Prosthetic Running Blade Project

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1 Introduction

This project aims to analyse a prosthetic running blade using finite element analysis. Running blades are lightweight prostheses designed to store and release elastic energy during running. As a result, both durability under cyclic loading and resistance to resonance are important design considerations. In this study, a baseline blade geometry was developed and assessed under the loading conditions given in the brief to evaluate its stress distribution, fatigue behaviour, and fundamental natural frequency. A geometric design iteration was then introduced to improve the vibration performance, and the effect of material selection was further examined through a comparison between CFRP and Aluminium 2014 T4.

2 Methods

2.1 Engineering Data

For Aluminium, it is recorded in the dataset, but for CFRP (Carbon Fibre Reinforced Composite), although an orthotropic woven CFRP material was available, an equivalent isotropic CFRP model was adopted in this study for simplicity and consistency. This avoided the need to define detailed laminate orientations while still providing a reasonable approximation of the overall structural response of the blade.

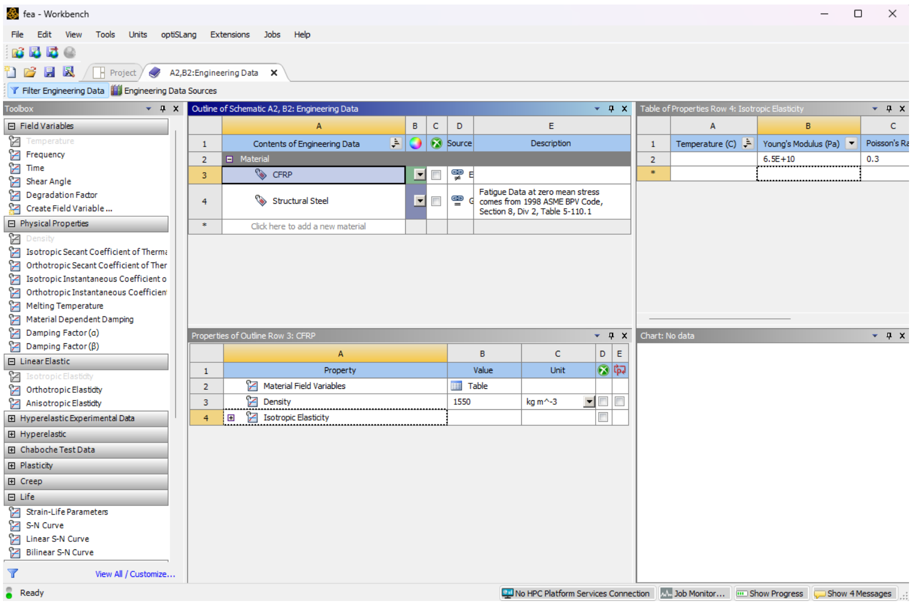

Figure 1 Engineering Dataset

As shown in Figure 1, the material was modelled with a Young's modulus of 65 GPa, a Poisson's ratio of 0.30, and a density of 1550 kg/m³. These values were selected as representative simplified properties based on published data [1].

2.2 Parameter Setup

In this project, stress, vibration and fatigue is analysed, so there are multiple parameters need to be set up.

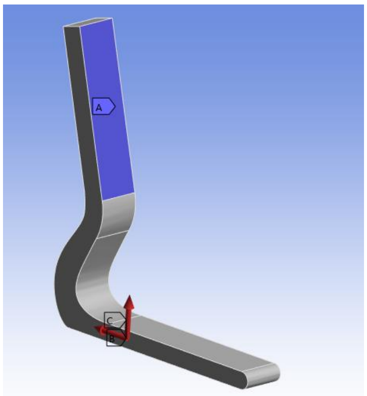

Figure 2 Ansys Setup Screenshots

In this analysis, the forces are simplified into a normal force and friction force due to motion. The direction of the motion is set to be positive x direction, so the friction is in negative x direction as shown in figure 2. The connection area, which is highlighted using blue, is set to be the fixed support.

2.3 Mesh Refinement Study

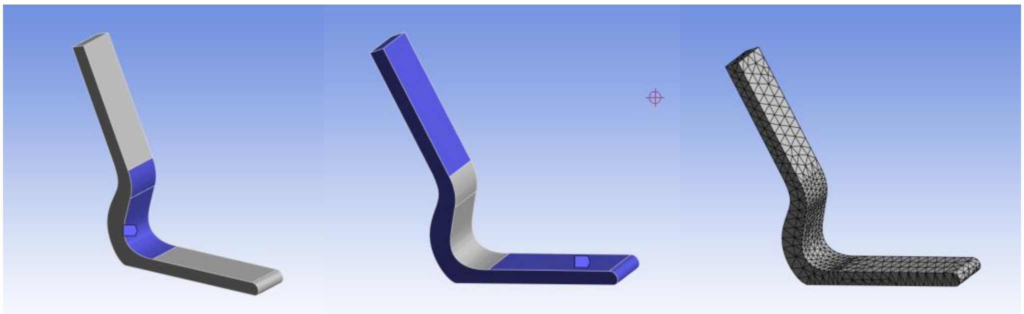

Figure 3 Mesh Sizing Refinement

For the refinement study, quadratic order of meshing is used. For the coarse mesh configuration, shown in figure 3, a global element size of 24 mm was applied to most of the blade surfaces, while a local element size of 12 mm was assigned to the inner curved region and the foot contact surface. These areas were refined because they were expected to experience higher stress gradients and more significant bending effects under loading. This mesh was used as the first configuration in the mesh refinement study. For a medium sizing, the global size is set to be 16mm and local size is 8mm. For the fine sizing, the global size is 10mm and local size is 5mm.

3 Initial Design

3.1 Initial Sketch and Model

Figure 4 Initial sketch and corresponding CAD model of the baseline running blade design

The baseline blade was developed from an initial sketch and then refined into a CAD model for analysis. The design adopted a curved geometry with a connecting region at the top, a narrowed midsection, and a straight lower section to represent the contact area with the ground. This baseline configuration was intended to provide sufficient flexibility for energy storage.

The baseline running blade was defined using the dimensions shown in the updated technical drawing. The model has an overall horizontal length of 296 mm and a foot section length of 250 mm.

3.2 Result Discussion

3.2.1 CFRP

A mesh refinement study was carried out for the CFRP baseline model.

3.2.1.1 Coarse sizing

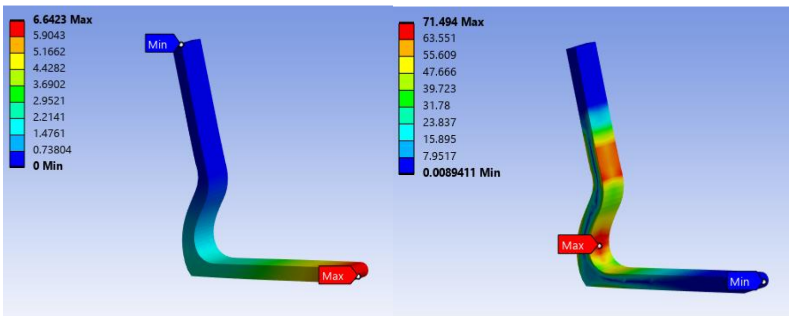

Figure 5 Stress and deformation analysis

The equivalent stress result shows that the maximum stress occurs at the inner curved transition region, with a peak value of approximately 71.5 MPa. This is consistent with the expected behaviour of the blade, since this area experiences a large geometric change and relatively high bending effects under loading. The result indicates that the inner curved region remains the most critical part of the baseline design.

The total deformation result shows a maximum displacement of 6.64 mm at the front end of the foot section, while the minimum deformation occurs at the fixed upper mounting region. This is reasonable as displacement increases away from the fixed support.

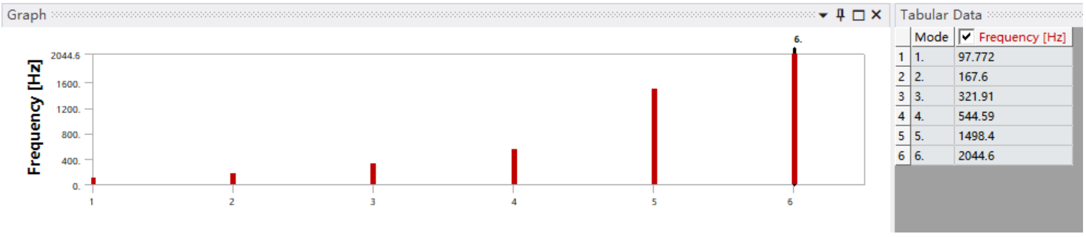

Figure 5 Natural Frequency analysis

The modal analysis showed that the first natural frequency of the baseline CFRP blade was 97.7 Hz. This value is well above the minimum required frequency of 50 Hz, indicating that the design satisfies the vibration criterion given in the brief.

3.2.1.2 Medium Sizing

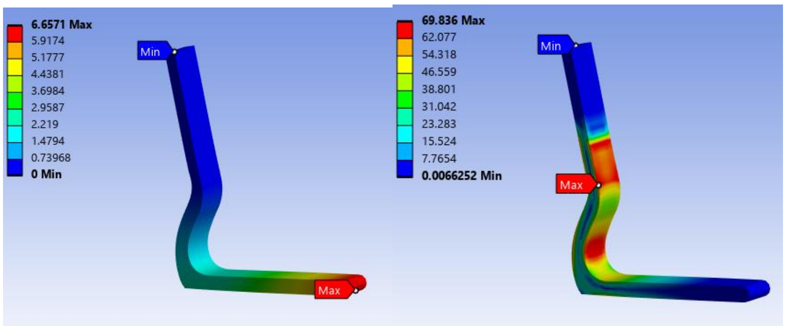

Figure 6 Stress and Deformation for medium mesh size

For the medium mesh configuration, the maximum total deformation was 6.66 mm, and the maximum equivalent stress was 69.8 MPa. Compared with the coarse mesh result, the change in both deformation and stress was very small (0.3% and 2%). This indicates that the solution was already approaching convergence.

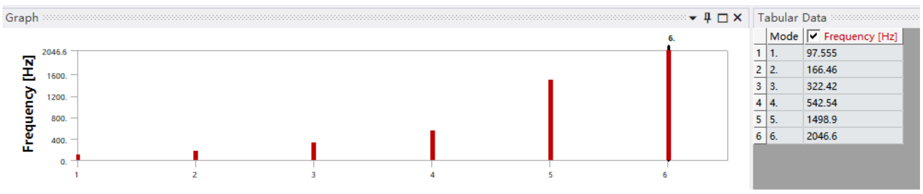

Figure 7 Natural Frequency for medium mesh

For the medium mesh configuration, the first natural frequency was 97.6 Hz. Compared with the coarse mesh result, the change was only 0.1%, indicating that the modal result was already relatively stable.

3.2.1.3 Fine Sizing

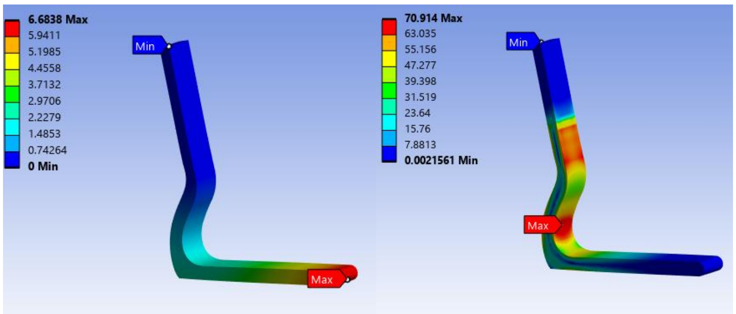

Figure 8 Stress and Deformation for fine mesh size

The maximum total deformation changed 0.4% for the fine mesh. Similarly, the maximum equivalent stress increased only 1.6%. These small changes indicate that the solution was approaching convergence.

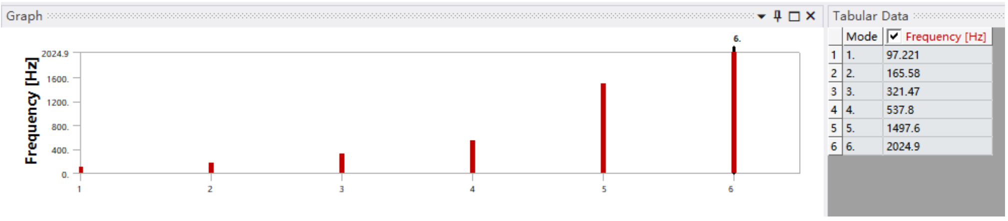

Figure 9 natural frequency for fine mesh size

For the fine mesh configuration, the first natural frequency was 97.2 Hz. Compared with the medium mesh result, the change was 0.3%, indicating that the modal result had nearly converged.

Fatigue tool analysis was not carried out because a reliable S-N curve for the selected equivalent isotropic CFRP material was not available in ANSYS. Therefore, a simplified strength-based fatigue assessment was used. A conservative safety factor of 3 was applied to the representative strength of 800 MPa, giving an allowable stress of 266.7 MPa. The maximum equivalent stress of the final CFRP design was 63.4 MPa, which is far below this allowable value. This suggests that the design has a large safety margin under the simplified fatigue criterion. [1].

The design achieved a mass of approximately 0.8 kg. It is acceptable for a lightweight running blade.

3.2.2 Aluminium 2014 T4

3.2.2.1 Coarse Sizing

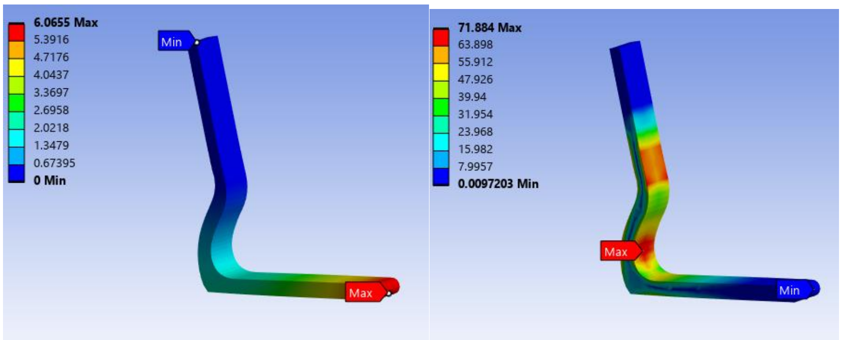

Figure 10 Stress and Deformation for coarse mesh size

For the coarse mesh configuration of the baseline aluminium blade, the maximum total deformation was 6.07 mm, and the maximum equivalent stress was 71.9 MPa. The highest stress occurred in the inner curved transition region, while the largest deformation was found at the front end of the foot section.

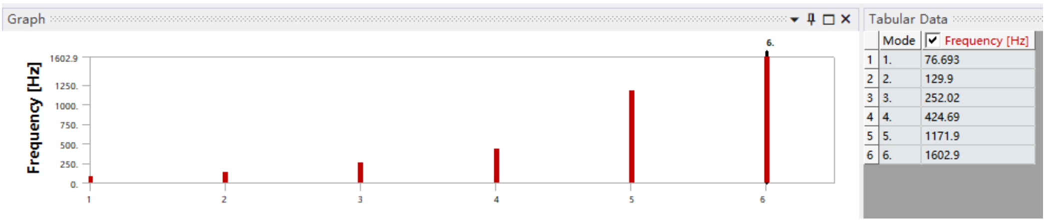

Figure 11 natural frequency for coarse mesh size

The modal analysis showed that the first natural frequency of the baseline aluminium blade was 76.7 Hz. Since this value is higher than the required minimum frequency of 50 Hz, the baseline aluminium design satisfies the vibration criterion given in the brief.

3.2.2.2 Medium Sizing

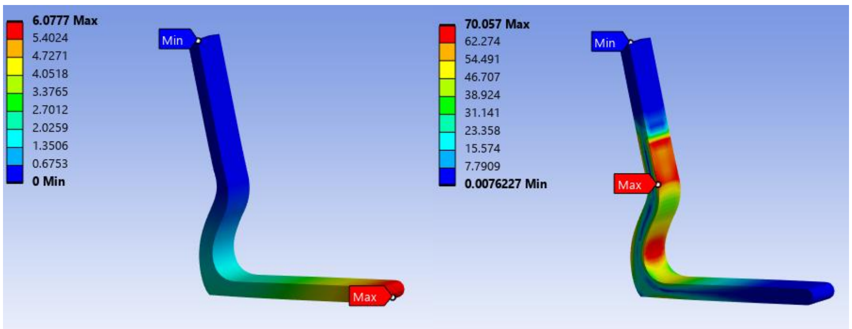

Figure 12 Stress and Deformation for medium mesh size

For the medium mesh configuration of the baseline aluminium blade, the maximum total deformation was 6.08 mm, and the maximum equivalent stress was 70.1 MPa. Compared with the coarse mesh result, both values changed only very slightly (0.33% and 1%).

Figure 13 natural frequency for medium mesh size

For the medium mesh configuration of the baseline aluminium blade, the first natural frequency was 76.5 Hz. Compared with the coarse mesh result, the change was only 0.1%.

3.2.2.3 Fine Sizing

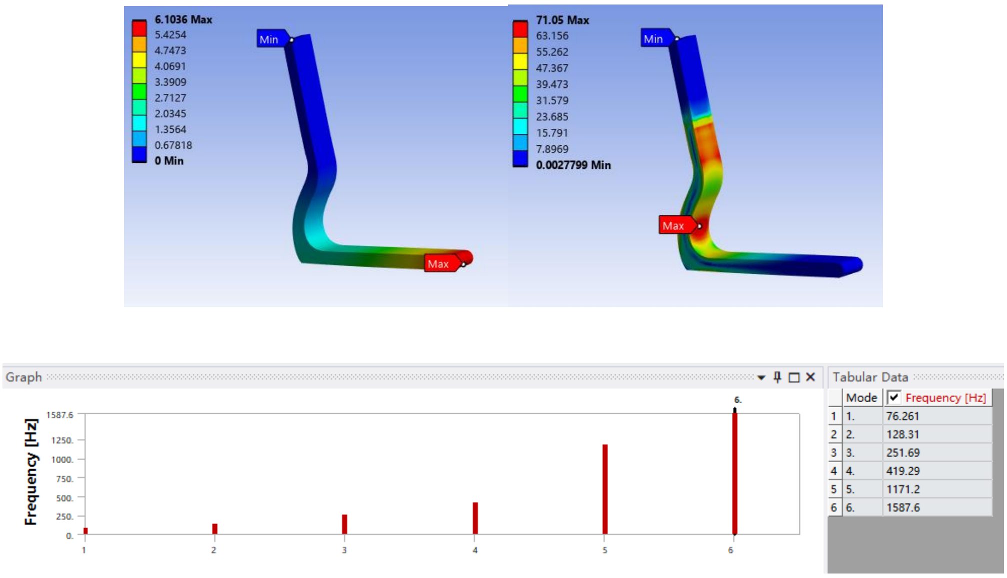

Figure 14 Stress, Deformation and frequency for fine mesh size

For the fine mesh configuration of the baseline aluminium blade, the maximum total deformation was 6.10 mm, the maximum equivalent stress was 71.1 MPa, and the first natural frequency was 76.3 Hz. Compared with the medium mesh results, all changes were only 0.3% and 0.1%.

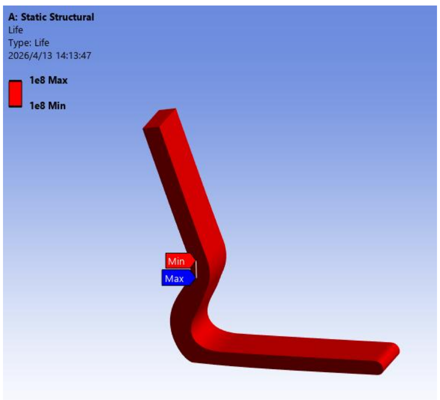

Figure 15 Fatigue for fine mesh size

The fatigue analysis of the aluminium blade showed a minimum predicted life of 1×10^8 cycles, which is significantly higher than the required minimum value of a million cycles. The mass is found to be around 1.80kg, which is heavier than CFRP.

4 Final Iteration

4.1 Model and Changes

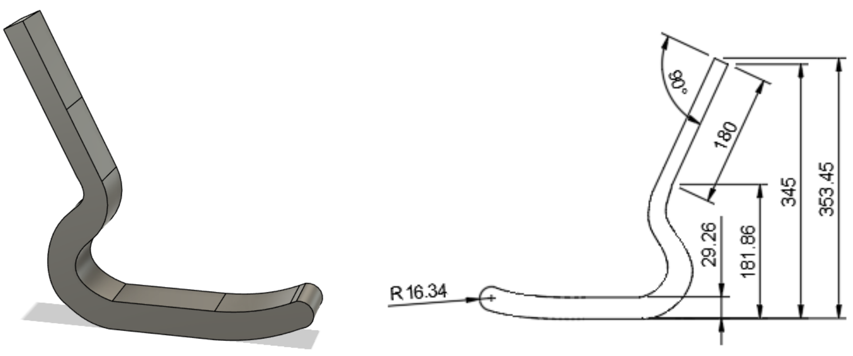

Figure 16 Final Iteration

The iterated design introduced a raised front foot section and a smoother lower curved profile compared with the baseline blade. The updated geometry has an overall height of 353.5 mm, a main curved transition radius of 90 mm, and a front tip radius of 16.3 mm. These changes were intended to produce a more blade-like geometry and improve the dynamic response of the structure.

4.2 Result Discussion

4.2.1 CFRP

4.2.1.1 Coarse Mesh

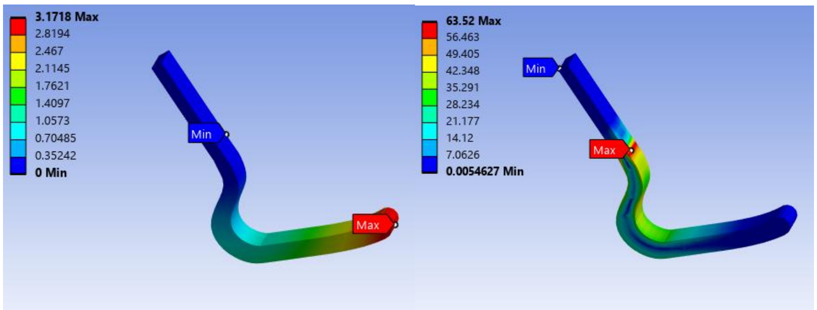

Figure 17 Coarse mesh analysis

For the coarse mesh configuration, the iterated design produced a maximum total deformation of 3.17 mm and a maximum equivalent stress of 63.5 MPa. Compared with the baseline design, both values were reduced. This suggests that the updated geometry improved the structural response of the blade by increasing stiffness and reducing the severity of local stress concentration in the curved transition region.

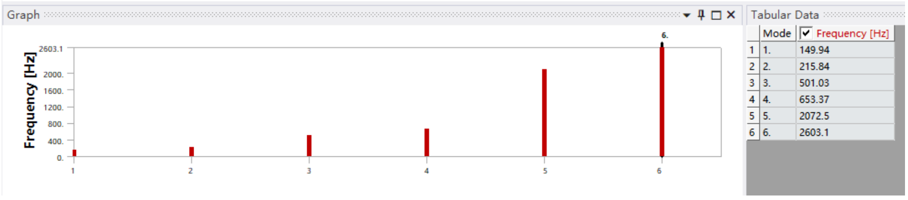

Figure 18 Coarse mesh frequency analysis

The first natural frequency of the iterated blade was 149 Hz, compared with the baseline design, meeting up with the 50 Hz criteria.

4.2.1.2 Medium Mesh

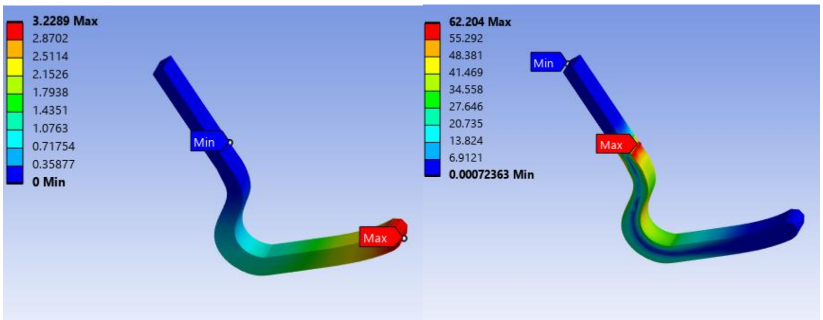

Figure 19 Medium mesh analysis

For the medium mesh configuration of the iterated design, the maximum total deformation was 3.22 mm, and the maximum equivalent stress was 62.2 MPa. Compared with the coarse mesh result, the deformation and stress changed only slightly within 1%. This suggests that the result was already highly stable.

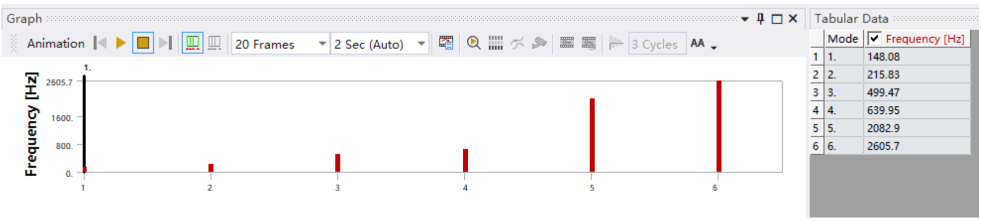

Figure 20 Medium mesh frequency analysis

For the medium mesh configuration of the iterated design, the first natural frequency was 148.1 Hz. Compared with the coarse mesh result, the change was very small, indicating that the modal result was already highly stable.

4.2.1.3 Fine Mesh

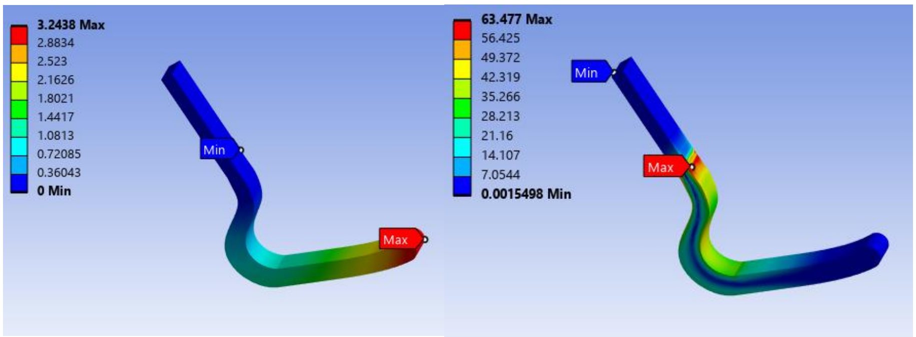

Figure 21 Fine mesh analysis

For the iterated design, the maximum total deformation changed only slightly for 0.6%. In contrast, the maximum equivalent stress increased for 1.6%. This indicates that the deformation and modal results were already highly stable.

Figure 22 Fine mesh frequency analysis

The first natural frequency changed only slightly from the medium mesh to 147 Hz for the fine mesh. This very small difference indicates that the modal result had effectively converged.

Using a strength value of 800 MPa and a safety factor 3, the allowable stress was 266.7MPa. Since the maximum equivalent stress predicted by the static analysis was only 63.4 MPa, the CFRP design satisfied the simplified fatigue criterion with a large safety margin. The mass is calculated to be 1.3kg, which is slightly heavier than the initial design, but it is still acceptable.

According to vibration theory, the natural frequency is related to the ratio between structural stiffness and mass. The iterated geometry reduced deformation and created a smoother load path, indicating increased effective stiffness. Although the mass increased slightly, the stiffness improvement was more significant.

4.2.2 Aluminium 2014 T4

4.2.2.1 Coarse Mesh

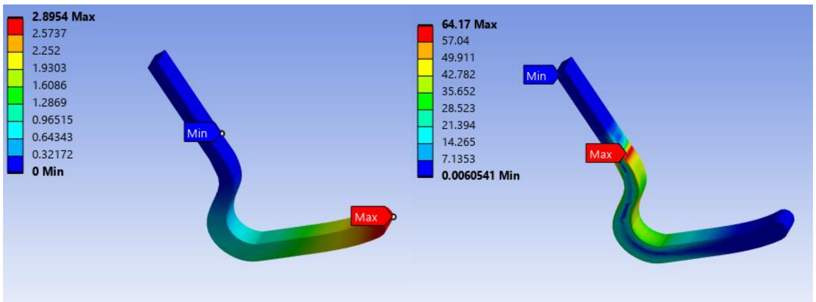

Figure 23 Coarse mesh analysis

For the coarse mesh configuration of the aluminium blade, the maximum total deformation was 2.90 mm, and the maximum equivalent stress was 64.2 MPa. The deformation remained concentrated towards the free front end, while the highest stress occurred in the upper curved transition region, indicating that the blade still behaved as a cantilever-like structure under the applied loads.

Figure 24 Coarse mesh frequency analysis

The modal analysis showed that the first natural frequency of the aluminium blade was 117.6Hz. Since this value is higher than the required minimum frequency of 50 Hz, the vibration criterion is satisfied.

4.2.2.2 Medium Mesh

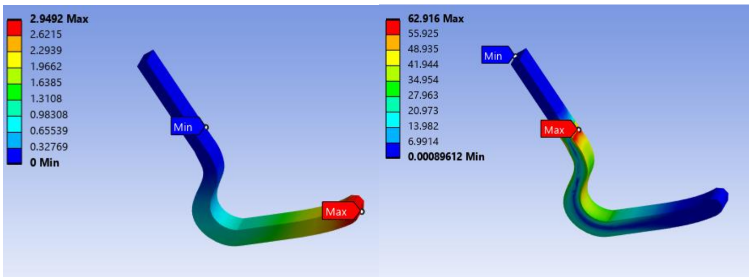

Figure 25 Medium mesh analysis

For the medium mesh configuration of the aluminium blade, the maximum equivalent stress was 62.9 MPa and the maximum total deformation was 2.95 mm. Compared with the coarse mesh result, both changed 1.8% and 2%.

Figure 26 Medium mesh frequency analysis

For the medium mesh configuration of the aluminium blade, the first natural frequency was 116 Hz. Compared with the coarse mesh result, the change was very small, indicating that the modal result was already relatively stable.

4.2.2.3 Fine Mesh

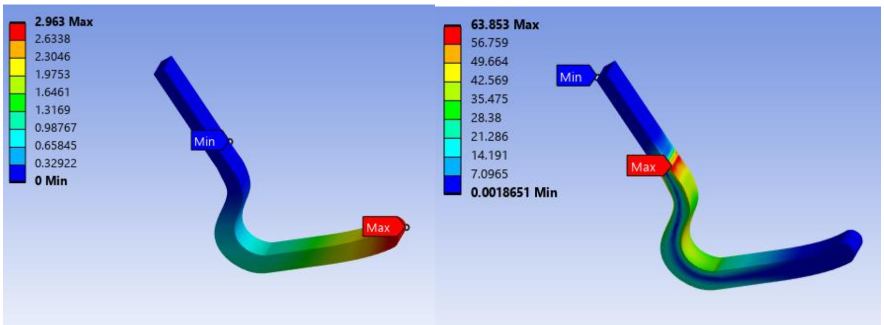

Figure 27 Fine mesh analysis

For the fine mesh configuration of the aluminium blade, the maximum total deformation was 2.96 mm and the maximum equivalent stress was 63.9 MPa. Compared with the medium mesh result, both changed very slightly, reaching convergence.

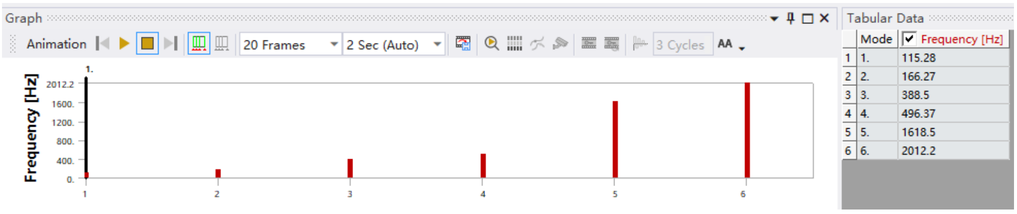

Figure 28 Fine mesh frequency analysis

For the fine mesh configuration of the aluminium blade, the first natural frequency was 115 Hz. Compared with the medium mesh result, the change was very small, indicating that the modal result was already highly stable.

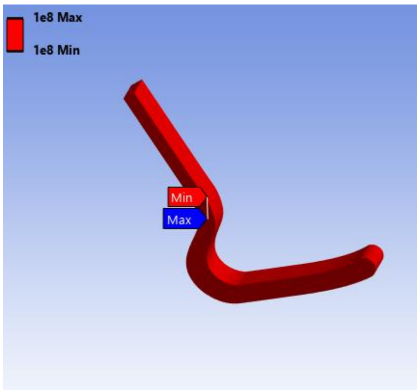

Figure 29 Fine mesh fatigue analysis

The fatigue analysis of the aluminium blade showed a minimum predicted life of 1×10^8 cycles, which is significantly higher than the required minimum value of a million cycles. This indicates that the design satisfies the fatigue life criterion given in the brief. The mass is calculated to be 2.1kg, which is quite heavy for a running blade.

5 Overall Discussion

Compared with the baseline design, the iterated blade produced higher first natural frequencies for both CFRP and aluminium, while the maximum deformation was reduced in both cases. The maximum equivalent stress also decreased after iteration, indicating that the modified geometry improved not only the overall stiffness of the blade but also the stress distribution in the main bending region. This suggests that the updated blade profile provided a more efficient load path, reducing the severity of local stress concentration while improving vibration performance.

From an FEA perspective, these results are physically reasonable because the blade behaves as a cantilever-like structure, with the largest deformation occurring towards the free end and the highest stresses developing in curved transition regions where bending effects are greatest. The mesh refinement studies further support the accuracy of the displacement and modal results, since both deformation, stress and natural frequency changed only slightly between the medium and fine meshes.

There are also several limitations. The ideal fixed support is likely to make the model stiffer than the real socket connection, so the predicted deformation may be underestimated, and the natural frequency may be overestimated. The static loading condition ignores impact and time-dependent force variation during running, so the fatigue and stress results may not represent the worst dynamic case. In addition, modelling CFRP as an equivalent isotropic material ignores fibre direction and laminate stacking effects, which may affect both stiffness and failure prediction.

6 Conclusion

Overall, the FEA results showed that both the baseline and iterated blade designs satisfied the required natural frequency criterion, while the aluminium blade also met the fatigue life requirement. The geometric iteration improved the structural response of the blade by increasing the fundamental frequency and reducing both deformation and peak stress.

7 Reference

[1] M. B. Dow and D. L. Smith, Properties of Two Composite Materials Made of Toughened Epoxy Resin and High-Strain Graphite Fiber, NASA Technical Paper 2826. Washington, DC, USA: National Aeronautics and Space Administration, 1988.