Report

Finite element analysis of: Brake pedal- a comparison between aluminum and carbon composite.

Contents

1. Technical description

In the field of automotive engineering, the brake pedal plays a crucial role as the main interface between the driver and the vehicle's braking system. It serves as the primary mechanism by which the driver commands the vehicle to slow down or stop. The construction and materials used in the pedal are fundamental to ensuring its effective operation, durability, and reliability under various conditions. This report delves into two different cases of brake pedals, each presenting distinct materials and geometric configurations, illustrating technological advancements and design considerations aimed at optimizing performance and safety. This report explores two distinct brake pedal cases, each showcasing different materials and geometric configurations, to illustrate technological advancements and design considerations aimed at optimizing performance and safety. The cases examined are as follows:

Case 1: Standard brake pedal made of aluminum

This pedal is distinguished by its classic, rectangular shape, designed with ergonomics and stability in mind for usage. Its aluminum construction strikes an excellent balance between lightness and strength, providing the necessary rigidity and efficient heat dissipation during braking. The pedal is mounted on a horizontal axis, allowing for rotational operation, which is standard in most vehicles. The robustness of the mounting ensures that the pedal's movements are confined to the rotational axis, contributing to the precise and dependable functioning of the braking mechanism. Aluminum alloys such as 2024 or 7075 are often chosen for their high strength and corrosion resistance.

Case 2: Brake pedal made of carbon composite

This pedal configuration is notable for its use of carbon composite, leading to alterations in its mechanical properties and necessitating a geometric redesign. The employment of lightweight yet strong carbon composites enable the creation of thinner structures without sacrificing rigidity or strength. As with the aluminum variant, the pedal's mounting facilitates its rotational motion around a horizontal axis. However, innovative materials and manufacturing techniques render the carbon composite pedal even more resistant to deformation and mechanical damage. Technologies like resin transfer molding and the strategic layering of composite materials are utilized to achieve optimal strength while minimizing weight.

The choice of material and precision in assembly play a crucial role in ensuring the highest functionality, longevity, and safety of the pedal. The differences between pedals made of aluminum and those made of carbon composite reflect a technological evolution and an ongoing quest for enhancements in automotive components. These distinctions not only suggest advancements in vehicle performance and safety but also demonstrate a commitment to innovation and development within automotive engineering.

2. Aim of analysis

The aim of this analysis is to investigate the effects of various usage conditions and the transition in construction materials for brake pedals from aluminum to carbon composite on their functionality, durability, and overall performance efficiency. Through an in-depth examination of diverse usage scenarios, such as standard and emergency braking, operation in extreme temperatures, braking in unconventional situations (e.g., while wearing high heels), and instances of pedal obstruction by foreign objects, this analysis seeks to achieve the following key objectives:

- **In-depth understanding of the impact of diverse operational conditions:**
  The goal is to precisely determine how different usage scenarios affect the performance and longevity of brake pedals made from two distinct materials, identifying which materials perform better under both standard and extreme conditions.

- **Evaluation of the advantages of using carbon composite:**
  By comparing with traditional aluminum pedals, this analysis aims to assess whether carbon composite offers significant improvements, particularly under the most demanding circumstances. It intends to verify whether this modern material provides superior pressure responsiveness, increased durability, and better adaptation to a variety of weather and temperature conditions.

- **Identification of opportunities for improvement in brake pedal design:**
  Through the analysis of test results across different scenarios, the study aims to identify potential shortcomings in both types of pedals and suggest possible enhancements. The goal is to improve braking efficiency and ensure safety across a broad spectrum of usage conditions.

3. Description of cases and operating conditions scenarios

3.1. Case 1, scenario 1

Standard Braking

The scenario analyzed pertains to a typical situation during normal driving, where the driver applies moderate force to the brake pedal to initiate the braking process. It is assumed that the pressure is evenly distributed across the middle part of the pedal.

- **Physical Input Data:**
    - **Force Applied:** 300 N – Represents the typical force exerted by a driver during standard braking.
    - **Material:** Aluminum – Selected for its properties such as lightness, strength, and ability to dissipate heat generated during braking.
    - **Force application point:** Center of the pedal – Corresponds to the driver's foot placement on the pedal.
    - **Ambient temperature:** Standard temperature of 20°C – Represents the average temperature in which most drivers operate their vehicles.

The schematic shows the brake pedal with the applied force vector indicated. The force is directed vertically downward, focusing on the central part of the pedal, which mimics the natural positioning of the foot during braking**.**

Figure 1

3.2. Case 1, scenario 2

Emergency braking

The scenario simulates a situation in which the driver must react very quickly to an unexpected obstacle and immediately apply maximum braking. In this scenario, the pressure on the brake pedal is applied swiftly and decisively, aiming for an instantaneous stop of the vehicle.

- **Physical input data:**

    - **Force Applied:** 700 N – This is a high value, indicating strong and abrupt force application by the driver in a situation requiring sudden stopping.

    - **Material:** Aluminum – Provides the necessary hardness and stability of the pedal during intensive use.

    - **Ambient temperature:** Constant temperature of 20°C, to maintain consistency in the tests.

    - **Force application point:** The force application point is in the lower part of the pedal, close to its mounting point, which corresponds to the natural reflex of pressing the pedal in situations requiring quick response.

The schematic illustrates the brake pedal with the applied force vector highlighted. The force is directed vertically downward but may focus on the edges of the pedal, simulating the adjusted positioning of the foot during braking in unusual conditions.

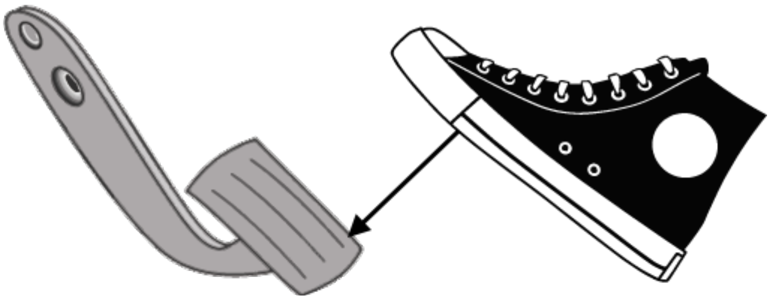

Figure 2

3.3. Case 1, scenario 3

Scenario 3a: Impact of high temperature
This scenario examines the impact of high temperature on the behavior of the brake pedal during standard braking. The simulation aims to determine how warm conditions, such as a hot day or prolonged exposure to sunlight, affect braking efficiency.

- **Physical input data:**

    - **Force applied:** 300 N – Represents the standard force used during braking.

    - **Ambient temperature:** 60°C; represents very hot conditions that might occur in summer or in a hot climate.

- **Material:** Aluminum – The analysis focuses on resistance to high temperature.
- **Force application point**: Center of the pedal – Corresponds to the driver's foot placement on the pedal.

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Scenario 3b: Impact of low temperature
This scenario explores how extremely low temperatures, such as those encountered in winter conditions, affect the behavior of the brake pedal during braking.

- **Physical input data:**
  - **Force applied:** 300 N – The force applied in typical braking.
  - **Ambient temperature:** -30°C; reflects winter conditions that might occur in very cold regions or when a vehicle is left outside on a frosty night.
  - **Material:** Aluminum – Testing for low-temperature resilience and possible changes in material behavior.

The schematic for each scenario illustrates the brake pedal with the applied force vector highlighted.

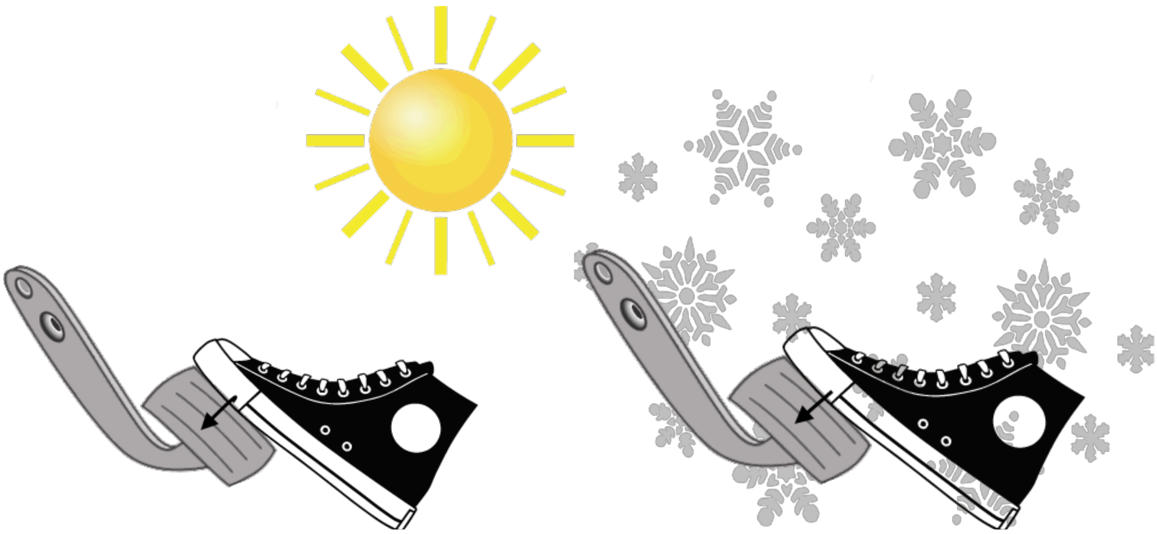


Figure 3

3.4. Case 1, scenario 4

Braking in high heels
This simulation examines the effect on the brake pedal when applied by high-heeled footwear, which is characterized by increased pressure at two distinct points, corresponding to the dual ends of the heel. The objective is to assess how the unique foot positioning on the pedal impacts force distribution and braking efficacy.

- **Physical input data:**

- **Force applied:** A total of 300 N, evenly divided between two contact points, each with an area of about 1 cm², located on the front and rear edges of the pedal.

- **Material:** Aluminum, to evaluate its capacity to withstand force concentrated at specific locations.

- **Force application point:** The pressure in each of the two points is presumed to be more localized and intense compared to the uniform force spread typical with standard footwear.

- **Ambient temperature:** A constant temperature of 20°C is maintained to ensure test consistency.

In this scenario, the schematic illustrates the brake pedal with an emphasis on the dual pressure points. The depiction aims to illustrate the effect of high heels on force application across the pedal's surface, potentially modifying the pedal's mechanical reaction.

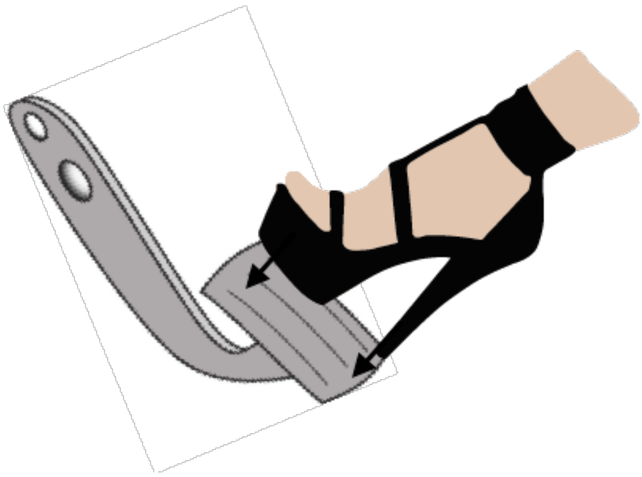


Figure 4

3.5. Case 1, scenario 5

Pedal obstruction by objects

This simulation models a situation where objects such as toys or bottles not only get under the brake pedal, causing it to jam, but also block the space beneath the pedal, limiting its ability to be fully depressed.

- **Physical input data:**
  - **Pedal force applied:** 300 N directed vertically downward, simulating the driver's foot pressure on the brake pedal.
  - **Constant obstruction load:** 100 N directed vertically upward from the point behind the pedal, imitating the pressure of an object that has jammed behind the pedal.
  - **Material:** Aluminum – The analysis focuses on the material's ability to withstand complex loads and unusual operating conditions.

- **Ambient temperature**: A constant temperature of 20°C is maintained to ensure test consistency.

In this scenario, the schematic illustrates the brake pedal with an emphasis on the obstruction caused by objects. The depiction aims to showcase the effect of such obstructions on the force application across the pedal's surface and its mechanical response.

Figure 5

3.6. Case 2, scenario 1

Standard braking

This scenario simulates a routine braking action where the driver applies moderate pressure on a brake pedal made of carbon composite, initiating the vehicle's stopping process. The simulation assumes that the pressure is evenly distributed by the driver across the central part of the pedal, corresponding to the typical foot positioning during braking. This modification focuses on the carbon composite material used in the brake pedal's construction, emphasizing its unique properties such as lightweight, exceptional durability, and maintaining structural integrity under stress, which contrasts with traditional materials like aluminum.

- **Physical input data:**
  - **Force applied:** 300 N – Represents the conventional force applied by a driver during standard braking operations.
  - **Material:** Carbon composite – Selected for its exceptional properties, including lightness, superior strength.
  - **Point of force application:** Center of the pedal –Typical foot placement by drivers, ensuring a uniform distribution of force over the pedal's surface.
  - **Ambient temperature:** 20°C – Denotes the typical temperature environment in which most vehicles are operated.

The schematic depicts the carbon composite brake pedal with the designated force vector applied. This vector is oriented vertically downwards, targeting the central part of the pedal to simulate the standard positioning of the foot during braking.

Figure 6

3.7. Case 2, scenario 2

Emergency Braking
This scenario depicts an extreme situation where the driver encounters an unexpected threat and must immediately perform maximal braking. In such a case, the driver presses the brake pedal forcefully and decisively to reduce the vehicle's speed as quickly as possible.

- **Physical input data:**
  - **Force applied:** 700 N – Represents the intense force exerted by the driver in a critical situation requiring sudden stop.
  - **Material:** Carbon Composite – This material is tested for its ability to absorb abrupt pressure without deformation.
  - **Ambient temperature:** 20°C, to ensure uniform conditions for comparing the impact of temperature on composite performance.
  - **Point of force application:** Pressure is applied to the lower part of the pedal in the moment of emergency braking.

The schematic displays the carbon composite brake pedal with the applied force vector emphasized. The force is directed vertically downward, potentially concentrating on the lower part of the pedal. This illustrates the immediate and forceful action taken by the driver in emergency conditions.

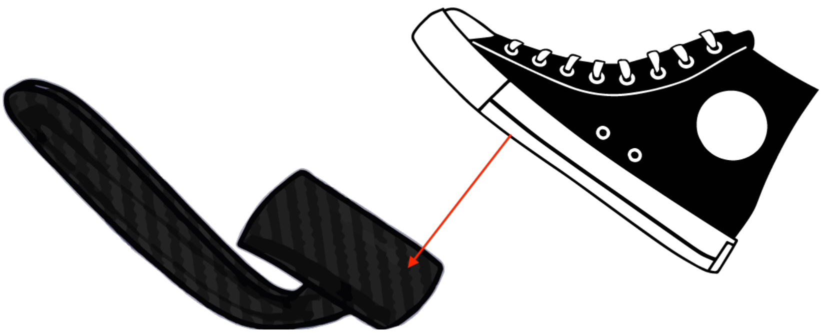


Figure 7

3.8. Case 2, scenario 3

Scenario 3a: Impact of high temperature

This scenario investigates the reaction of a brake pedal made from carbon composite to high temperatures, which might occur during hot summer days or due to prolonged exposure of the vehicle to direct sunlight. The aim is to understand how extreme thermal conditions affect the functionality.

- **Physical Input Data:**
  - **Force applied:** 300 N, representing the force typical for the braking process.
  - **Ambient temperature:** 60°C, simulating extremely high temperature conditions.
  - **Material:** Carbon Composite, examined for its mechanical property behavior and reaction to high temperatures.

Scenario 3b: Impact of low temperature

This simulation explores the effect of very low temperatures on the properties and operation of a brake pedal made from carbon composite. The study focuses on understanding how freezing conditions, typical for winter climates or nights spent outdoors, affect the pedal's response to the driver's pressure.

- **Physical input data:**
  - **Force applied:** 300 N, corresponding to the standard braking force.
  - **Ambient temperature:** -30°C, representing extremely cold conditions.
  - **Material:** Carbon Composite, examined for its mechanical property behavior and reaction to low temperatures.

The schematic for each scenario will illustrate the carbon composite brake pedal with the applied force vector emphasized.

Figure 8

3.9. Case 2, scenario 4

Braking in high heels
This scenario simulates the impact of wearing high-heeled footwear on a brake pedal made from carbon composite. The characteristic increased pressures at two points, corresponding to the heel ends, may affect the composite material differently than aluminum.

- **Physical input data:**
  - **Force Applied:** 300 N, evenly distributed between two pressure points, with each point having an area of about 1 cm², located on the front and rear parts of the pedal.
  - **Material:** Carbon Composite, analyzed for its response to pinpointed and increased loads, crucial for assessing the durability and behavior of the pedal under unconventional use conditions.
  - **Force application point:** The pressure in each of the two points is presumed to be more localized and intense compared to the uniform force spread typical with standard footwear.
  - **Ambient temperature:** 20°C, ensuring consistent conditions for all tests.

The schematic will showcase the carbon composite brake pedal with a focus on the dual pressure points applied by high heels. This visualization aims to highlight how such footwear influences force application across the pedal's surface, potentially altering the pedal's mechanical response.

Figure 9

3.10. Case 2, scenario 5

Pedal obstruction by objects

This scenario investigates a situation where objects, such as toys or bottles, accidentally get under a brake pedal made from carbon composite, causing it to jam while also blocking its ability to be fully depressed. The aim of this study is to understand how a pedal made from advanced material reacts to the presence of foreign objects that may restrict its functionality.

- **Physical input data:**
  - **Pedal force applied:** 300 N directed vertically downward, simulating the driver's foot pressure on the brake pedal.

- **Constant obstruction load:** 100 N directed vertically upward from the point behind the pedal, imitating the pressure of an object that has jammed behind the pedal.

- **Material:** Carbon Composite, scrutinized for its durability under atypical loads to evaluate its robustness against unexpected scenarios.

- **Ambient temperature**: A constant temperature of 20°C is maintained to ensure test consistency.

The schematic demonstrates the carbon composite brake pedal with an emphasis on the obstruction caused by objects. This visualization is intended to highlight how such obstructions influence the force application across the pedal's surface and its mechanical response.

Figure 10

4. Model of geometry

Case 1: Aluminum brake pedal render

Figure 11

Case 2: Carbon composite brake pedal render

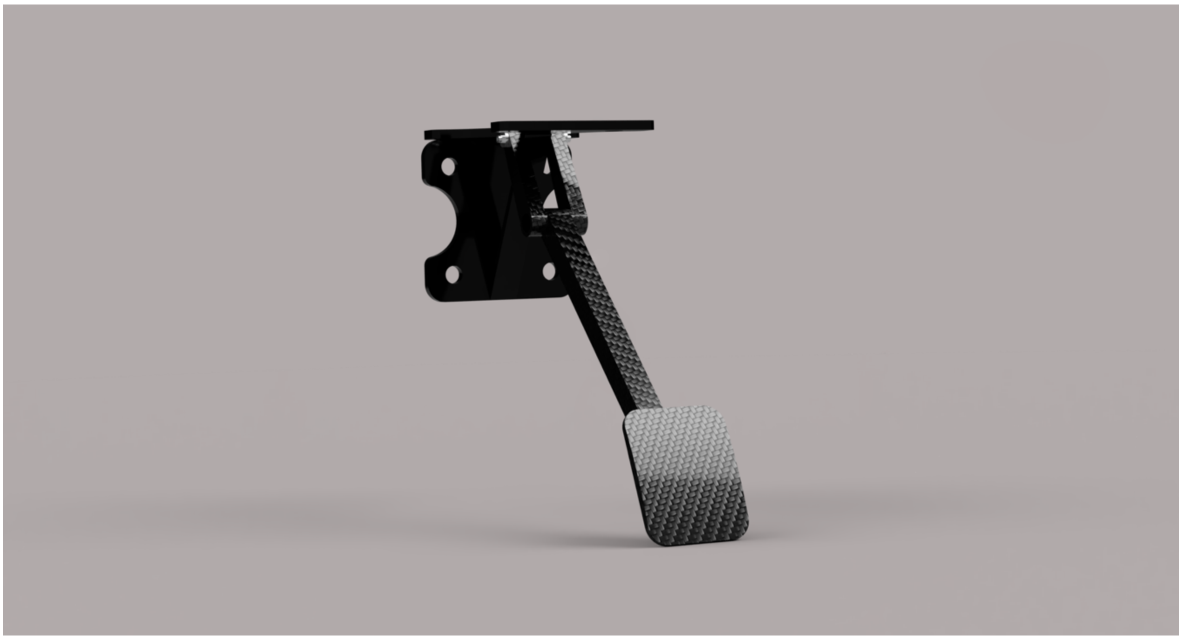


Figure 12

Case 1: Aluminum brake pedal technical documentation

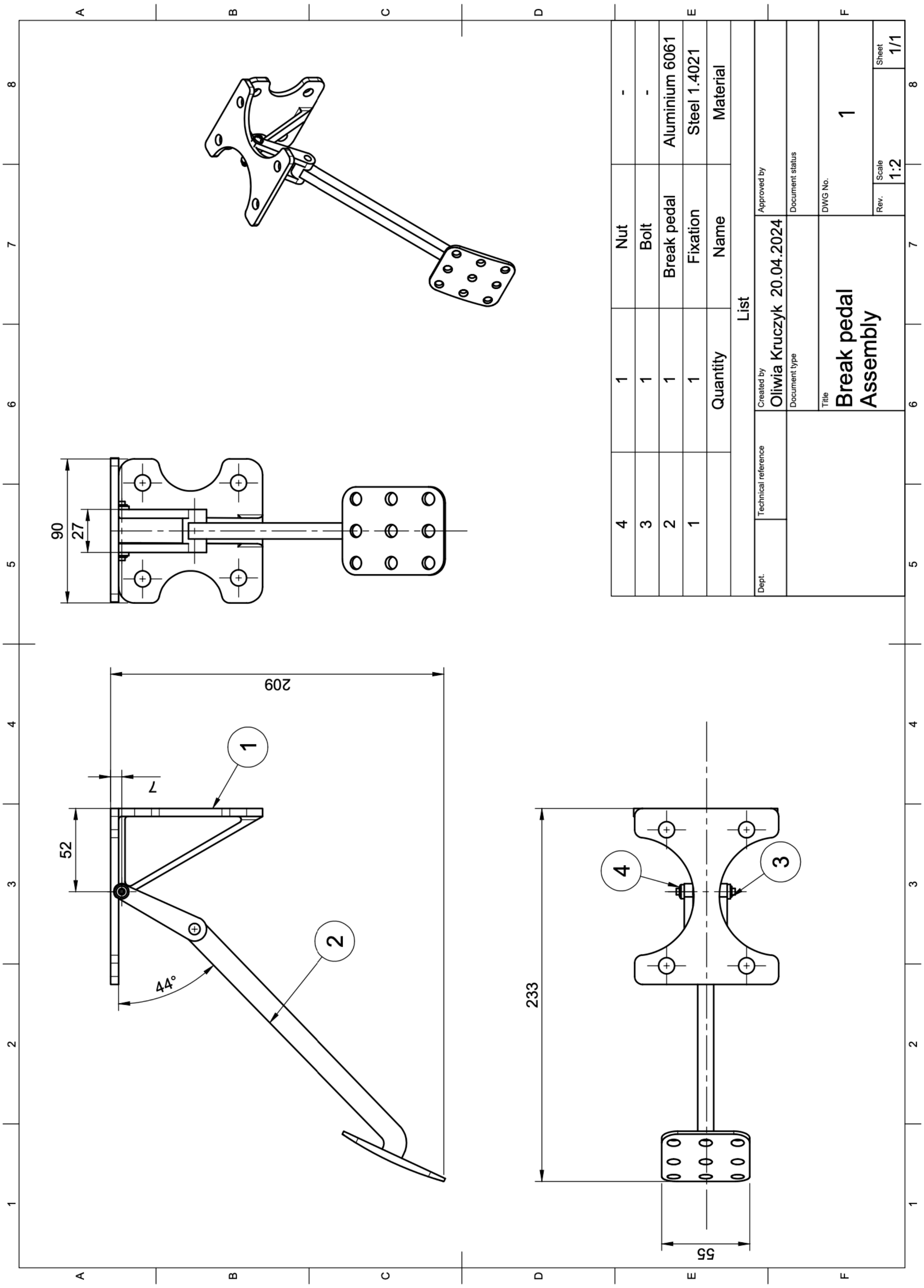


Figure 13

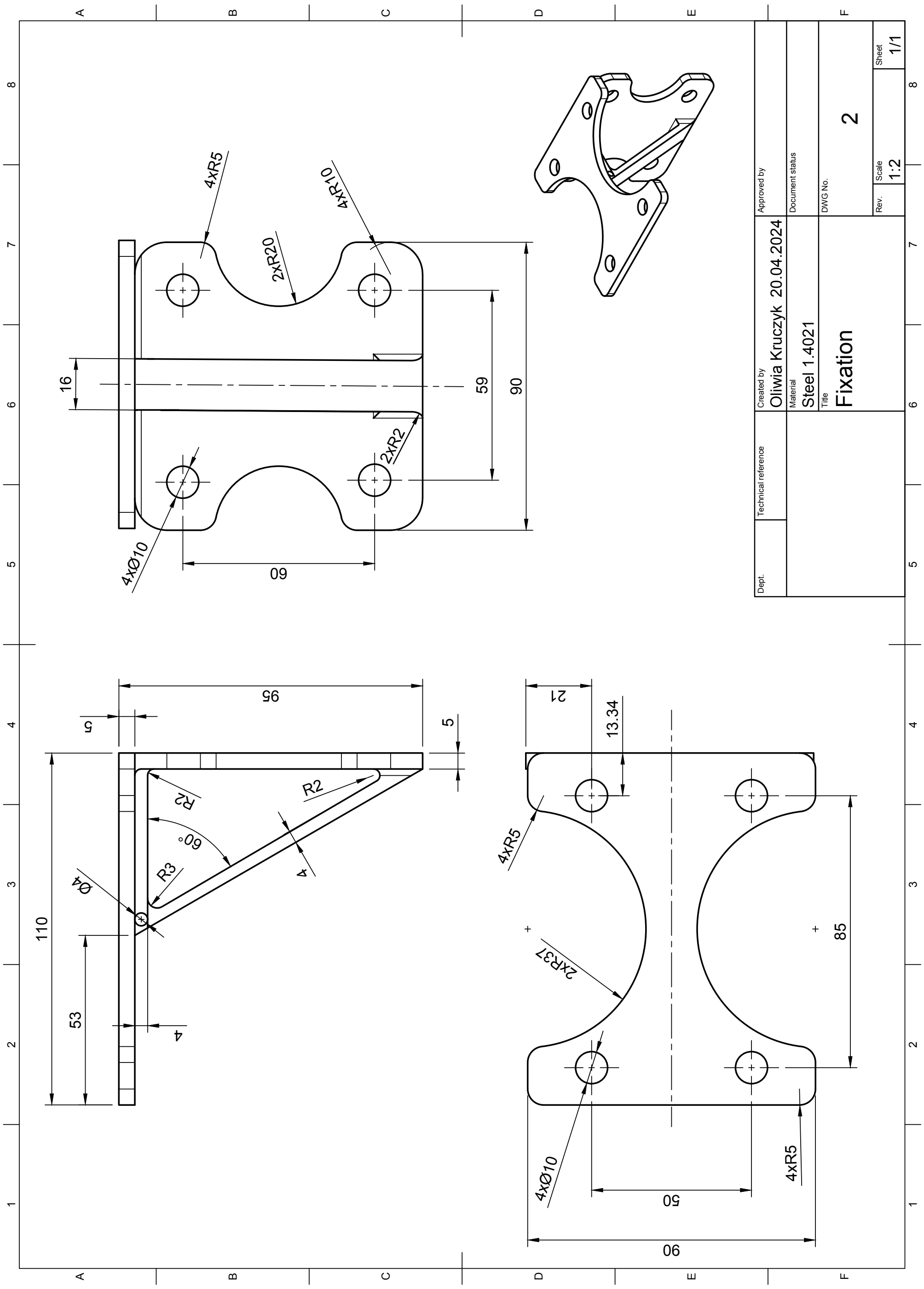


Figure 14

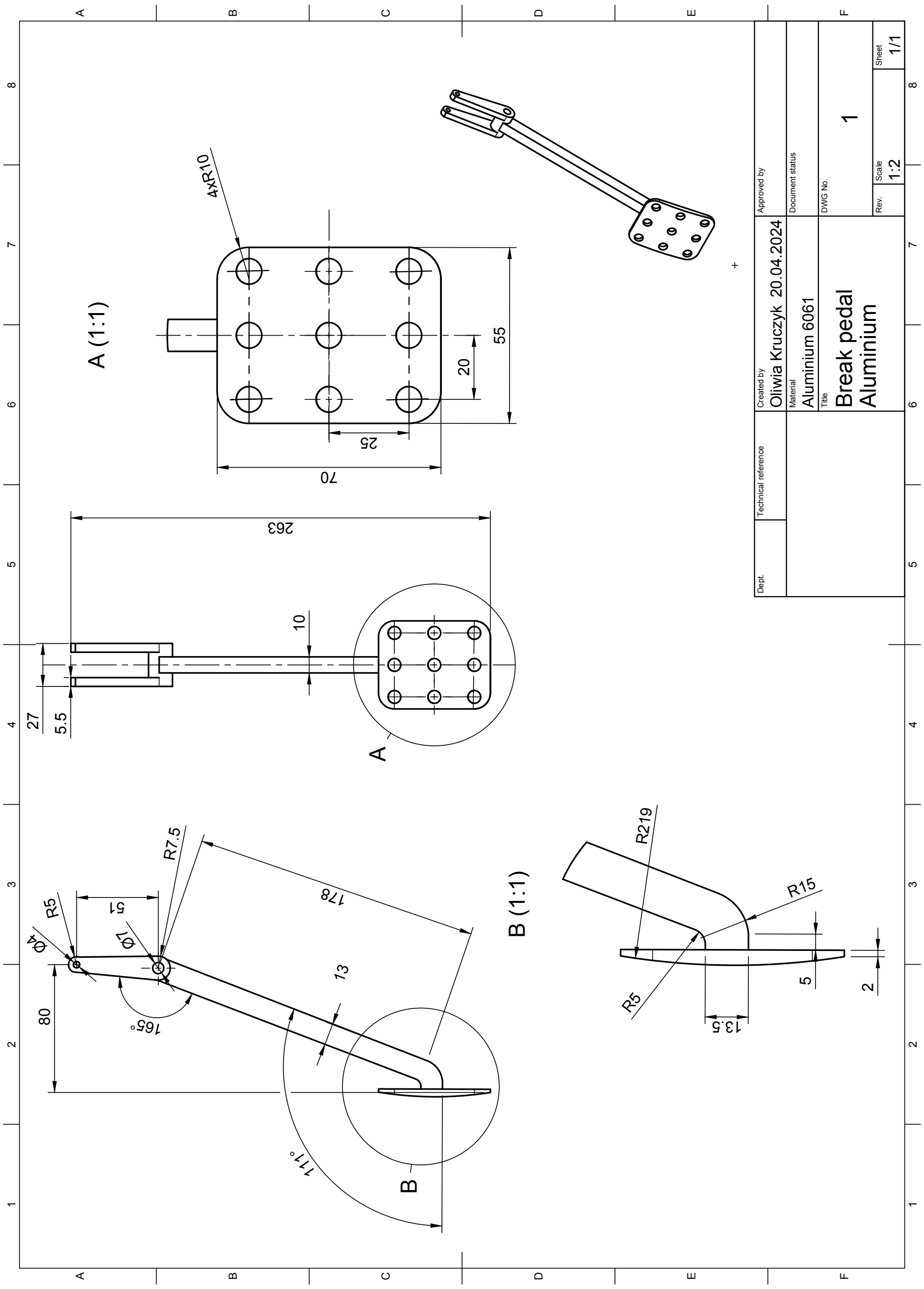
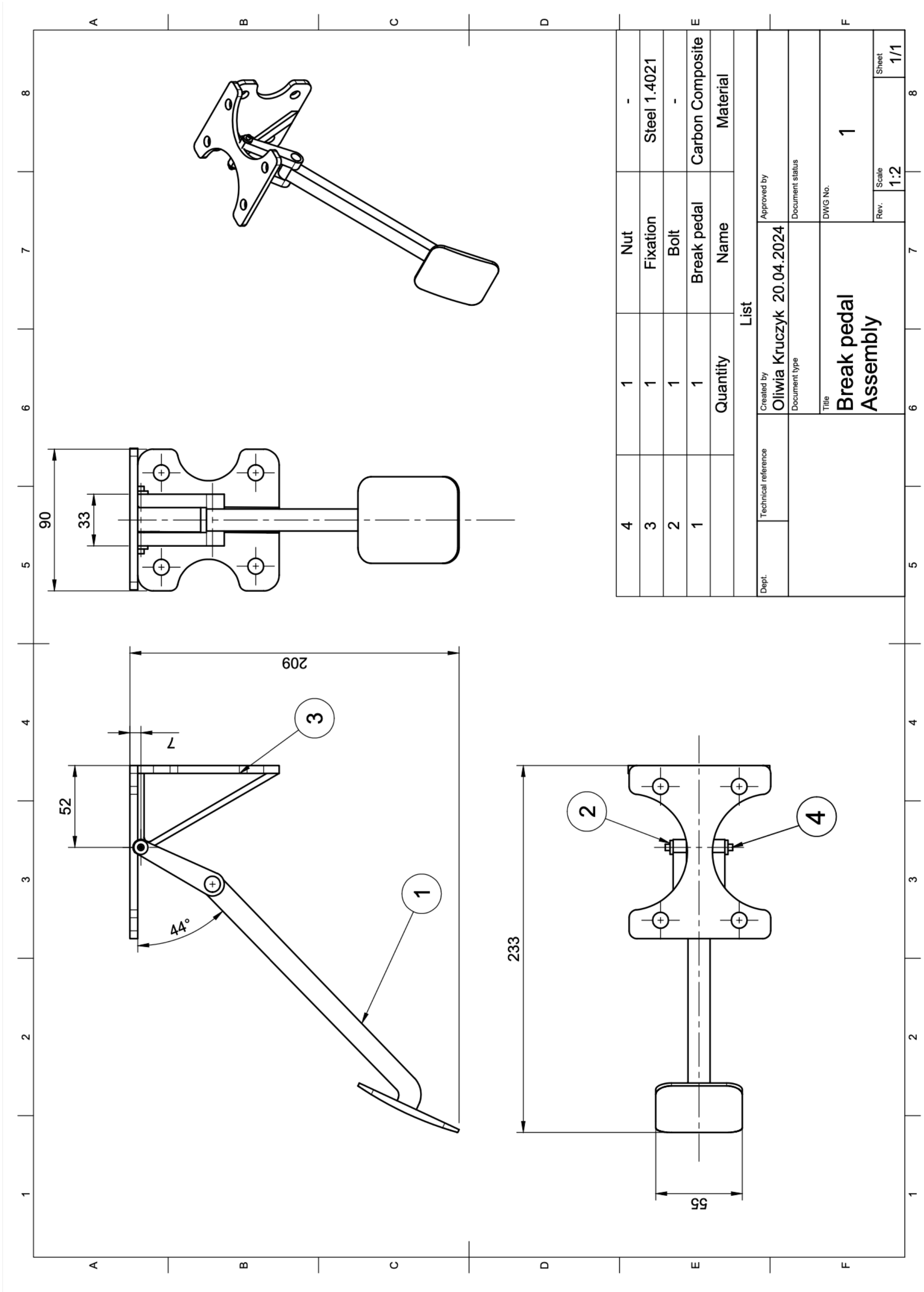


Figure 15

Case 2: Carbon composite brake pedal technical documentation



4 | 1 | Nut | -
3 | 1 | Fixation | Steel 1.4021
2 | 1 | Bolt | -
1 | 1 | Break pedal | Carbon Composite
Quantity | Name | Material
List
Dept.
Technical reference
Created by
Oliwia Kruczyk 20.04.2024
Approved by
Document type
Document status
Title
Break pedal Assembly
DWG No.
1
Rev.
Scale
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1/1
90
33
209
7
52
44°
233
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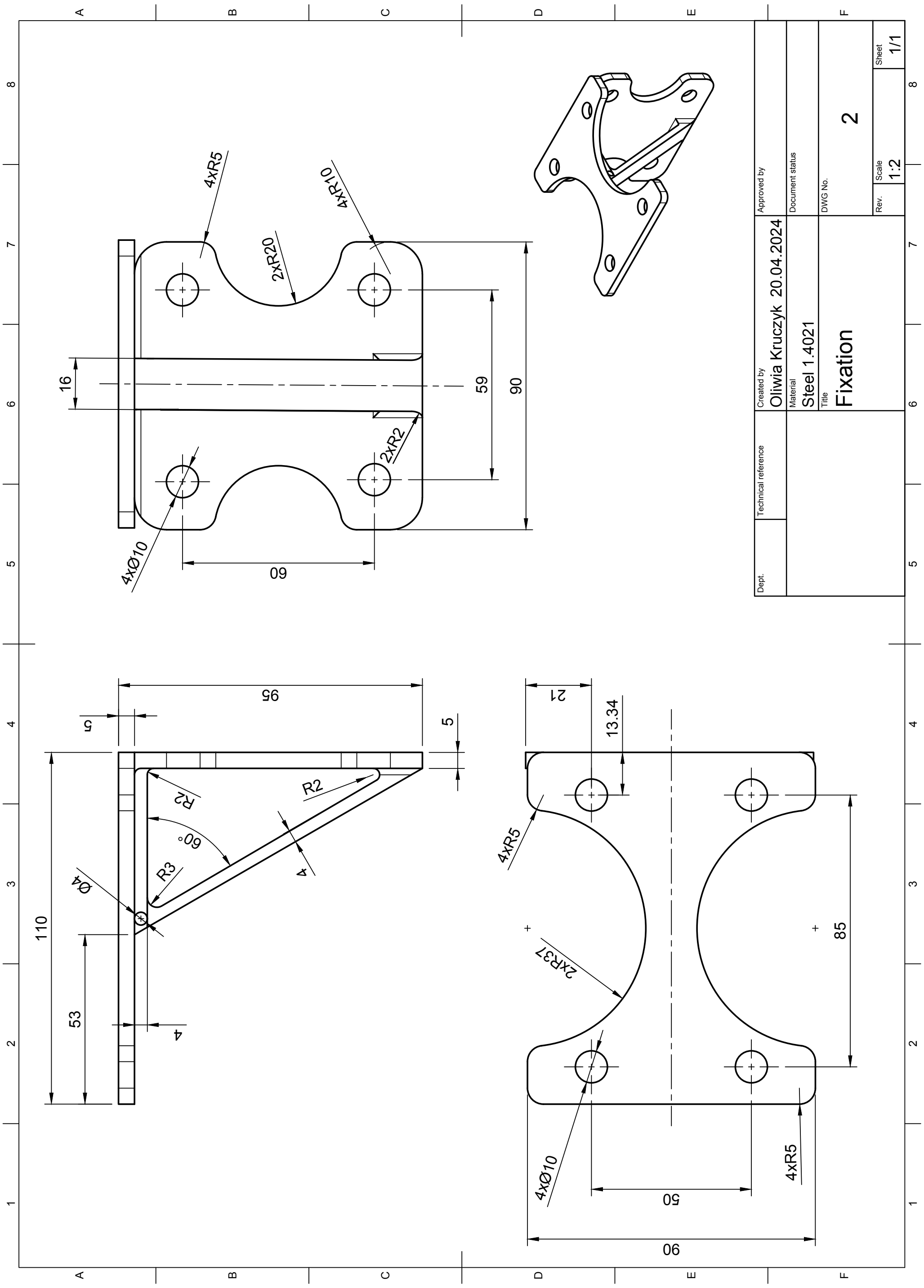
Figure 16


Dept.
Technical reference
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Approved by
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Rev.
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16
59
90
60
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5
R2
60°
R3
Ø4
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53
4
21
13.34
2xR37
85
50
90

Figure 17

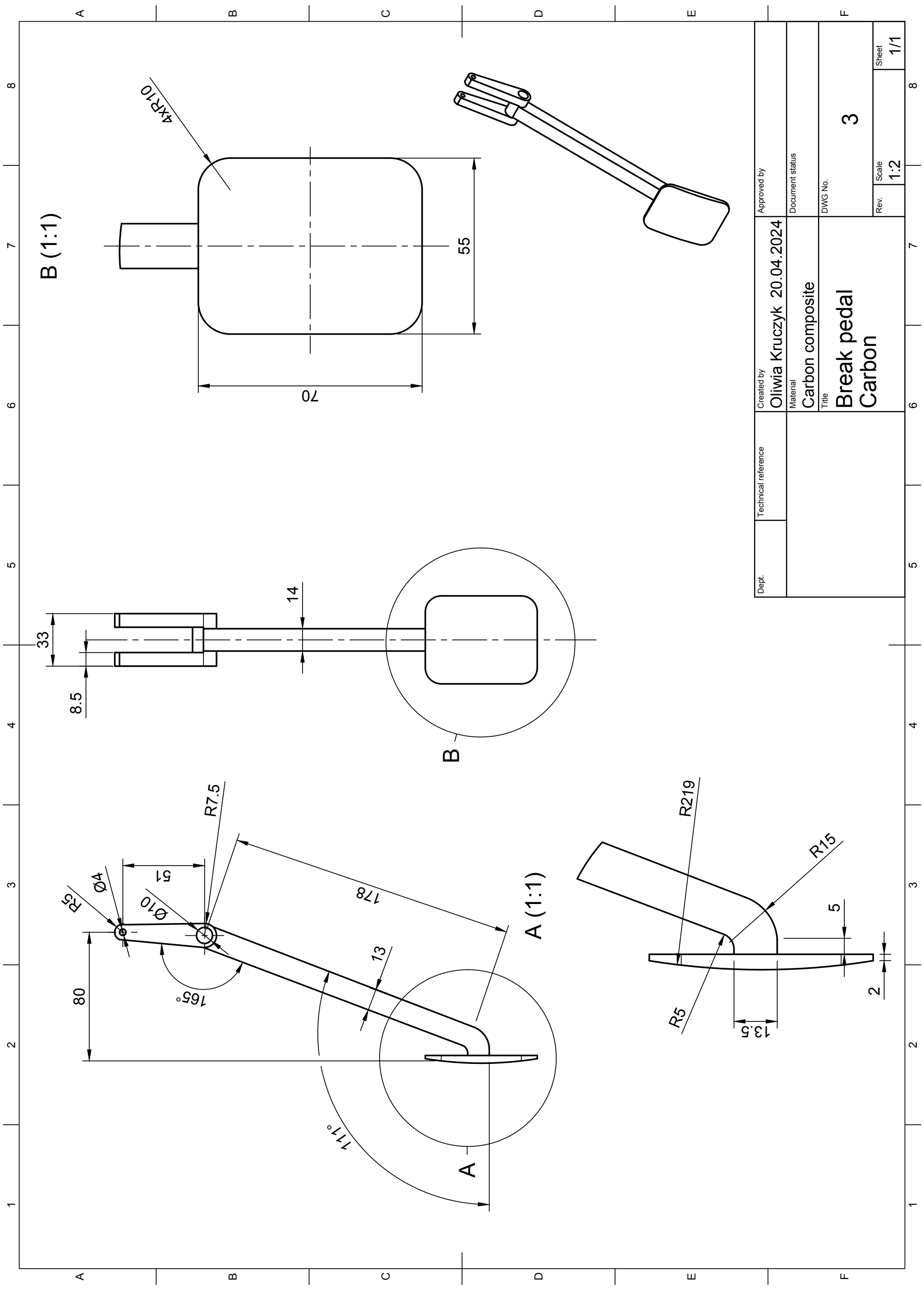

Figure 18

In the assembly, an additional connecting component are utilized which enhances the structural integrity and functionality of the brake pedal mechanism. (Bolt and nut). It is important to note that the technical drawing for this additional component is not included in this documentation as it will not be considered in the calculations.

5. Description of the methodology

In this project, the primary models used were beam models, specifically focusing on two different brake pedal designs: one made from aluminum and the other from carbon composite. Here's a detailed description of the methodology:

- The beam model was chosen for its effectiveness in simulating the behavior of elongated structures such as brake pedals under various loads and conditions. This model type is particularly suited for components that are primarily subject to bending and axial loads, providing a reliable representation of the mechanical response of the brake pedals.
- By using the beam model, the analysis could capture the essential deformation characteristics and stress distributions, ensuring that the critical aspects of the brake pedal's performance are accurately represented.

The primary objective of geometric simplification was to streamline the model to facilitate more efficient and accurate finite element analysis (FEA).

- Small fillets and roundings that do not significantly affect the stress distribution were removed from the model. These features often add unnecessary complexity to the geometry, increasing computational load without providing substantial benefits in terms of analysis accuracy.
- The simplification process ensured that all critical features that influence the structural integrity and performance of the brake pedal were retained. This included the primary load-bearing surfaces and attachment points, which are essential for a realistic simulation of the pedal's behavior.
- The resulting simplified geometry maintained the essential structural characteristics of the original design while being optimized for FEA. This balance between detail and simplicity helped in achieving accurate results with reduced computational resources.

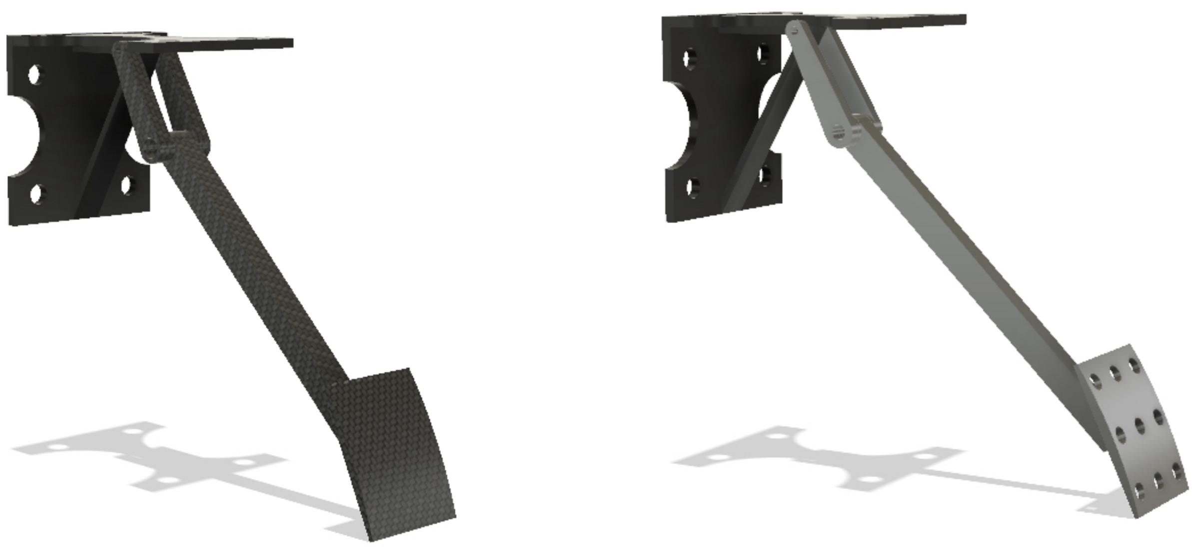

Figure 19

6. Model for numerical FEA simulation

In the project, the following materials were utilized for different components of the brake pedal system. The specific parameters for each material are detailed below:

Materials Used:

- Steel 1.4021 for fixation
- Aluminium Alloy 6061 for the brake pedal
- Carbon Composite for the second brake pedal

Steel 1.4021

Properties	Value	Unit
Density	7750	$\frac{kg}{m^3}$
Young Moduls	190	GPa
Tensile Yield Strenght	415	MPa
Tensile Ultimate Strenght	650	MPa
Compresisve Yield Strenght	414	MPa
Poisson Ratio	0,28	-

Tab. 1

Aluminium Alloy 6061

Properties	Value	Unit
Density	2713	$\frac{kg}{m^3}$
Young Moduls	69040	MPa
Tensile Yield Strenght	259	MPa
Tensile Ultimate Strenght	313	MPa
Compresisve Yield Strenght	276	MPa
Poisson Ratio	0,33	-

Tab. 2

Carbon composite

Properties	Value	Unit
Density	1800	$\frac{kg}{m^3}$
Young Moduls X direction Y direction	 290 23	GPa

Z direction	23	
Poisson Ratio XY YZ XZ	 0,2 0,4 0,2	-
Tensile Yield Strenght X direction Y direction Z direction	 2900 40 40	MPa
Tensile Ultimate Strenght X direction Y direction Z direction	 870 50 50	MPa

Tab. 3

The detailed material properties and analysis parameters provided above form the basis for evaluating the brake pedal's performance under different scenarios. By analyzing the total deformation, equivalent stress, and force reaction, we can assess the structural integrity and functionality of the brake pedal system, ensuring it meets safety and performance standards.

6.1. Case 1

To achieve a high-quality mesh, the brake pedal model was divided into smaller elements using surface splitting techniques. This approach enhances the mesh quality by ensuring a more uniform and fine mesh distribution across complex geometries. The mesh for the brake pedal model was created using the multizone method in Ansys software, ensuring a high-quality representation.

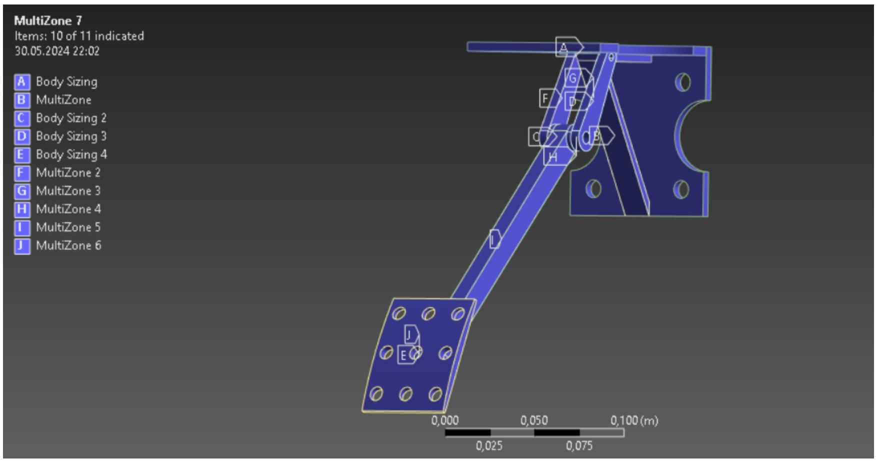

Figure 20

Mesh quality parameters:

- The element quality score was maintained above 0.5, indicating a high-quality mesh suitable for accurate simulations.

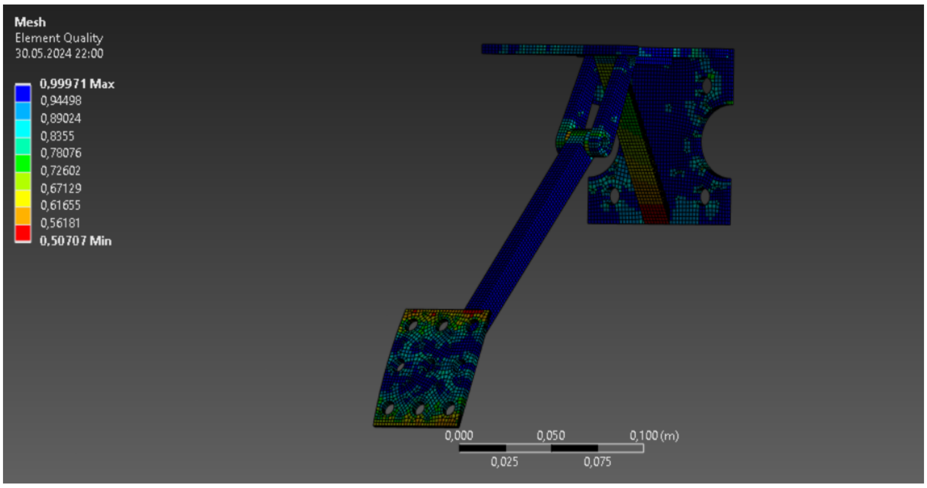

Figure 21

- The aspect ratio of the elements was carefully controlled to avoid distortion, with values ranging between 1.004 (minimum) and 10.077 (maximum).

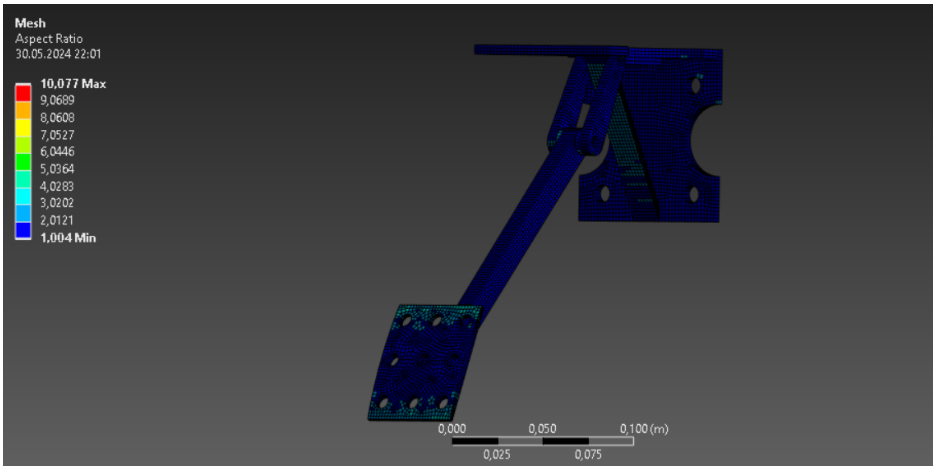

Figure 22

- Skewness values were kept low, with the maximum value being 0.83376, ensuring that elements are as close to ideal shapes as possible.

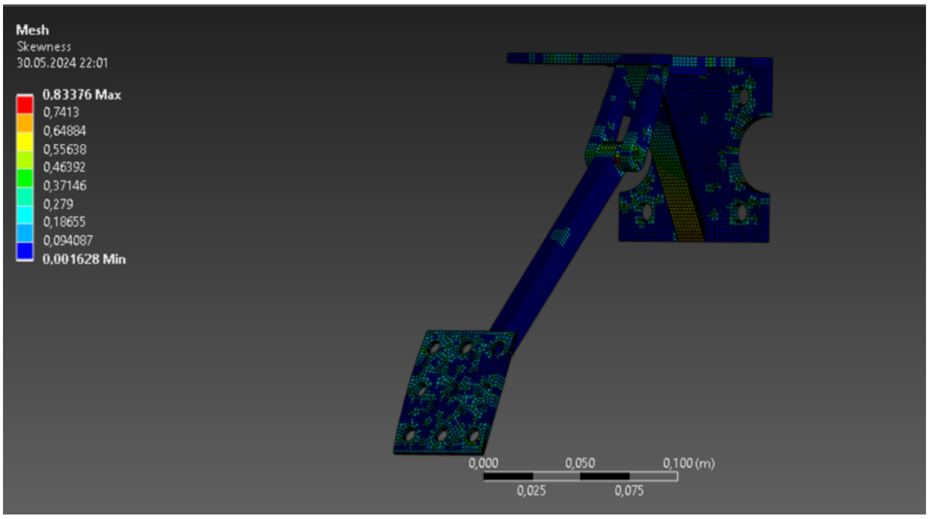

Figure 23

Boundary conditions for all scenarios
The following boundary conditions were applied consistently across all scenarios to simulate realistic operating conditions:

- The fixation points, simulating the screws attaching the brake pedal to the vehicle, were modeled using fixed supports to prevent any movement.

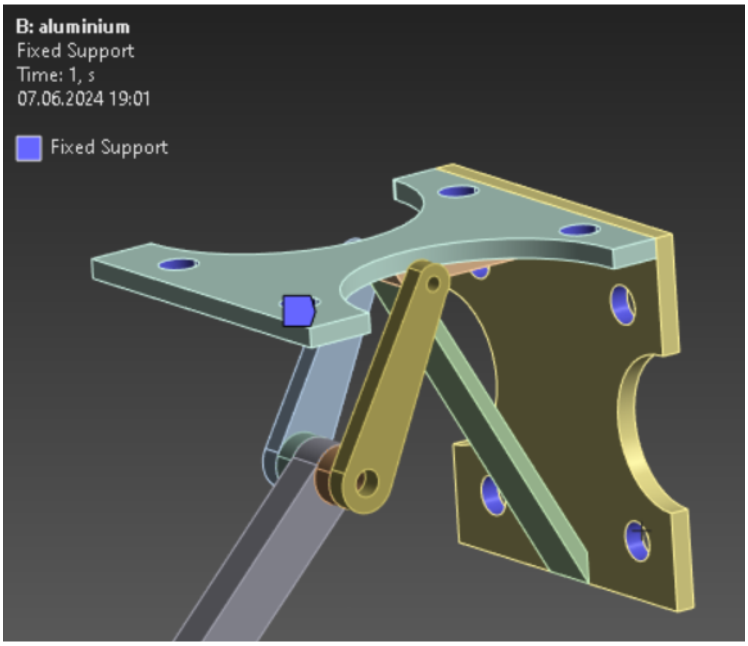

Figure 24

- Frictional contact was modeled between the contacting parts of the brake pedal and the fixation, with a friction coefficient of 0.2.

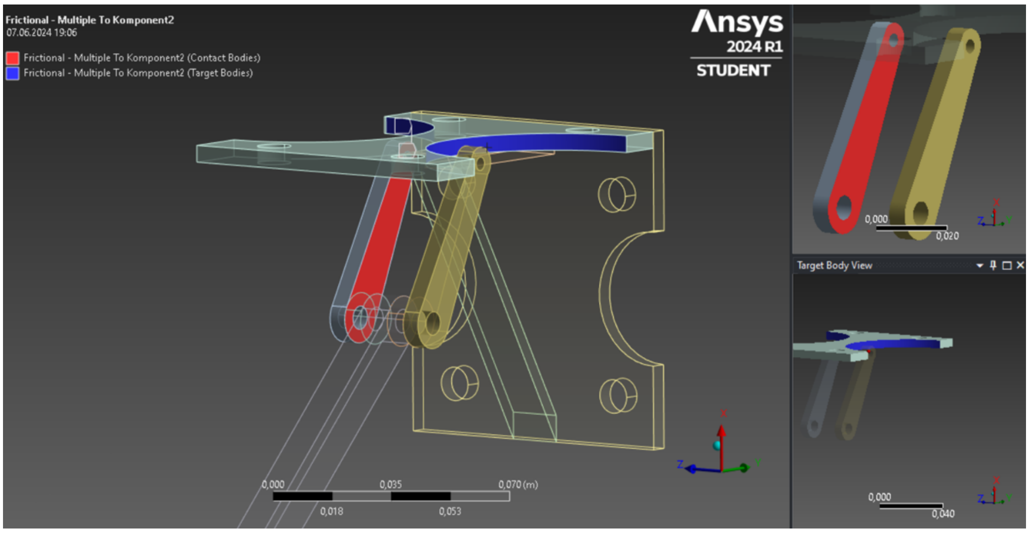

Figure 25

- A remote displacement boundary condition was applied at the pedal's attachment point to the brake system, allowing rotation only around the Z-axis. This simulates the real-life connection of the pedal to the brake mechanism.

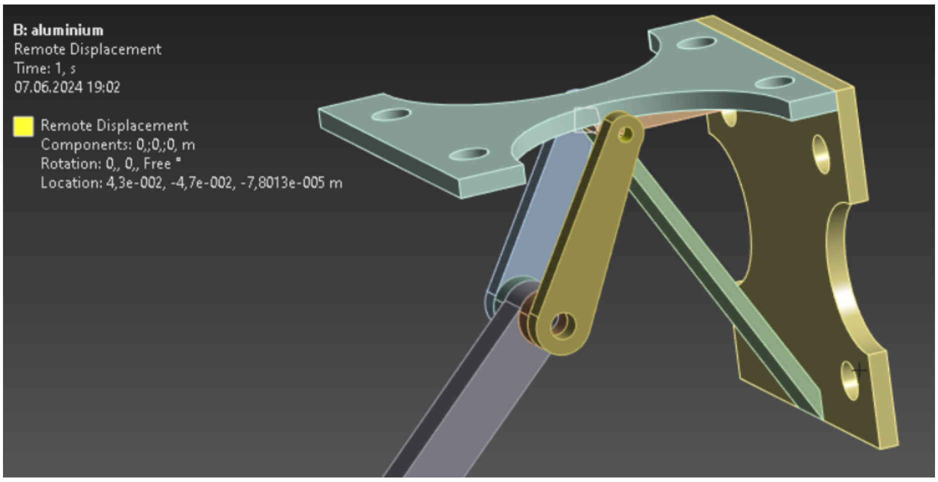

Figure 26

- Another remote displacement was applied to simulate the connection to the brake pump, again allowing rotation only around the Z-axis to mimic the actual brake system's functionality.

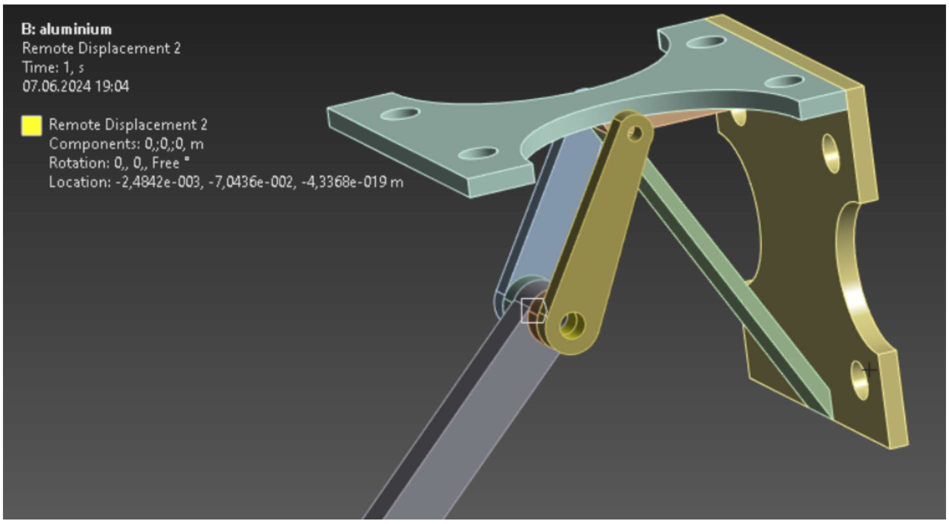

Figure 27

By adhering to these setup parameters, the finite element analysis accurately reflects the operational conditions of the brake pedal, providing reliable data for further analysis and optimization.

Scenario 1:
For Scenario 1, the aluminum brake pedal was analyzed under the following additional conditions:

- A force of 300 N was applied to the central part of the pedal at an angle of 65 °. The force components were resolved into the X and Y directions using trigonometric functions.

$$F_x = 300N \cdot \cos 65° \approx 126{,}78\ N$$
$$F_y = 300N \cdot \sin 65° \approx 271{,}89\ N$$

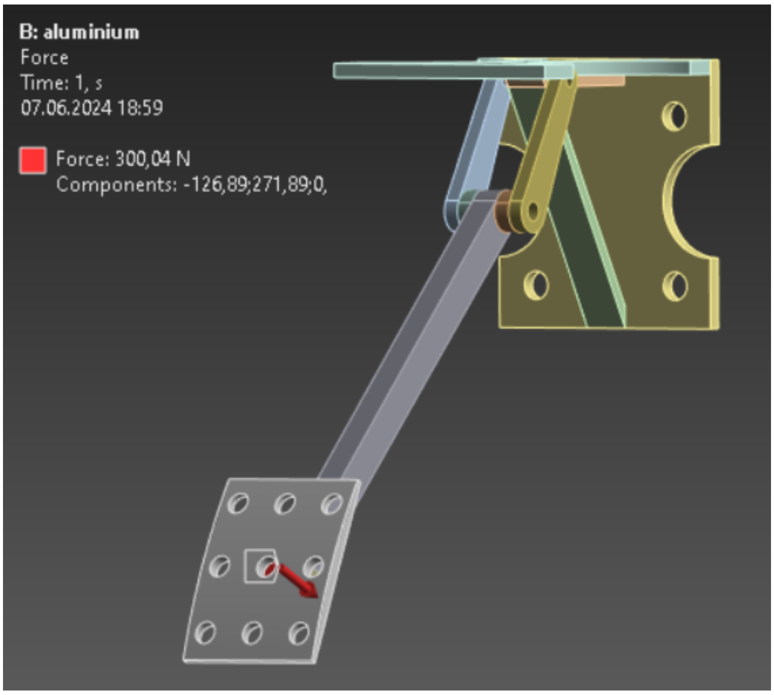

Figure 28

- The ambient temperature was set to 20 ° Celsius, representing typical operating conditions.

These conditions were applied to ensure that the analysis accurately reflects the behavior of the brake pedal under normal usage scenarios. The force application and temperature settings provide a realistic simulation environment, allowing for the assessment of the pedal's performance and structural integrity.

Scenario 2:

For Scenario 2, the aluminum brake pedal was analyzed under the following additional conditions:

- A force of 700 N was applied to the central part of the pedal at an angle of 65 °. The force components were resolved into the X and Y directions using trigonometric functions.

$$F_x = 700N \cdot \cos 65° \approx 295{,}82\ N$$
$$F_y = 700N \cdot \sin 65° \approx 634{,}41\ N$$

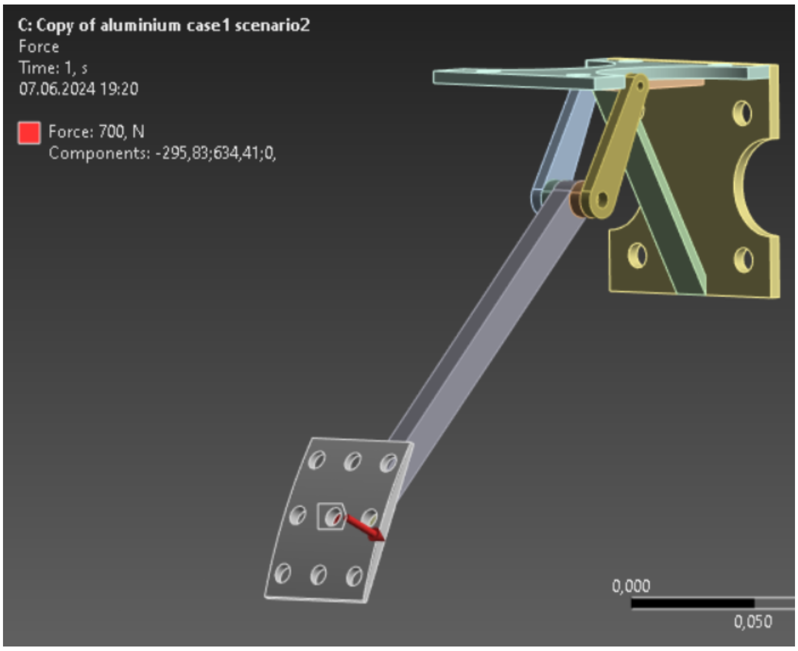

Figure 29

- The ambient temperature was set to 20 ° Celsius, representing typical operating conditions.

These conditions were applied to ensure that the analysis accurately reflects the behavior of the brake pedal under emergency braking scenarios. The force application and temperature settings provide a realistic simulation environment, allowing for the assessment of the pedal's performance and structural integrity under higher stress conditions.

Scenario 3:
For Scenario 3, the aluminum brake pedal was analyzed under the following additional conditions:

- A force of 300 N was applied to the central part of the pedal at an angle of 65 °. The force components were resolved into the X and Y directions using trigonometric functions.

$$F_x = 300N \cdot \cos 65° \approx 126{,}78\ N$$
$$F_y = 300N \cdot \sin 65° \approx 271{,}89\ N$$

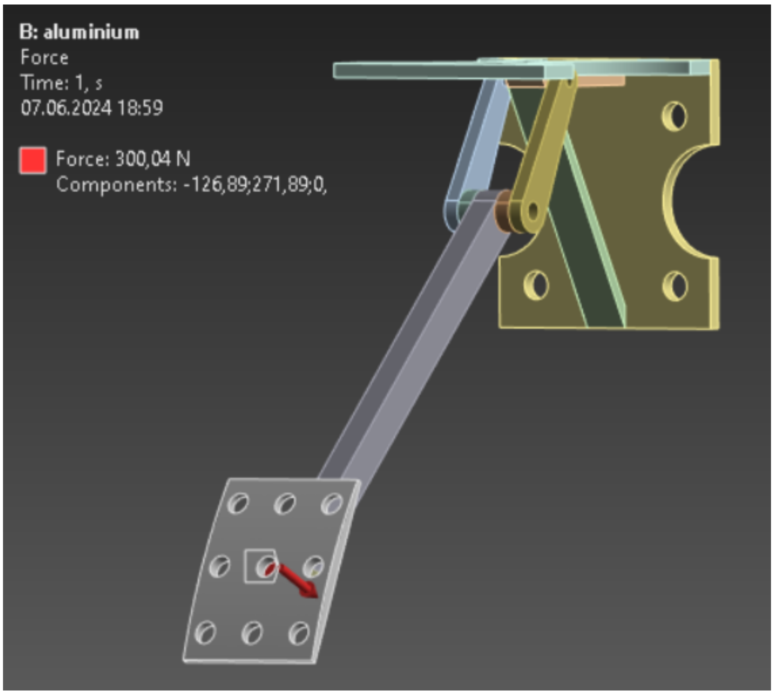

Figure 30

Scenario 3a:

- The ambient temperature was set to 60 ° Celsius to simulate high-temperature conditions.

Scenario 3b:

- The ambient temperature was set to -30 ° Celsius to simulate low-temperature conditions.

These conditions ensure that the analysis accurately reflects the behavior of the brake pedal under extreme temperature scenarios, allowing for the assessment of the pedal's performance and structural integrity under both high and low thermal stress.

Scenario 4:
For Scenario 4, the aluminum brake pedal was analyzed under the following additional conditions:

- A total force of 300 N was applied, evenly divided between two contact points, each representing the front and rear edges of a high-heeled shoe.
- Each contact point experiences a force of $\frac{300N}{2} = 150N$
- Each force is applied over an area of approximately 1 cm² at the front and rear edges of the pedal.

$$F_x = 150N \cdot \cos 65° \approx 63{,}39\ N$$
$$F_y = 150N \cdot \sin 65° \approx 135{,}95\ N$$

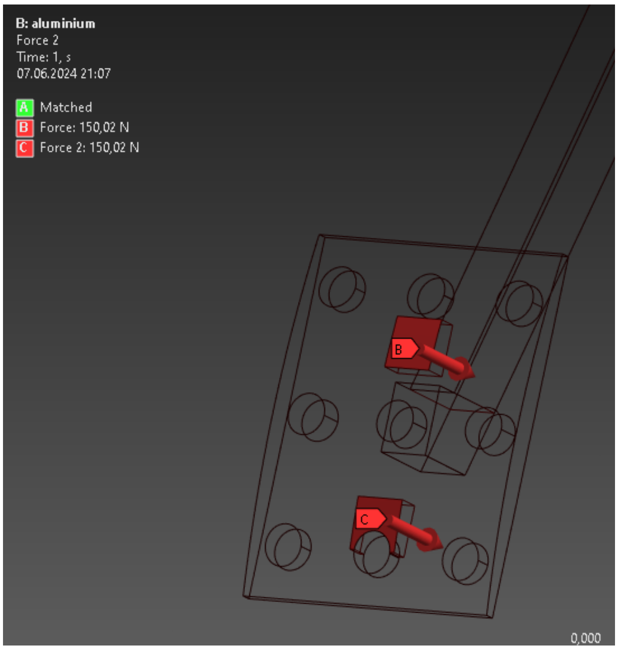

Figure 31

- The ambient temperature was set to 20 ° Celsius, representing typical operating conditions.

These conditions were applied to simulate the unique pressure distribution and force application when braking in high heels. This scenario helps in assessing the structural integrity and performance of the brake pedal under unconventional and potentially high-stress conditions, providing insights into the pedal's ability to withstand localized and intense loads.

Scenario 5:

For Scenario 5, the aluminum brake pedal was analyzed under the following additional conditions:

- A force of 300 N was applied to the central part of the pedal, simulating the driver's foot pressure.

$$F_x = 300N \cdot \cos 65° \approx 126{,}78\ N$$
$$F_y = 300N \cdot \sin 65° \approx 271{,}89\ N$$

- An additional constant load of 100 N was applied vertically upward from the point behind the pedal to simulate the obstruction caused by an object jammed under the pedal.

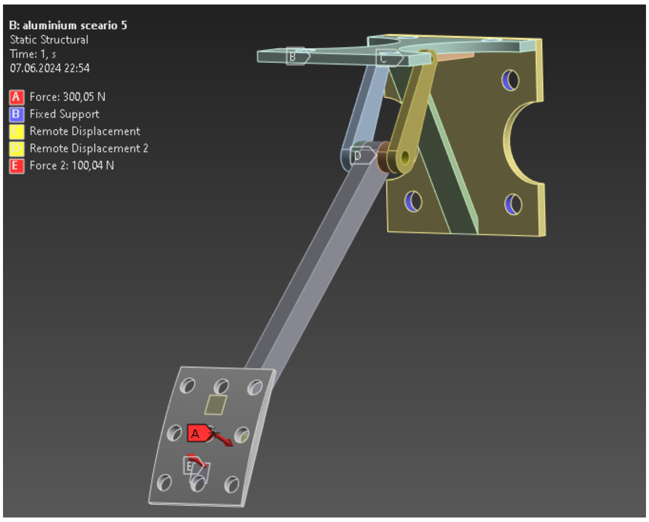

Figure 32

- The ambient temperature was set to 20 ° Celsius, representing typical operating conditions.\

These conditions were applied to simulate the presence of an obstruction under the brake pedal, which could occur due to objects like toys or bottles. This scenario helps in evaluating the pedal's performance and structural integrity when subjected to complex loading conditions, including both downward force from the driver's foot and upward force from the obstructing object.

6.2. Case 2

To achieve a high-quality mesh, the brake pedal model was divided into smaller elements using surface splitting techniques. This approach enhances the mesh quality by ensuring a more uniform and fine mesh distribution across complex geometries. The mesh for the brake pedal model was created using the multizone method in Ansys software, ensuring a high-quality representation suitable for finite element analysis. The element size for all components was set to 2mm to achieve a fine and consistent mesh.

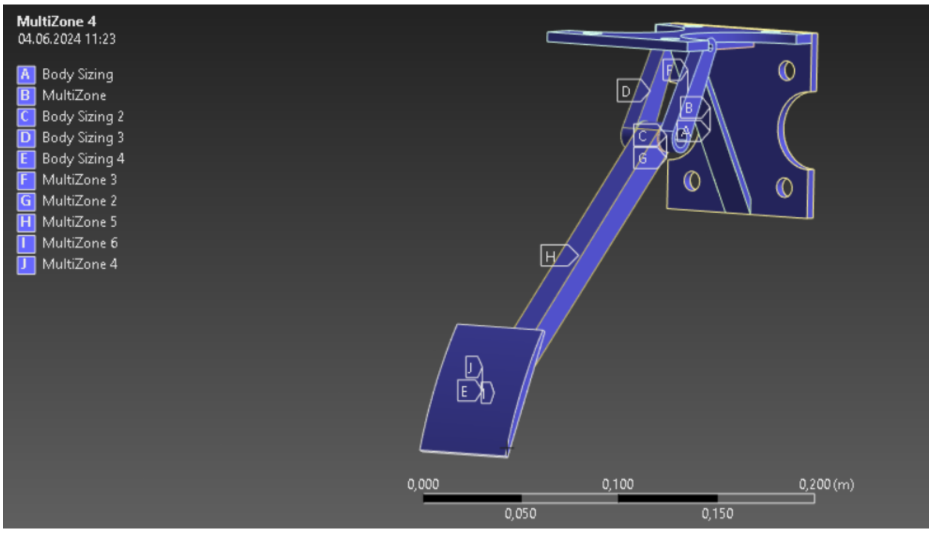

Figure 33

Mesh quality parameters:

- The element quality score was maintained above 0.5, indicating a high-quality mesh suitable for accurate simulations.

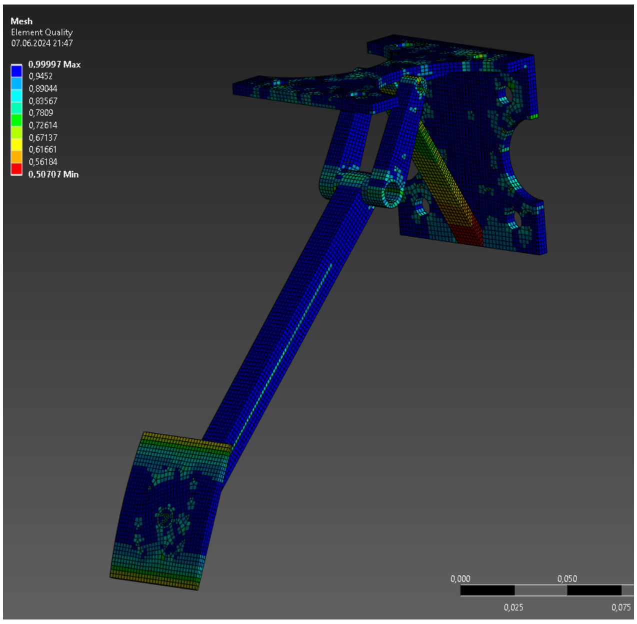

Figure 34

- The aspect ratio of the elements was carefully controlled to avoid distortion, with values ranging between 1.004 (minimum) and 10.077 (maximum).

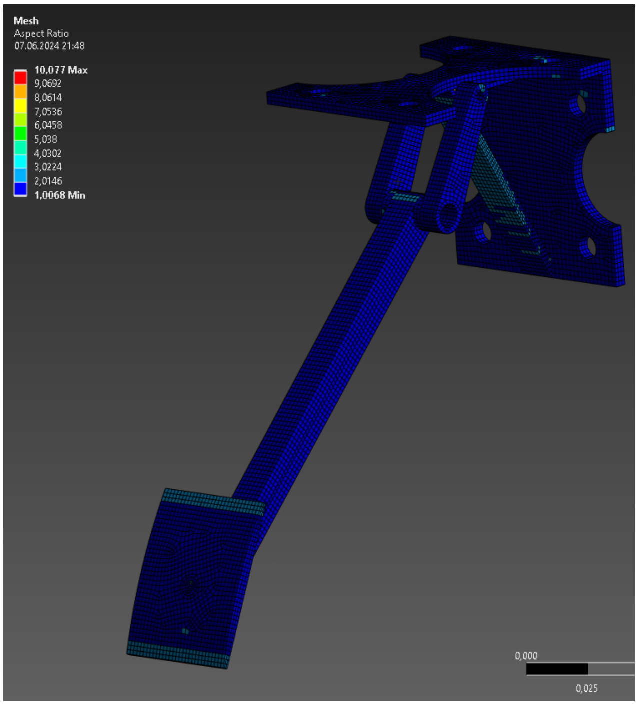

Figure 35

- Skewness values were kept low, with the maximum value being 0.66646, ensuring that elements are as close to ideal shapes as possible.

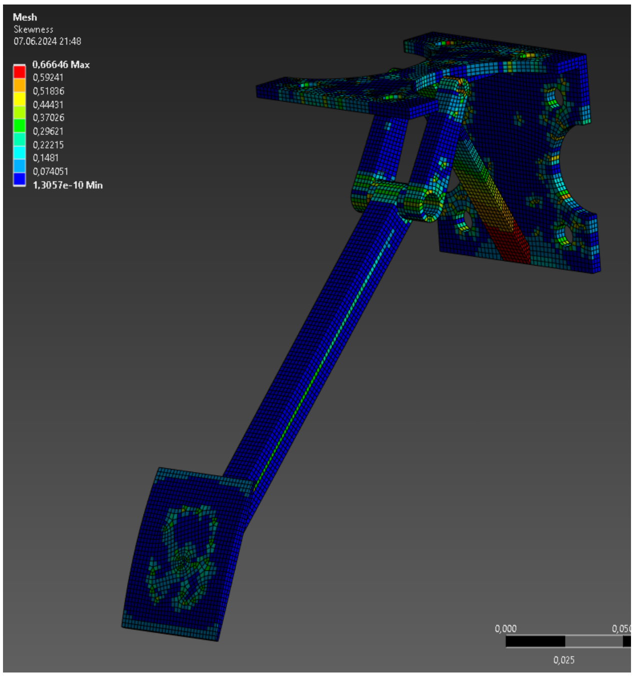

Figure 36

Boundary conditions for all scenarios
The following boundary conditions were applied consistently across all scenarios to simulate realistic operating conditions:

- The fixation points, simulating the screws attaching the brake pedal to the vehicle, were modeled using fixed supports to prevent any movement.

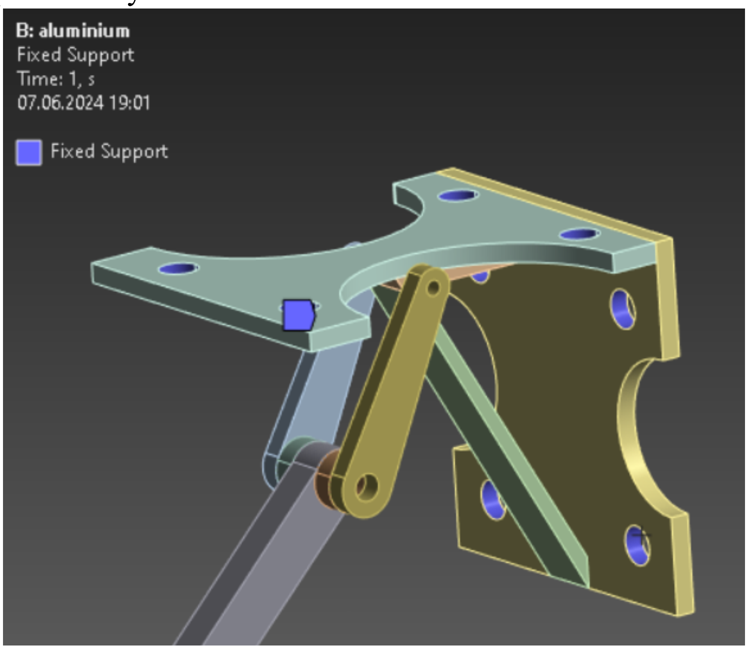

Figure 37

- Frictional contact was modeled between the contacting parts of the brake pedal and the fixation, with a friction coefficient of 0.2.

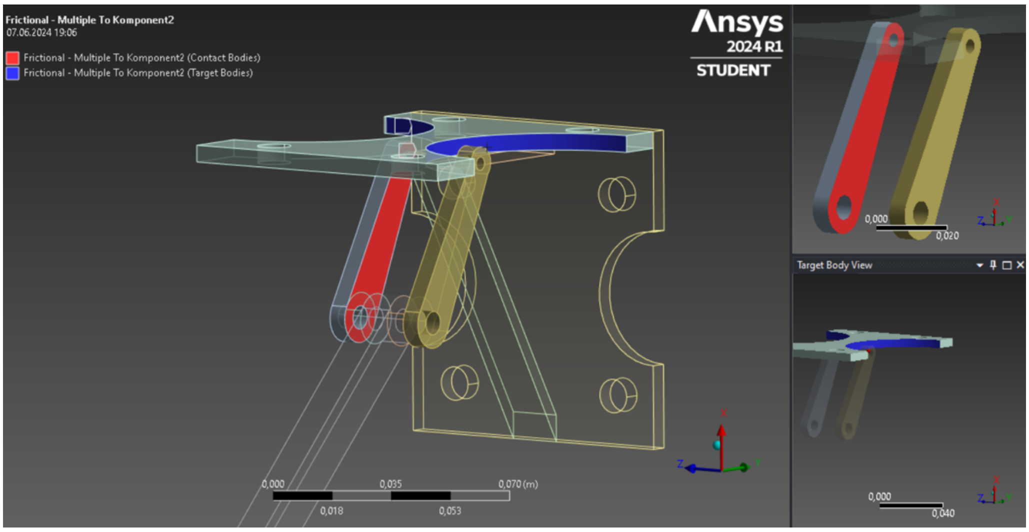

Figure 38

- A remote displacement boundary condition was applied at the pedal's attachment point to the brake system, allowing rotation only around the Z-axis. This simulates the real-life connection of the pedal to the brake mechanism.

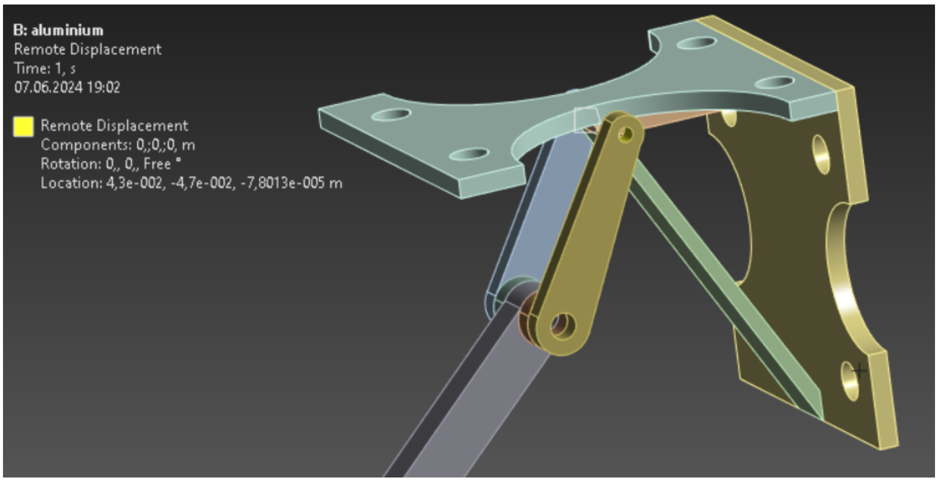

Figure 39

- Another remote displacement was applied to simulate the connection to the brake pump, again allowing rotation only around the Z-axis to mimic the actual brake system's functionality.

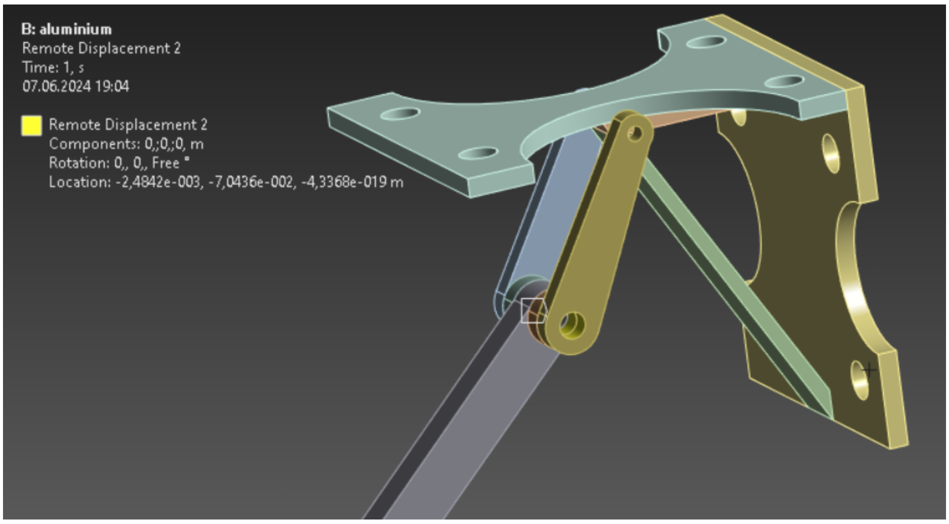

Figure 40

By adhering to these setup parameters, the finite element analysis accurately reflects the operational conditions of the brake pedal, providing reliable data for further analysis and optimization.

Scenario 1:
For Scenario 1, the carbon composite brake pedal was analyzed under the following additional conditions:

- A force of 300 N was applied to the central part of the pedal at an angle of 65 °. The force components were resolved into the X and Y directions using trigonometric functions.

$$F_x = 300N \cdot \cos 65° \approx 126{,}78\ N$$
$$F_y = 300N \cdot \sin 65° \approx 271{,}89\ N$$

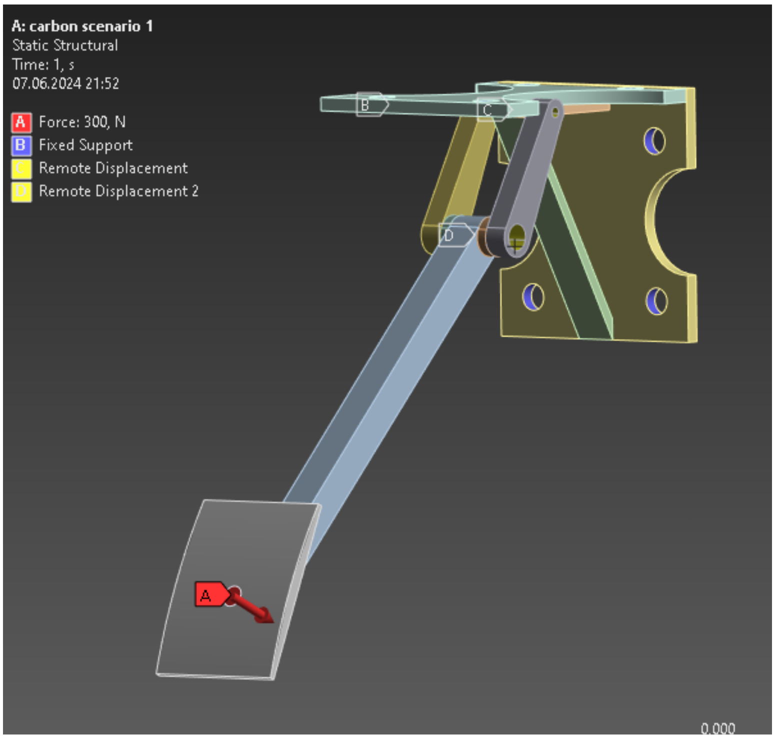

Figure 41

- The ambient temperature was set to 20 ° Celsius, representing typical operating conditions.

These conditions were applied to ensure that the analysis accurately reflects the behavior of the brake pedal under normal usage scenarios. The force application and temperature settings provide a realistic simulation environment, allowing for the assessment of the pedal's performance and structural integrity.

Scenario 2:

For Scenario 2, the carbon composite brake pedal was analyzed under the following additional conditions:

- A force of 700 N was applied to the central part of the pedal at an angle of 65 °. The force components were resolved into the X and Y directions using trigonometric functions.

$$F_x = 700N \cdot \cos 65° \approx 295{,}82\ N$$
$$F_y = 700N \cdot \sin 65° \approx 634{,}41\ N$$

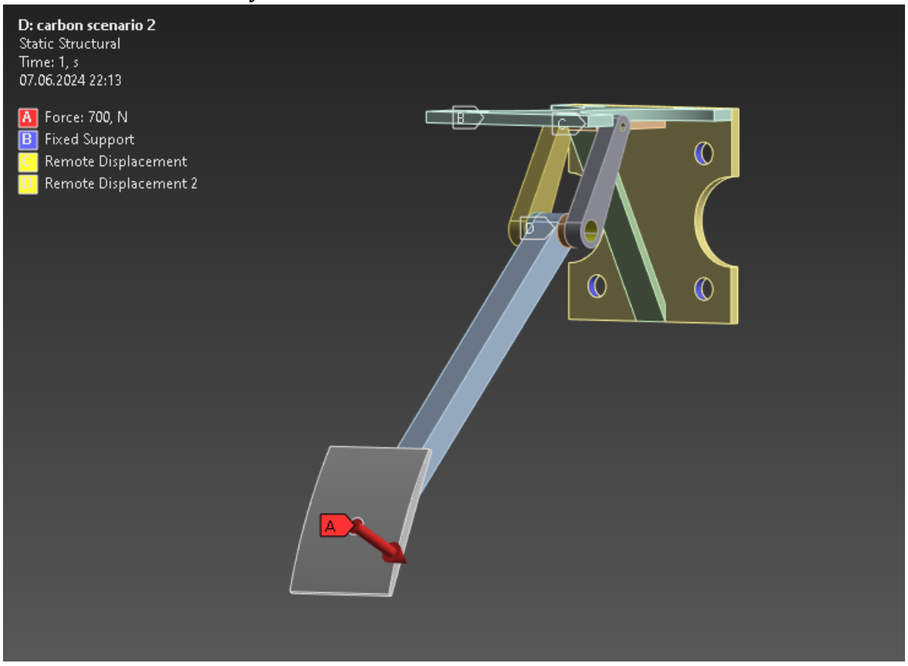

Figure 42

- The ambient temperature was set to 20 ° Celsius, representing typical operating conditions.

These conditions were applied to ensure that the analysis accurately reflects the behavior of the brake pedal under emergency braking scenarios. The force application and temperature settings provide a realistic simulation environment, allowing for the assessment of the pedal's performance and structural integrity under higher stress conditions.

Scenario 3:
For Scenario 3, the carbon composite brake pedal was analyzed under the following additional conditions:

- A force of 300 N was applied to the central part of the pedal at an angle of 65 °. The force components were resolved into the X and Y directions using trigonometric functions.

$$F_x = 300N \cdot \cos 65° \approx 126{,}78\ N$$
$$F_y = 300N \cdot \sin 65° \approx 271{,}89\ N$$

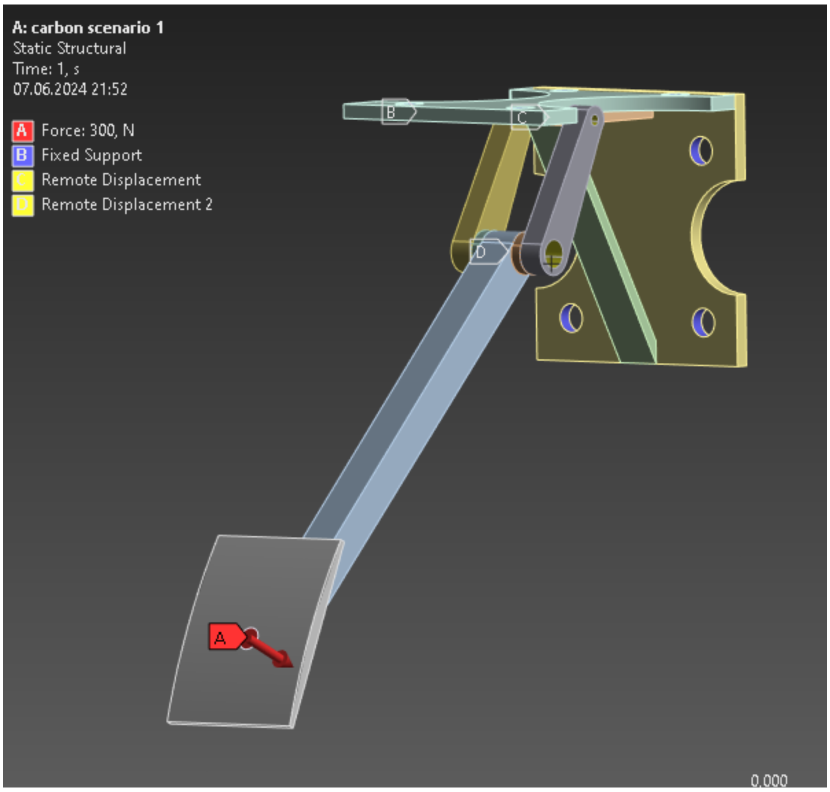

Figure 43

Scenario 3a:

- The ambient temperature was set to 60 ° Celsius to simulate high-temperature conditions.

Scenario 3b:

- The ambient temperature was set to -30 ° Celsius to simulate low-temperature conditions.

These conditions ensure that the analysis accurately reflects the behavior of the brake pedal under extreme temperature scenarios, allowing for the assessment of the pedal's performance and structural integrity under both high and low thermal stress.

Scenario 4:
For Scenario 4, the carbon composite brake pedal was analyzed under the following additional conditions:

- A total force of 300 N was applied, evenly divided between two contact points, each representing the front and rear edges of a high-heeled shoe.
- Each contact point experiences a force of $\frac{300N}{2} = 150N$
- Each force is applied over an area of approximately 1 cm² at the front and rear edges of the pedal.

$$F_x = 150N \cdot \cos 65° \approx 63{,}39\ N$$
$$F_y = 150N \cdot \sin 65° \approx 135{,}95\ N$$

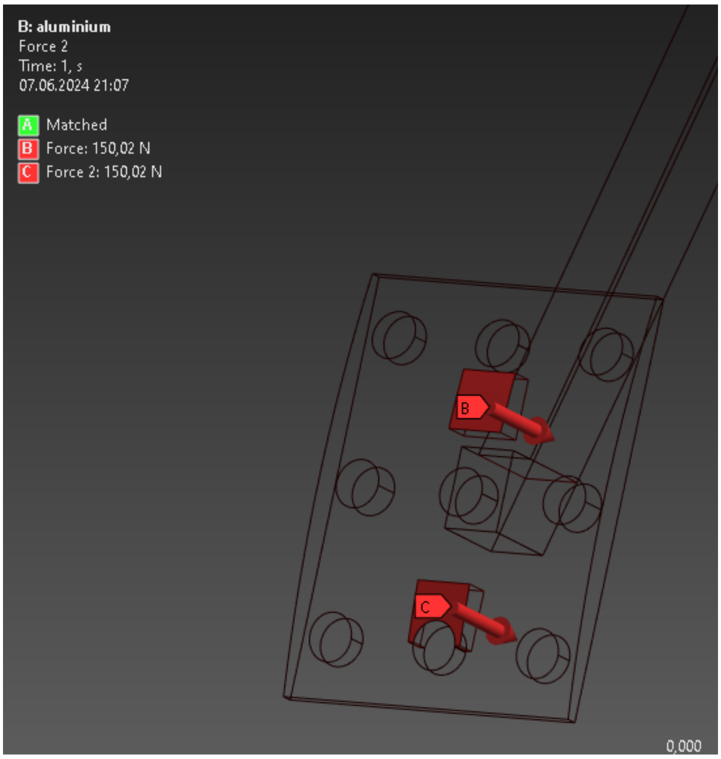

Figure 44

- The ambient temperature was set to 20 ° Celsius, representing typical operating conditions.

These conditions were applied to simulate the unique pressure distribution and force application when braking in high heels. This scenario helps in assessing the structural integrity and performance of the brake pedal under unconventional and potentially high-stress conditions, providing insights into the pedal's ability to withstand localized and intense loads.

Scenario 5:

For Scenario 5, the carbon composite brake pedal was analyzed under the following additional conditions:

- A force of 300 N was applied to the central part of the pedal, simulating the driver's foot pressure.

$$F_x = 300N \cdot \cos 65° \approx 126{,}78\ N$$
$$F_y = 300N \cdot \sin 65° \approx 271{,}89\ N$$

- An additional constant load of 100 N was applied vertically upward from the point behind the pedal to simulate the obstruction caused by an object jammed under the pedal.

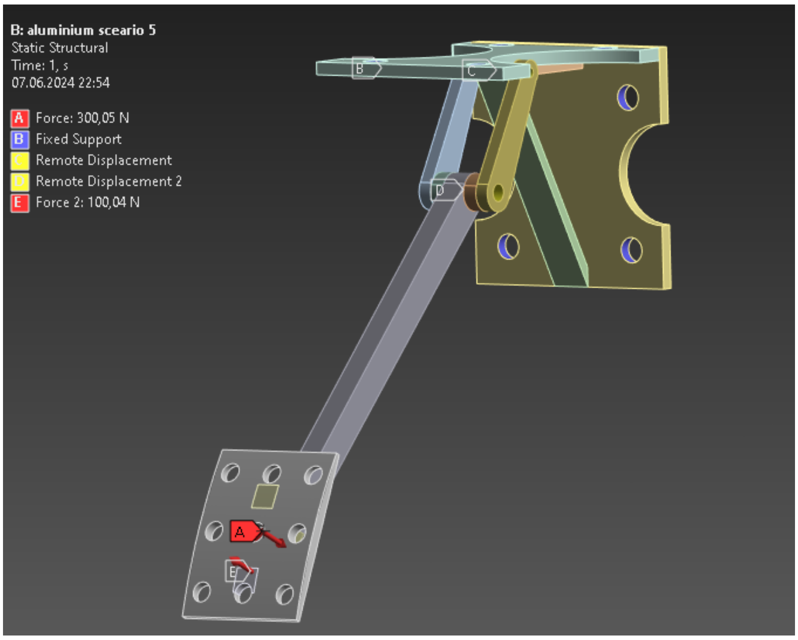

Figure 45

- The ambient temperature was set to 20 ° Celsius, representing typical operating conditions.\

These conditions were applied to simulate the presence of an obstruction under the brake pedal, which could occur due to objects like toys or bottles. This scenario helps in evaluating the pedal's performance and structural integrity when subjected to complex loading conditions, including both downward force from the driver's foot and upward force from the obstructing object.

7. Results of FEA simulations

The safety factor for a brake pedal made of aluminum, particularly Aluminum Alloy 6061, should be determined based on the criticality of the application, regulatory standards, and best engineering practices. For automotive applications, a typical safety factor ranges from 1.5 to 2.5 to account for uncertainties in material properties, loading conditions, and potential defects.

7.1. Case 1, scenario 1

Total deformation:

- Maximum deformation: 0.0076713 m

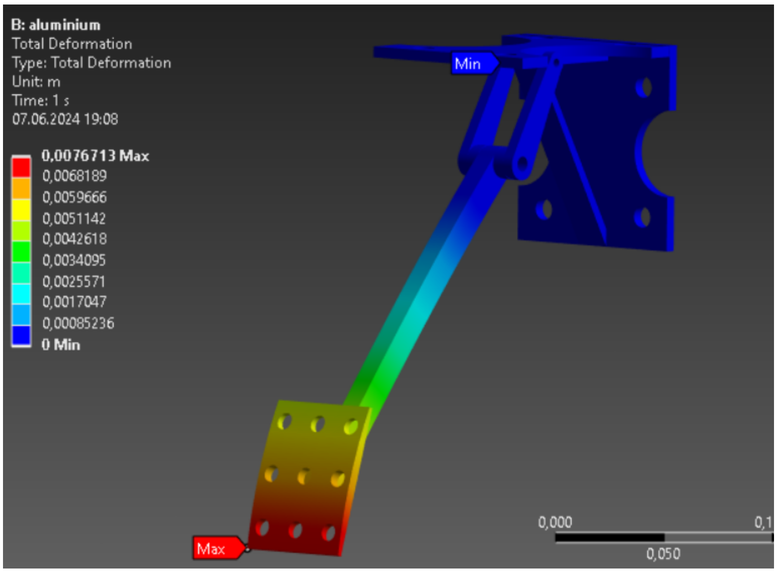

Figure 46

The maximum deformation of 0.0076713 m is within acceptable limits for the brake pedal, indicating that the pedal retains its functional shape under the applied load.

Equivalent stress (Von Mises Stress):

- Maximum equivalent stress: 247.42 MPa

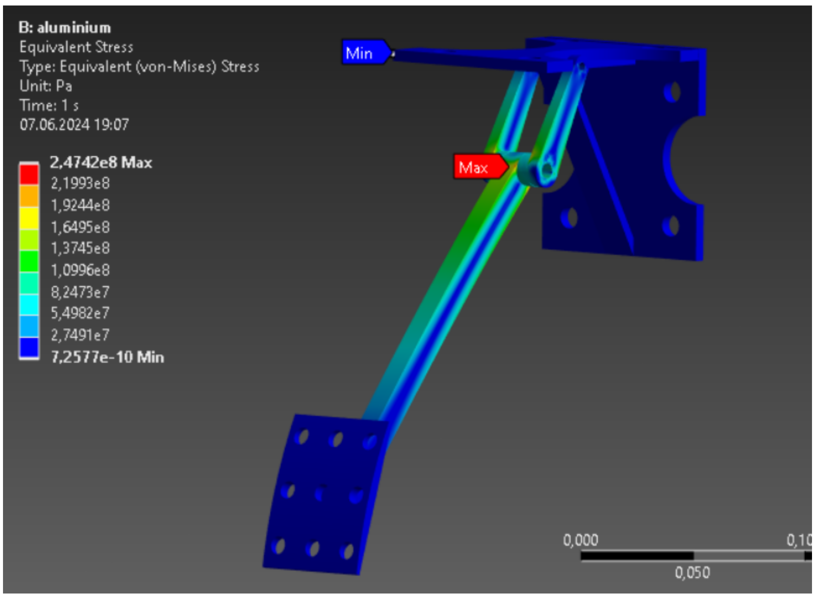

Figure 47

Safety factor calculation:

- Yield stress of Aluminum Alloy 6061: 259 MPa
- Maximum equivalent stress: 247.42 MPa
- Safety factor: $\frac{259\,MPa}{247{,}42\,MPa} \approx 1{,}05$

The maximum equivalent stress of 247.42 MPa is very close to the yield strength of Aluminum Alloy 6061 (259 MPa). With a safety factor of approximately 1.05, the design is marginally safe but may be considered borderline under normal conditions. It is advisable to consider reinforcement or design modifications to ensure a higher safety margin.

Force reaction:

- Fixed Support:

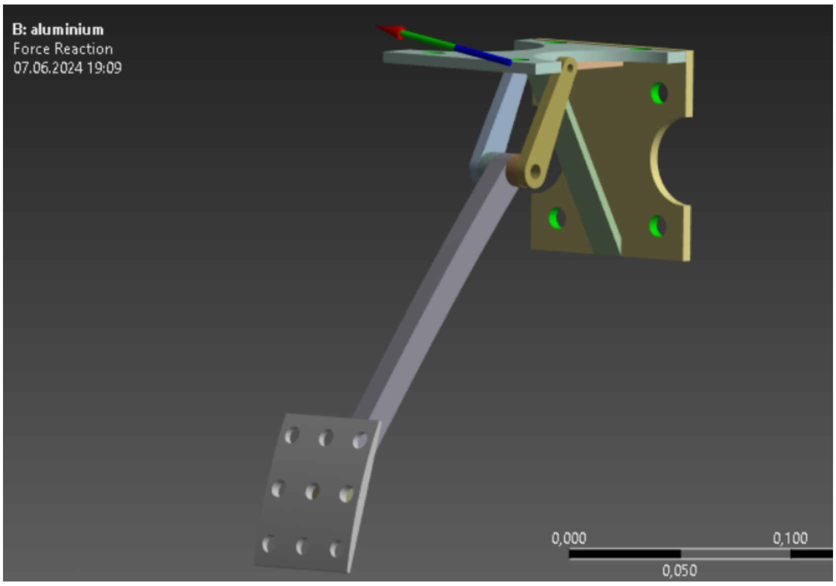

Figure 48

- Remote displacement:

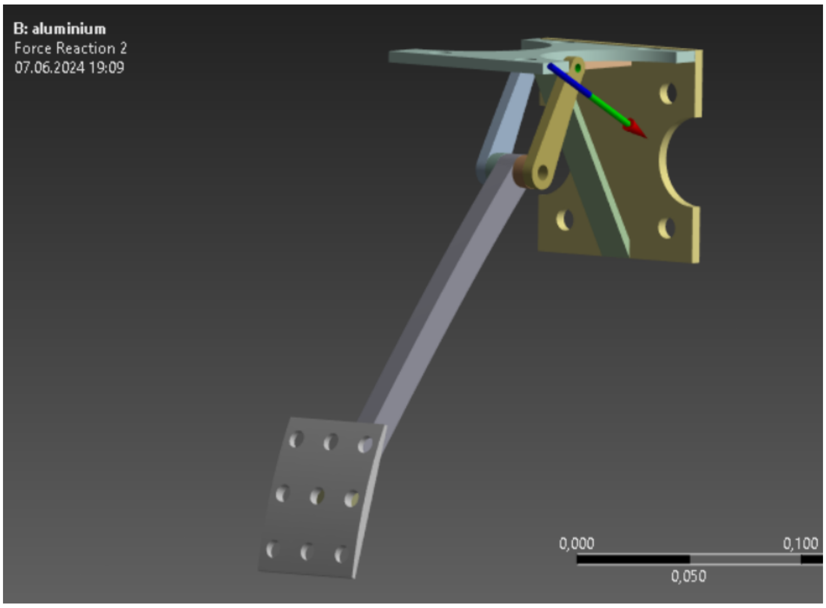

Figure 49

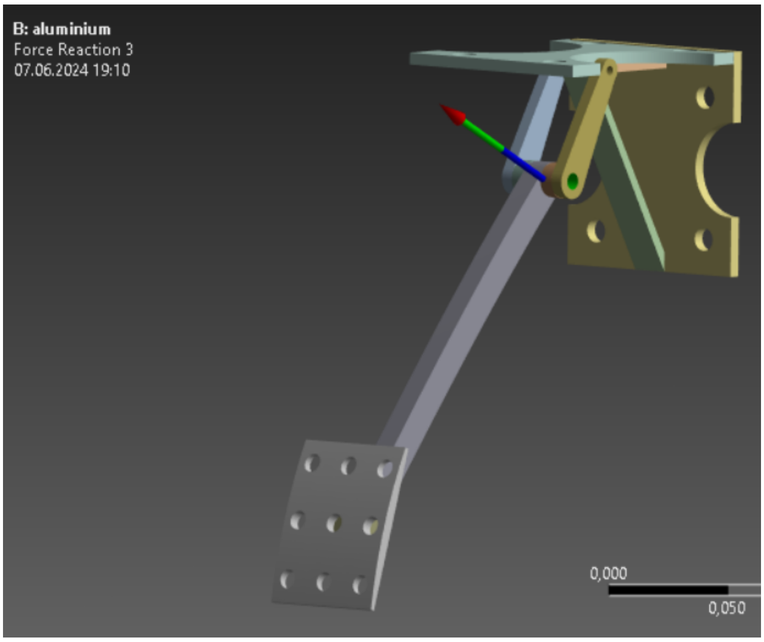

Figure 50

The force reactions at the fixed support and remote displacement points show that the brake pedal can handle the applied loads without significant issues, but the proximity to the material's yield strength indicates potential for yielding under slightly higher loads or repeated use.

Overall, while the brake pedal design for Aluminum Alloy 6061 can handle the standard load scenario, the safety factor is quite low. This suggests a need for design optimization to enhance the safety and reliability of the pedal under such conditions.

7.2. Case 1, scenario 2

Total deformation:

- Maximum deformation: 0.017544 m

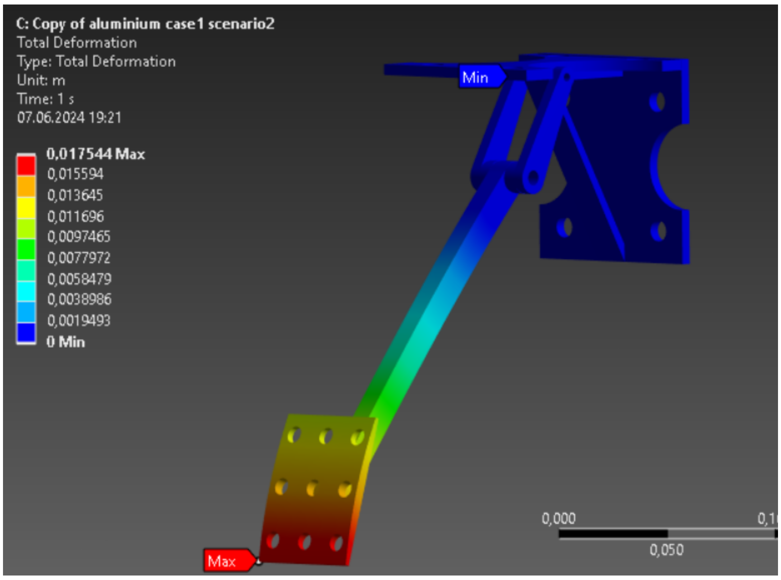

Figure 51

The maximum deformation of 0.017544 m indicates significant deflection of the brake pedal under the applied emergency load, which could affect its functionality and safety.

Equivalent stress (Von Mises Stress):

- Maximum equivalent stress: 568.56 MPa

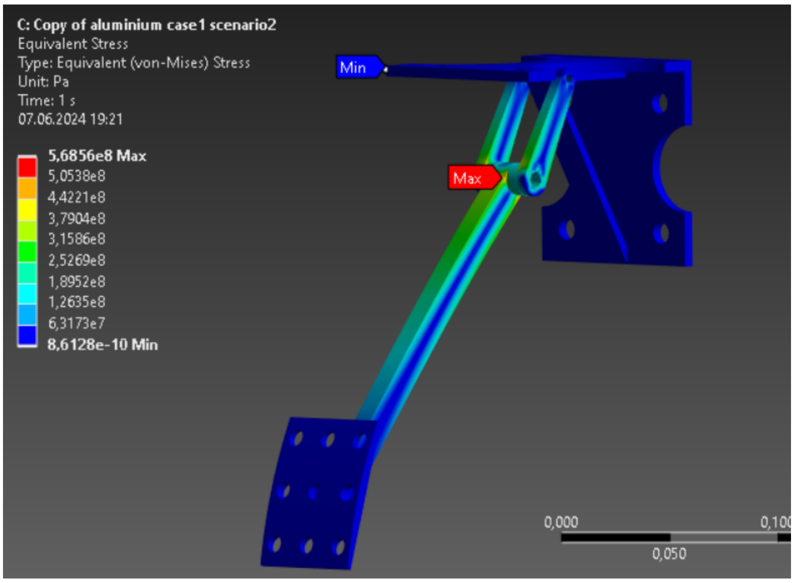

Figure 52

Safety factor calculation:

- Yield stress of Aluminum Alloy 6061: 259 MPa
- Maximum equivalent stress: 568.56 MPa
- Safety factor: $\frac{259\ MPa}{568.56\ \text{MPa}} \approx 0.46$

he maximum equivalent stress of 568.56 MPa far exceeds the yield strength of Aluminum Alloy 6061 (259 MPa). With a safety factor of approximately 0.46, the design is not safe under the emergency load scenario. The pedal is likely to yield and potentially fail under such high stress.

Force reaction:

- Fixed Support:

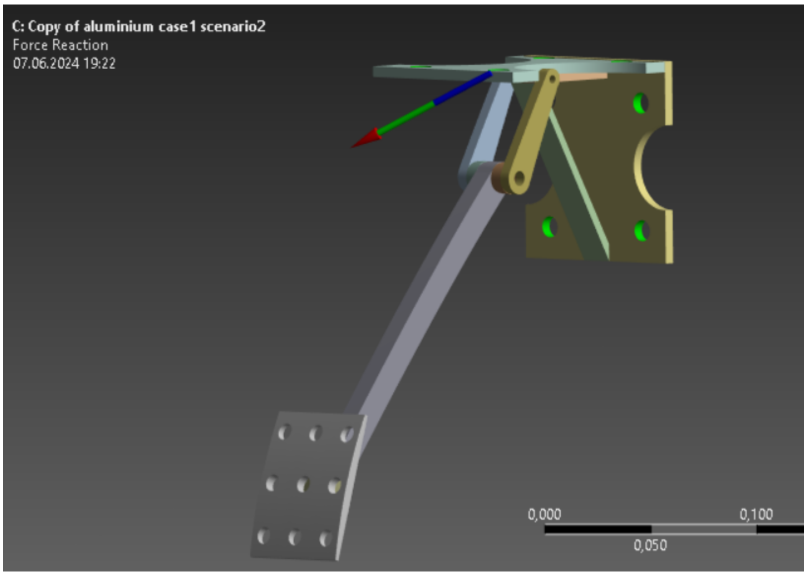

Figure 53

- Remote displacement:

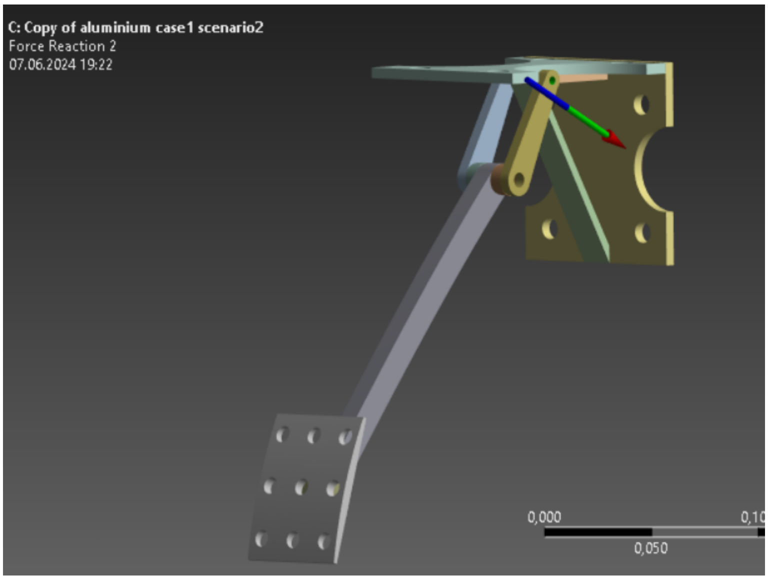

Figure 54

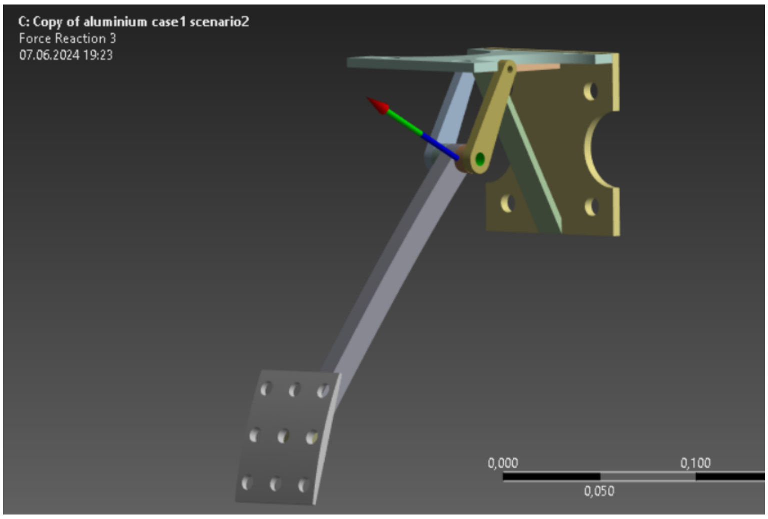

Figure 55

The force reactions at the fixed support and remote displacement points show that the brake pedal experiences significant stress and force under the emergency load. The stress levels indicate that the current design is not adequate to handle such extreme conditions.
Overall, the brake pedal design for Aluminum Alloy 6061 is not suitable for the emergency load scenario. The high levels of deformation and equivalent stress, along with the inadequate safety factor, suggest that significant design modifications or the use of a stronger material are necessary to ensure the pedal's safety and reliability under such extreme conditions.

The high equivalent stress observed in the simulation is concentrated at the pivot point where the pedal arm connects to the fixed support bracket. This concentration of stress c
an be attributed to several factors:

- The pivot point represents a change in geometry where the relatively slender arm of the pedal meets the more robust fixed support. This geometric discontinuity naturally leads to higher stress concentrations.
- At this pivot point, the applied forces are transmitted from the pedal arm to the fixed support, resulting in higher localized stresses. The pivot serves as the primary fulcrum around which the pedal operates, amplifying stress in this area.
- The force applied at the pedal pad generates a significant bending moment of the pivot point. The bending moment is at its maximum at the pivot, leading to elevated stress levels in this region.

To address the high stress concentration at the pivot point and improve the safety factor under emergency load conditions, the following design modifications could be considered:

- Using a material with higher yield strength and better mechanical properties, such as a high-strength alloy or composite material, could help in reducing the risk of yielding.

- Smoothing out the geometric transition between the pedal arm and the fixed support, and possibly increasing the cross-sectional area at the pivot point, could help in distributing the stresses more evenly and reducing the peak stress.

- Adding reinforcements or fillets at the pivot point can help in reducing stress concentration by providing additional support and distributing the load more effectively.

Overall, while the brake pedal design for Aluminum Alloy 6061 is not suitable for the emergency load scenario in its current form, these design modifications and material upgrades can significantly enhance its safety and reliability under extreme conditions.

7.3. Case 1, scenario 3 a

Total deformation:

- Maximum deformation: 0.0076713 m

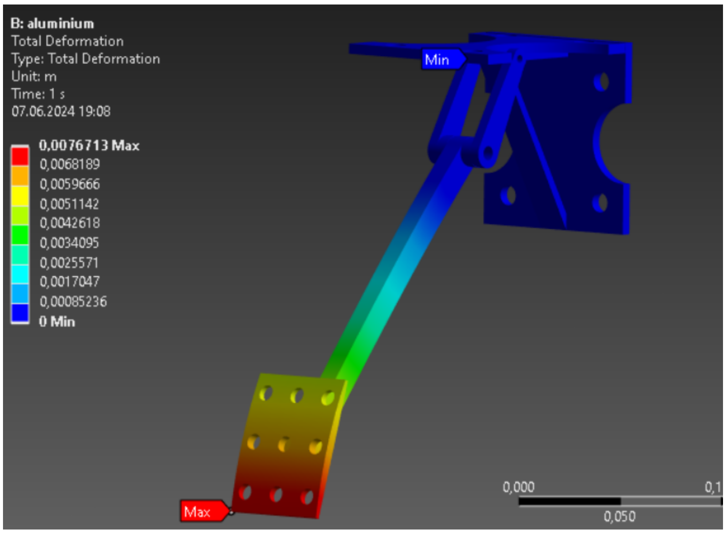

Figure 56

The maximum deformation of 0.0076713 m is within acceptable limits for the brake pedal, indicating that the pedal retains its functional shape under the applied load even at higher temperatures.

Equivalent stress (Von Mises Stress):

- Maximum equivalent stress: 247.42 MPa

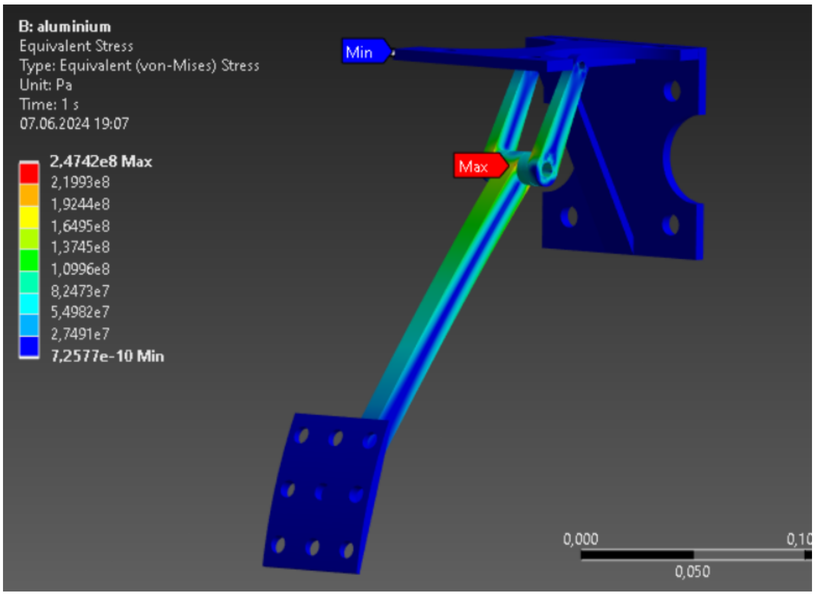

Figure 57

Safety factor calculation:

- Yield stress of Aluminum Alloy 6061: 259 MPa
- Maximum equivalent stress: 247.42 MPa
- Safety factor: $\frac{259\ MPa}{247{,}42\ MPa} \approx 1{,}05$

The maximum equivalent stress of 247.42 MPa is close to the yield strength of Aluminum Alloy 6061 (259 MPa). With a safety factor of approximately 1.05, the design is marginally safe under high-temperature conditions. This suggests that while the brake pedal can handle the load, it is operating close to its material limits.

Force reaction:
- Fixed Support:

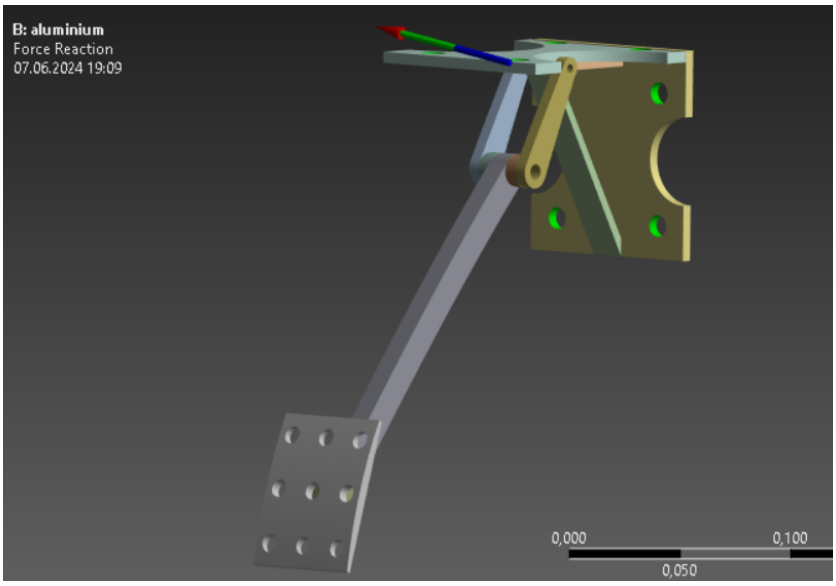

Figure 58

- Remote displacement:

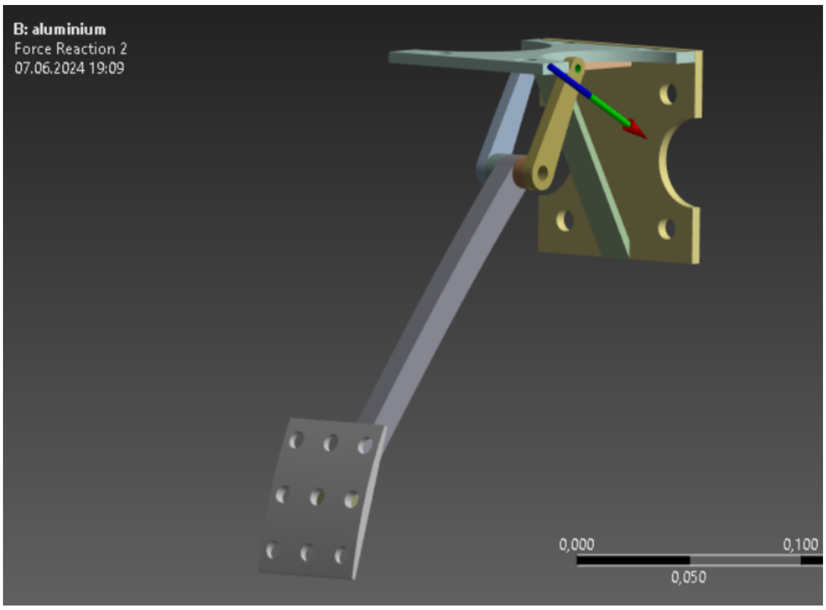

Figure 59

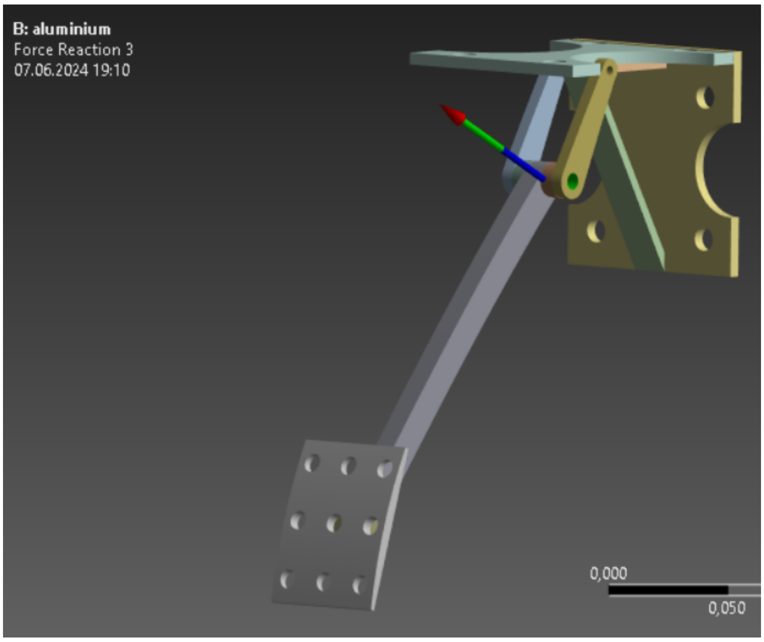

Figure 60

The force reactions at the fixed support and remote displacement points show that the brake pedal can handle the applied loads, but the stress levels indicate that the pedal is operating near its material capacity, especially at higher temperatures.

Interestingly, the simulation results show that the impact of the high temperature (60°C) on the equivalent stress and total deformation is minimal compared to the scenario at 20°C. The equivalent stress and deformation values remain similar, indicating that the material properties of Aluminum Alloy 6061 are not significantly affected by this increase in temperature. This consistency suggests that the brake pedal design remains robust under moderate temperature variations typical in automotive applications.

Overall, while the brake pedal design for Aluminum Alloy 6061 can handle the high-temperature load scenario, the safety factor is quite low. This suggests a need for design optimization to enhance the safety and reliability of the pedal under such conditions.

7.4. Case 1, scenario 3b

Total deformation:

- Maximum deformation: 0.0076713 m

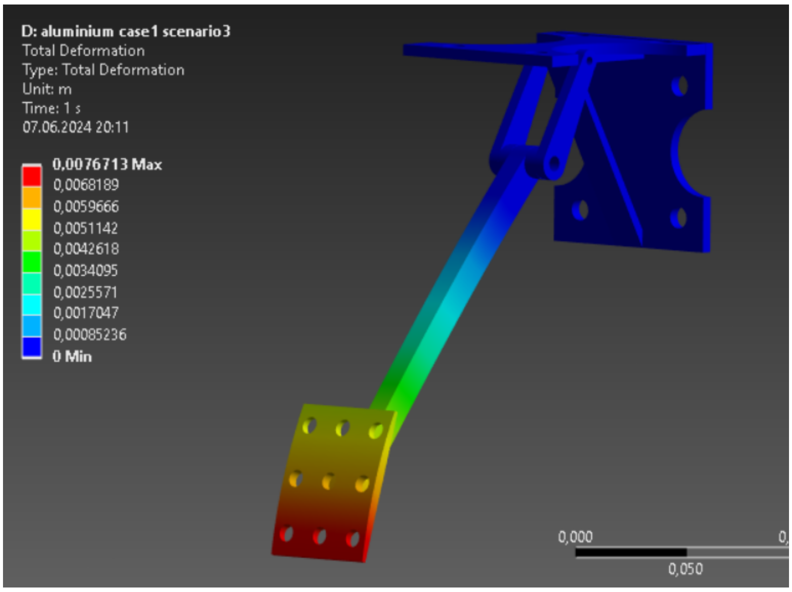

Figure 61

The maximum deformation of 0.0076713 m is within acceptable limits for the brake pedal, indicating that the pedal retains its functional shape under the applied load even at lower temperatures.

Equivalent stress (Von Mises Stress):

- Maximum equivalent stress: 247.42 MPa

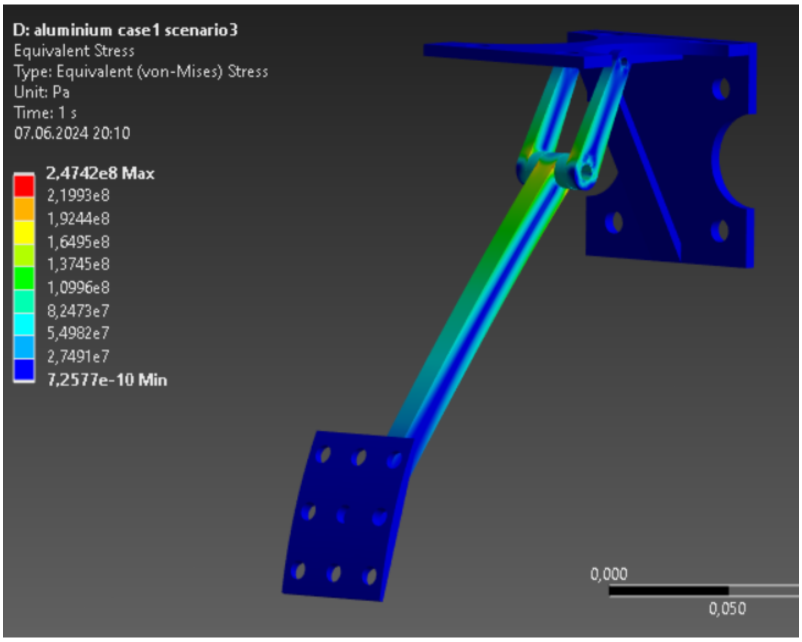

Figure 62

Safety factor calculation:

- Yield stress of Aluminum Alloy 6061: 259 MPa
- Maximum equivalent stress: 247.42 MPa
- Safety factor: $\frac{259\ MPa}{247{,}42\ MPa} \approx 1{,}05$

The maximum equivalent stress of 247.42 MPa is close to the yield strength of Aluminum Alloy 6061 (259 MPa). With a safety factor of approximately 1.05, the design is marginally safe under low-temperature conditions. This suggests that while the brake pedal can handle the load, it is operating close to its material limits.

Force reaction:

- Fixed Support:

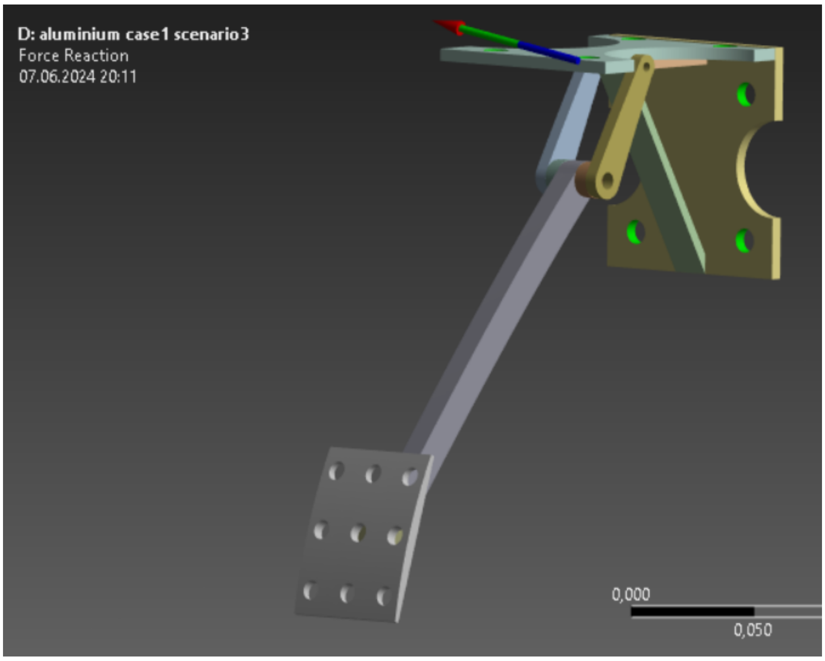

Figure 63

- Remote displacement:

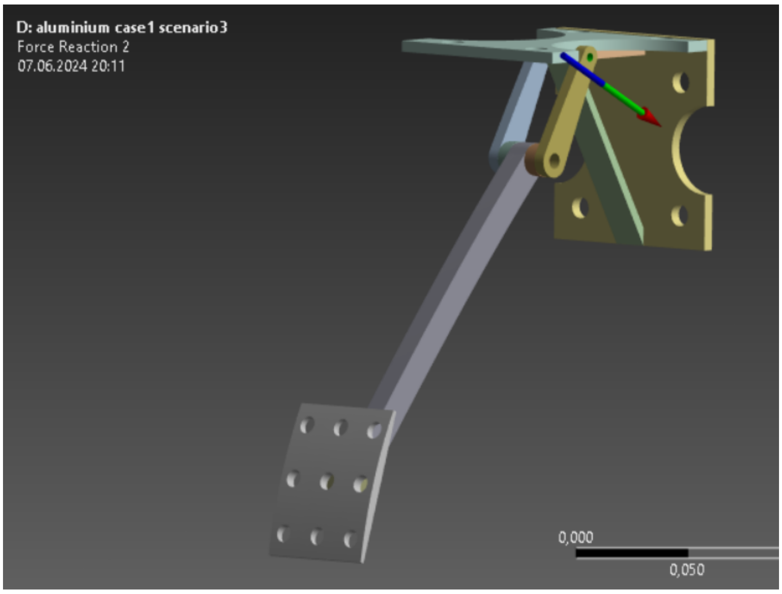

Figure 64

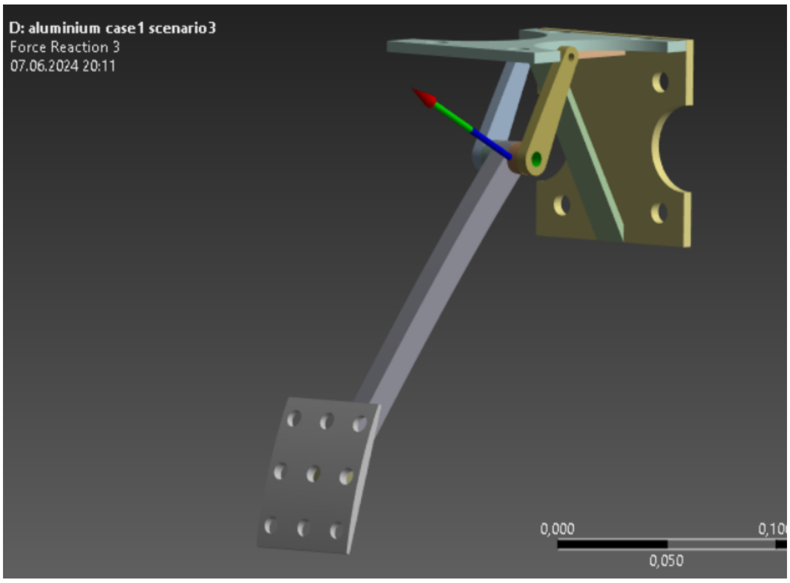

Figure 65

The force reactions at the fixed support and remote displacement points show that the brake pedal can handle the applied loads, but the stress levels indicate that the pedal is operating near its material capacity, even at lower temperatures.

Like the high-temperature scenario, the simulation results show that the impact of the low temperature (-30°C) on the equivalent stress and total deformation is minimal compared to the scenario at 20°C. The equivalent stress and deformation values remain similar, indicating that the material properties of Aluminum Alloy 6061 are not significantly affected by this decrease in temperature. This consistency suggests that the brake pedal design remains robust under moderate temperature variations typical in automotive applications.

7.5. Case 1, scenario 4

Total deformation:

- Maximum deformation: 0.0071379 m

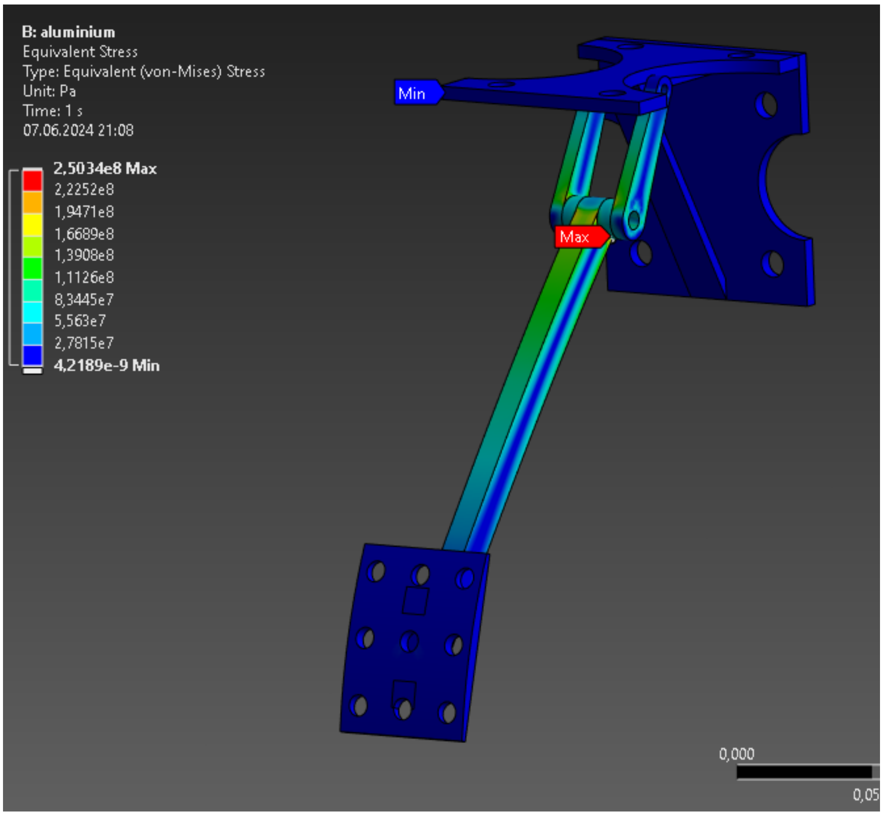

Figure 66

The maximum deformation of 0.0071379 m is within acceptable limits for the brake pedal, indicating that the pedal retains its functional shape under the applied combined load.

Equivalent stress (Von Mises Stress):

- Maximum equivalent stress: 250.34 MPa

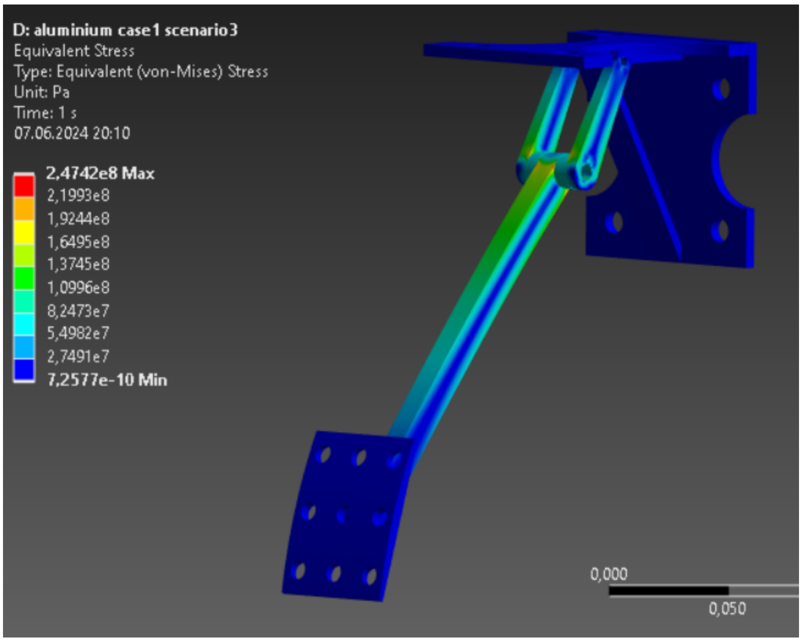

Figure 67

Safety factor calculation:

- Yield stress of Aluminum Alloy 6061: 259 MPa
- Maximum equivalent stress: 250.34 MPa
- Safety factor: $\frac{259\ MPa}{250.34\ \text{MPa}} \approx 1{,}03$

The maximum equivalent stress of 250.34 MPa is very close to the yield strength of Aluminum Alloy 6061 (259 MPa). With a safety factor of approximately 1.03, the design is marginally safe under this combined load condition. This suggests that while the brake pedal can handle the load, it is operating extremely close to its material limits.

Force reaction:
- Fixed Support:

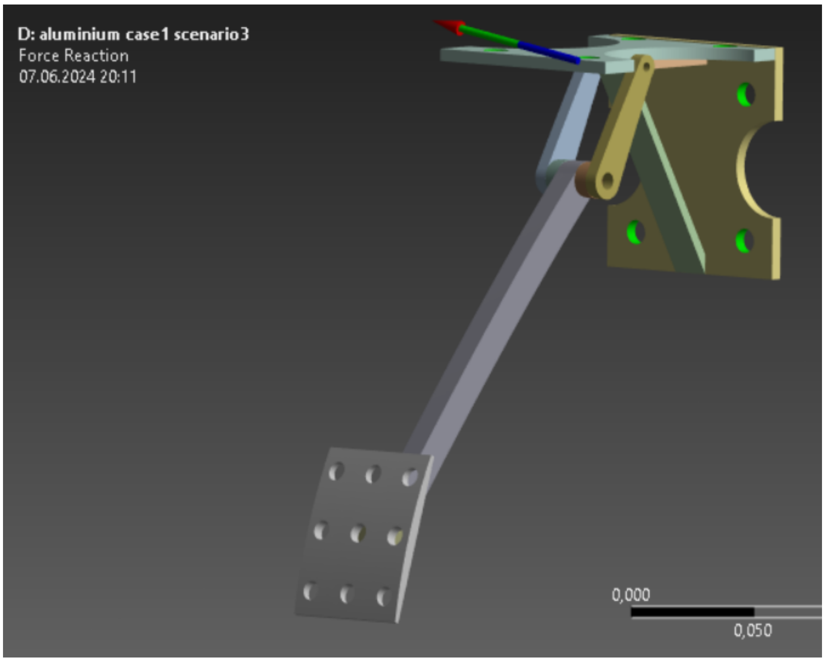

Figure 68

- Remote displacement:

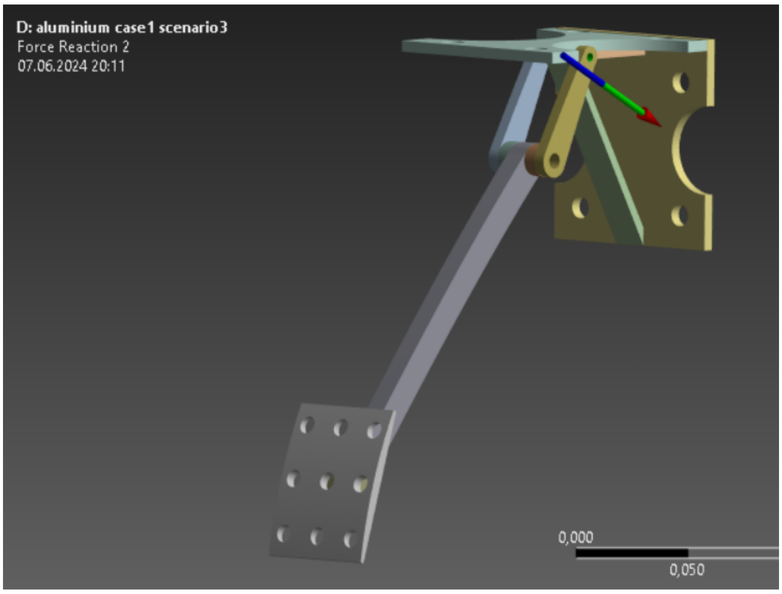

Figure 69

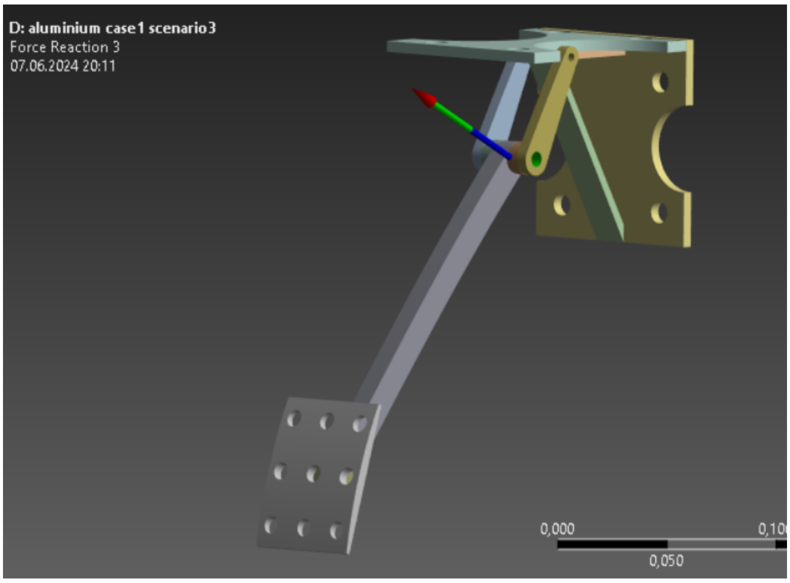

Figure 70

The force reactions at the fixed support and remote displacement points show that the brake pedal can handle the applied loads, but the stress levels indicate that the pedal is operating near its material capacity under combined load conditions.

The simulation results show that the combined load scenario increases the equivalent stress and total deformation compared to individual load scenarios. The equivalent stress and deformation values indicate that the material properties of Aluminum Alloy 6061 are being utilized to their maximum capacity under these conditions. This consistency suggests that the brake pedal design needs optimization to enhance its safety and reliability under such combined load conditions.

7.6. Case 1, scenario 5

Total deformation:

- Maximum deformation: 0.0041732 m

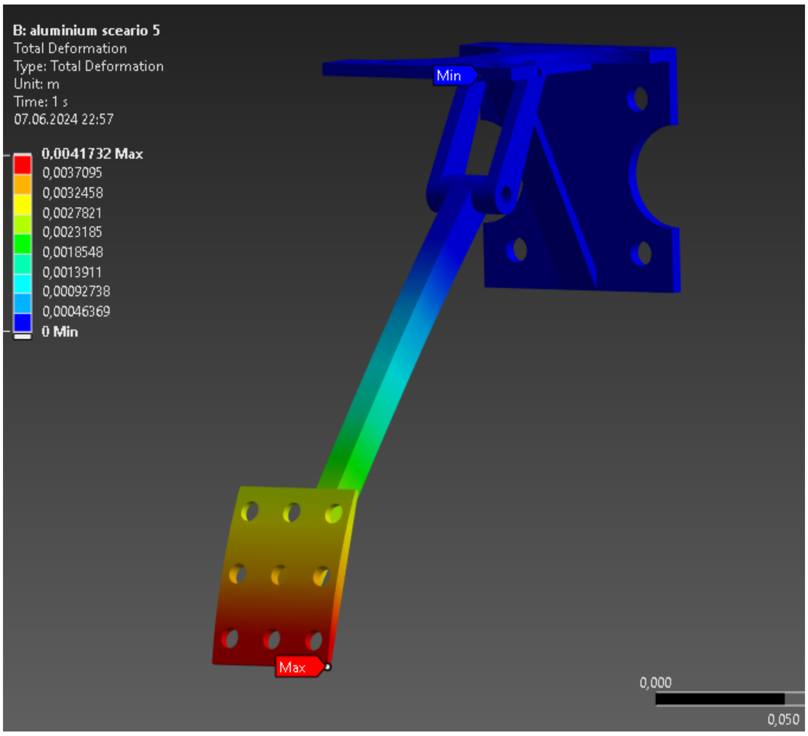

Figure 71

The maximum deformation of 0.0041732 m is within acceptable limits for the brake pedal, indicating that the pedal retains its functional shape under the applied combined load.

Equivalent stress (Von Mises Stress):
- Maximum equivalent stress: 153.51 MPa

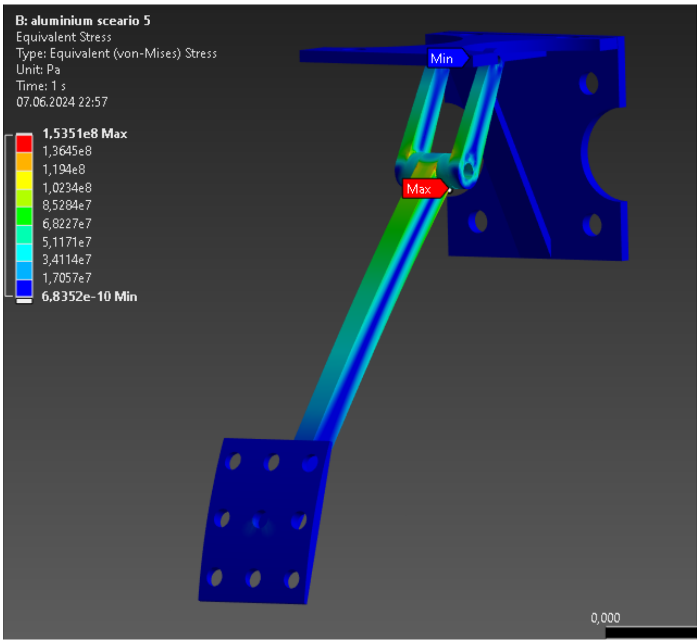

Figure 72

Safety factor calculation:

- Yield stress of Aluminum Alloy 6061: 259 MPa

- Maximum equivalent stress: 153.51 MPa
- Safety factor: $\frac{259\,MPa}{153.51\ \text{MPa}} \approx 1{,}69$

The maximum equivalent stress of 153.51 MPa is well within the yield strength of Aluminum Alloy 6061 (259 MPa). With a safety factor of approximately 1.69, the design is considered safe under this combined load condition. This suggests that the brake pedal can handle the load without reaching its material limits.

Force reaction:

- Fixed Support:

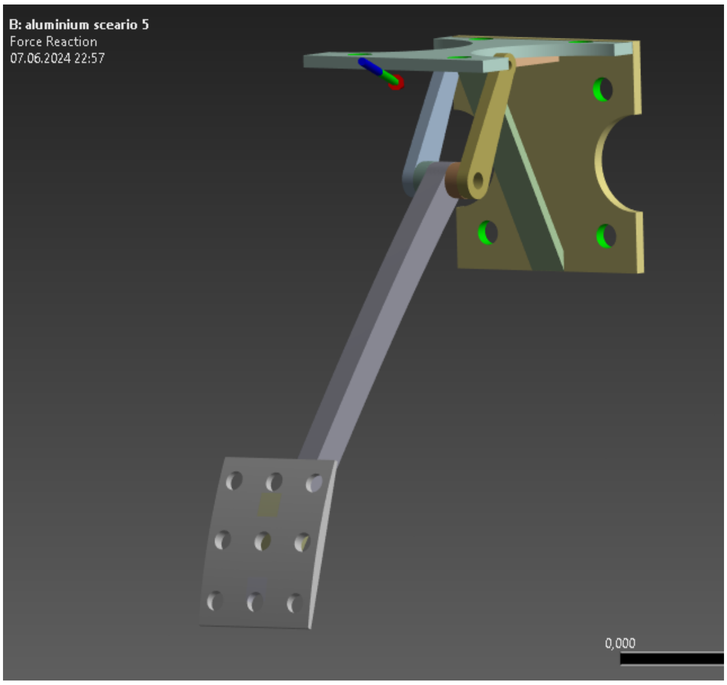

Figure 73

- Remote displacement:

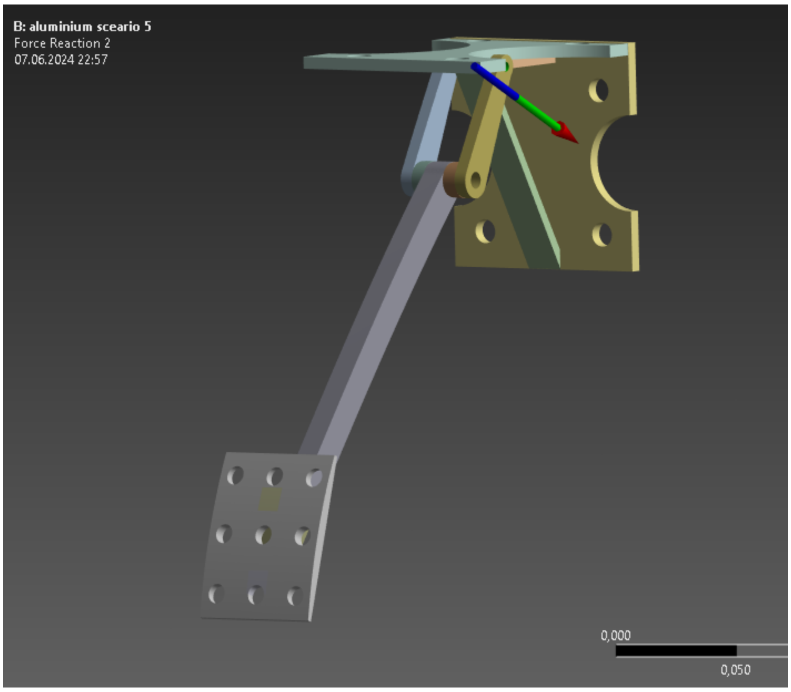

Figure 74

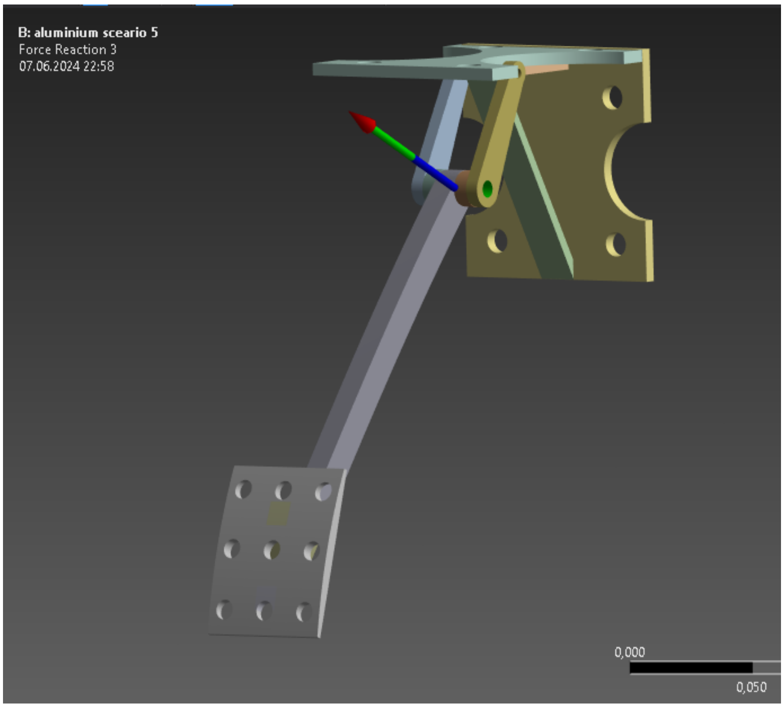

Figure 75

The force reactions at the fixed support and remote displacement points show that the brake pedal can handle the applied loads effectively. The stress levels indicate that the pedal is operating safely within its material capacity under combined load conditions.

The simulation results for Scenario 5, which includes the combined load conditions, demonstrate that the equivalent stress and total deformation are within acceptable limits. The equivalent stress of 153.51 MPa is significantly below the yield strength of Aluminum Alloy 6061, providing a safety factor of approximately 1.69. The deformation remains minimal at 0.0041732 m, ensuring the brake pedal maintains its structural integrity and functionality. The consistent force reactions at the support points indicate reliable performance under combined loads. Overall, the brake pedal design in this scenario is robust and meets safety and performance standards effectively.

Case 1 summary

The comprehensive analysis across all scenarios demonstrates that the current brake pedal design for Aluminum Alloy 6061 is insufficiently robust for safe operation under varied load conditions. While it performs adequately under standard loads, it approaches or exceeds material limits in emergency and combined load scenarios, posing significant safety risks. Therefore, substantial design improvements, including material upgrades and structural reinforcements, are necessary to ensure the brake pedal can operate safely and reliably under all expected conditions.

In contrast, the fixation made of Steel 1.4021 was found to be safe and effective, providing the necessary support and stability for the brake pedal system without encountering significant stress or deformation issues.

Carbon fiber composites generally exhibit excellent strength-to-weight ratios and can be tailored for high-stress applications. However, their performance can be influenced by factors such as manufacturing quality, environmental conditions, and the orientation of fibers.

For automotive applications, a typical safety factor ranges from 2.0 to 3.0 due to the high safety demands. Given the critical nature of brake systems, a more conservative safety factor is advisable. Therefore, it is recommended to adopt a safety factor of 2.5 to 3.0 for the brake pedal made from Carbon Fiber 290 to ensure safety and reliability under all operating conditions.

In the analysis of the brake pedal made from carbon fiber, the maximum stresses and yield strength were evaluated along the X-axis. This approach was chosen due to the inherent properties of carbon fiber and the expected load conditions of the brake pedal.

Carbon fiber composites are highly anisotropic, meaning their mechanical properties vary significantly in different directions. The fibers in carbon fiber composites are typically aligned along a specific direction to maximize strength and stiffness in that orientation. For this brake pedal, the fibers are oriented along the X-axis, which is the primary direction of the applied load. This alignment ensures that the brake pedal can withstand the maximum stresses it will encounter during operation.

Evaluating the yield strength along the X-axis is crucial because this is the direction in which the material exhibits its greatest strength. The load on the brake pedal is primarily transmitted from the pedal pad to the mounting point, predominantly along the X-axis. By focusing on this direction, the analysis accurately reflects the real-world performance of the brake pedal under typical operating conditions.

Additionally, analyzing the stresses along the X-axis provides a conservative approach to design. It ensures that the pedal's structural integrity is maintained even under the highest stress scenarios, thereby maximizing safety and reliability. This method also leverages the full potential of the carbon fiber material, ensuring that the brake pedal is both efficient and effective.

In conclusion, the choice of evaluating maximum stresses and yield strength along the X-axis is justified by the directional properties of carbon fiber and the operational load conditions of the brake pedal. This approach ensures an accurate, safe, and efficient design that fully utilizes the strengths of the carbon fiber material.

7.7. Case 2, scenario 1

Total deformation:

- Maximum deformation: 0.013336 m

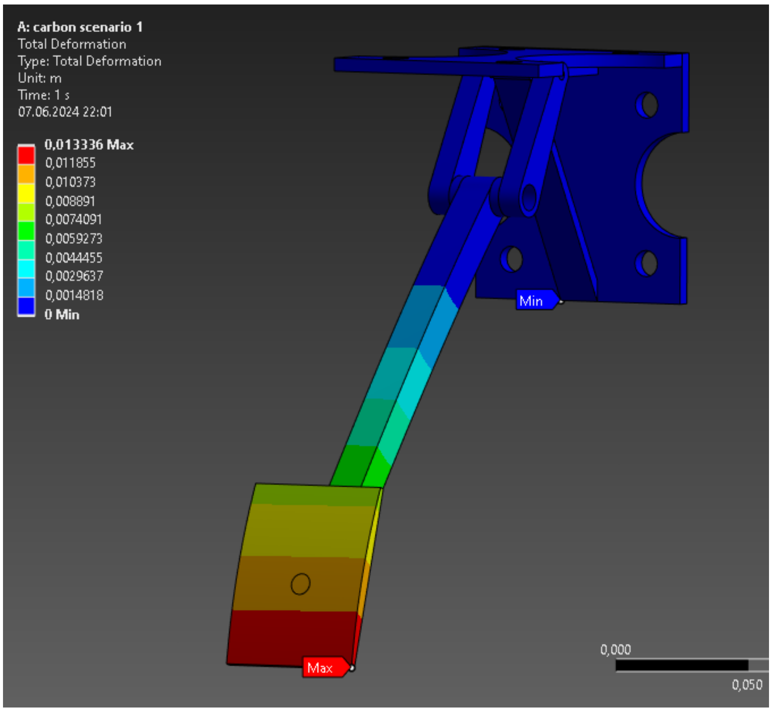

Figure 76

The maximum deformation of 0.013336 m is within acceptable limits for the brake pedal, indicating that the pedal retains its functional shape under the applied load.

Equivalent stress (Von Mises Stress):

- Maximum equivalent stress: 348.01 MPa

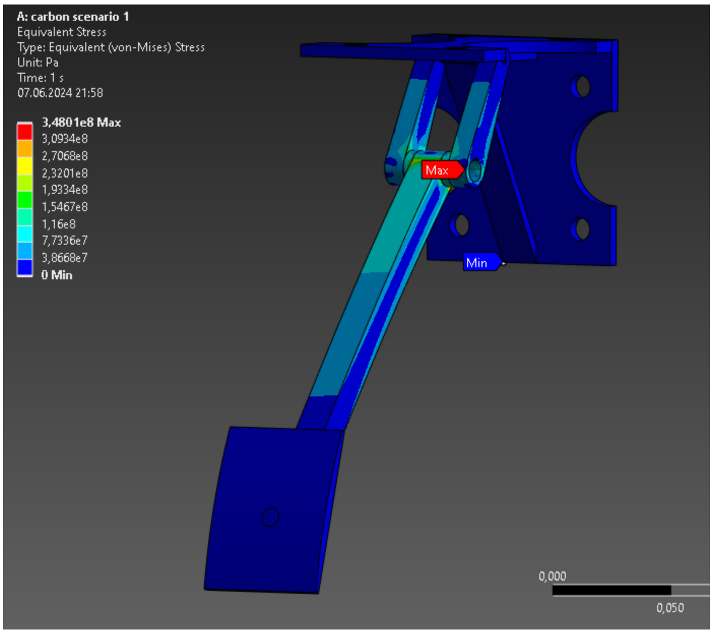

Figure 77

Safety factor calculation:

- Yield stress of Carbon Fiber: 2900 MPa
- Maximum equivalent stress: 348.01 MPa
- Safety factor: $\frac{2900\ MPa}{348.01\ \text{MPa}} \approx 8.34$

The maximum equivalent stress of 348.01 MPa is well below the yield strength of Carbon Fiber (2900 MPa). With a safety factor of approximately 8.34, the design is considered highly safe under the applied load condition. This suggests that the brake pedal can handle the load with a significant margin of safety, making it a reliable choice for this application.

Force reaction:

- Fixed Support:

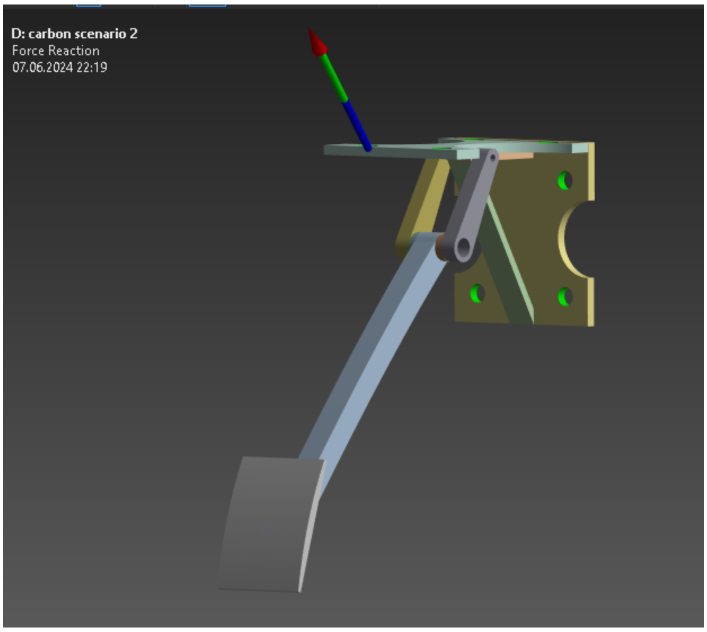

Figure 78

- Remote displacement:

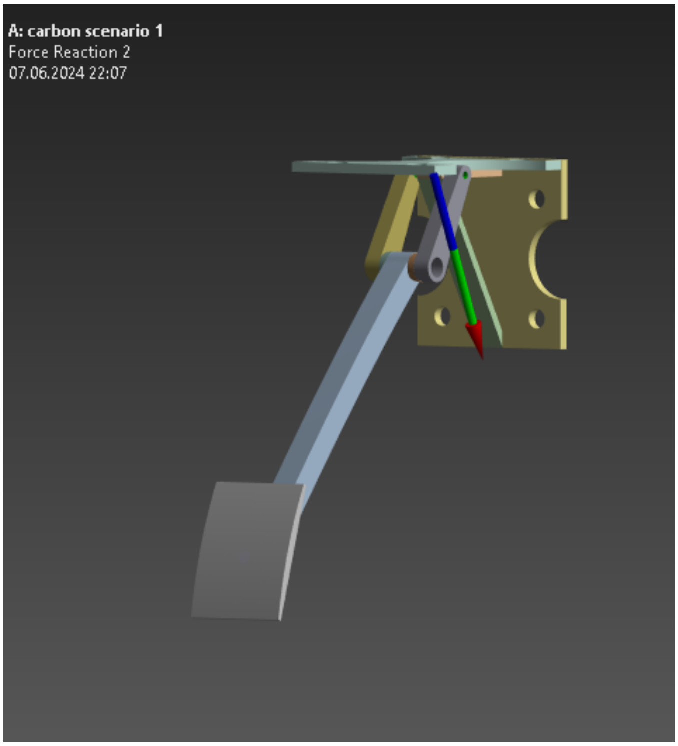

Figure 79

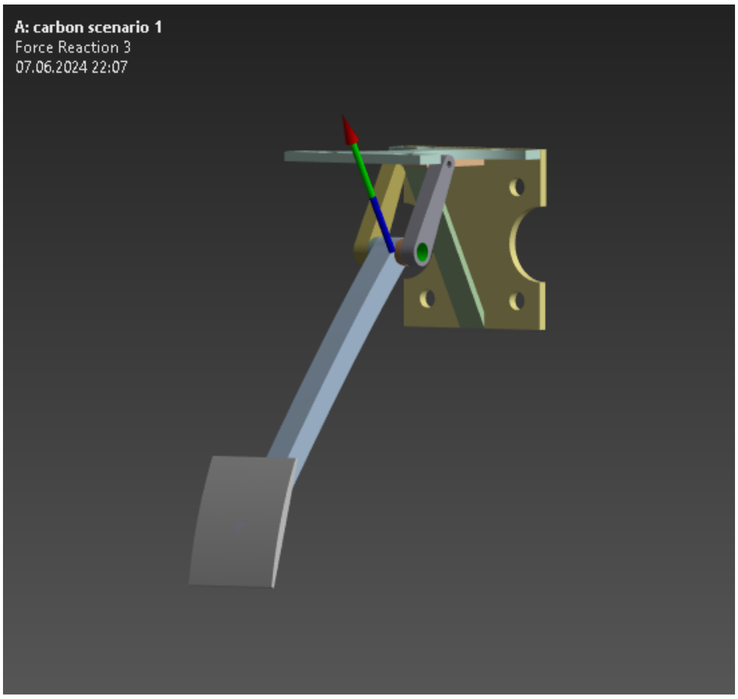

Figure 80

The force reactions at the fixed support and remote displacement points show that the brake pedal can handle the applied loads effectively. The stress levels indicate that the pedal is operating safely within its material capacity under the applied load conditions.

The simulation results for Scenario 1, which includes the standard load conditions, demonstrate that the equivalent stress and total deformation are well within acceptable limits. The equivalent stress of 348.01 MPa is significantly below the yield strength of Carbon Fiber, providing a high safety factor of approximately 8.34. The deformation remains minimal at 0.013336 m, ensuring the brake pedal maintains its structural integrity and functionality. The consistent force reactions at the support points indicate reliable performance under standard loads. Overall, the brake pedal design in this scenario is robust and meets safety and performance standards effectively.

7.8. Case 2, scenario 2

Total deformation:

- Maximum deformation: 0.03312 m

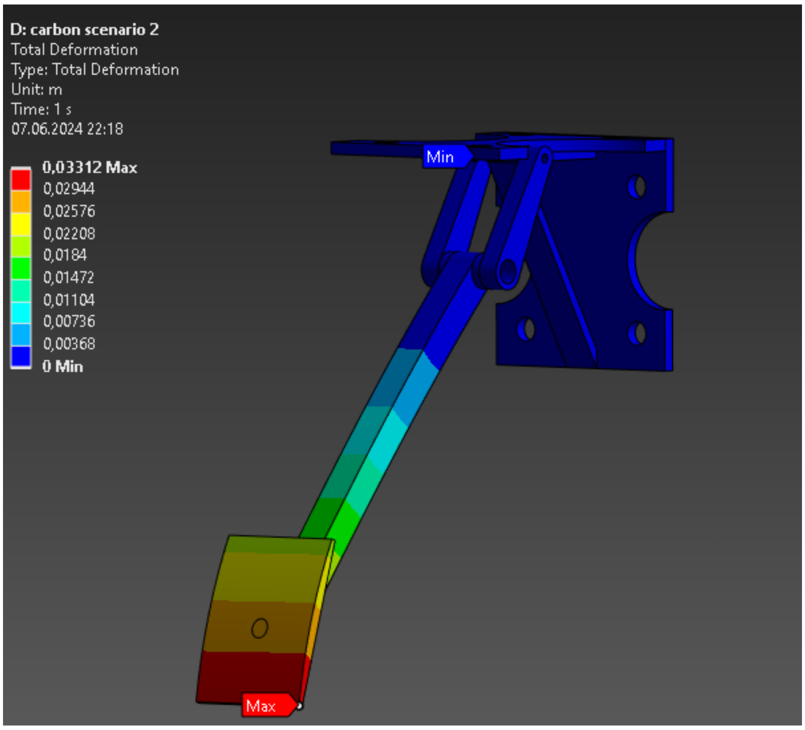

Figure 81

The maximum deformation of 0.03312 m indicates significant deflection of the brake pedal under the applied emergency load, which could affect its functionality and safety.

Equivalent stress (Von Mises Stress):

- Maximum equivalent stress: 922.44 MPa

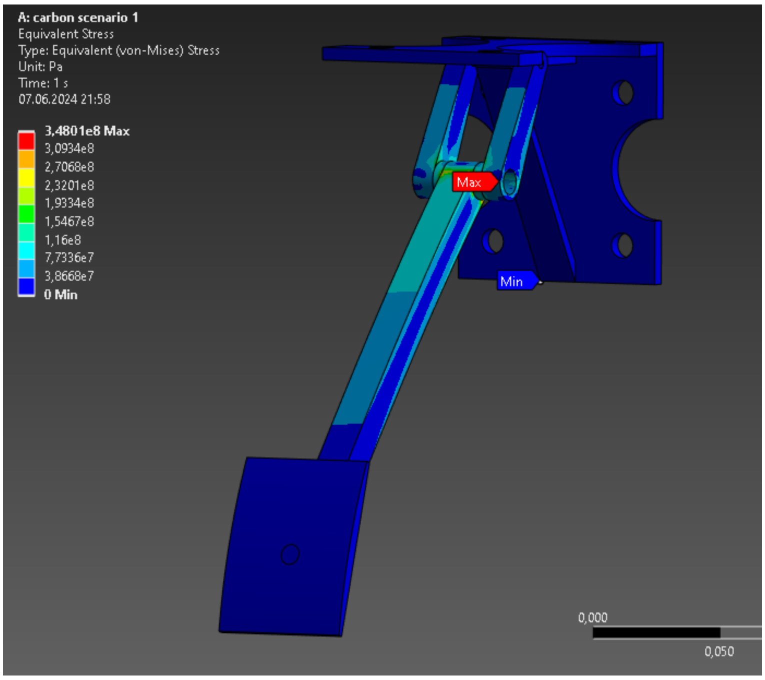

Figure 82

Safety factor calculation:

- Yield stress of Carbon Fiber: 2900 MPa

- Maximum equivalent stress: 922.44 MPa
-
- Safety factor: $\frac{2900\ MPa}{922{,}44\ MPa} \approx 3.14$

The maximum equivalent stress of 922.44 MPa is significantly below the yield strength of Carbon Fiber (2900 MPa). With a safety factor of approximately 3.14, the design is considered safe under the emergency load condition. This suggests that the brake pedal can handle the load without reaching its material limits.

Force reaction:

- Fixed Support:

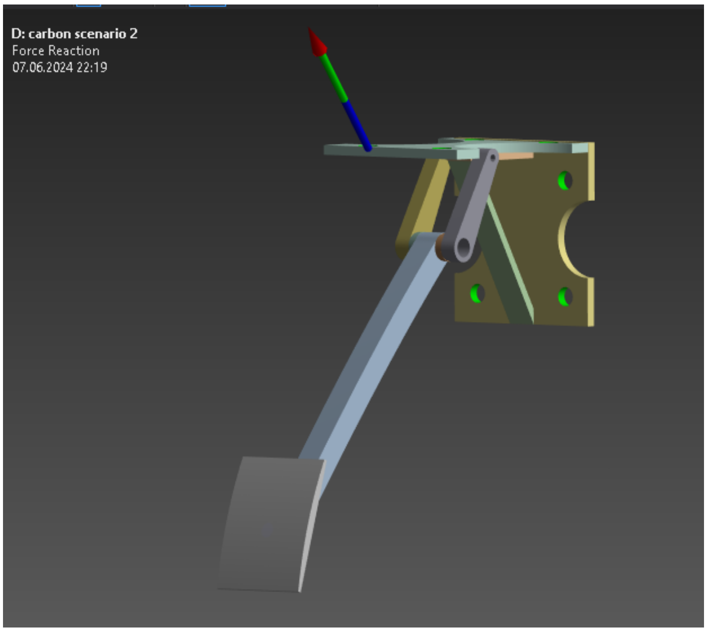

Figure 83

- Remote displacement:

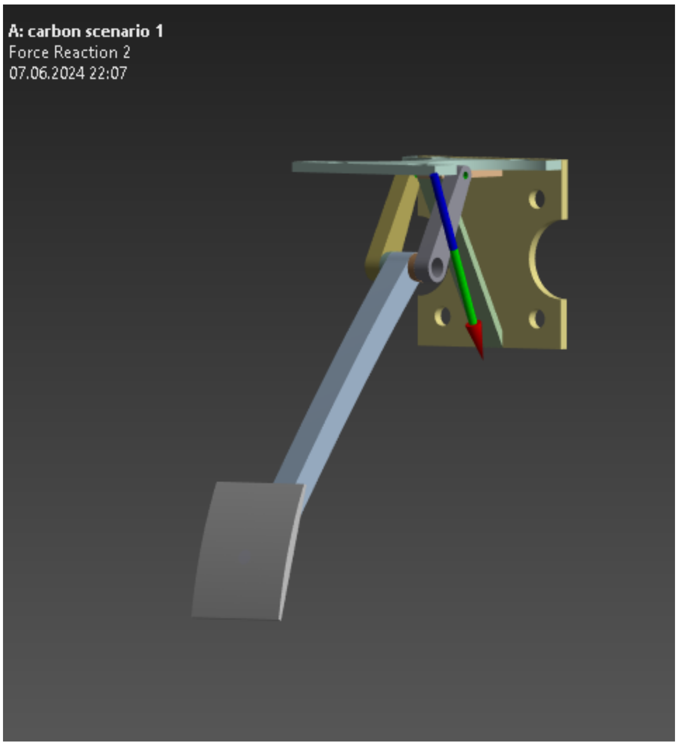

Figure 84

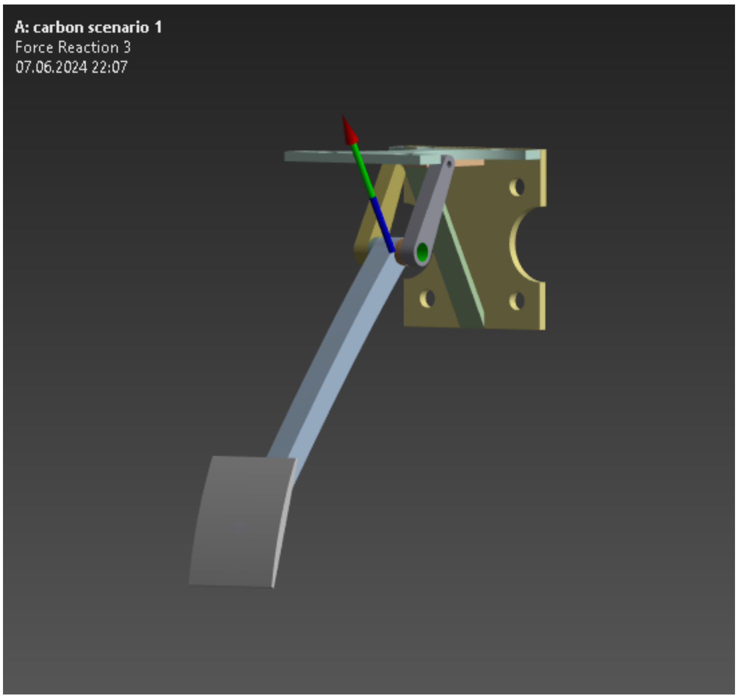

Figure 85

The force reactions at the fixed support and remote displacement points show that the brake pedal can handle the applied loads effectively. The stress levels indicate that the pedal is operating safely within its material capacity under emergency load conditions.

The simulation results for Scenario 2 demonstrate that the equivalent stress and total deformation are within acceptable limits. The equivalent stress of 922.44 MPa is well below the yield strength of Carbon Fiber, providing a safety factor of approximately 3.14. The deformation, while significant, does not compromise the structural integrity and functionality of the brake pedal. The consistent force reactions at the support points indicate reliable performance under emergency loads. Overall, the brake pedal design in this scenario is robust and meets safety and performance standards effectively.

7.9. Case 2, scenario 3a

Total deformation:

- Maximum deformation: 0.014564 m

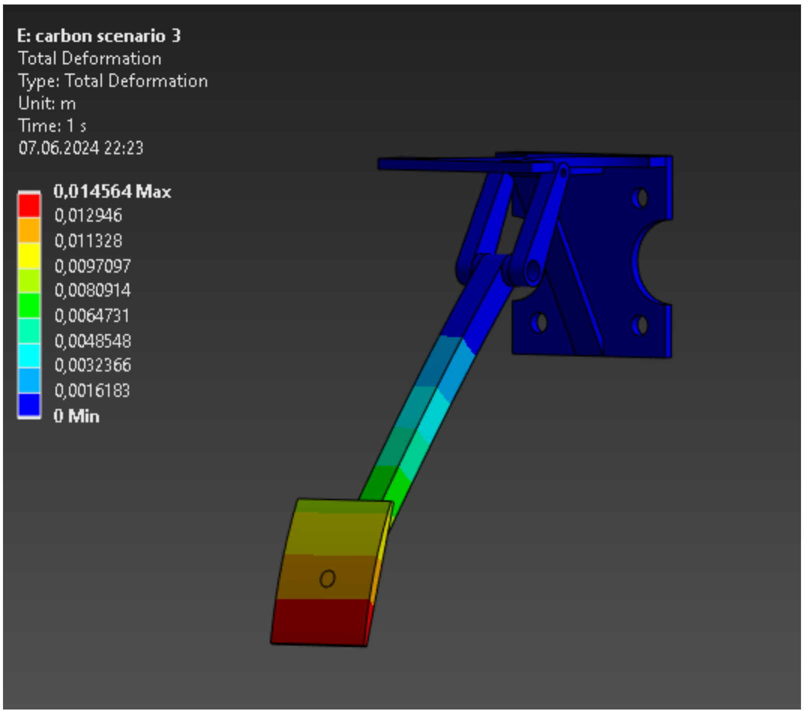

Figure 86

The maximum deformation of 0.014564 m indicates significant deflection of the brake pedal under the applied load, which could affect its functionality and safety.

Equivalent stress (Von Mises Stress):

- Maximum equivalent stress: 340.71 MPa

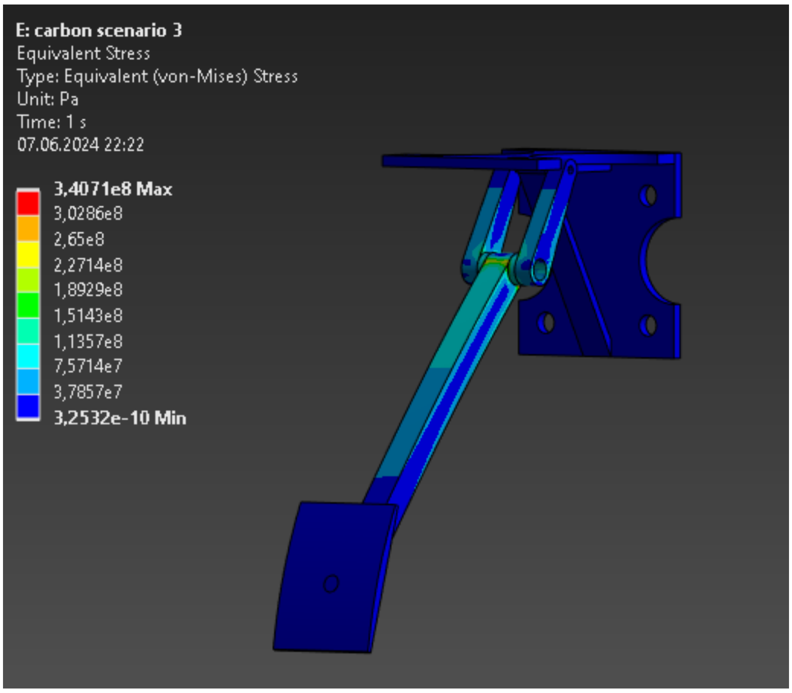

Figure 87

Safety factor calculation:

- Yield stress of Carbon Fiber: 2900 MPa
- Maximum equivalent stress: 340.71 MPa
-
- Safety factor: $\frac{2900\ MPa}{340.71\ \text{MPa}} \approx 8{,}51$

The maximum equivalent stress of 340.71 MPa is well within the yield strength of Carbon Fiber (2900 MPa). With a safety factor of approximately 8.51, the design is considered very safe under this load condition. This suggests that the brake pedal can handle the load without approaching its material limits.

Force reaction:
- Fixed Support:

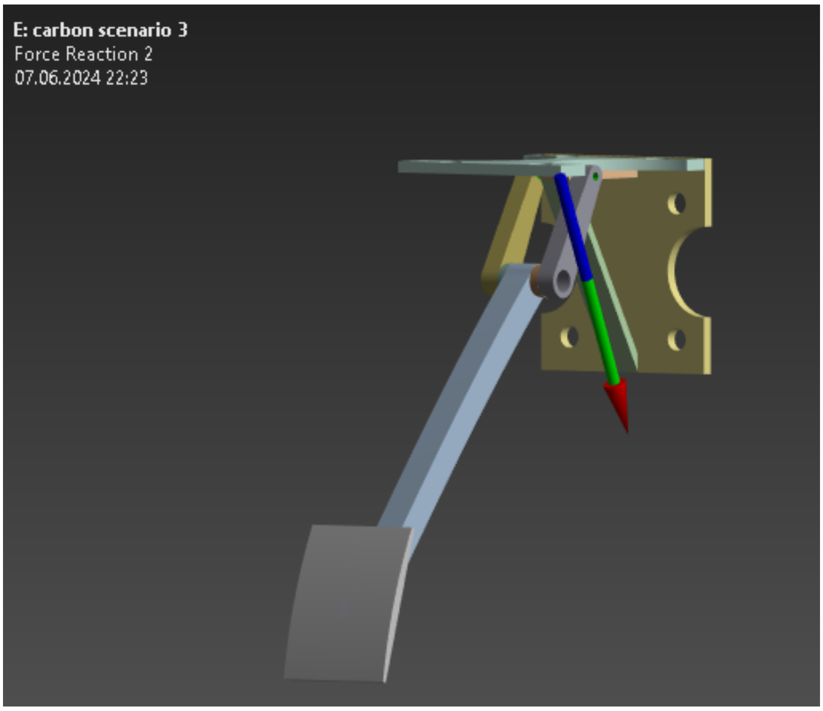

Figure 88

- Remote displacement:

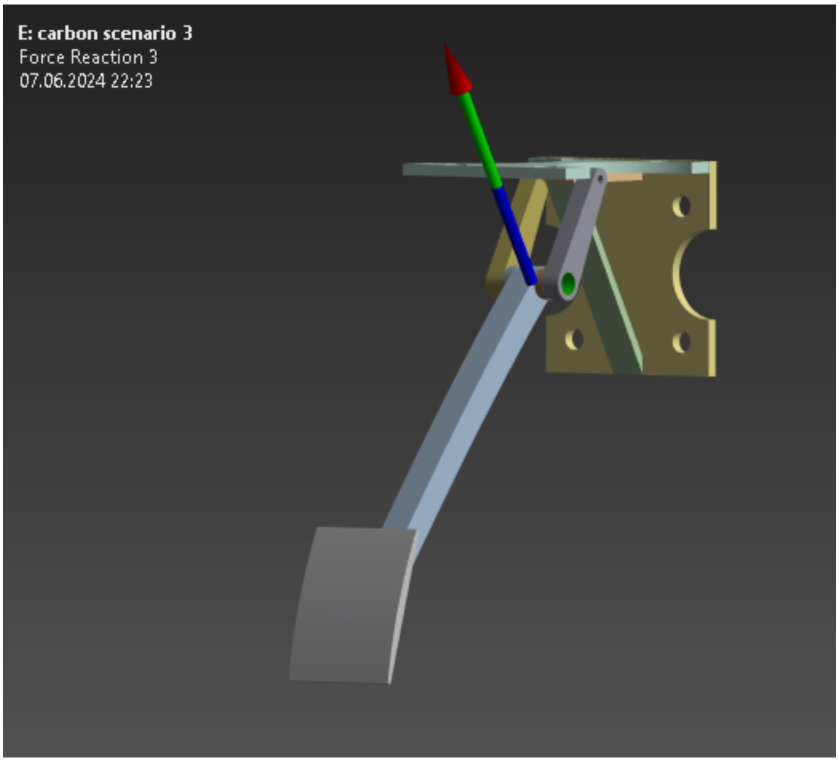

Figure 89

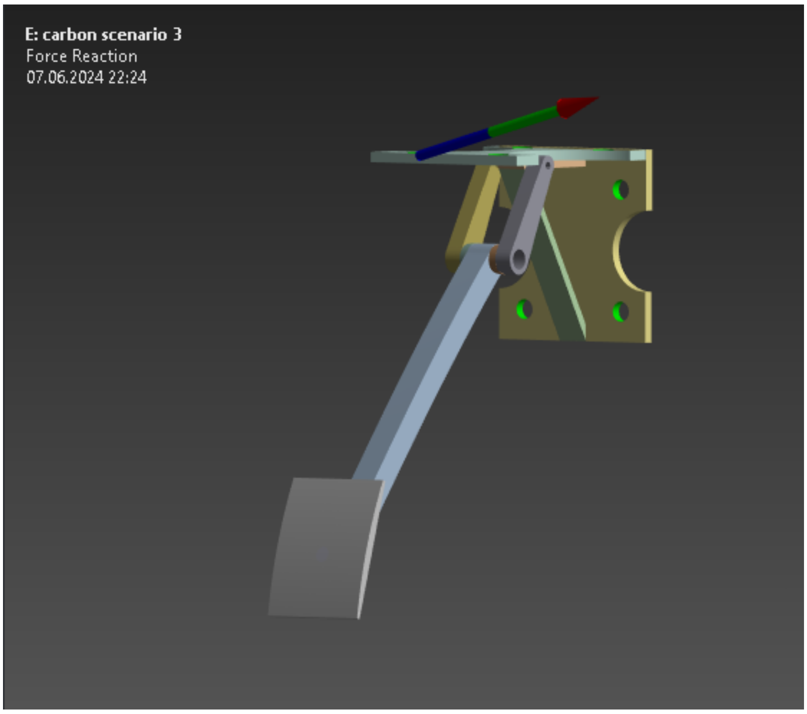

Figure 90

The force reactions at the fixed support and remote displacement points show that the brake pedal can handle the applied loads effectively. The stress levels indicate that the pedal is operating safely within its material capacity under the applied load conditions.

The simulation results for Scenario 3a demonstrate that the equivalent stress and total deformation are within acceptable limits. The equivalent stress of 340.71 MPa is significantly below the yield strength of Carbon Fiber, providing a high safety factor of approximately 8.51. The deformation remains moderate at 0.014564 m, ensuring the brake pedal maintains its structural integrity and functionality. The consistent force reactions at the support points indicate reliable performance under the applied loads. Overall, the brake pedal design in this scenario is robust and meets safety and performance standards effectively.

Additionally, the change in temperature does not significantly impact the performance of the brake pedal, indicating that the material properties of Carbon Fiber remain stable under varying thermal conditions.

7.10. Case 2, scenario 3b

Total deformation:

- Maximum deformation: 0.014564 m

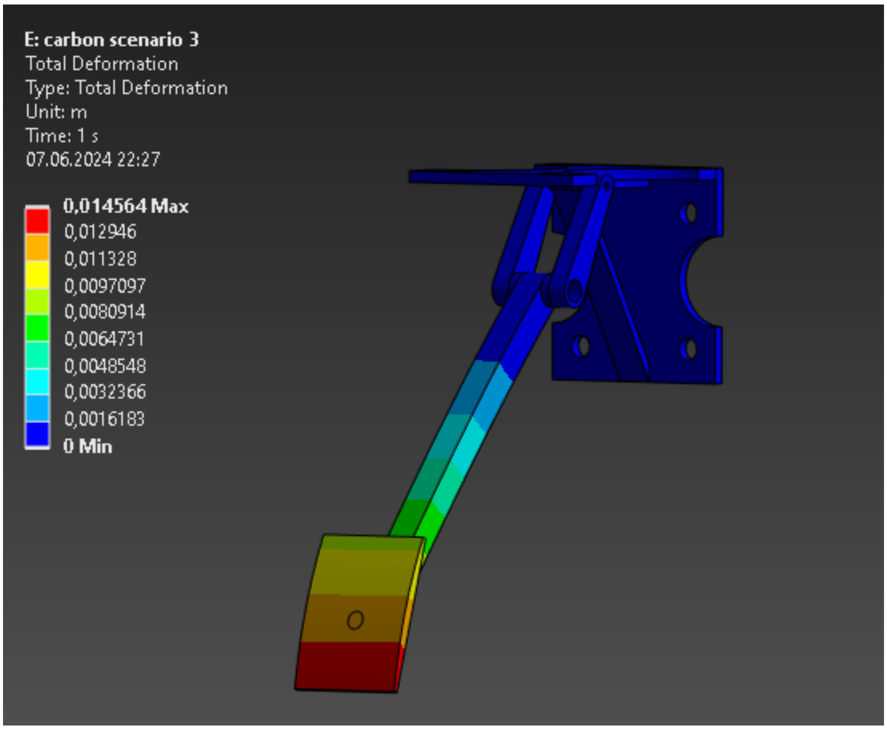

Figure 91

The maximum deformation of 0.014564 m is within acceptable limits for the brake pedal, indicating that the pedal retains its functional shape under the applied load even at lower temperatures.

Equivalent stress (Von Mises Stress):

- Maximum equivalent stress: 340.71 MPa

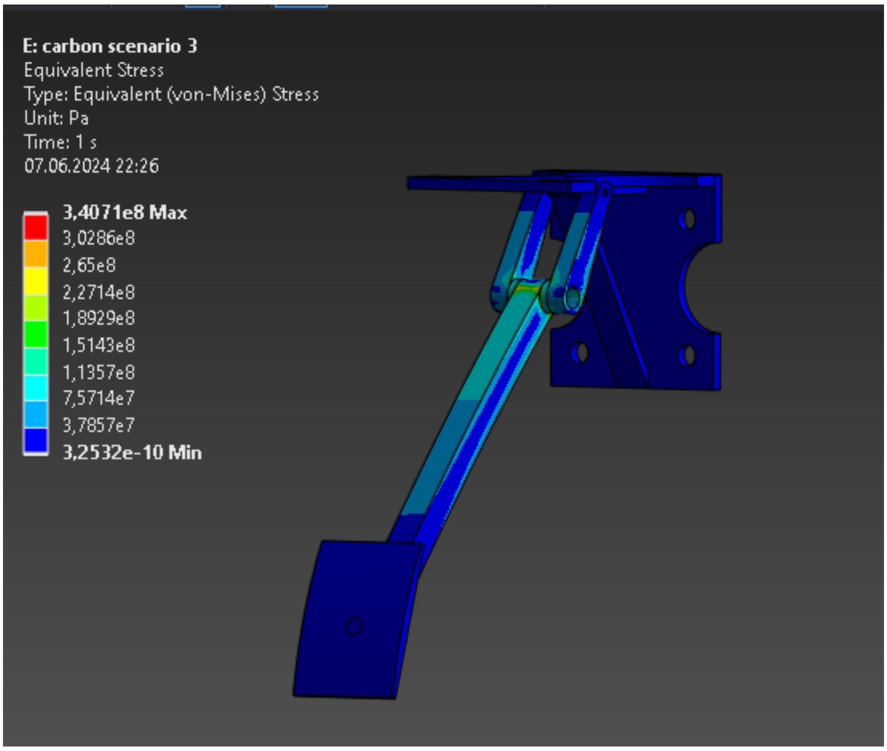

Figure 92

Safety factor calculation:

- Yield stress of Carbon Fiber: 2900 MPa
- Maximum equivalent stress: 340.71 MPa
-
- Safety factor: $\frac{2900\ MPa}{340.71\ \text{MPa}} \approx 8{,}51$

The maximum equivalent stress of 340.71 MPa is well within the yield strength of Carbon Fiber (2900 MPa). With a safety factor of approximately 8.51, the design is considered very safe under this load condition. This suggests that the brake pedal can handle the load without approaching its material limits.

Force reaction:

- Fixed Support:

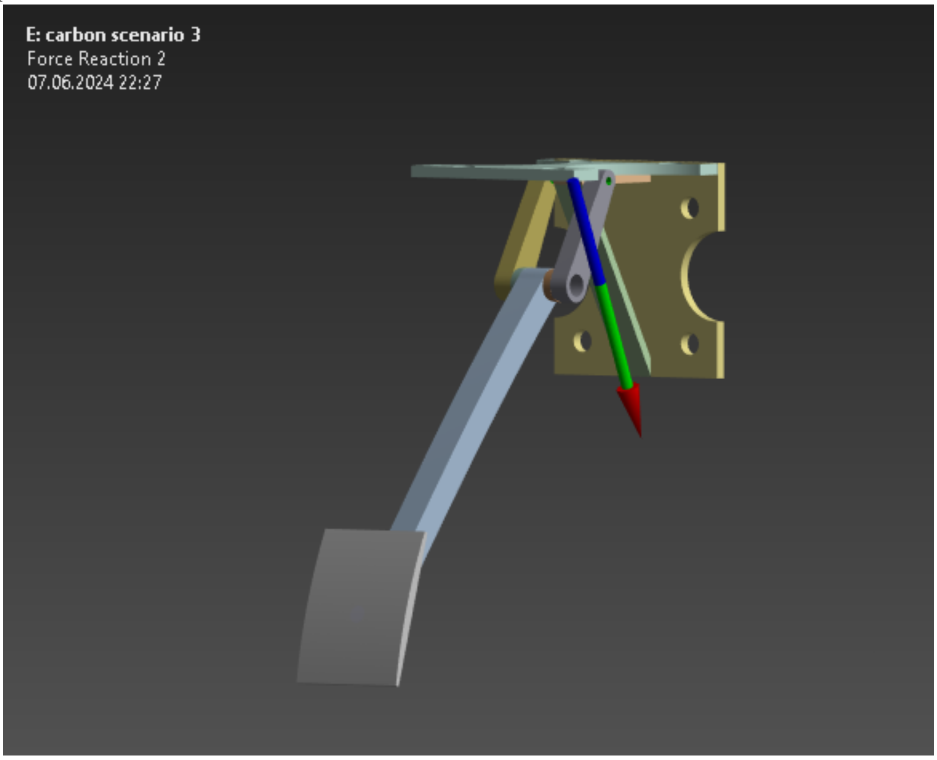

Figure 93

- Remote displacement:

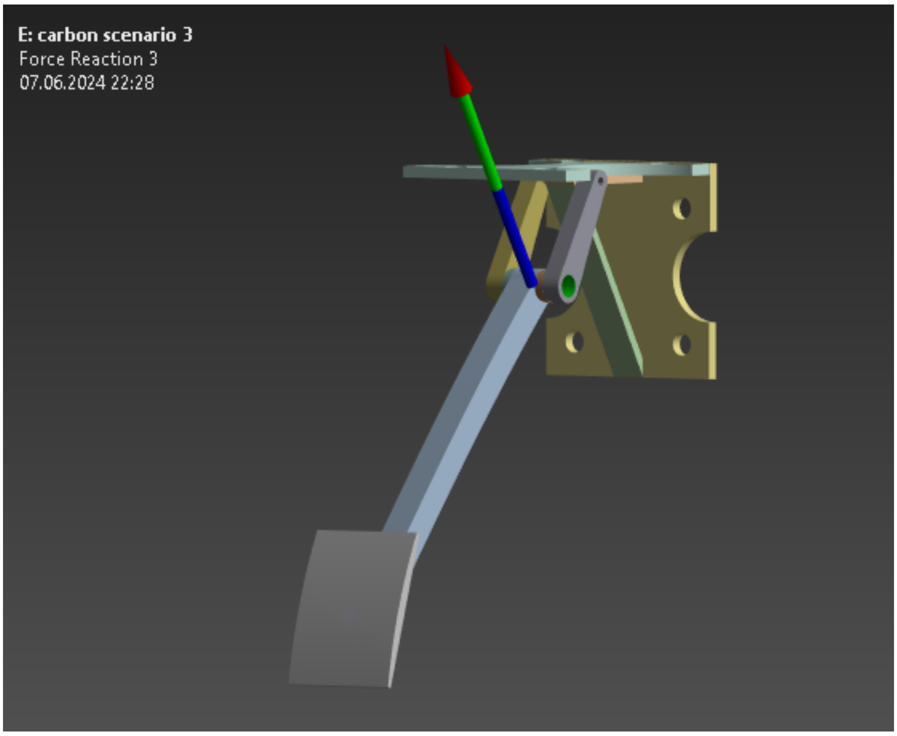

Figure 94

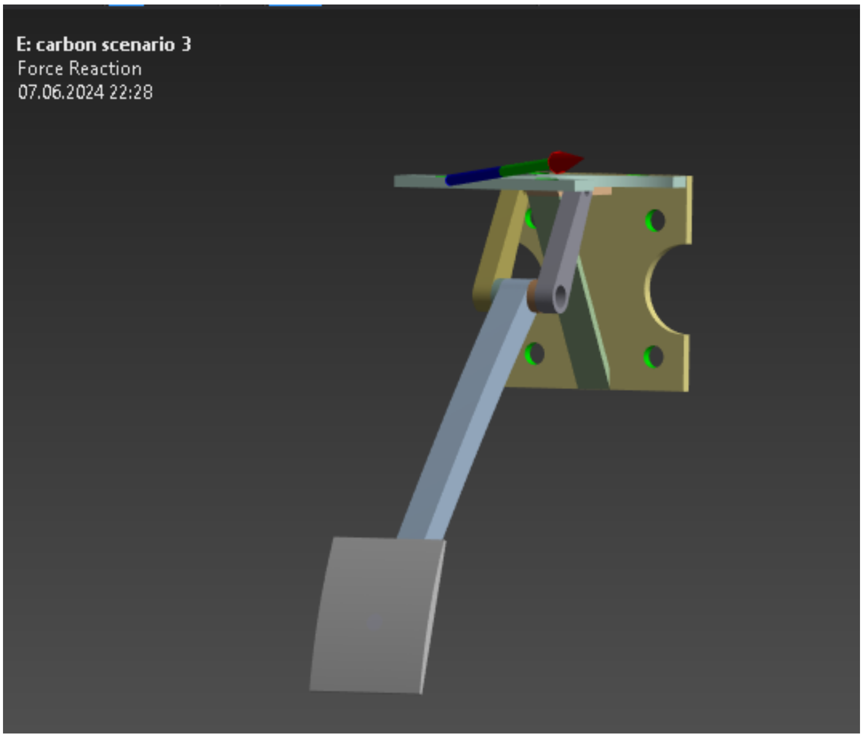

Figure 95

The force reactions at the fixed support and remote displacement points show that the brake pedal can handle the applied loads effectively. The stress levels indicate that the pedal is operating safely within its material capacity under low-temperature conditions.

The simulation results for Scenario 3b, which includes the low-temperature conditions, demonstrate that the equivalent stress and total deformation are within acceptable limits. The equivalent stress of 340.71 MPa is significantly below the yield strength of Carbon Fiber, providing a safety factor of approximately 8.51. The deformation remains minimal at 0.014564 m, ensuring the brake pedal maintains its structural integrity and functionality. The consistent force reactions at the support points indicate reliable performance under low-temperature conditions. Overall, the brake pedal design in this scenario is robust and meets safety and performance standards effectively.

Interestingly, the simulation results show that the impact of the low temperature (-30°C) on the equivalent stress and total deformation is minimal compared to the scenario at 20°C. The equivalent stress and deformation values remain similar, indicating that the material properties of Carbon Fiber are not significantly affected by this decrease in temperature. This consistency suggests that the brake pedal design remains robust under moderate temperature variations typical in automotive applications.

7.11. Case 2, scenario 4

Total deformation:

- Maximum deformation: 0.013881 m

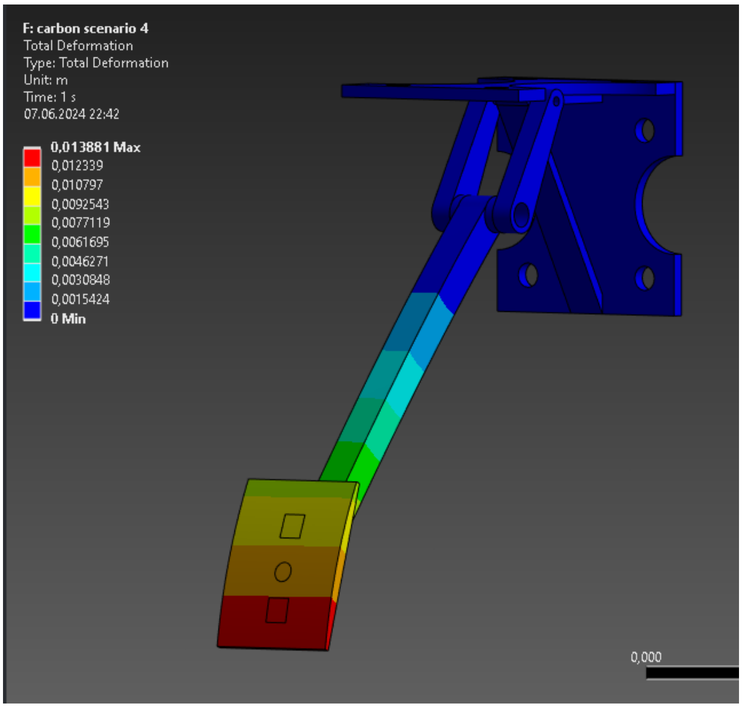

Figure 96

The maximum deformation of 0.013881 m indicates that the brake pedal retains its functional shape under the applied combined load, although the deformation is noticeable.

Equivalent stress (Von Mises Stress):

- Maximum equivalent stress: 332.98 MPa

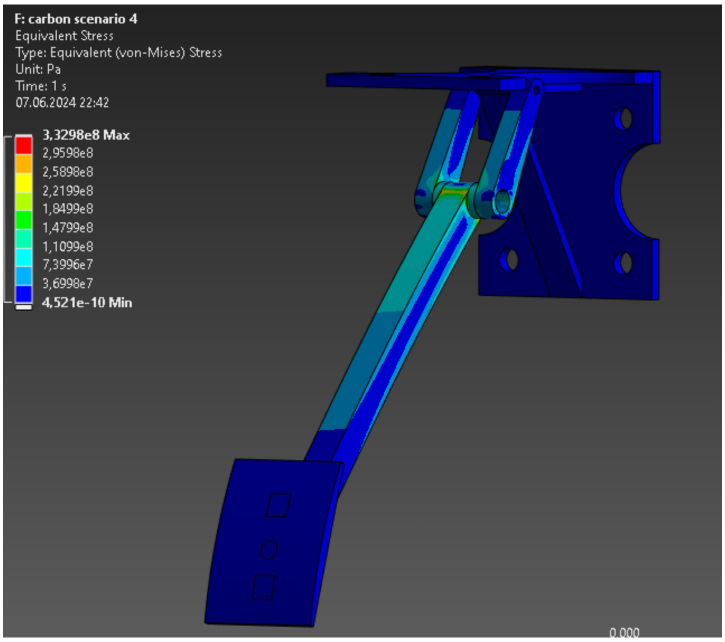

Figure 97

Safety factor calculation:

- Yield stress of Carbon Fiber: 2900 MPa
- Maximum equivalent stress: 332.98 MPa
-
- Safety factor: $\frac{2900\ MPa}{340.71\ \text{MPa}} \approx 8{,}71$

The maximum equivalent stress of 332.98 MPa is significantly below the yield strength of Carbon Fiber (2900 MPa). With a safety factor of approximately 8.71, the design is considered very safe under this combined load condition. This indicates that the brake pedal can handle the load without reaching its material limits.

Force reaction:
- Fixed Support:

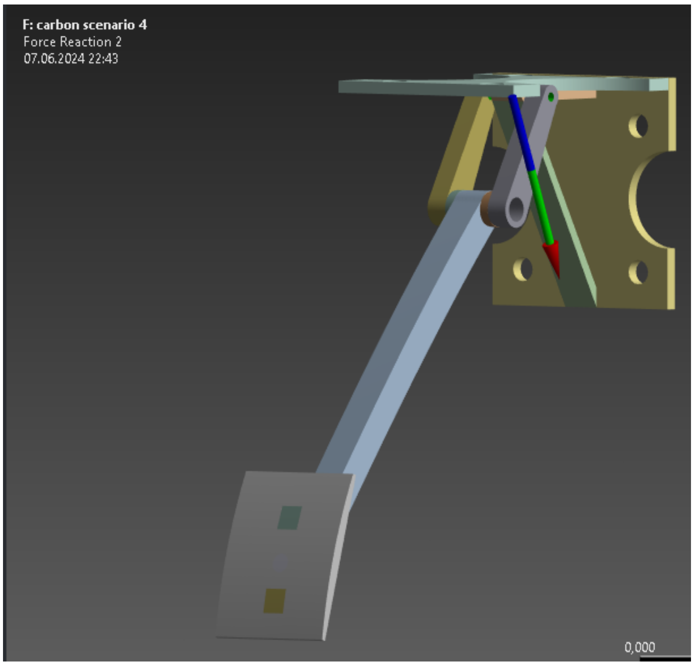

Figure 98

- Remote displacement:

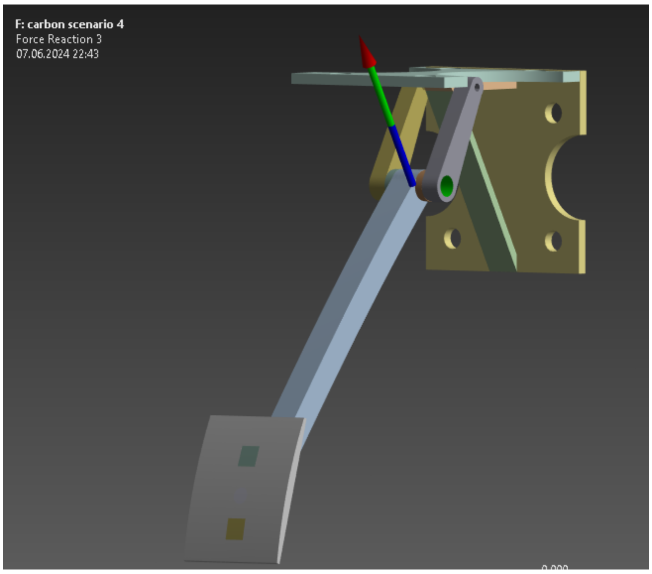

Figure 99

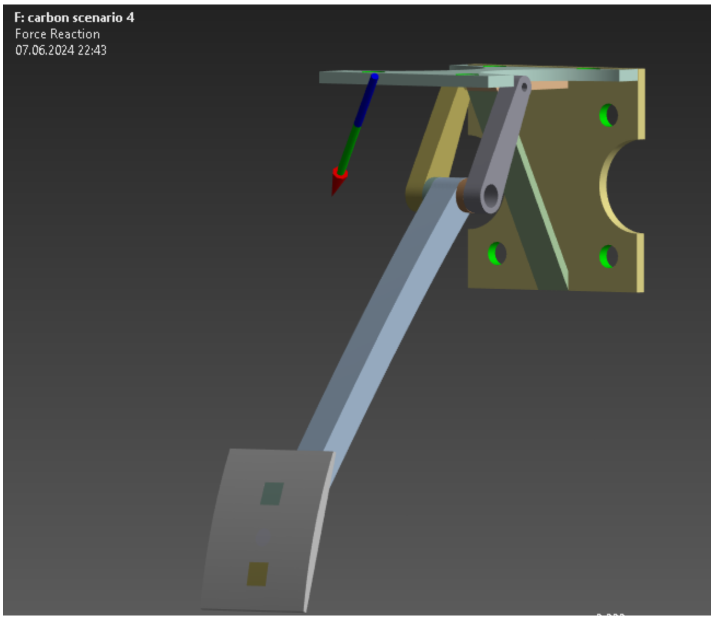

Figure 100

The force reactions at the fixed support and remote displacement points show that the brake pedal effectively handles the applied loads. The stress levels indicate that the pedal operates safely within its material capacity under combined load conditions.

The combined load scenario demonstrates that the equivalent stress and total deformation are within acceptable limits. The equivalent stress of 332.98 MPa is well below the yield strength of Carbon Fiber, providing a high safety factor of approximately 8.71. The deformation remains minimal at 0.013881 m, ensuring that the brake pedal maintains its structural integrity and functionality. The consistent force reactions at the support points indicate reliable performance under combined loads. Overall, the brake pedal design in this scenario is robust and meets safety and performance standards effectively.
Additionally, the fixation points show no significant issues, ensuring the pedal is securely held in place, which is crucial for the overall safety and reliability of the braking system.

7.12. Case 2, scenario 5

Total deformation:

- Maximum deformation: 0.008597 m

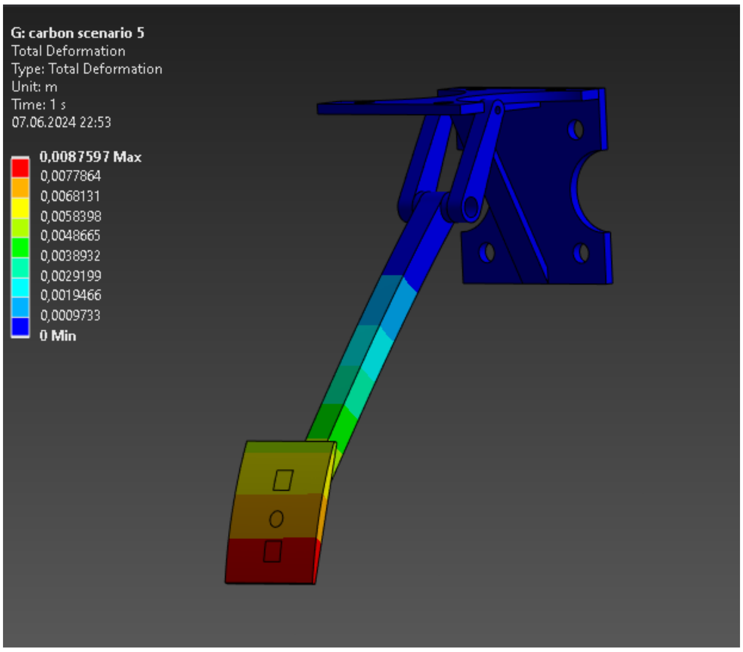

Figure 101

he maximum deformation of 0.008597 m indicates that the brake pedal retains its functional shape under the applied load, with only minor noticeable deformation.

Equivalent stress (Von Mises Stress):

- Maximum equivalent stress: 214.81 MPa

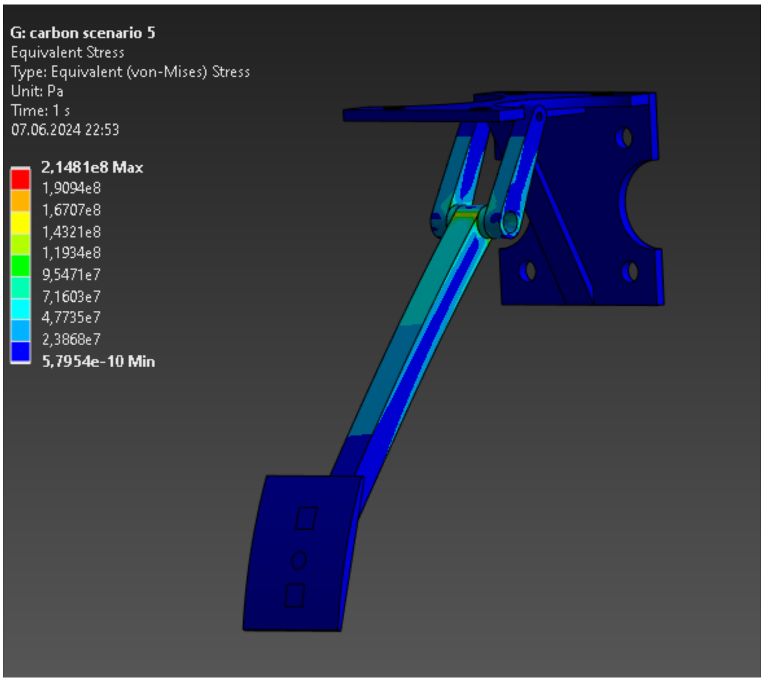

Figure 102

Safety factor calculation:

- Yield stress of Carbon Fiber: 2900 MPa
- Maximum equivalent stress: 214.81 MPa

-
- Safety factor: $\frac{2900\ MPa}{340.71\ \text{MPa}} \approx 13.50$

The maximum equivalent stress of 214.81 MPa is significantly below the yield strength of Carbon Fiber (2900 MPa). With a safety factor of approximately 13.50, the design is considered extremely safe under this load condition. This indicates that the brake pedal can handle the load without reaching its material limits.

Force reaction:

- Fixed Support:

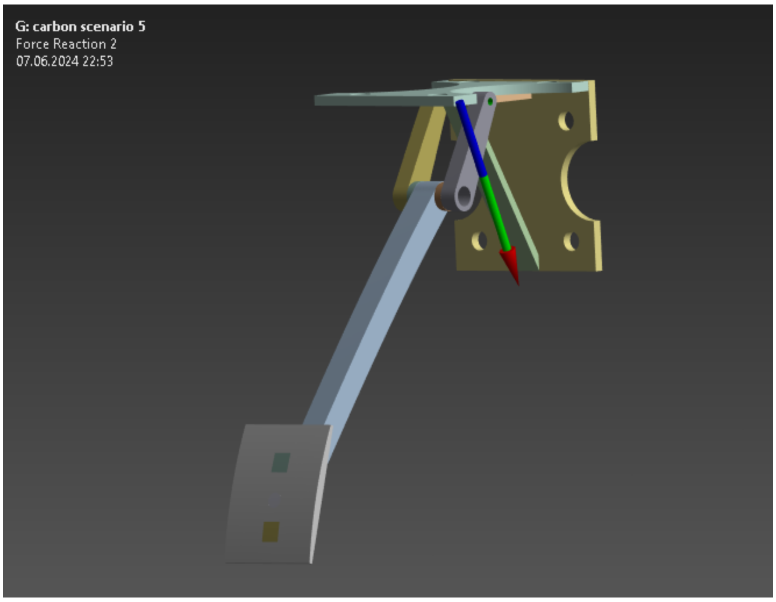

Figure 103

- Remote displacement:

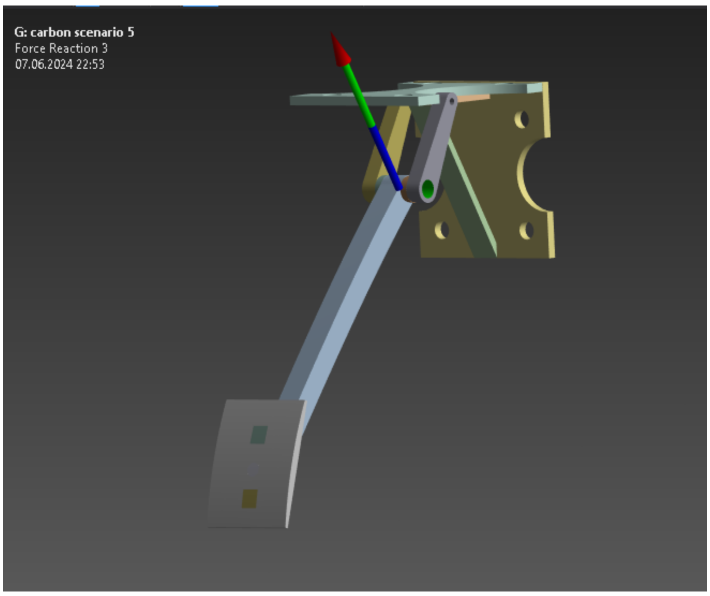

Figure 104

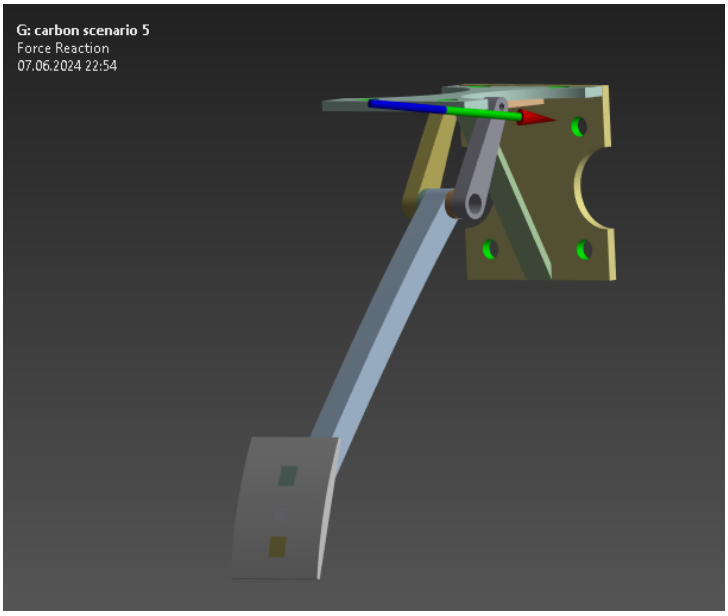

Figure 105

The force reactions at the fixed support and remote displacement points show that the brake pedal effectively handles the applied loads. The stress levels indicate that the pedal operates safely within its material capacity under the given load conditions.

The analysis of scenario 5 demonstrates that both equivalent stress and total deformation are within acceptable limits. The equivalent stress of 214.81 MPa is well below the yield strength of Carbon Fiber, providing a high safety factor of approximately 13.50. The deformation remains minimal at 0.008597 m, ensuring that the brake pedal maintains its structural integrity and functionality. The consistent force reactions at the support points indicate reliable performance under the load. Overall, the brake pedal design in this scenario is robust and meets safety and performance standards effectively. Additionally, the fixation points show no significant issues, ensuring the pedal is securely held in place, which is crucial for the overall safety and reliability of the braking system.

Case 2 summary

In conclusion, scenario 2 demonstrates that the brake pedal made of Carbon Fiber offers a substantial improvement in performance and safety compared to Aluminum Alloy 6061. The high safety factors and minimal deformation confirm that the design is reliable and can endure the operational demands. The Carbon Fiber brake pedal ensures safe and effective performance, reducing the risk of material failure under extreme conditions.

Furthermore, the fixation made of Steel 1.4021 remains effective, providing the necessary support and stability for the brake pedal system without encountering significant stress or deformation issues. This combined material approach ensures the overall safety and reliability of the braking system, making it a viable solution for high-performance applications.

8. Final conclusions

The comparative analysis of brake pedals constructed from Aluminum Alloy 6061 and Carbon Composite under various scenarios reveals critical insights into their performance, safety, and optimization potential. Both materials demonstrate unique advantages and challenges, with the carbon composite showing superior mechanical properties but at a higher material cost.

The cost of materials plays a significant role in selecting the optimal design for automotive components. Below is a comparison of the material costs for Aluminum Alloy 6061 and Carbon Composite:

Material	Cost per kg (USD)
Aluminum Alloy 6061	$3.50
Carbon Composite	$40.00

Tab. 4

Analysis summary

Aluminum Alloy 6061:
- The aluminum brake pedal shows adequate performance under standard load conditions with a safety factor of approximately 1.05. However, this is marginal and suggests the need for further reinforcement.
- Under emergency load conditions, the aluminum pedal's safety factor drops to around 0.46, indicating a high risk of failure. This scenario highlights the necessity for either a stronger material or significant design modifications.
- The pedal maintains its integrity across a range of temperatures, with minimal impact on deformation and stress levels.
- When subjected to high-heeled footwear pressure points, the aluminum pedal performs within acceptable deformation limits but still operates close to its material limits.

Carbon Composite:
- The carbon composite pedal excels under standard load conditions, offering a high safety factor. This material's high strength and stiffness ensure minimal deformation.
- Even under emergency conditions, the carbon composite pedal maintains a high safety factor, far exceeding that of aluminum.
- The carbon composite's performance remains consistent across various temperatures, indicating excellent thermal stability.
- The pedal effectively manages the concentrated loads from high-heeled footwear, maintaining structural integrity without significant deformation.

Despite the high safety factors, especially in carbon composite pedals, there is potential to reduce material usage by optimizing the geometry. This could involve thinning certain sections without compromising overall strength, thus reducing weight and material cost.

Carbon Composite: While offering superior performance, the high cost of carbon composite ($40/kg) necessitates careful consideration. For applications requiring maximum safety and performance, this material is justified.

Aluminum Alloy 6061: Given its lower cost ($3.50/kg), aluminum can be optimized through design modifications to enhance safety under higher loads. This might involve increasing the pedal's thickness or adding reinforcements at critical points.

Given the significant cost difference, a thorough cost-benefit analysis is essential. In scenarios where extreme performance is not critical, optimizing aluminum designs could provide a cost-effective solution. Conversely, for high-performance or safety-critical applications, the investment in carbon composite may be warranted.

Additional research into alternative materials or hybrid designs that combine the benefits of both aluminum and carbon composite could offer balanced solutions in terms of cost, weight, and performance.

The transition from Aluminum Alloy 6061 to Carbon Composite for brake pedal construction presents a significant improvement in mechanical performance, albeit at a higher material cost. Careful consideration of cost, safety requirements, and potential for geometric optimization should guide the choice of material. While carbon composite offers exceptional performance, strategic design improvements to aluminum pedals could provide a viable, cost-effective alternative for less demanding applications. The ongoing pursuit of optimization in both materials and design will ensure the development of robust, reliable brake systems for future automotive applications.