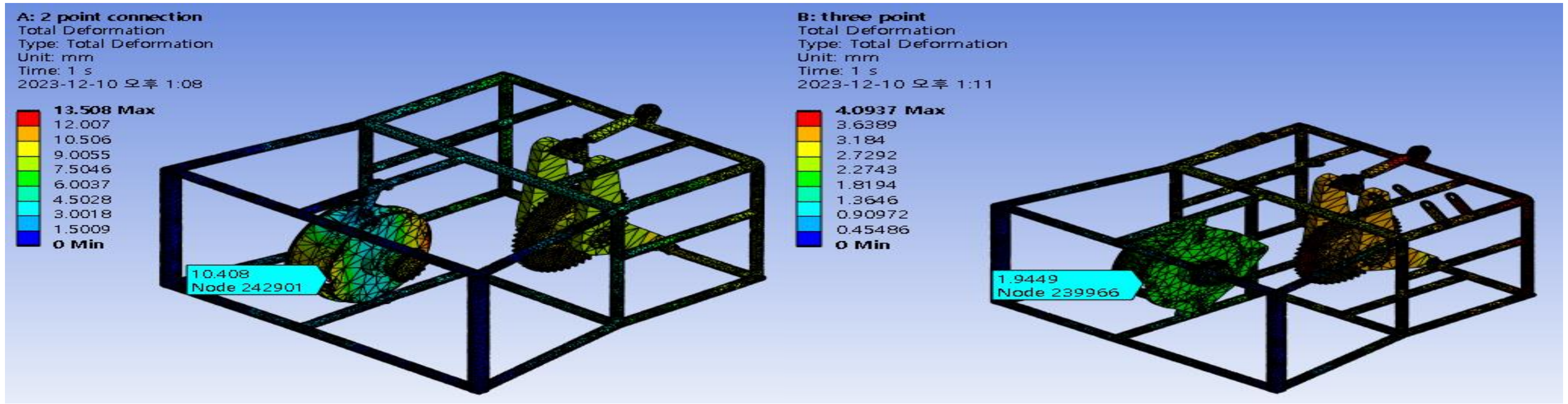


Figure #. Comparison of total deformation values

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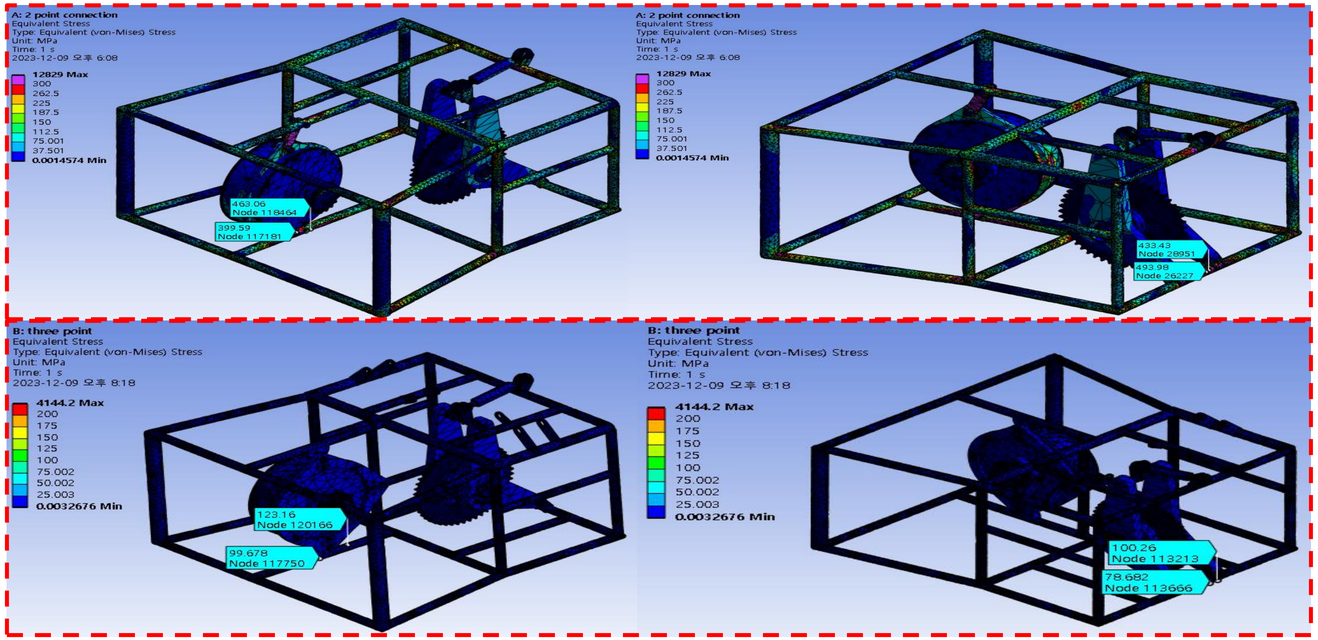
▣ Simulation result comparison

Equivalent stress

The comparison of simulation results for stress values between the problem model and the improved model is as follows.

Table #. Comparison of equivalent stress value

Problem model		**Developed model**	
Part	Values $[MPa]$	Part	Values $[Mpa]$
Front frame	$390 \sim 480$	Front frame	$99 \sim 123.16$
Rear frame	$433 \sim 490$	Rear frame	$78 \sim 100.26$



Problem model

Developed model

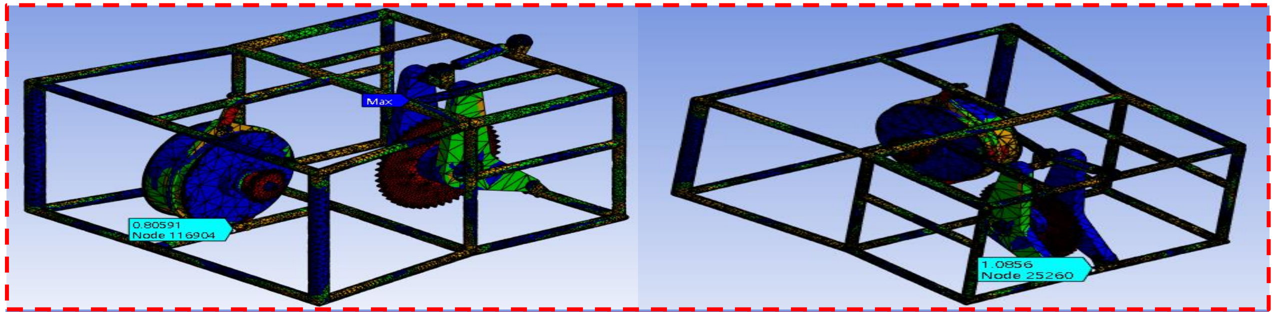
▣ Simulation result comparison

Fatigue safety factor

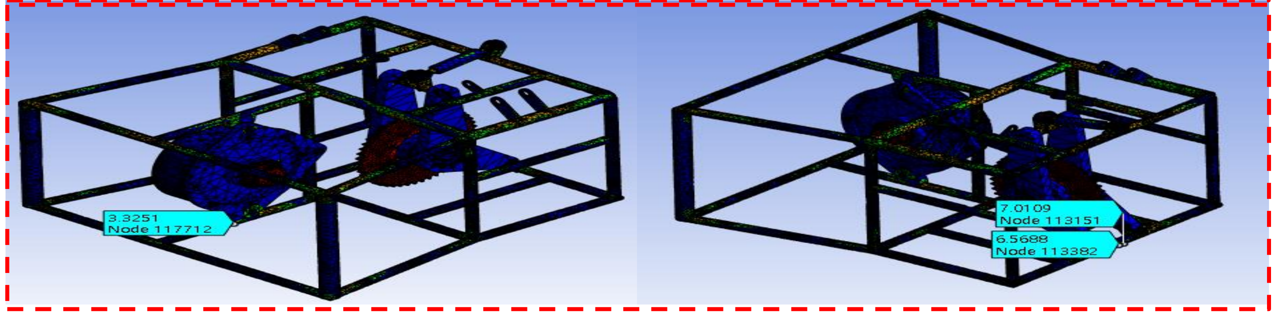
The comparison of fatigue analysis results between the problem model and the improved model is as follows.

Table #. Comparison safety factor values

Problem model		**Developed model**	
Part	Values [–]	Part	Values [–]
Front frame	0.81	Front frame	3.3251
Rear frame	1.09	Rear frame	6.75



Problem model



Developed model

▣ Discussion

Result analysis

Table #. Decreased deformation

Changes of deformation	
Parameter	Change $[mm]$
x deformation	-9.179
y deformation	-0.2098
z deformation	-2.3754
total deformation	-8.4631

Table #. Decreased equivalent stress

Changes of equivalent stress	
Part	Change $[MPa]$
Front frame	-323.92
Rear frame	-372.37

Table #. Increased fatigue safety factor

Changes of equivalent stress	
Part	Change [−]
Front frame	2.52
Rear frame	5.66

The tables above show changes in simulation results when analysis was performed from the existing problematic model to the improved model through the development process. First, when one more vertical frame is added to create a 3-point contact fixation condition for the motor case, it can be seen that the total deformation is reduced by about 8 $[mm]$, which solves the chain loosening problem in actual driving. I think it will be sufficient. Additionally, by adding two more frames in the below rear part, the expected load distribution effect was achieved, and as a result, a load reduction effect of over 300 $[MPa]$ was seen for the two problematic frames. Accordingly, the effect of increasing the fatigue safety factor for 10^5 cycles can also be confirmed.

▣ Conclusion

First, it is essential to identify elements that may be problematic in the actual operation of the vehicle, and to look at the deformation form of the material to find elements that may be problematic. In our case, the problem was the phenomena caused by chain tension that occurs when the electric vehicle's motor runs at its maximum.

- Chain loosening problem due to horizontal rotation of motor case which is fixed with 2 point contact
- Yield behavior of materials in specific frames

A 3D model was created to accurately identify the problems, and analysis was performed by setting connection and boundary conditions similar to reality in ANSYS software. After that, we confirmed that problems similar to actual problems occurred under the driving conditions, and we were also able to confirm the numbers. Accordingly, by designing an improved model and conducting structural analysis under the same conditions for the model, the expected improved results were also obtained.

▣ Reference

- Jin-Ho Kook (2022). Simulation-based Light Weight Design of A Self-made Electric Vehicle Frame

▣ Appendix

Motor specifications

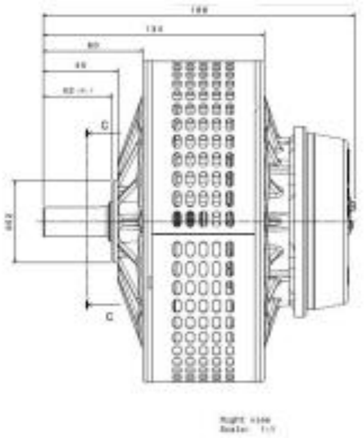
SAIETTA BR-119-R-68

COMPOSITE CONTACT AXIAL FLUX DC MOTOR

Light, Compact, Power Dense and Ultra Efficient

Technical Specification

119R					
Voltage (V)	12	24	36	48	60
Cont. Current (A)	90	120	150	200	200
Torque (Nm)	12.1	17.6	20.3	27.2	27.0
Rpm	748	1539	2329	3103	3919
Power (KW)	1.0	2.6	4.9	8.8	11.1
Peak Power @400A (kW)	2.8	7.6	12.3	17.0	21.6
Peak Torque @400A (Nm)			55.7		



SAIETTA 119R MOTOR
WEIGHT: 11KG

SAIETTA

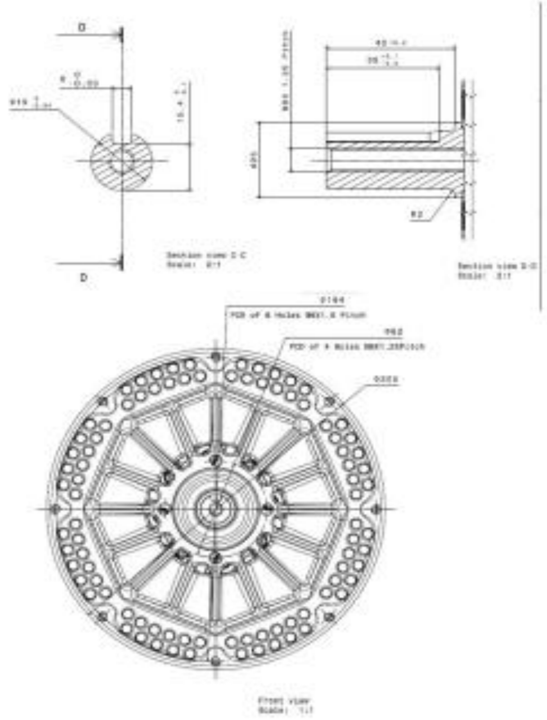


Figure #. Motor specifications

▣ Appendix

Calculation of parameters (MATLAB code)

```
clear;

% parameter definitions -------------------------
% 1. motor
rpm       =  2600;                             % [rpm]
power     =  7e3;                              % [W]  &  구동파워 : 7kW로 계산
m_motor   =  11;                               % [kg]
w_motor   =  m_motor * 9.81;                   % [N]
d_small   =  69.12;                            % diameter of small chain sprocket[mm]


% 2. chain sprocket
d_large   =  220;                              % diameter of big chain sprocket [mm]
l_diff    =  285;                              % center - center distance between two sprockets [mm]

% 3. main frame
d_frame   =  21.7;                             % diameter of main frame [mm]

% 4. suspension part
F_s       =  732;                              % suspension part spring force [N]
F_tx      =  682.1;                            % specified with x component of main force in thesis
F_ty      =  1214.2;                           % specified with y component of main force in thesis

F_s_xarm  =  60;                               % [mm]
F_s_yarm  =  36.0555;                          % [mm]
F_t_xarm  =  40;                               % [mm]
F_t_yarm  =  44.721;                           % [mm]

psi_alph  =  atan2(53.8516, 140);              % [rad]
psi_beta  =  atan2(36.0555, 60);               % [rad]

F_s_x     =  F_s * cos(pi/2 - psi_alph - psi_beta);  % [N]
F_s_y     =  F_s * sin(pi/2 - psi_alph - psi_beta);  % [N]
```

```
% calculation part  -----------------------------
% 1. Tension of chain
w_mot      =  2*pi*rpm/60;                    % [rad/s]
tau_mot    =  power/w_mot;                    % [Nm]
tension    =  tau_mot/(d_small*1e-3/2);       % [N]


% 2. chain  angle
psi_chain_rad   =  atan2(d_large/2 - d_small/2, l_diff);   % [rad]
psi_chain_deg   =  rad2deg(psi_chain_rad);                 % [deg]


% 3. chain tension : horizontal & vertical component
% -  Moment will be calculated automatically in Ansys when force is applied
%    to the shaft

T_hori     =  tension * cos(psi_chain_rad);
T_vert     =  tension * sin(psi_chain_rad);

% 4. Maximum stress calculation use / vel / impact coef
use_coef     =  1.2;
vel_coef     =  1.6;
impact_coef  =  2.0;

tension_max =  7 * tension;

Tmax_hori   =  tension_max * cos(psi_chain_rad);
Tmax_vert   =  tension_max * sin(psi_chain_rad);
```

Figure #. MATLAB code for calculation

▣ Appendix

Manual : mesh generation