Ansys Analysis of Gyroid Shank and Original Shank

ABSTRACT

This report researches **gyroids' stress and strain behaviour in the shank of quadruped robotic legs.** Mass reduction is an excellent way to have reasonable control in robotics as it also reduces the inertia of legs. In this report, I tried to reduce mass by using biomimicry and inserting some nature-inspired structures in the central portion of the shank and covering it with thick plates. Butterfly wings have inspired this design **with beams enclosing gyroids**. Butterfly wings require a high strength-to-weight ratio, so we decided to mimic them.

INTRODUCTION

Mass reduction in high payload-carrying robotics is always an area of concern. The robot must be robust enough to carry a high payload. However, this led to an undesirable increment in mass due to increased inertia, making robotic legs unstable and challenging to control. So we must find a way to increase its strength but reduce mass, increasing strength to weight ratio.

One quite popular way to do this is topology optimization. Topology optimization is a mathematical method that optimizes material layout within a given design space for a given set of loads, boundary conditions, and constraints to maximize the system's performance. Nowadays, this can be done using software like Solidworks and Ansys. Another way is to use topology-optimized structures like gyroids and Schwartz. In this report, I tried to use gyroids to experiment with increasing strength to weight ratio.

What are gyroids?

Gyroid structures are complex, three-dimensional structures characterized by repeating patterns of interconnected, curved surfaces. They are often found in nature[1], such as in certain corals and butterfly wings[2], but can be created synthetically using 3D printing or other fabrication methods.

The gyroid structure is unique because it is a triply periodic minimal surface(TPMS). It has a relatively higher surface area for a given volume and can be repeated infinitely in three dimensions without intersecting itself. This makes it an ideal structure for various applications, from materials science and engineering to architecture and design. Gyroids can also be used for robotic applications like drones[3], which have significant torsional and bending loads due to thrust forces at their ends.

One notable feature of gyroid structures is their surface area-to-volume ratio, making them useful for energy storage, filtration, and catalysis applications. In addition, their interconnected pore network provides a high degree of structural stability and mechanical strength, making them ideal for lightweight and strong materials.

My finding through this experiment indicates that adding the shank's internal mesh helps decrease mass by 30 g while increasing strength in torsional loads. This experiment tests the novelty of the application of gyroids in various fields. Nowadays, it is widely used in aerial robotics. In on-ground robotics, the application of gyroids is still less researched and implemented due to the complexity of manufacturing. Still, we tested it for on-ground robotics in quadruped robotic legs.

The cellular structure of the gyroid

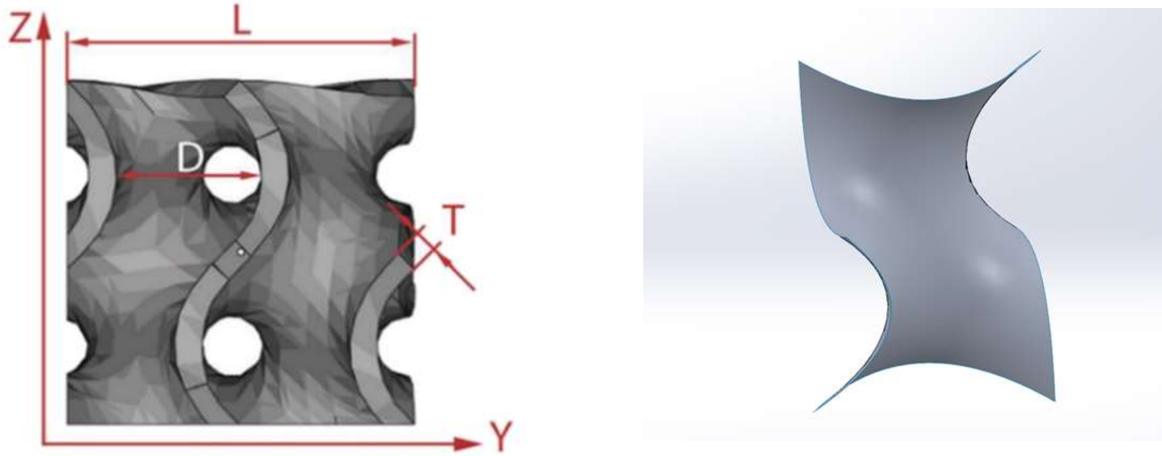


Fig 1- Fig 2: Design parameters of gyroid cell and CAD model of the gyroid cell[4]

The principal design parameters in the gyroid cell are **unit cell size (L)** and **thickness (T).** The thickness of the gyroid cell is the main parameter that provides strength to the gyroid cell. In other words, **the strength of the gyroid cell is directly proportional to the thickness of the gyroid cell.** [2]

In the following sections, this report delves into the comprehensive analysis of the design, simulation, and observations related to the gyroid and original shanks. **Section 1** covers the design of the original shank and the modifications made to incorporate gyroids, providing a detailed account of the changes and their impact. **Section 2** outlines the boundary conditions and loads applied during the Ansys simulation, detailing the setup required for the analysis. **Section 3** presents the stress-strain results derived from the Ansys simulations, offering a thorough examination of the performance metrics. **Section 4** discusses the accuracy and convergence of the results, focusing on the reliability and consistency of the simulation data. **Section 5** provides a critical discussion and observations on the trends observed from the results, highlighting key findings and their implications. Finally, **Section 6** concludes the report and explores potential future directions for applying the gyroid design in various contexts.

Section 1:Design and modification of original shank

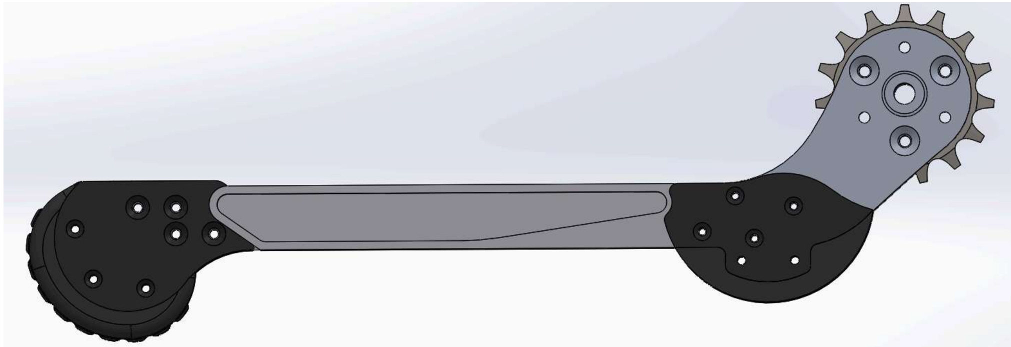


Fig 3: Shank with the initial central part

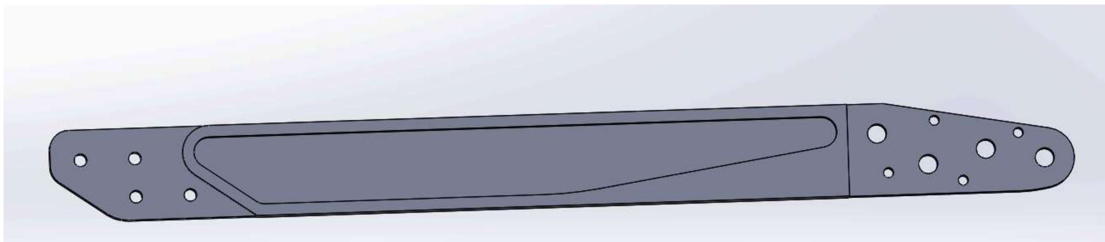


Fig 4: The initial central part

Initially, the original shank had a solid I-beam structure in its centre, solid from the inside. It is **made of aluminium 6061 alloy weighted 180g**. We optimize shank weight by doing design modifications in this central portion by inserting gyroids. This **reduced its mass by 30 g**.

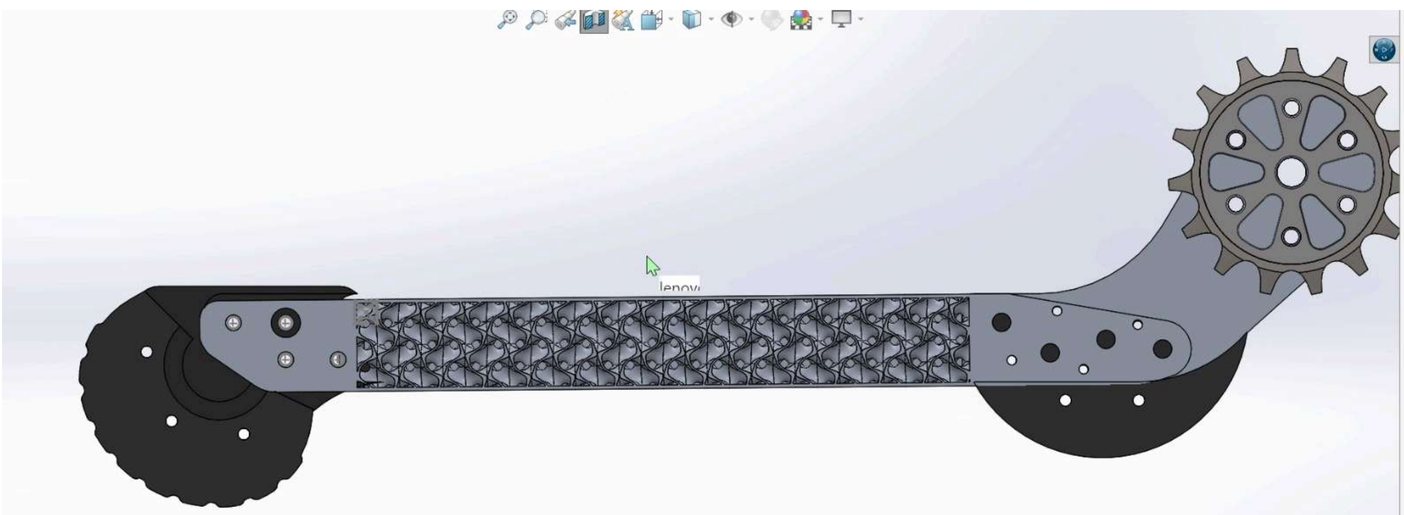


Fig 5: Section view of the shank with the central portion filled with gyroids

Fig 6: Section view of the central portion filled with gyroids

In the centre, there are gyroid cells of 0.5 mm thickness, and in its outer portion, there are 1mm thick plates on all sides. I have finalized this thickness because increasing more than these values will increase weight while decreasing it will lead to high stress. So we are transmitting all the load outside while making some cavities in the central portion to reduce weight. This is exactly how butterfly wings have been made, which gives them strength and makes them lightweight at the same time.

In the initial design of the gyroid shank, there were sharp edges where high-stress concentrations were coming, so fillets and chamfers were added in those parts, which can be seen in Fig 8.

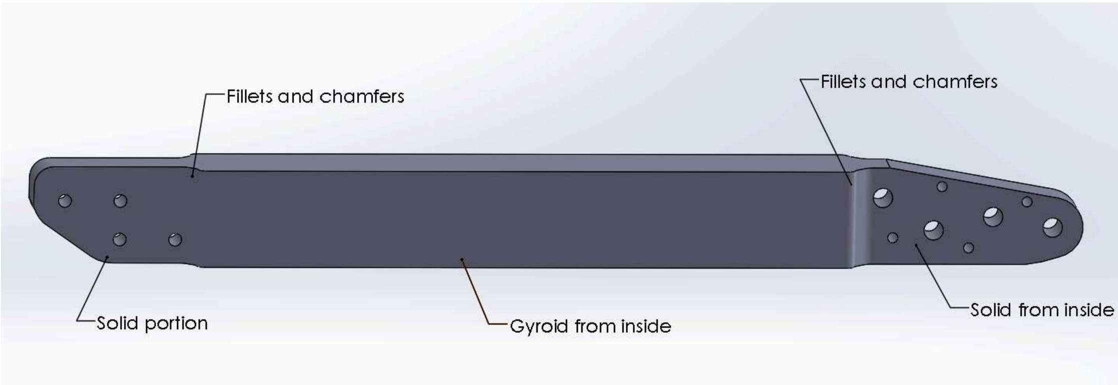


Fig 7: Fillets and chamfers in gyroid shank design

Those portions in Fig 8 that have been kept solid from the inside are critical areas where nut bolts will be fitted.

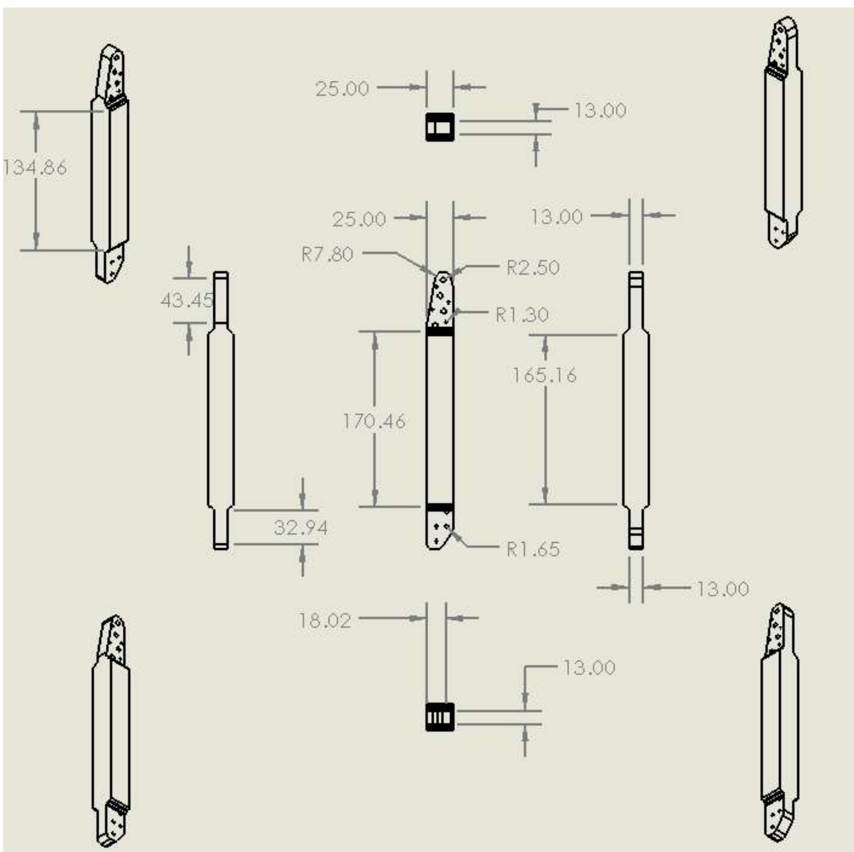


Fig 8: Multiple views of the gyroid central part (all dimensions are in mm)

Section 2:- Design models, Boundary conditions, and loads used in Ansys for simulation

Ansys software was utilized to compare the strength of the original shank and the gyroid-filled central parts through structural analysis using Finite Element Analysis (FEA). Employing the Cartesian mesh method, simulations were conducted with element sizes of 1 mm, 0.5 mm, and 0.4 mm to ensure result accuracy. Both the original and three design models were analyzed.

- The original shank's central portion is an I-beam type structure, completely solid from the inside.

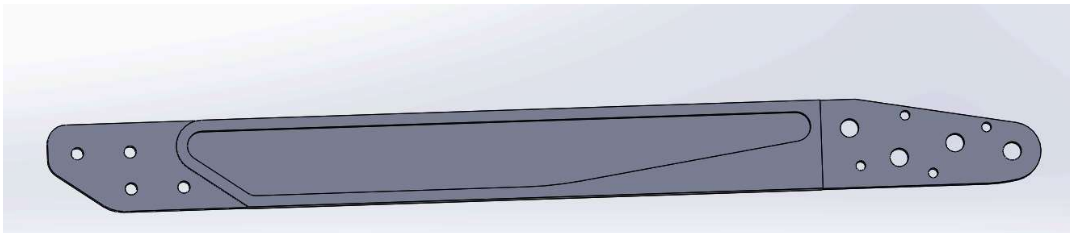


Fig 9: Original shank

- In gyroid shank_v6, there are no fillets and sharp edges at the intersection of gyroid filled central part with the critical portion of bolts.

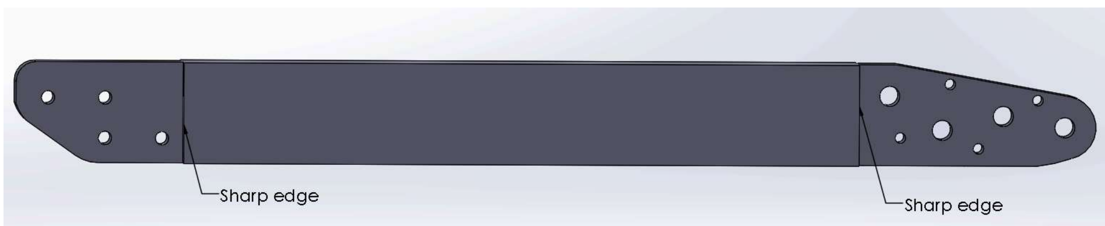


Fig 10: Gyroid shank_v6

- In the gyroid shank_v13, fillets and chamfers are added on the upper edges of the intersection of the gyroid gyroid-filled central part with the critical portion of bolts. These fillets and chamfers are added just on the above edges because those are the areas where there is quite a lot of stress concentration.

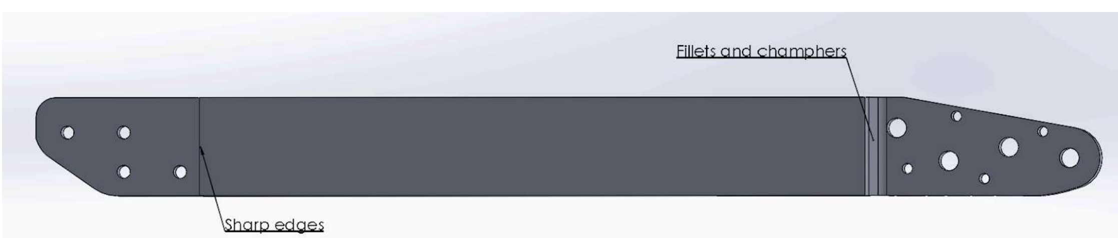


Fig 11: Gyroid shank_v13

- In gyroid shank_v18, fillets and chamfers are added on both lower and upper intersection edges. Also, there are sharp edges inside, so fillets are added there also to minimize stress concentrations.

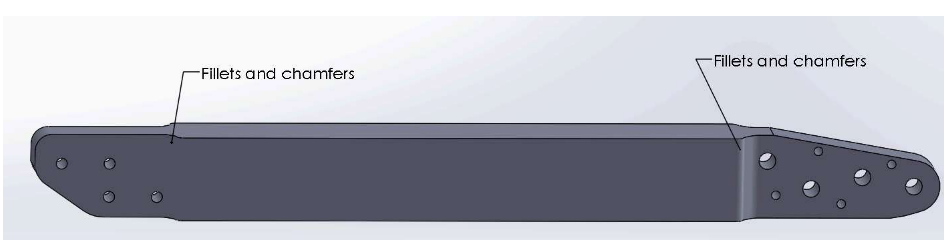


Fig12: Gyroid shank_v18

I did six Ansys mechanical simulations on each model by applying **forces of 400 N** and **moments of 200 N.m** in all three directions separately. I fixed the holes in the upper portion while applying forces and moments on the opposite bottom part, as depicted in Fig 13 - Fig 18.

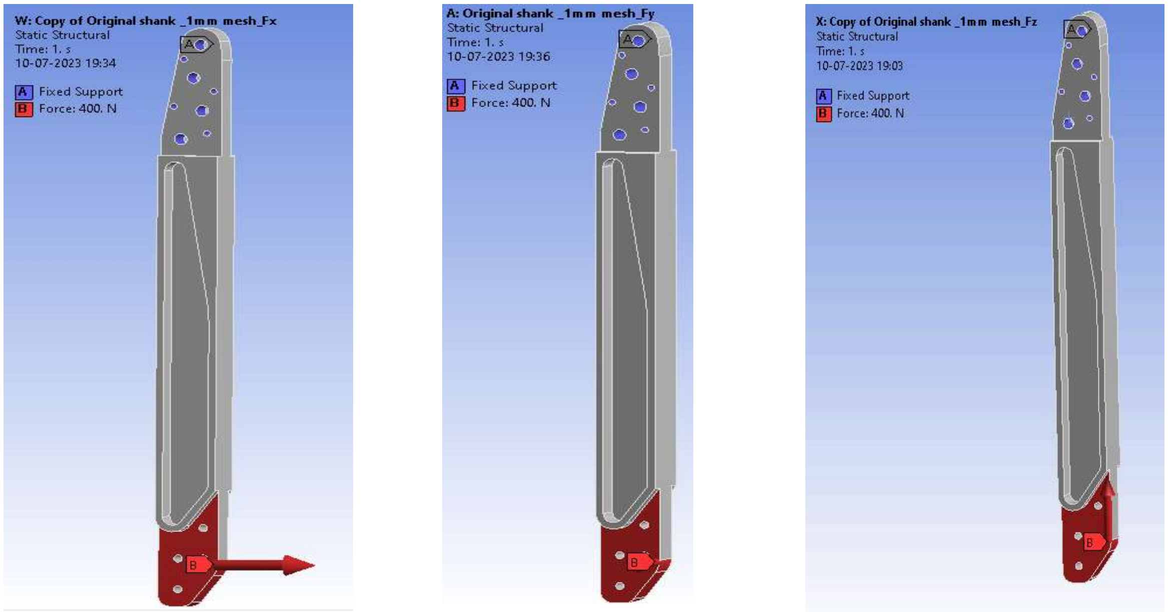


Fig 13 - Fig 15: Forces loading condition in x,y, and z directions

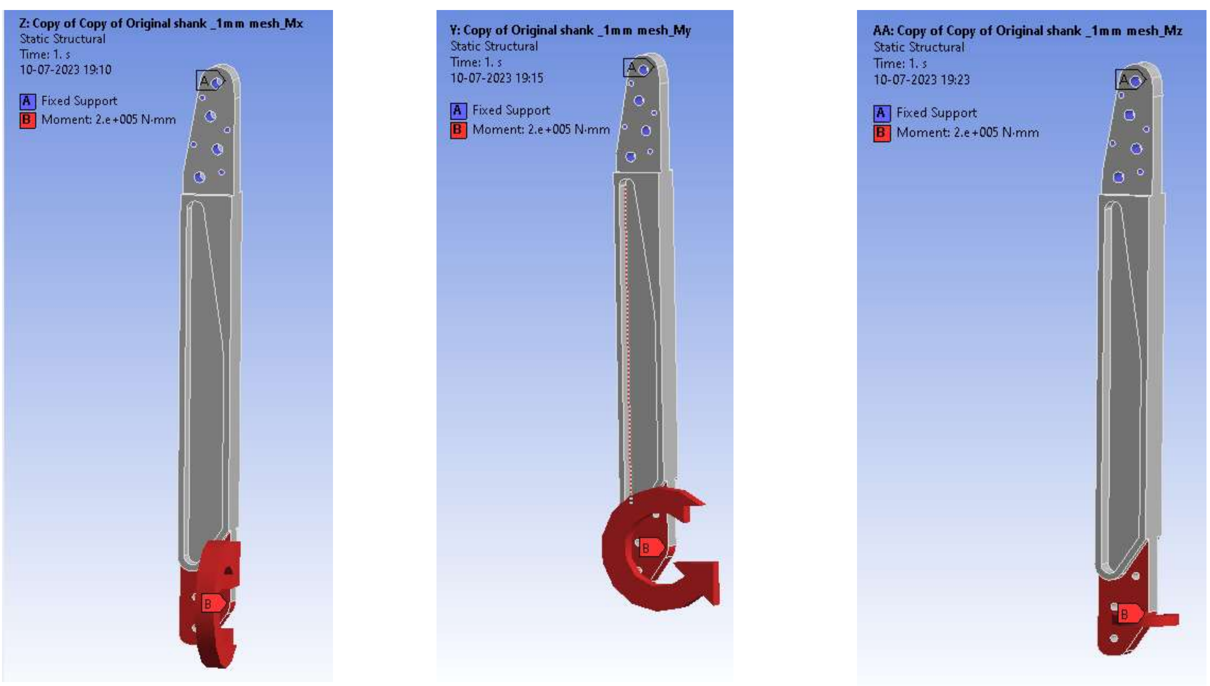


Fig 16 - Fig 18: Moment loading condition in x,y, and z directions

Section 3: - Stress-strain results from Ansys simulation

Ansys Mesh parameters for 1 mm

	Element size	Mesh Type	Avg Element quality	Avg Skewness
Original Shank	1 mm	Cartesian	0.96132	4.34e-002
Gyroid shank_v6	1 mm	Cartesian	0.8045	0.3571
Gyroid shank_v13	1 mm	Cartesian	0.80488	0.35797
Gyroid shank_v18	1 mm	Cartesian	0.80452	0.35966

Ansys results for 1 mm mesh

1.) Fx

	Avg Equivalent Stress (MPa)	Avg Equivalent Strain	Avg Total Deformation (mm)	Max Total Deformation (mm)	Factor of Safety (FOS)
Original Shank	14.991	2.18e-004	0.33245	1.0955	2.0067
Gyroid shank_v6	16.395	2.68e-004	0.60574	1.8834	0.40801
Gyroid shank_v13	16.102	2.62e-004	0.56383	1.7846	0.50803
Gyroid shank_v18	16.191	2.63e-004	0.56883	1.7956	0.50803

2.) Fy

	Avg Equivalent Stress (MPa)	Avg Equivalent Strain	Avg Total Deformation (mm)	Max Total Deformation (mm)	Factor of Safety (FOS)
Original Shank	20.895	3.05e-004	0.72329	2.5436	0.98891
Gyroid shank_v6	20.2	3.33e-004	1.0829	3.0993	0.32166
Gyroid shank_v13	18.226	2.967e-004	0.75879	2.2935	0.58565
Gyroid shank_v18	18.134	2.9452e-004	0.759	2.2797	0.56677

3.) Fz

	Avg Equivalent Stress (MPa)	Avg Equivalent Strain	Avg Total Deformation (mm)	Max Total Deformation (mm)	Factor of Safety (FOS)
Original Shank	1.2503	1.82e-005	2.31e-003	0.0063439	15

Gyroid shank_v6	1.6683	2.78e-005	4.92e-003	0.012047	6.758
Gyroid shank_v13	1.6391	2.73e-005	4.6061e-003	0.01155	6.758
Gyroid shank_v18	1.6238	2.69e-005	4.5928e-003	0.011423	7.764

4.) Mx

	Avg Equivalent Stress (MPa)	**Avg Equivalent Strain**	**Avg Total Deformation (mm)**	**Max Total Deformation (mm)**	**Factor of Safety (FOS)**
Original Shank	106	1.55e-003	2.5369	10.414	0.21917
Gyroid shank_v6	96.661	1.58e-003	3.2221	10.897	0.12704
Gyroid shank_v13	91.253	1.48e-003	2.3718	8.7866	0.15465
Gyroid shank_v18	88.65	1.42e-003	2.344	8.4227	0.22761

5.) My

	Avg Equivalent Stress (MPa)	**Avg Equivalent Strain**	**Avg Total Deformation (mm)**	**Max Total Deformation (mm)**	**Factor of Safety (FOS)**
Original Shank	68.973	1.00e-003	1.0817	4.1355	0.56173
Gyroid shank_v6	74.698	1.21e-003	1.9448	7.0205	0.16583
Gyroid shank_v13	73.839	1.19e-003	1.8354	6.7651	0.20724
Gyroid shank_v18	73.878	1.19e-003	1.8385	6.7349	0.20791

6.) Mz

	Avg Equivalent Stress (MPa)	**Avg Equivalent Strain**	**Avg Total Deformation (mm)**	**Max Total Deformation (mm)**	**Factor of Safety (FOS)**
Original Shank	355.73	5.27e-003	3.1732	16.563	0.09624
Gyroid shank_v6	111.47	1.82e-003	0.4019	1.5244	0.30257
Gyroid shank_v13	110.02	1.79e-003	0.3834	1.4561	0.30257
Gyroid shank_v18	109.87	1.79e-003	0.3823	1.4468	0.37482

Ansys Mesh parameters for 0.5 mm

	Element size	Mesh type	Element quality	Skewness
Original Shank	0.5 mm	Cartesian	0.99861	1.89e-002
Gyroid shank_v6	0.5 mm	Cartesian	0.92416	0.18997
Gyroid shank_v13	0.5 mm	Cartesian	0.9239	0.19088
Gyroid shank_v14	0.5 mm	Cartesian	0.92322	0.19327

Ansys results for 0.5 mm mesh

1.) Fx

	Avg Equivalent Stress (MPa)	Avg Equivalent Strain	Avg Total Deformation (mm)	Max Total Deformation (mm)	Factor of Safety (FOS)
Original Shank	15.084	2.19e-004	0.33236	1.0918	1.6496
Gyroid shank_v6	18.627	2.86e-004	0.66609	2.0112	0.5791
Gyroid shank_v13	18.328	2.81e-004	0.61452	1.8915	0.96373
Gyroid shank_v18	18.426	2.82e-004	0.61939	1.9012	0.96647

2.) Fy

	Avg Equivalent Stress (MPa)	Avg Equivalent Strain	Avg Total Deformation (mm)	Max Total Deformation (mm)	Factor of Safety (FOS)
Original Shank	20.733	3.015e-004	0.723	2.5338	0.75377
Gyroid shank_v6	23.273	3.59e-004	1.2984	3.6226	0.24799
Gyroid shank_v13	20.878	3.19e-004	0.8483	2.5053	0.62413
Gyroid shank_v18	20.756	3.17e-004	0.8446	2.476	0.6358

3.) Fz

	Avg Equivalent Stress (MPa)	Avg Equivalent Strain	Avg Total Deformation (mm)	Max Total Deformation (mm)	Factor of Safety (FOS)
Original Shank	1.2584	1.83e-005	2.31e-003	0.0063093	15
Gyroid shank_v6	1.8631	2.89e-005	5.41e-003	0.012964	9.6529

Gyroid shank_v13	1.8291	2.83e-005	5.02e-003	0.01236	9.6529
Gyroid shank_v18	1.8126	2.80e-005	5.003e-003	0.012246	10.943

4.) Mx

	Avg Equivalent Stress (MPa)	**Avg Equivalent Strain**	**Avg Total Deformation (mm)**	**Max Total Deformation (mm)**	**Factor of Safety (FOS)**
Original Shank	105.07	1.53e-003	2.5294	10.367	0.2018
Gyroid shank_v6	112.23	1.72e-003	3.8598	12.53	0.0909
Gyroid shank_v13	105.59	1.62e-003	2.6798	9.6061	0.0909
Gyroid shank_v18	101.74	1.55e-003	2.6258	9.0835	0.149

5.) My

	Avg Equivalent Stress (MPa)	**Avg Equivalent Strain**	**Avg Total Deformation (mm)**	**Max Total Deformation (mm)**	**Factor of Safety (FOS)**
Original Shank	69.393	1.01e-003	1.0794	4.1194	0.56569
Gyroid shank_v6	85.453	1.31e-003	2.1519	7.4446	0.217
Gyroid shank_v13	84.508	1.29e-003	2.0179	7.1374	0.217
Gyroid shank_v18	84.344	1.28e-003	2.0192	7.0928	0.292

6.) Mz

	Avg Equivalent Stress (MPa)	**Avg Equivalent Strain**	**Avg Total Deformation (mm)**	**Max Total Deformation (mm)**	**Factor of Safety (FOS)**
Original Shank	339.05	4.95e-003	3.1672	16.417	0.0759
Gyroid shank_v6	126.9	1.94e-003	0.43645	1.6113	0.2511
Gyroid shank_v13	125.05	1.91e-003	0.41638	1.5408	0.2511
Gyroid shank_v18	124.15	1.89e-003	0.41442	1.5352	0.359

Ansys Mesh parameters for 0.4 mm

	Element size	Mesh type	Element quality	Skewness
Original Shank	0.4 mm	Cartesian	0.98499	0.10953
Gyroid shank_v6	0.4 mm	Cartesian	0.9261	0.17211
Gyroid shank_v13	0.4 mm	Cartesian	0.9263	0.17255
Gyroid shank_v18	0.4 mm	Cartesian	0.92585	0.17457

Ansys results for 0.4 mm mesh

1.) Fx

	Avg Equivalent Stress (MPa)	Avg Equivalent Strain	Avg Total Deformation (mm)	Max Total Deformation (mm)	Factor of Safety (FOS)
Original Shank	14.845	2.16e-004	0.333	1.0931	1.6647
Gyroid shank_v6	19.924	3e-004	0.66182	1.9945	0.62036
Gyroid shank_v13	19.653	2.96e-004	0.6102	1.874	1.3292
Gyroid shank_v18	19.77	2.97e-004	0.61505	1.8846	1.3286

2.) Fy

	Avg Equivalent Stress (MPa)	Avg Equivalent Strain	Avg Total Deformation (mm)	Max Total Deformation (mm)	Factor of Safety (FOS)
Original Shank	20.472	2.977e-004	0.72437	2.5359	0.63311
Gyroid shank_v6	24.527	3.72e-004	1.2921	3.5982	0.28226
Gyroid shank_v13	22.209	3.34e-004	0.84176	2.4815	0.72732
Gyroid shank_v18	22.116	3.32e-004	0.83903	2.4551	0.72234

3.) Fz

	Avg Equivalent Stress (MPa)	Avg Equivalent Strain	Avg Total Deformation (mm)	Max Total Deformation (mm)	Factor of Safety (FOS)
Original Shank	1.2383	1.7989e-005	2.32e-003	0.0063699	15
Gyroid shank_v6	1.9439	2.95e-005	5.36e-003	0.01277	14.436

Gyroid shank_v13	1.9124	2.89e-005	4.96e-003	0.01219	14.762
Gyroid shank_v18	1.8993	2.87e-005	4.95e-003	0.01209	15

4.) Mx

	Avg Equivalent Stress (MPa)	Avg Equivalent Strain	Avg Total Deformation (mm)	Max Total Deformation (mm)	Factor of Safety (FOS)
Original Shank	103.78	1.51e-003	2.5437	10.376	0.21043
Gyroid shank_v6	117.96	1.78e-003	3.8371	12.426	0.10731
Gyroid shank_v13	111.51	1.67e-003	2.656	9.5039	0.10835
Gyroid shank_v18	107.96	1.61e-003	2.6059	8.999	0.2579

5.) My

	Avg Equivalent Stress (MPa)	Avg Equivalent Strain	Avg Total Deformation (mm)	Max Total Deformation (mm)	Factor of Safety (FOS)
Original Shank	68.25	9.92e-004	1.0848	4.1248	0.58439
Gyroid shank_v6	91.536	1.37e-003	2.1364	7.3781	0.23379
Gyroid shank_v13	90.632	1.36e-003	2.0023	7.0708	0.23379
Gyroid shank_v18	90.568	1.35e-003	2.0036	7.0268	0.49332

6.) Mz

	Avg Equivalent Stress (MPa)	Avg Equivalent Strain	Avg Total Deformation (mm)	Max Total Deformation (mm)	Factor of Safety (FOS)
Original Shank	329.45	4.806e-003	3.1514	16.474	0.077445
Gyroid shank_v6	135.46	2.04e-003	0.447	1.5966	0.26468
Gyroid shank_v13	133.5	2e-003	0.4265	1.5272	0.26468
Gyroid shank_v18	132.54	1.99e-003	0.4244	1.5229	0.32605

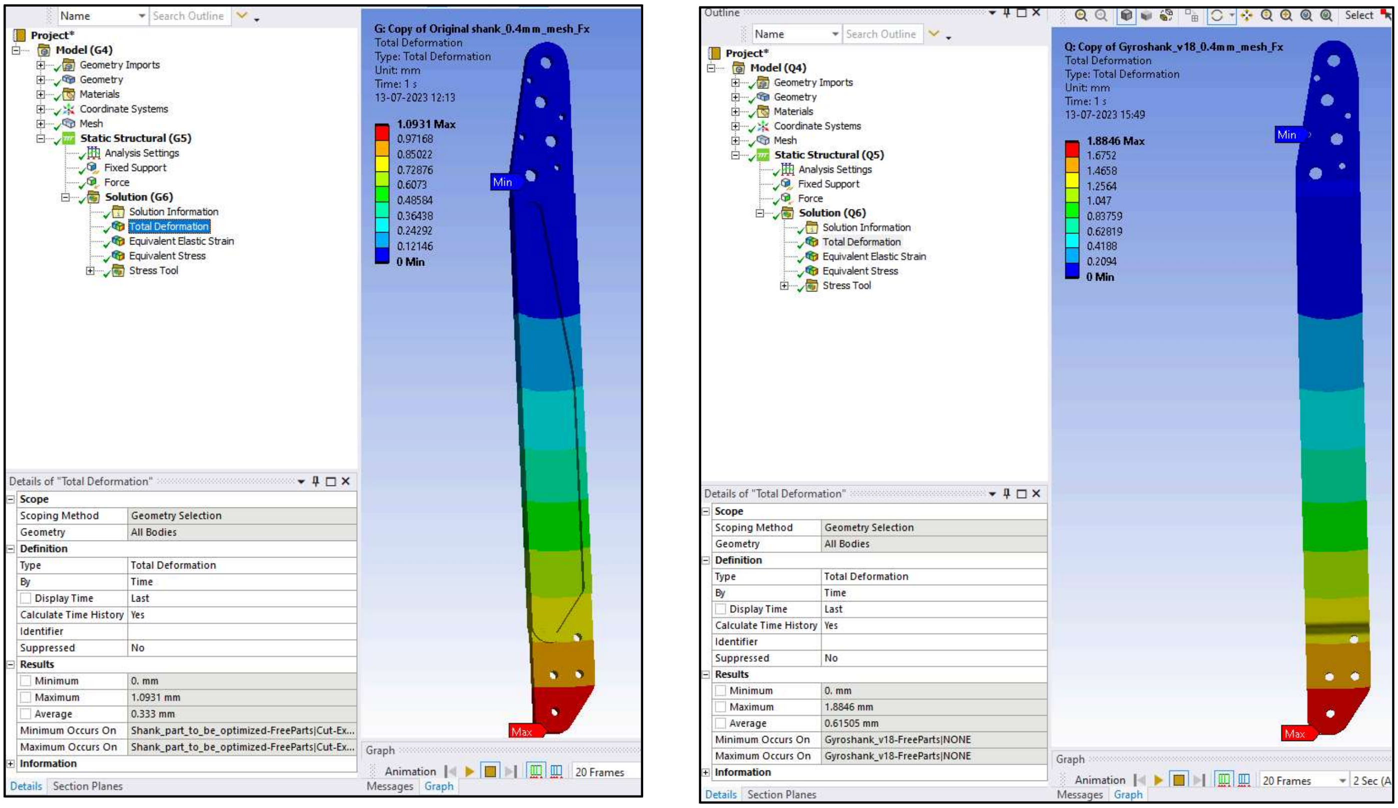


Fig 19: Total deformation in original and gyroid shank while applying Fx

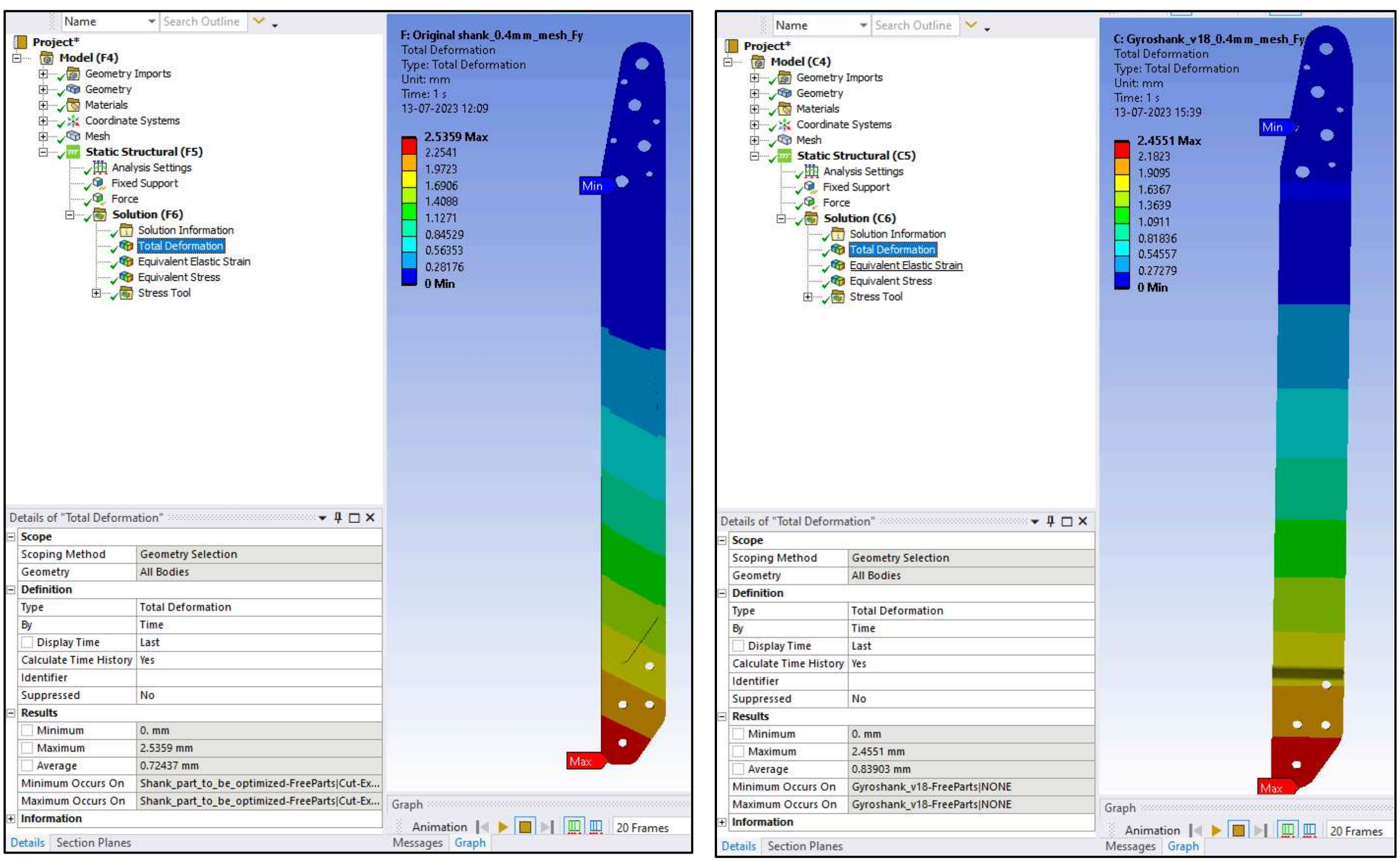


Fig 20: Total deformation in original and gyroid shank while applying Fy

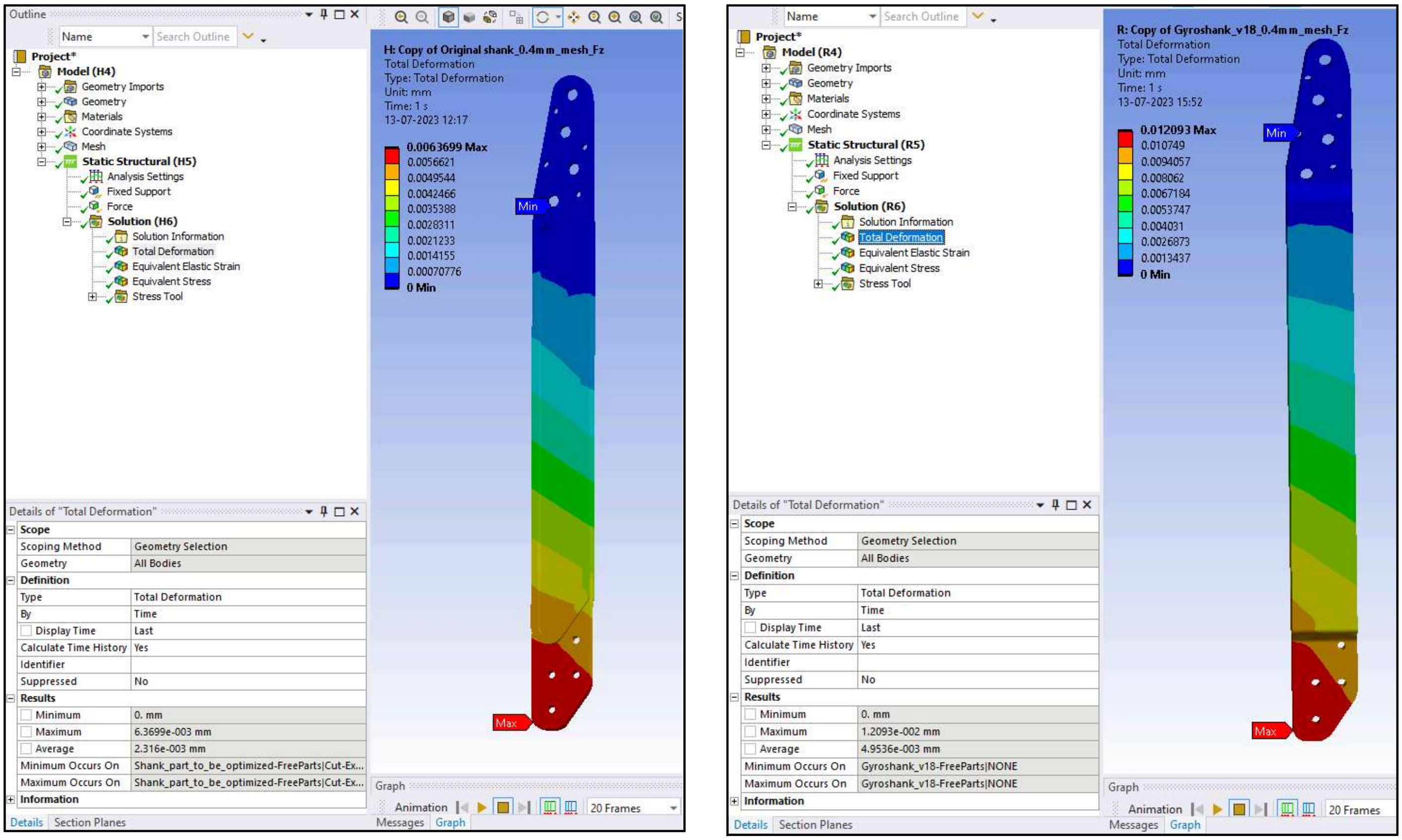


Fig 21: Total deformation in original and gyroid shank while applying Fz

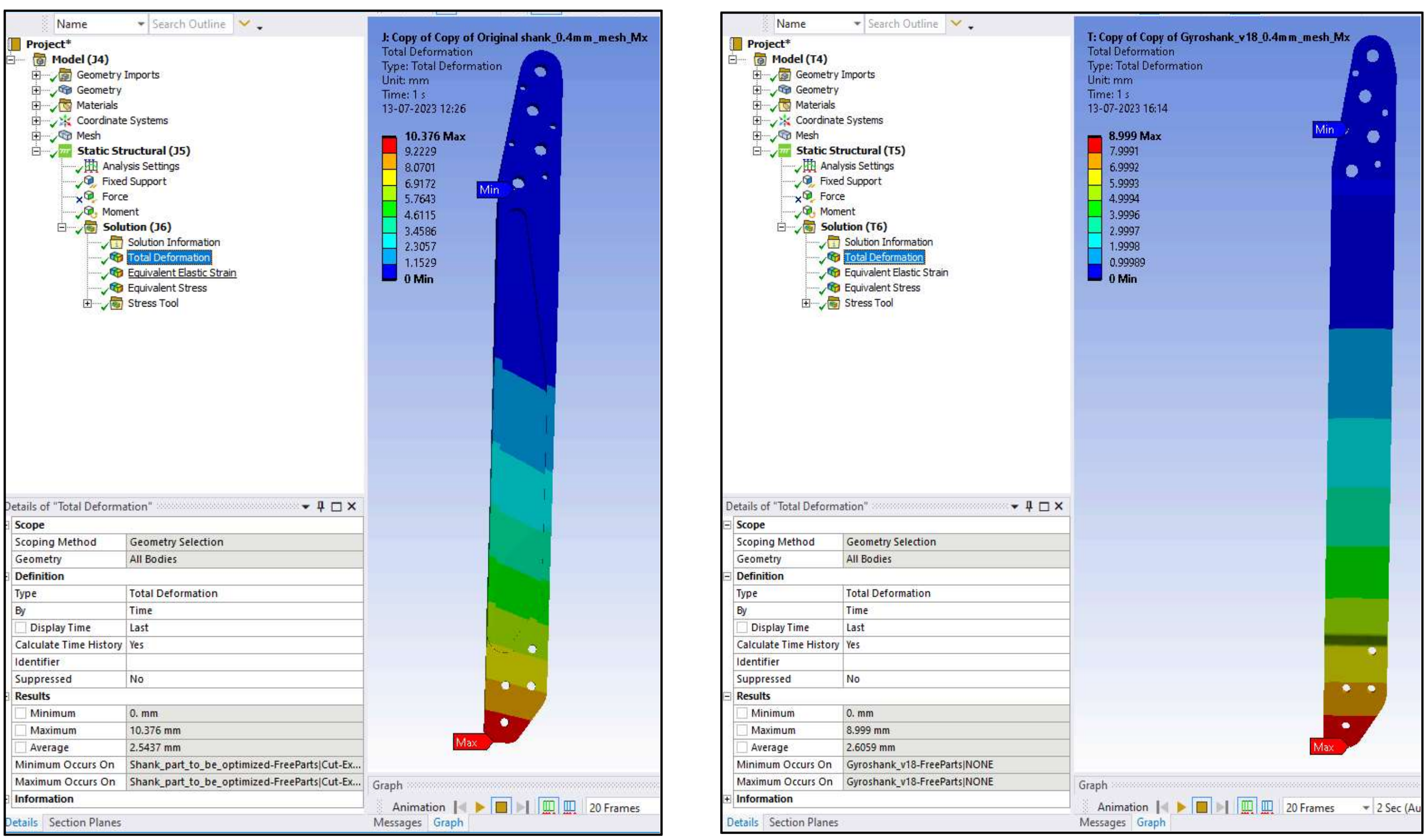
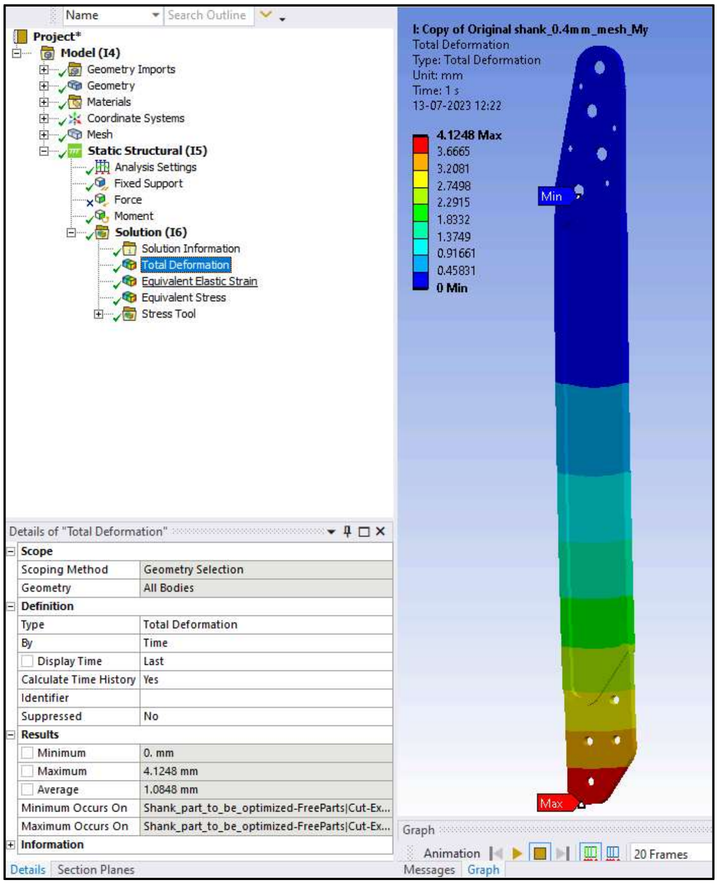


Fig 22: Total deformation in original and gyroid shank while applying Mx



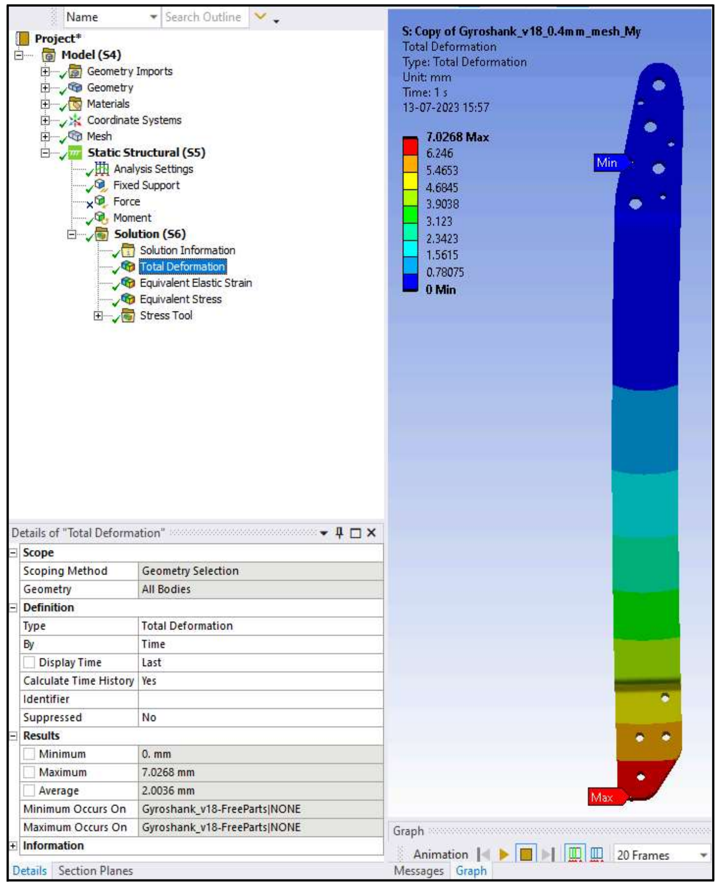
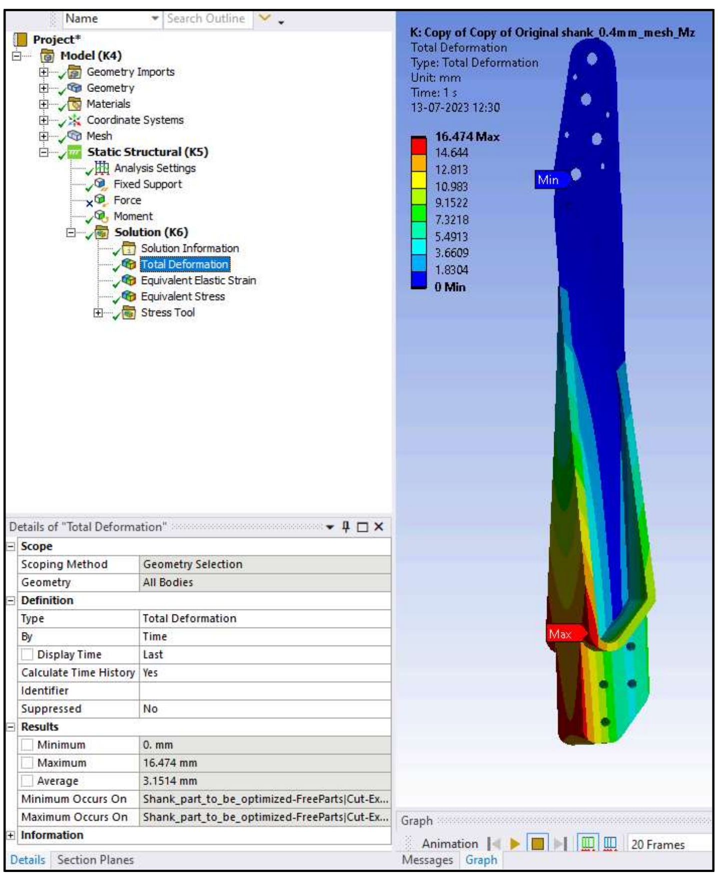


Fig 23: Total deformation in original and gyroid shank while applying My



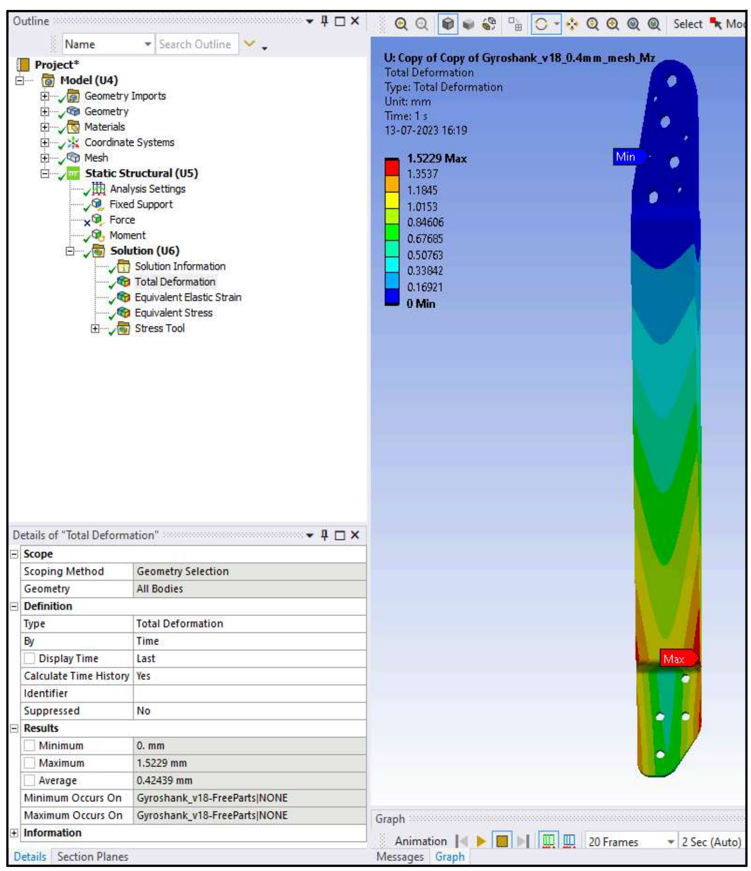


Fig 24: Total deformation in original and gyroid shank while applying Mz

Section 4: - Accuracy and convergence of results

To check of accuracy and convergence of results, we will be looking at **Max Total Deformation** [5]. The reason for using these two parameters only is that the other parameters will be affected by stress singularities, which will give inaccurate error percentages.

A **stress singularity**[6] is a mesh point where the stress does not converge towards a specific value. As we keep refinement the mesh, the stress at this point keeps increasing, and increasing, and increasing… Theoretically, the stress at the singularity is infinite. However, **these stress singularities do not affect deformations because they are calculated directly and thus have no relation to stresses, unlike strain and Factor Of Safety (FOS).**

For **checking convergence,** we will be using the following formula[5]:-

$$\boxed{\textbf{Error} = 100 \cdot \left|(\phi_{i+1} - \phi_i) / \phi_i\right| < E}$$

Where: ϕ : Max Total Deformation
E: User-defined accuracy
i: Refinement iteration

We will be keeping **E = 5%,** and if **we get an error less than 5%, then we can say that the results are accurate and the meshes are converging.**

Checking of convergence using Max Total deformation for original shank

SNo.	Forces/Moments	i+1	i	ϕ_{i+1}(mm)	ϕ_i(mm)	Error
1.	Fx	0.5 mm mesh	1 mm mesh	1.0918	1.0955	0.338%
		0.4 mm mesh	0.5 mm mesh	1.0931	1.0918	0.119%
2.	Fy	0.5 mm mesh	1 mm mesh	2.5338	2.5436	0.385%
		0.4 mm mesh	0.5 mm mesh	2.5359	2.5338	0.083%
3.	Fz	0.5 mm mesh	1 mm mesh	0.0063093	0.0063439	0.545%
		0.4 mm mesh	0.5 mm mesh	0.0063699	0.0063093	0.960%
4.	Mx	0.5 mm mesh	1 mm mesh	10.367	10.414	0.451%
		0.4 mm mesh	0.5 mm mesh	10.376	10.367	0.087%
5.	My	0.5 mm mesh	1 mm mesh	4.1194	4.1355	0.389%
		0.4 mm mesh	0.5 mm mesh	4.1248	4.1194	0.131%
6.	Mz	0.5 mm mesh	1 mm mesh	16.417	16.563	0.881%
		0.4 mm mesh	0.5 mm mesh	16.474	16.417	0.347%

Checking of convergence using Max Total deformation for Gyroid shank_v6

SNo.	Forces/Moments	i+1	i	ϕ_{i+1}(mm)	ϕ_i(mm)	Error
1.	Fx	**0.5 mm mesh**	**1 mm mesh**	2.0112	1.8834	6.786%
		0.4 mm mesh	**0.5 mm mesh**	1.9945	2.0112	0.830%
2.	Fy	**0.5 mm mesh**	**1 mm mesh**	3.6226	3.0993	16.884%
		0.4 mm mesh	**0.5 mm mesh**	3.5982	3.6226	0.674%
3.	Fz	**0.5 mm mesh**	**1 mm mesh**	0.012964	0.012047	7.612%
		0.4 mm mesh	**0.5 mm mesh**	0.01277	0.012964	1.496%
4.	Mx	**0.5 mm mesh**	**1 mm mesh**	12.53	10.897	14.986%
		0.4 mm mesh	**0.5 mm mesh**	12.426	12.53	0.830%
5.	My	**0.5 mm mesh**	**1 mm mesh**	7.4446	7.0205	6.041%
		0.4 mm mesh	**0.5 mm mesh**	7.3781	7.4446	0.893%
6.	Mz	**0.5 mm mesh**	**1 mm mesh**	1.6113	1.5244	5.701%
		0.4 mm mesh	**0.5 mm mesh**	1.5966	1.6113	0.912%

Checking of convergence using Max Total deformation for Gyroid shank_v13

SNo.	Forces/Moments	i+1	i	ϕ_{i+1}(mm)	ϕ_i(mm)	Error
1.	Fx	**0.5 mm mesh**	**1 mm mesh**	1.8915	1.7846	5.990%
		0.4 mm mesh	**0.5 mm mesh**	1.874	1.8915	0.925%
2.	Fy	**0.5 mm mesh**	**1 mm mesh**	2.5053	2.2935	9.235%
		0.4 mm mesh	**0.5 mm mesh**	2.4815	2.5053	0.949%
3.	Fz	**0.5 mm mesh**	**1 mm mesh**	0.01236	0.01155	7.013%
		0.4 mm mesh	**0.5 mm mesh**	0.01219	0.01236	1.375%
4.	Mx	**0.5 mm mesh**	**1 mm mesh**	9.6061	8.7866	9.327%
		0.4 mm mesh	**0.5 mm mesh**	9.5039	9.6061	1.064%
5.	My	**0.5 mm mesh**	**1 mm mesh**	7.1374	6.7651	5.503%
		0.4 mm mesh	**0.5 mm mesh**	7.0708	7.1374	0.933%
6.	Mz	**0.5 mm mesh**	**1 mm mesh**	1.5408	1.4561	5.817%
		0.4 mm mesh	**0.5 mm mesh**	1.5272	1.5408	0.883%

Checking of convergence using Max Total deformation for Gyroid shank_v18

SNo.	Forces/Moments	i+1	i	ϕ_{i+1}(mm)	ϕ_i(mm)	Error
1.	Fx	**0.5 mm mesh**	**1 mm mesh**	1.9012	1.7956	5.881%
		0.4 mm mesh	**0.5 mm mesh**	1.8846	1.9012	0.873%
2.	Fy	**0.5 mm mesh**	**1 mm mesh**	2.476	2.2797	8.611%
		0.4 mm mesh	**0.5 mm mesh**	2.4551	2.476	0.844%
3.	Fz	**0.5 mm mesh**	**1 mm mesh**	0.012246	0.011423	7.205%
		0.4 mm mesh	**0.5 mm mesh**	0.01209	0.012246	1.274%
4.	Mx	**0.5 mm mesh**	**1 mm mesh**	9.0835	8.4227	7.845%
		0.4 mm mesh	**0.5 mm mesh**	8.999	9.0835	0.930%
5.	My	**0.5 mm mesh**	**1 mm mesh**	7.0928	6.7349	5.314%
		0.4 mm mesh	**0.5 mm mesh**	7.0268	7.0928	0.931%
6.	Mz	**0.5 mm mesh**	**1 mm mesh**	1.5352	1.4468	6.110%
		0.4 mm mesh	**0.5 mm mesh**	1.5229	1.5352	0.801%

Section 5: - Observations and discussion about the trend of results

- For the original shank, the results are **converging from 1 mm mesh to 0.5 mm mesh and from 0.5 mm mesh to 0.4 mm mesh** as in both of the cases the error is less than 5% **as calculated in section 4.**

- For all gyroid shanks, the results **converge from 0.5 mm mesh to 0.4 mm mesh,** showing an error of less than 5%, but **they do not converge with 1 mm mesh** which shows significant large errors greater than 5%.

- The stress singularity trend can be seen as we refine mesh more and more; the average equivalent stresses also increase.

- The gyroid shank_v13 and gyroid shank_v18 show better results in all forces and moments than the gyroid shank_v6. So we can say that adding fillets and chamfers at sharp edges where the structure transitions from gyroid to solid improves stress distribution and deformations.

- Compared to the original shank, gyroid shanks v13 and v18 show better Fx, Fy, Mx, and Mz results when considering total deformations.

- In Mz, the results between gyroid and original shanks in all three meshes have a huge difference. So we may conclude that gyroids help manage torsional loads better than the solid beam structure of the original shank.

- Although there is inaccuracy in stress and strain results due to stress singularities, still, according to St. Venant's Principle[6], it doesn't mean that stresses in every part will be incorrect. That is why average stresses and average strains have been considered in the results.

- A general conclusion can be made that in linear forces, although the original shank shows better results, there is still not quite a difference between its strength and the strength of gyroid shanks. While applying moments, especially Mz, the gyroid shank shows better results than the original one with a significant difference.

- Gyroid shank_v18 shows improvement in max total deformation by 5.3% compared to gyroid shank_v13 while applying Mx . Thus, we can conclude that adding fillets at the outside and inner portion of the central part and all intersections with the solid part has improved the performance while reducing the error of stress singularity a little bit.

- Decreasing gyroid thickness to 0.25mm will decrease weight by 15 grams, and reducing wall thickness to 0.75mm will decrease weight by 10 grams. But in both cases, the strength will also get reduced further.

Section 6: - Conclusion and future scope of this Idea

The central part made of gyroids, though reduces weight by 30g, but it will have greater manufacturing complexity and will require greater cost than the original one. Also, there is not a significant difference in strength between the two parts other than Mz, and in the real world, there is very little magnitude of Mz, which will act on the shank of a quadruped robotic leg. So considering all these factors, it has been decided not to bring this design into development yet.

Given the gyroids' effectiveness in managing torsional loads, they could be applied to other parts of the robotic leg, such as the thigh and torso, which experience significant torsional stress. While sandwich structures can reduce weight, they are less effective against torsional loads. Gyroid structures could enhance load management in these areas. Also, the scope of using graded gyroids instead of uniform gyroids exists [7]. Graded gyroids, with variable cell sizes, offer improved energy absorption compared to uniform gyroids, presenting promising new applications and benefits.

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SUPPLEMENTARY MATERIAL

https://drive.google.com/drive/folders/18CN2HM5j6G-d_1-8VBAWLtPgmjL0pXag?usp=sharing - Ansys simulation images and Solidworks step files of the central part of the shank.