Bladena´s Blade Design Philosophy

Bladena Whitepaper

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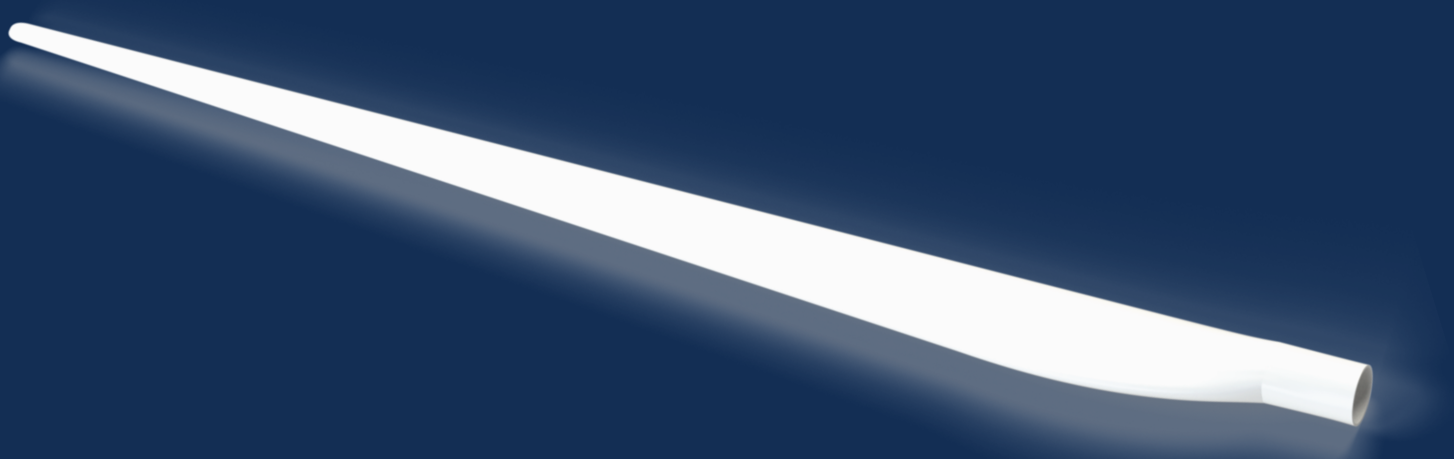

1. Introduction

The wind energy industry is a relatively new industry compared to others such as aircraft industry or marine industry. Inspiration from these other sectors has always played a relevant role in the development of the wind industry.

During the first years of growth, progress focused on improving areas such as manufacturing and material properties, as well as on optimizing generators for an efficient conversion of energy into an electrical output. As blades grew in size, aerodynamic performance gained more importance. Manufacturers managed to apply knowledge from the aircraft industry into the wind industry, leading to blade airfoils with an efficient aerodynamic performance.

Nowadays, forced by the unprecedented fast growth of blade size in a short period of time, the main challenge lays on the new types of structural damages or failures that blades are experiencing during turbine operation. In the same way as the industry successfully addressed the areas of manufacturing, material properties, energy conversion, and aerodynamics, the main focus is now moved to the structural integrity of the blade.

Inspired by the marine industry, Bladena was born as a knowledge company to solve the first structural challenges that, already 13 years ago, started to be a problem. Since then, the continuous scale up of blades without significant changes in the structural design has confirmed a concerning trend into less and less structurally reliable blades on turbines in operation.

Bladena's mission aims to raise awareness of this topic, educating the wind turbine design professionals and providing knowledge upgrades that, aim to identify the root cause of the threatening increasing structural damage rate seen in todays' large modern blades.

2. Structural chain

In Bladena's opinion, the structural considerations on modern large blades could be considered as the weakest link of a chain. In case this chain is only related to structural aspects, both strong and weak links can be identified as visualized in Figure 1 [1].

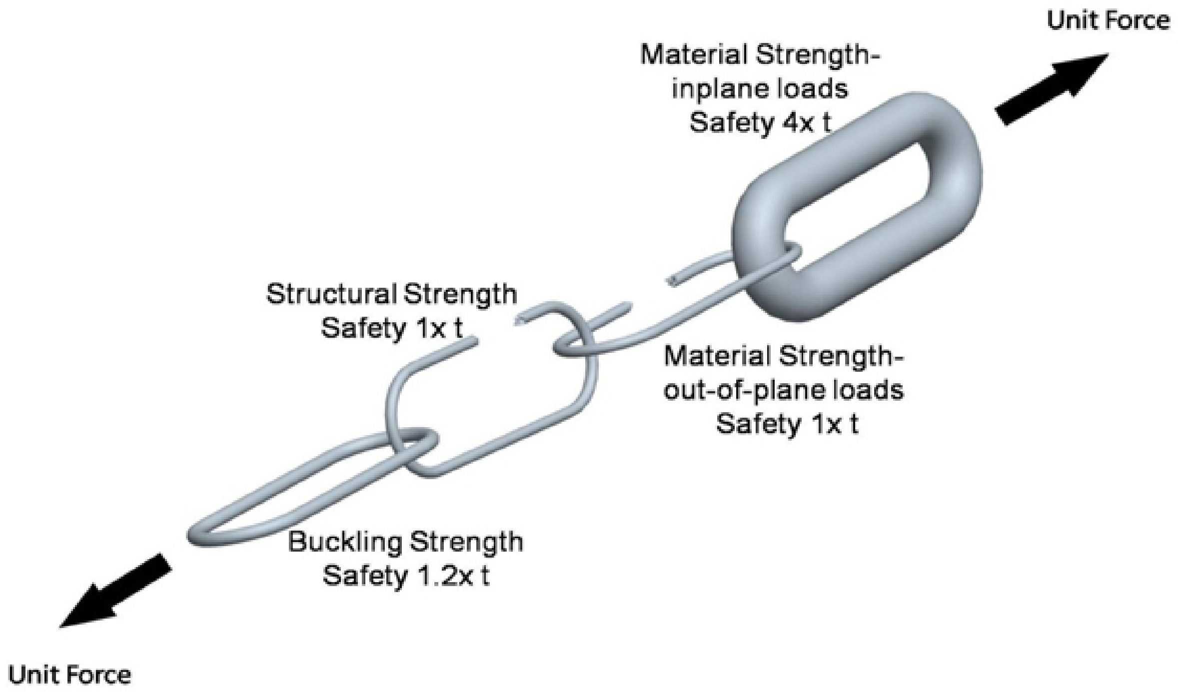

Figure 1 - Structural chain showing how some structural design areas need improvements. [1]

The figure above shows that specific structural aspects, such as the material strength for in-plane loading, are over-designed for large blades, meaning that the blade is not expected to fail when forces are applied in the in-plane direction. For further information about this topic, see [2].

On the other hand, areas covering general structural strength safety, buckling capacity, bending capacity or strength to out-of-plane deformation loading, are directly related to the drivers behind current structural damages seen in the field, indicating that there is significant room for improvements (for further information about common structural damages, see section 4 in [2,3,4]).

Under this industry framework, the objective of Bladena is to fully understand the root cause of the most concerning field damages, offering technical solutions to the wind industry, either in terms of structural advice for O&M professionals, or in terms of mechanical structural blade upgrades. Our success will be obtained whenever a balance in the industry is found between all the important structural links of the chain, visualized in Figure 2, [1] strengthening the weakest links, and turning focus and resources away from unnecessary strong links.

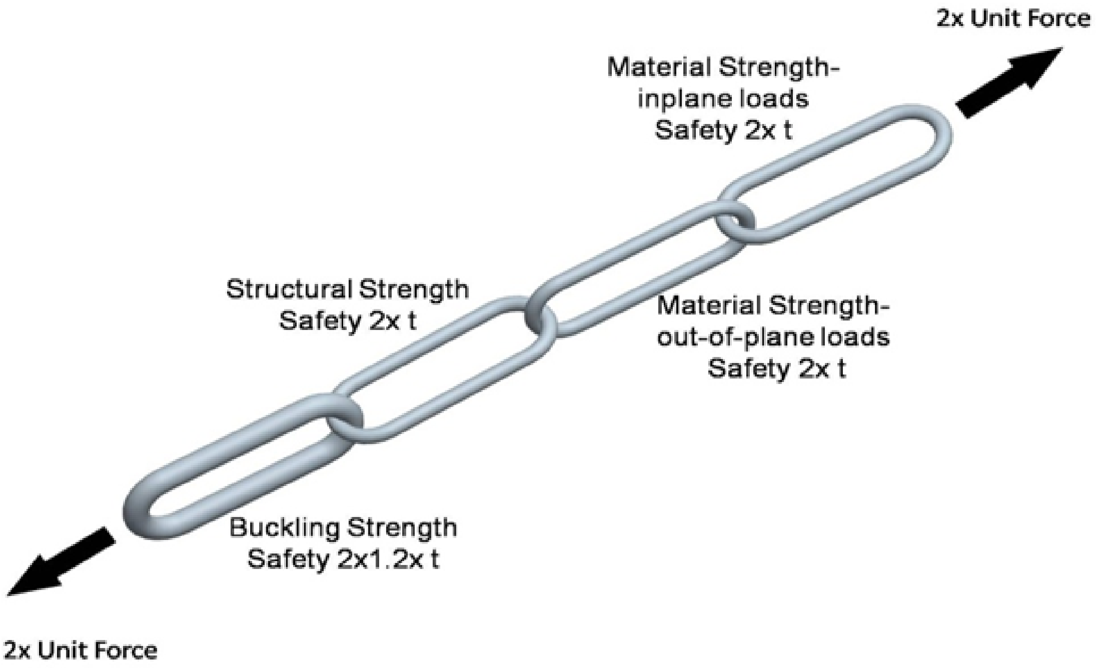

Figure 2 - Structural chain with a balance between the most significant structural elements. [1]

2.1. Structural regions of the blade

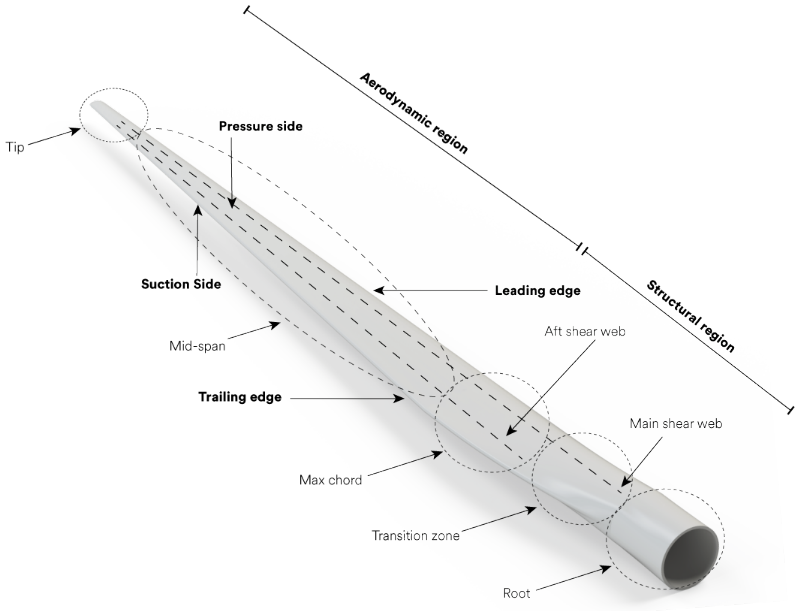

Figure 3 - Differentiating between the structural region and the aerodynamic region in a typical blade design.

Understanding the critical sections of the blade and their role in the blade structural functionality is essential to conduct any type of structural analysis. The anatomy of a typicalblade is presented in Figure 3, in which two main areas have defined, the aerodynamic region and the structural region.

Damages in the structural region of the blade will lead to a lower load-carrying capacity which may add risks to the structural integrity and making the blade more sensitive to operational load conditions. Consequently, damages in this area must be prevented with a proactive attitude that recognizes the structural risks that blades, operating in the field, are facing. Otherwise, they may force the wind turbine operator to immediate O&M actions with high associated Operational Expenses (OpEx), in order to avoid critical damages with an even higher associated cost due to long downtimes and extensive repair actions.

The structural region is composed of the root, the transition zone, and the maximum chord area.

Among these three sections, the root transition zone of the blade is the one that requires most attention. The transition zone may have large unsupported blade shell panels in the TE box, as the aft shear web tends to start around the maximum chord area or at the very end of the root transition zone. On the other hand, the blade shell geometry changes in the root-transition zone, from a convex at the root to a concave at the pressure side of the blade, combined with tapering shell panels in two directions. Consequently, damages on the transition zone may be critical.

For structural risk reduction purposes, the areas that need to be structurally improved are primarily the maximum chord area and the root-transition zone.

2.2. Blade design evolution

The evolution of the structural design of wind turbine blades has not evolved sufficiently during the last years of development. Meanwhile, significant advances were made in almost all the other relevant blade technology areas.

For instance, for the composite material area, carbon fiber was introduced to achieve higher stiffness capacity compared to glass fiber, and it is now widely used in the spar caps in new blade designs.

Different design combinations are used in the industry, with different number of shear webs, spar caps, or even with an integrated “box spar” design as illustrated below. All of them however will experience the two main sources of structural risk described in section 3.

Figure 4 - Cross sections for different structural designs

The most significant change in the last years might be in the trailing edge. In some modern blade designs, the trailing edge has changed from a sharp TE to a flatback TE. Field experiences show that if a blade with a flatback design suffers substantially from cross-sectional shear distortion, there is a high risk of an angle deviation between the two corners of the flatback trailing edge and the blade shell panels. The most vulnerable corner is between the flatback and the pressure side panel.

Field experiences also show cracks in the middle of the flatbacks and in some cases, a large increase in peeling stress induced bonding failures that is often seen on blades with the flatback design.

The most common root causes of structural blade failures are, according the Bladena's field experience, cross-section shear distortion, and out-of-plane blade shell deformations (see section 3).

3. Structural damages driven by out-of-plane deformation and cross-sectional shear distortion

3.1. Out-of-plane deformations

Many modern wind turbine blades are designed with large unsupported panels. These panels are deforming under operational conditions. Out-of-plane deformations ("breathing" and panel bending) can be experienced both on the suction side and pressure side panels, but due to the high curvature of the pressure side panel, more issues are commonly observed on this side. Figure 5 illustrates a blades cross section with large unsupported panels.

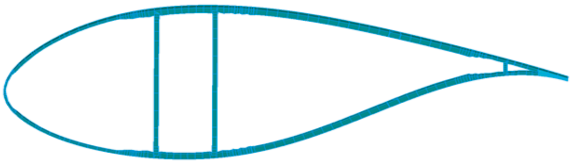

Figure 5 - Illustration of a blade cross section with large unsupported panels. The pressure side is significantly more curved than the suction side.

The out-of-plane deformations of the panels can lead to several failure modes depending on the blade region experiencing these phenomena. The range of damages include bondline failures, skin debonding, and crack formation.

The movement of the panels increases peeling stresses in the adhesive bond lines in some cases at the trailing edge connection and in some cases in the bond lines between the shear webs and spar caps most commonly seen in the transition zone area of large, modern blades. The geometry in the transition zone is not only heavily curved/shaped in transverse direction, but also in longitudinal direction. This will, according to Bladena's experience, result in increased out-of-plane panel deformations, see illustration on Figure 6. The deformations generated by the longitudinal tapering usually result in longitudinal waves and this means local bending stresses. These phenomena are taking place in an area where there are no shear webs, hence the panels are free to deform in out-of-plane directions. In many cases this leads to increased peeling stresses in the bondline between the aft shear web and the corresponding spar cap, which can result in shear web disbond, which is a potential root cause of severe blade failures (in some instances even blade collapse). In [3,4] more details can be found about a test campaign focusing on this failure mode.

Another common failure mode due to the out-of-plane deformation of the panels is skin debonding which often leads to transverse cracks. Due to the bending of the panel, the interlaminar stresses between the layers of the composite or sandwich panel will lead to skin debonding which later due to fatigue bending will result in transverse cracks. The development of these failure modes is illustrated below on Figure 7. More details on this damage type and a relevant test campaign can be found in [5].

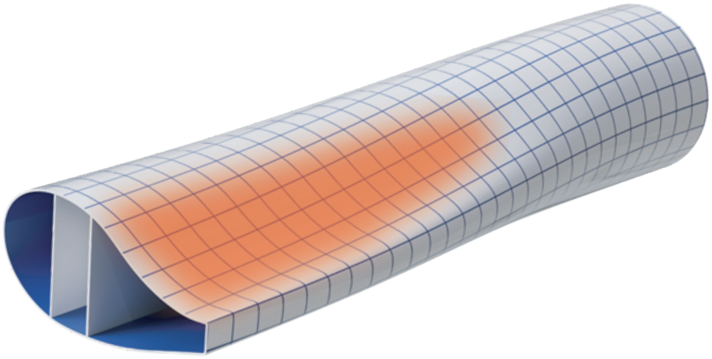

Figure 6 - Illustration of a blade's double curved, complex transition zone.

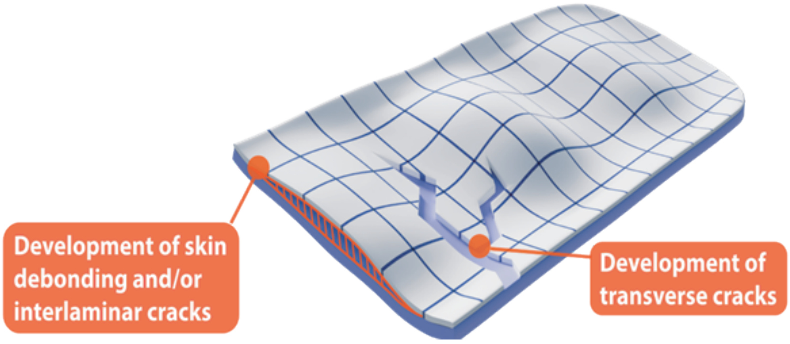

Figure 7 - Development of a transverse crack and of skin (face sheet) debonding from the sandwich core.

Some of the out-of-plane panel deformation can be relieved using an extra aft shear web, supporting the trailing edge panels. Whenever an extra aft shear web is present, the width of the unsupported panel gets reduced compared to a configuration with two main shear webs with a long distance between the trailing edge and the first shear web. In these cases, the sandwich panel may experience severe out-of-plane deformations, followed by bending strains and corresponding interlaminar stresses between skin and sandwich core material. The presence of the extra aft shear web reduces the creation of out-of-plane deformations, even though high breathing and bending of the panels should be expected, especially on the pressure side, as this is more curved than the suction side. This situation may lead to a process in which skin debonding takes place, creating a debond on the skin of the sandwich panel, leading to a final formation of a crack. Even though the extra aft shear web, to some extent, addresses the above failure mode, it creates potential for a more critical problem that is "Aft shear web disbond" and is therefore not recommended by Bladena [6].

3.2. Cross-sectional shear distortion

Cross-sectional Shear Distortion (CSSD) is a common phenomenon, more prominent in large blades, that makes the shear webs tilt due to the distortion of the whole cross section as the blade rotates. For the aft shear web, this may lead to adhesive bondline failures between the aft shear web and the spar cap. So, CSSD during blade rotation add risks to the structural integrity of the blade in critical areas, such as the transition zone. CSSD on a blade cross section is illustrated on Figure 8. More details about the phenomenon and a corresponding project can be found in [7].

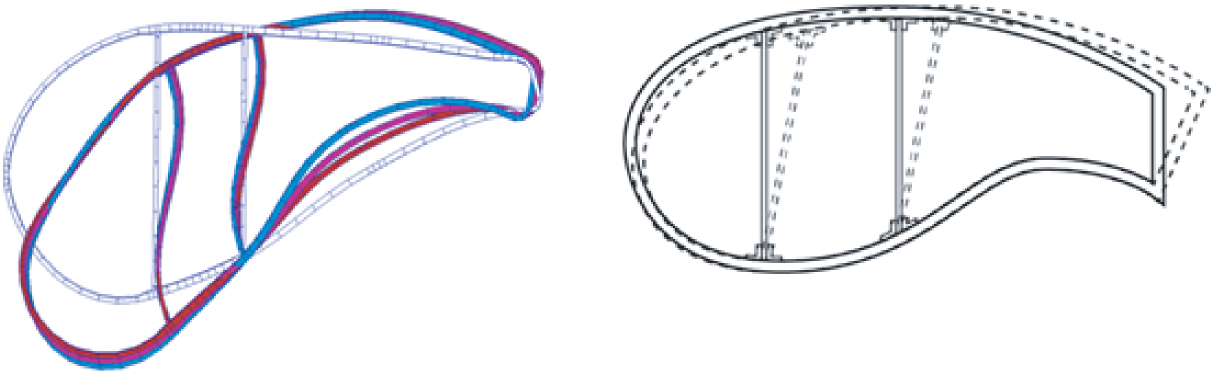

Figure 8 - CSSD seen in a FEM study (on the left), 2D illustration of CSSD (on the right).

4. Torsional loads

The current design basis considers the loads associated with displacements in the edgewise and flapwise direction independently and not their combined three-dimensional effect equivalent to what is found under actual turbine operating conditions.

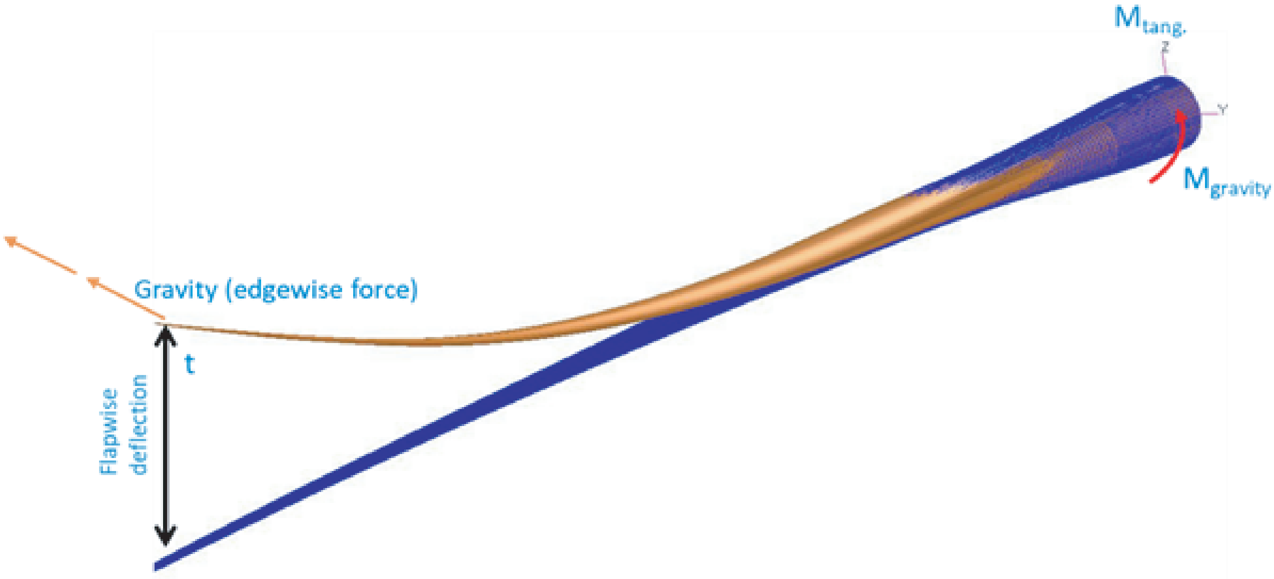

Figure 9 - Flapwise and edgewise load components and tip deflection generate Root Torsional Moments (RTM).

Figure 9 shows the three-dimensional tip deflection in both directions when the blade is in operation. This deflection is a consequence of the combination of flapwise loads due to the aerodynamic impact from the incoming wind, and edgewise loads, substantially due to gravity forces and blade dynamics during rotation. These movements cause forces to act not precisely at the blade's shear center, thereby creating an "arm" that generates a Root Torsional Moment (RTM). The direction of this RTM depends on the magnitude of the applied loads and the blade's stiffness. The load contributions that introduce a root torsional moment on the blade arise from the aerodynamic forces and gravity working on the already deformed blade under operation. As blades increase in length, tip deflection also increases significantly, leading to notable rise in the RTM. More details about torsional loads and their impact on the blades in operation can be found in [3,4].

Acknowledgement

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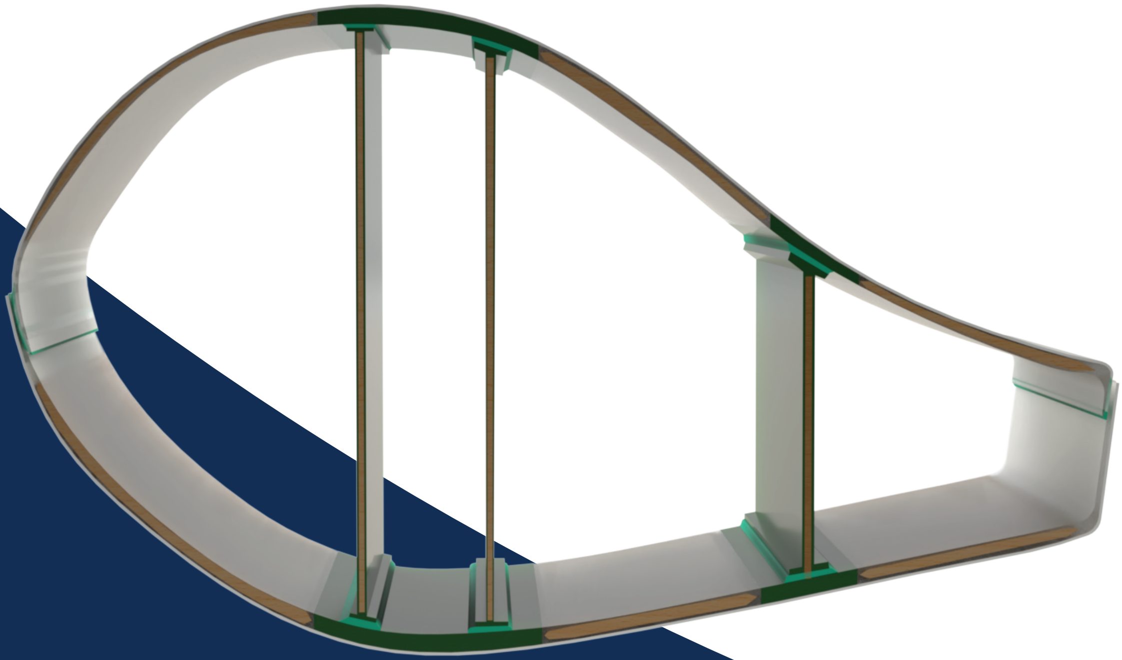

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