Bladena

BLADE ENABLER

Stronger blades, more energy

Structural weaknesses of blades in operation

White paper 1 of 3

April, 2022

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Introduction

This white paper presents the design of the current blades in operation and weaknesses from the structural perspective based on field experience and structural knowledge.

Wind turbines are the largest contributors to renewable energy in Denmark and the rest of Europe. With the rise in installed capacity, the length of blades has also increased. The direct impact is that the blades loads have scaled up as well. Consequently, increasing the risk of structural damage, with the most vulnerable blade element being the adhesive bondlines.

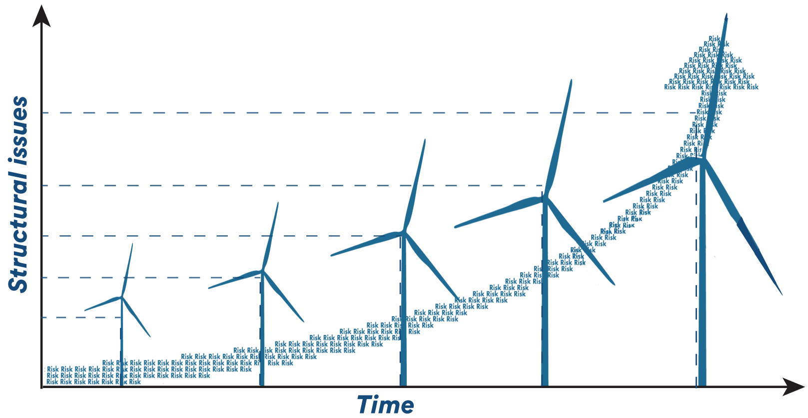


Figure 1 - Sketch illustrates that as blades grow in size, the occurance of structural issues is increasing, therefore the risk of failure is rapidly growing too

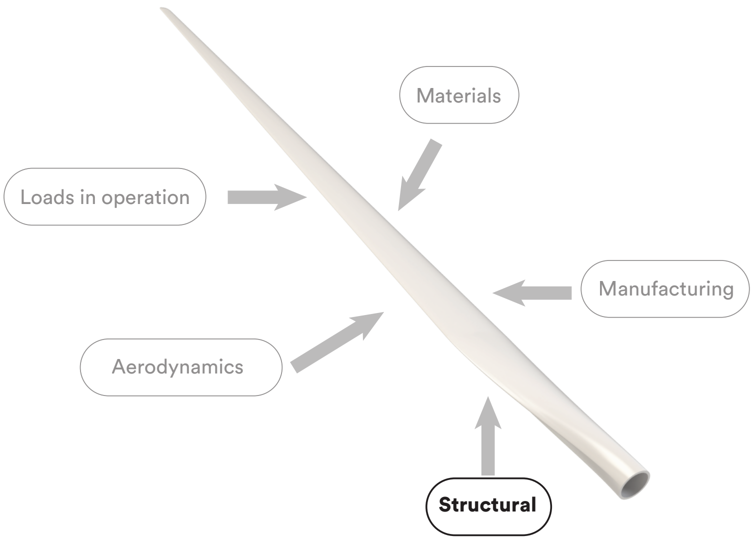


Figure 2 - Competences needed for designing and manufacturing a blade.

Today, blades are designed with five disciplines in consideration: Materials, Loads, Aerodynamics, Manufacturing and Structural. Figure 2 shows the design considerations for producing a blade. Only the structural aspect of the blade's design can be improved for blades in operation to avoid structural damages.

Blade's Structural and Aerodynamic regions

A typical modern blade is with two shells and 1-4 shear webs, and load-carrying spar caps running down the length of the blade above and below the shear webs. Figure 3 shows the structure of a blade, depicting different regions of a blade.

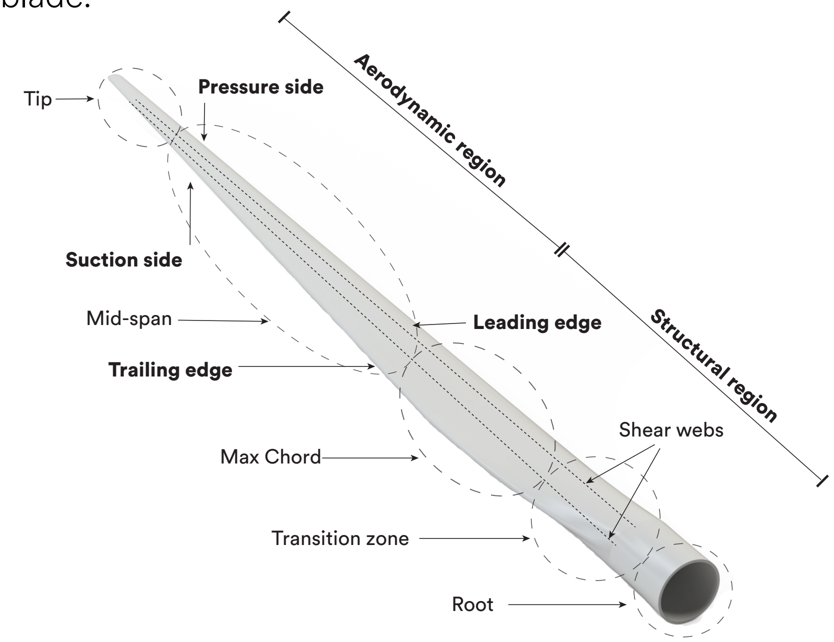


Figure 3 - 3D sketch showing different sections of a blade

The two aerodynamic shells and shear webs are assembled by adhesive bondline connections at TE, LE and shear webs. Figure 4 shows a cross section of a modern blade with flatback geometry.

The load carrying structure is divided into:

- Spar caps/Shear webs conections
- Trailing Edge
- Leading Edge

The rest of the blade is seen as an aerodynamic shell.

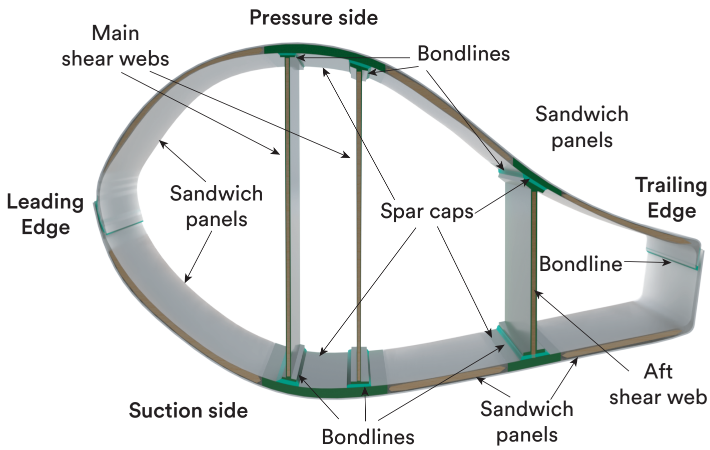


Figure 4 - Drawing showing a typical cross-section of a blade's Max chord region.

Loads acting on the blade

The blades experience three primary loads in operation:

1) Edgewise loads
2) Flapwise loads
3) Torsional loads

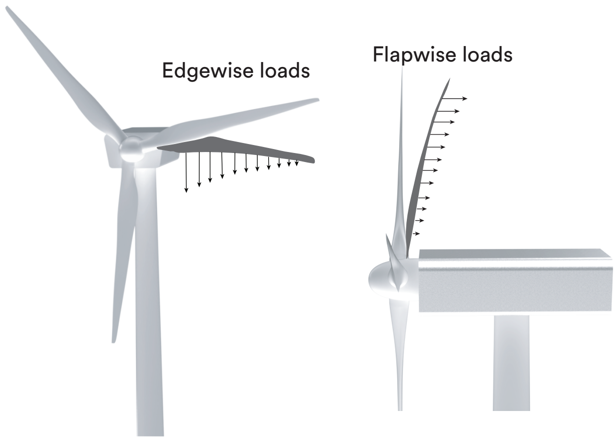


Figure 5 - An illustration of flapwise and edgewise loads on the blade.

Edgewise loads

The edgewise loads increase when the blades increase in size. In the past, when blades were small, the edgewise loads had little impact on the overall loading of the turbine.

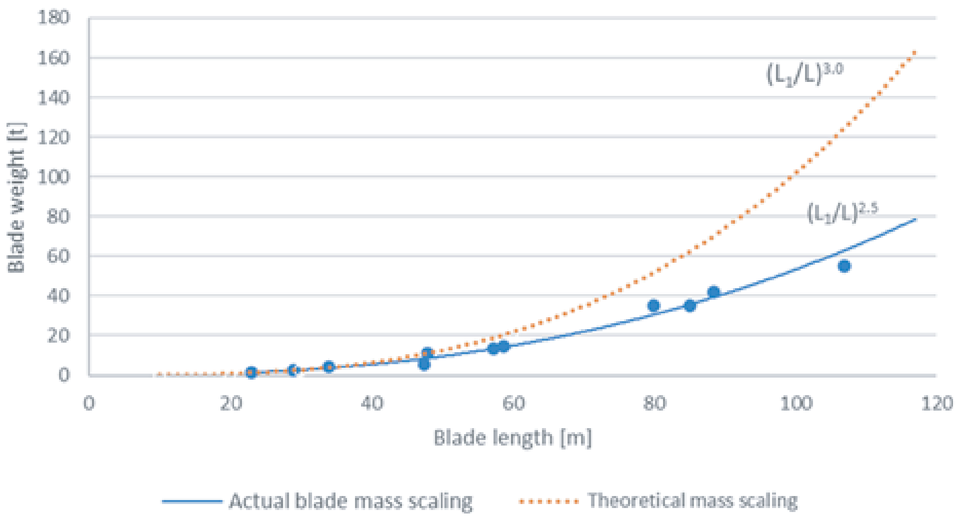


Figure 6 - Comparison of actual and theoretical blade weight scaling for increasing length. Data is obtained through public information available online

However, theoretically weight increases with a power of 3 as blades scale up, the edgewise component became the main load on modern wind turbine blades. This has a direct connection to the edgewise root bending moment since the root bending moment scales up with a power of 4. Figure 6 shows that the blade weight has increased by the power of 2.5, as blade manufacturers have successfully improved the aerodynamic performance and control of the wind turbines, as well as the structural design, and have optimized the use of materials and process technology.

Flapwise loads

In the flapwise direction, the dominant load is the thrust, which has increased as well with the scaling up of blades. The flapwise loading is lower than the edgewise loading for modern wind turbines.

Another aspect is the wind class of the turbine, and considering wind turbines operate in wind farms; thus, in most cases, the blades are subjected to more turbulence than the site due to the wake effect of the neighbouring turbines. This, together with the tower effect and wind shear, adds up to the dynamic response of the blade. In other words, the blade root flapwise bending moment increases as turbines scale up.

Furthermore, modern blades are designed to have sufficient flapwise stiffness to avoid hitting the tower. In the past, flapwise stiffness was the main design driver. Today, the edgewise loads have become the main design driver, together with the torsional loads.

Today, the tip deflection is solved by a combination of different methods, e.g., pre-bending, coning, tilting, carbon usage, and thick airfoil design.

Torsional loads

The torsional loads act on the aerodynamic centre of the blade instead of the shear centre. The combination of the flapwise and edgewise loads also contributes to the torsional load component forcing the blades to deflect [1], as seen in Figure 7.

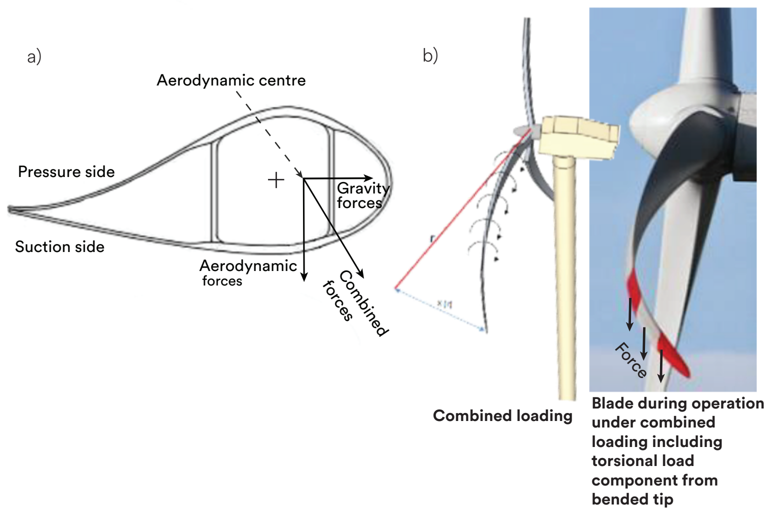


Figure 7 - Illustration explaining combined loading. Cross section drawing presents that the torsional loads act on the aerodynamic centre instead of the shear centre (a). The illustration shows combined loading on a blade in operation. The blade here is bent and a torsional moment is created due to tip deflection (b).

The flapwise and edgewise deformations during operation make the blade twist around its longitudinal axis resulting in a generation of a torsional load component [2]. The torsional load component significantly influences localized deformations, strains and stresses in the Max Chord and Root Transition Zone. In operation torsional load acts on the aerodynamic centre, see Figure 8.

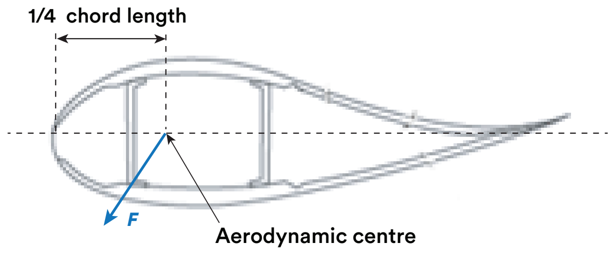


Figure 8 - Illustration of applied combined load vector. The blue arrow illustrates a combined load vector applied in the aerodynamic centre (1/4 of chord length from LE).

Non-linear FEM analysis and Large-Scale experimental testing have shown that the torsional loads arising from the combination of flapwise and edgewise loads result in the increased out-of-plane deformations, also known as breathing. The out-of-plane deformations mainly occur in the trailing edge Max Chord region and Root-Transition Zone [3]. Figure 9 shows the out-of-plane deformation of the curved pressure side trailing edge panel.

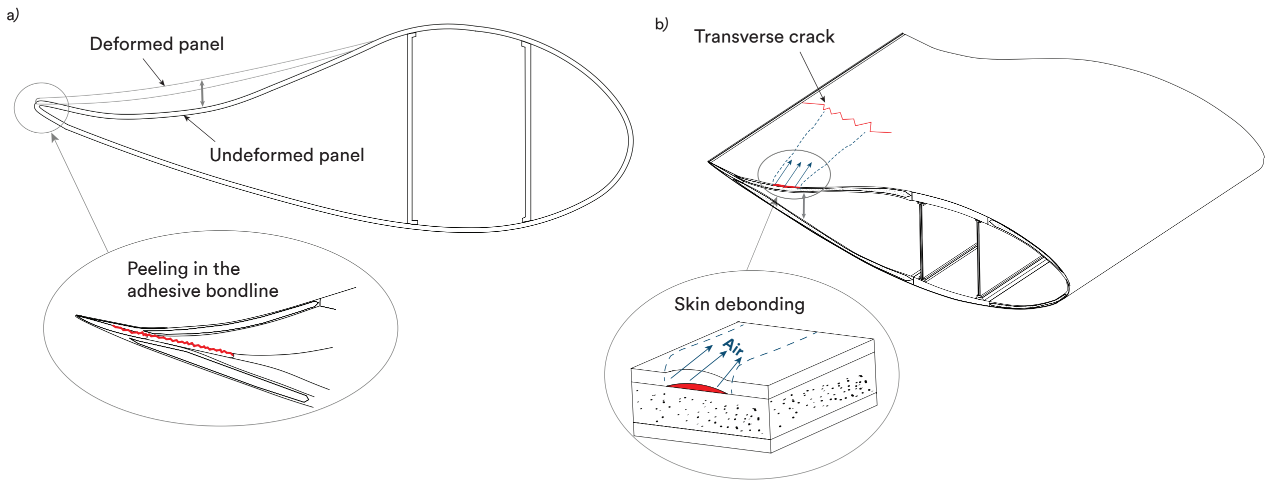
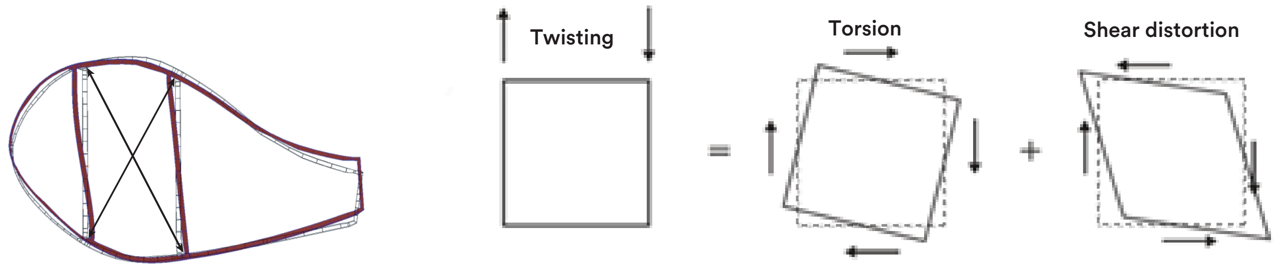


Figure 9 - Cross-section showing breathing on the pressure side trailing edge panel (a), the to- and from movement will lead to peeling stresses in the bondline. The out-of-plane deformation of the trailing edge panel can also lead to skin debonding what would be followed by transverse cracks.

Additionally, torsional loads leads to Cross-Sectional Shear Distortion, see Figure 10.



a) Sketch of Cross-Sectional Shear Distortion (CSSD) b) Twisting sketch, sum of torsion and shear distortion [4]

Figure 10 - Cross-Sectional Shear Distortion (CSSD) also called bookshelf phenomena [4]. When a cross section is distorted in transverse direction, adhesive bondlines and flatback corners experience increased stresses.

Loads to be applied in a full-scale test

The requirements for full-scale blade testing are provided in international standards such as IEC-61400-23. The full-scale testing is seen as final design validation. However, the loads applied during the testing does not full mimic the loads experienced by the blade in operation. Currently, scale testing is performed by applying edgewise and flapwise loading separately. Nevertheless, this is not representative for the blades in operation. The increased out-of-plane deformations and Cross-Sectional Shear Distortion are not initiated during the required tests [5]. Figure 11 shows a comparison of a full-scale test with a blade in operation.

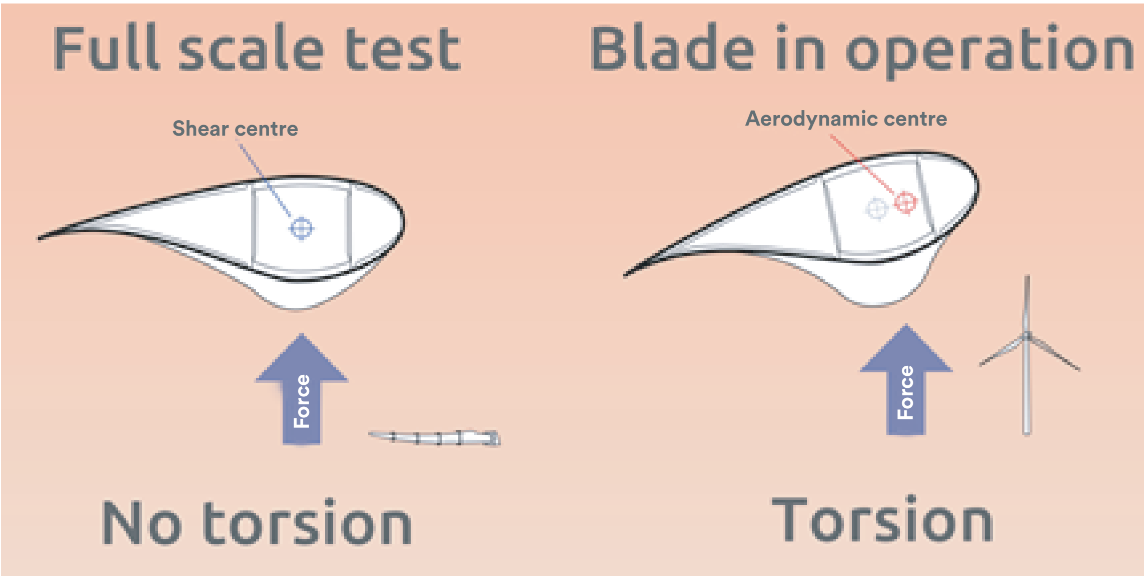


Figure 11 - Comparison of full-scale tests with a blade during operation. No torsion load are usuall taken into account when blades are tested during certification.

Weaknesses in the structural design

To meet the energy demands, manufacturers turn to longer blades where aerodynamic design has dominated the blade's appearance. However, this, on the one hand, may produce the optimal energy. On the other hand, the risk of blade failure is expected to increase significantly. The impact of torsion loads is increasing in long blades where phenomena such as Breathing and Cross-Sectional Shear Distortion (CSSD) dominate and are root causes of the structural damages such as transverse cracks, bondline failure, and shear web bondline cracks. In some cases, it leads to catastrophic failures. Figure 12 presents the areas which are prone to damage in blades in the structural region.

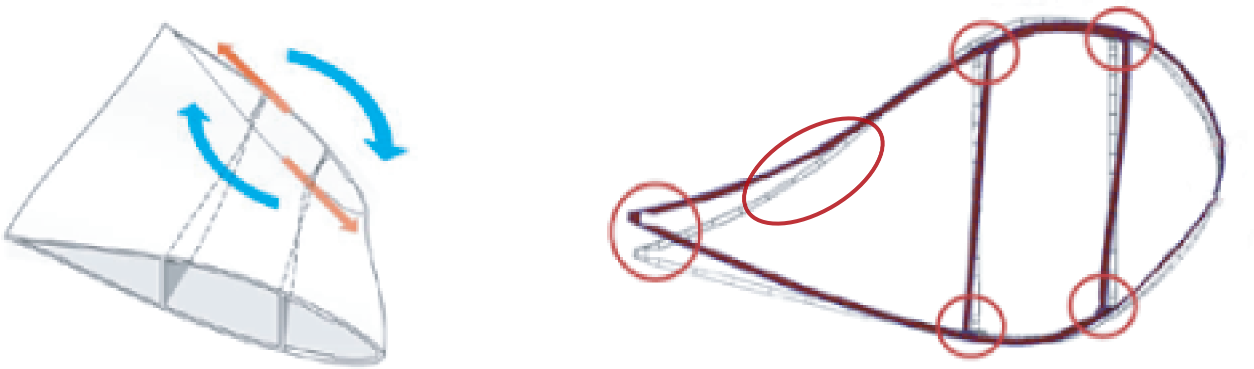


Figure 12 - Sketch showing the cross-sectional shear distortion phenomenon. Left: 3D view of the blade deformation. Right: Cross-sectional shear distortion (CSSD) seen on a cross-section. Red circles point out the weak spots of the section.

The pressure side panel and adhesive bondlines are two components prone to damage in the blade's structural region. Phenomena such as CSSD and Breathing create peeling stresses in the adhesive bondlines, leading to failures. This can be avoided by strengthening the structural region of the blade by eliminating breathing and CSSD by structural up-tower retrofit solutions such as D-String®, D-Stiffener™, and X-Stiffener™.

Figure 13 - Bladena's solutions for different regions of the blade, specifically engineered to address root causes.

References

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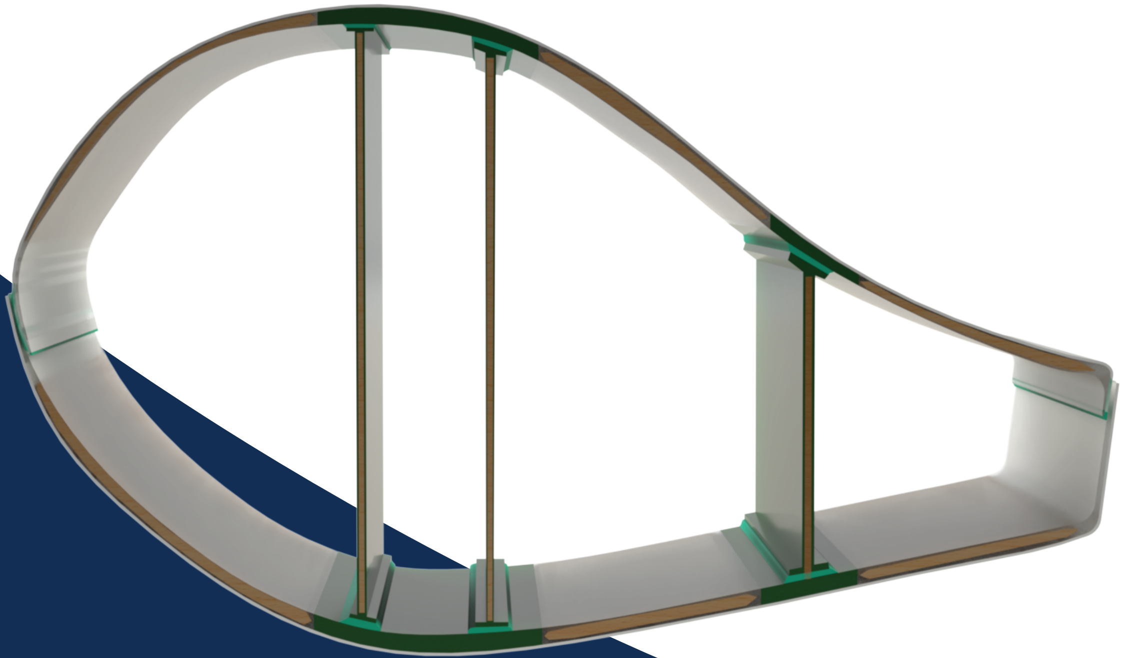

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