<u>Keels Falling Off</u>

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Within the last fifty years there has been a significant number of high profile, catastrophic failures related to sail boat keels and the structures that are supposed to hold them in place. A small percentage of these failures have resulted in fatalities and have therefore been well documented. But most of the time when “keels fall off”, or come close to it, they are rarely heard about or discussed. The causes for these failures can be complex and are often a combination of factors as discussed below.

There are four primary causes for keels falling off:

1) Failing to reach an expected or required standard of engineering
    a) The designer or engineer fails to fully appreciate the loads on the keel and the structure that attaches it to the hull – a brief look into basic engineering principles and regulatory rules such as the ABS and ISO rule as they apply to structure associated with keels.
    b) The over-optimization of a structure so as to reduce weight (typically in race boats) while also not anticipating material fatigue and cyclic loadings with appropriate factors of safety.
2) Sub-standard building practices
    a) What can happen when construction plans aren’t followed (real life examples)
    b) The cost of fixing mistakes……do it right the first time!
3) Inadequate maintenance
    a) Putting a band aid on a gushing wound almost always leads to significant structural problems in the long run, and sometimes with fatal implications
4) Coming in contact with an immovable object

1) Failing to reach an expected or required standard of engineering

a) i) The designer or engineer fails to fully appreciate the loads on the keel and on the hull structure that it attaches to.

In order to better understand those loads, it’s necessary to have a global view of the stresses that a sailing vessel’s structure is subject to.

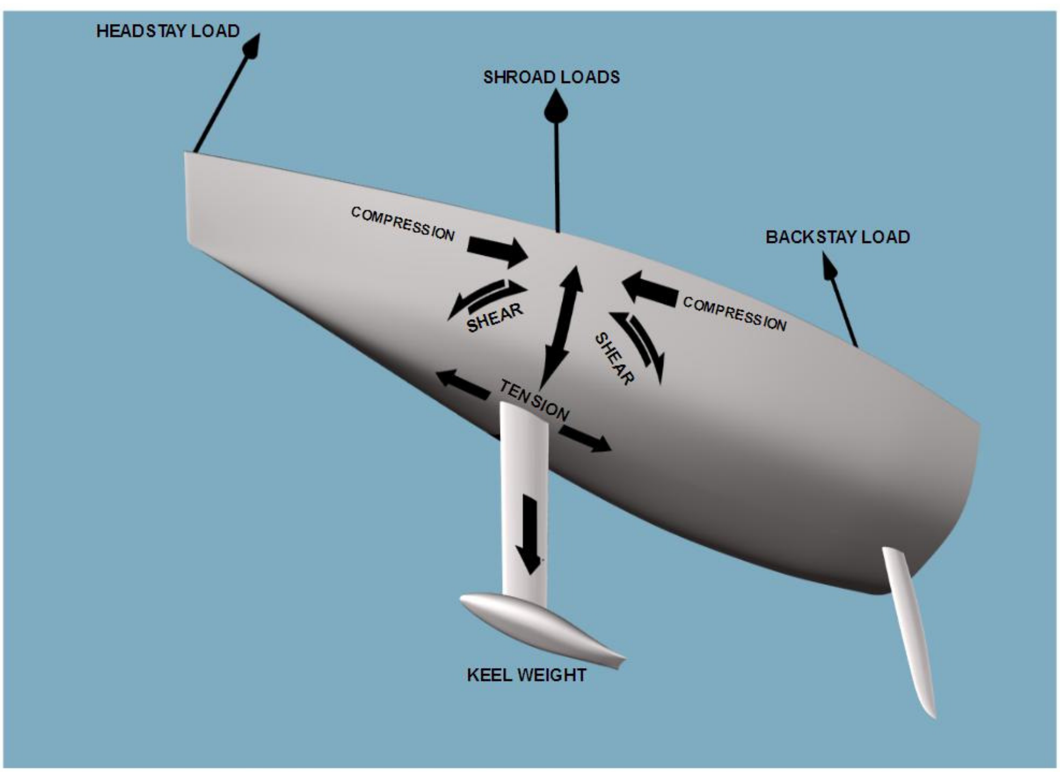
There are a number of critical loading conditions that are imposed upon the structure of a sailing boat, both in a static condition (the vessel sitting at rest), or in a dynamic condition (the vessel underway….typically sailing).

Static loads primarily come from the rig and keel. Forces from the headstay, backstay and side shrouds impose significant bending moments upon the structure of the vessel, as does the weight of the keel which is attached to it.

The stresses that are induced into the structure are as shown below:

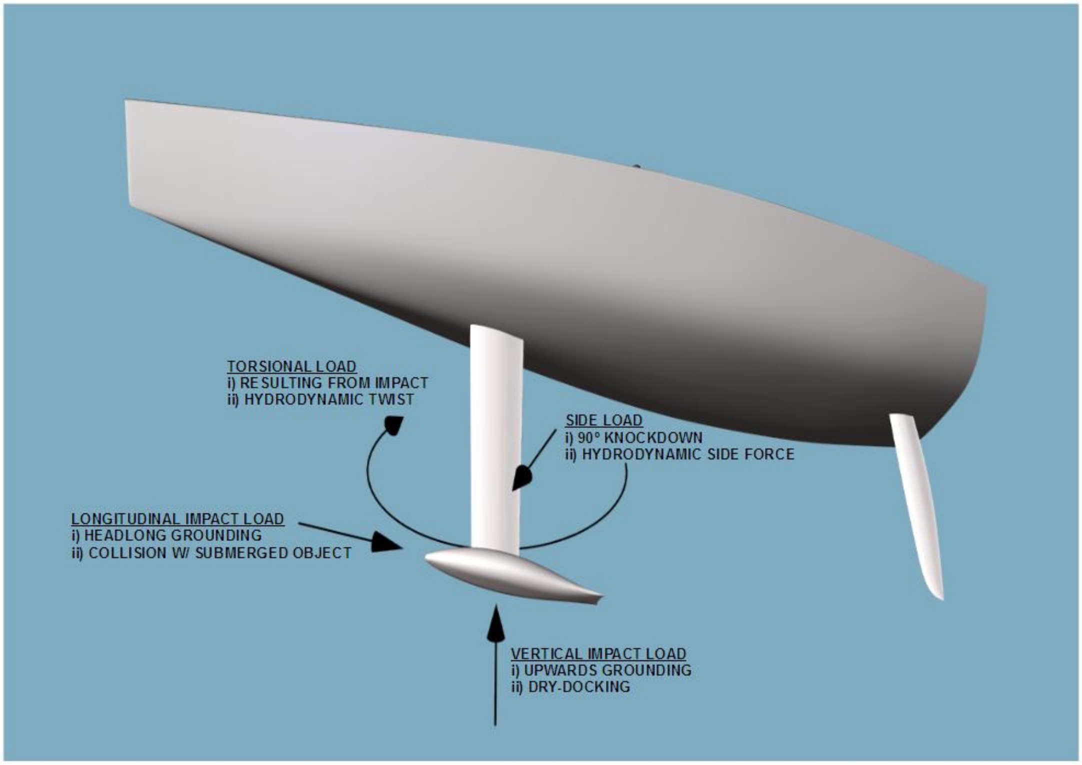
- fore and aft compression loading along the sheer and topsides
- tension along the back bone of the boat and vertically in way of the shroud chainplates and keel attachment
- shear stress in the shell plating and supporting structure as the boat tries to fold in on itself

Depending upon the conditions, these stresses can be greatly amplified when the vessel is under sail and generating a counter moment to the heeling force from the wind upon the sails, otherwise known as righting moment. In fact righting moment is at the heart of the loads being transmitted throughout a sailing boat’s structure.



Righting moment (RM) is at the heart of the loads throughout the boat and its structure

If we isolate the keel and look at specific load cases, there are a number of forces that will have an impact upon the engineering of the keel and hull and must be accounted for by the designer in their structural calculations.



Keels are subject to various load cases or a combination thereof, affecting both keel and hull structures.

- <u>Side load</u> - i) occurs when a sailing boat takes a 90 degree knockdown so that the keel is out of the water, the weight of the keel creates a moment about the root of the foil where it attaches to, or penetrates, the hull.

  ii) The same reaction can be said about the hydrodynamic load on the keel or keel fin which is a result of righting moment (countering the heeling moment). Working in the opposite direction is the hydrodynamic side force generated from the lift and drag characteristics of the foil.

  These load conditions are typically modeled as cantilever beams from which are derived design stresses in the structure.

- <u>Torsion load</u> – i) can result from an off-axis impact at the leading edge of the keel or nose of the bulb.

  ii) Hydrodynamic side force in the keel fin and/or bulb can produce a twisting effect in the blade. High aspect ratio foils are particularly prone to this type of torsional load.

These loads can result in extreme shear stresses in the surface region of the foil and at the attachment point to the hull.

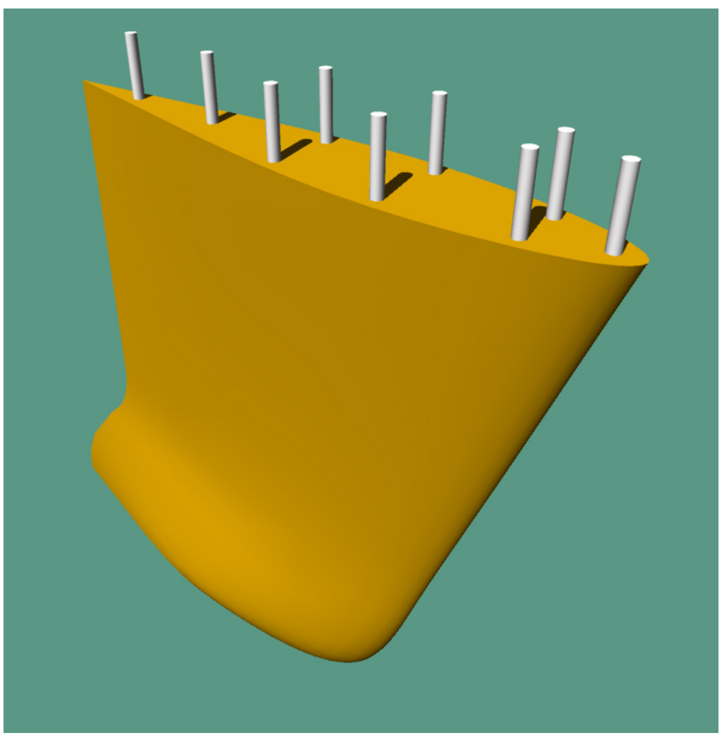
- Longitudinal impact load – i & ii) occurs with a headlong grounding or a collision with a submerged object, and is associated with the majority of keel repairs.

Traditional full keels on classic wooden boats tend to be subject to huge shear loads in their fasteners, while trapezoidal and fin keels have a tendency to want to rotate up into the boat transmitting massive loads into the vessel's structure.

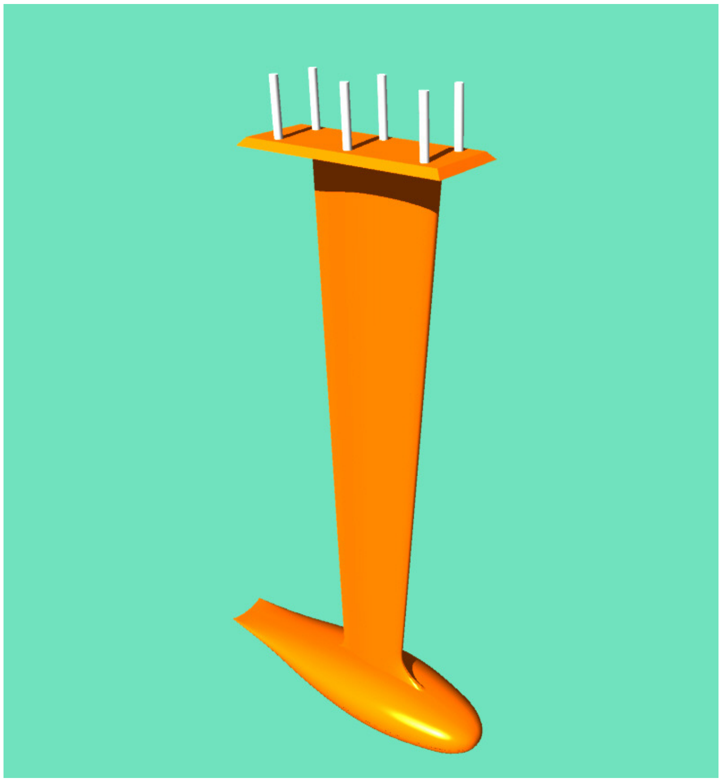
- Vertical impact load – i & ii) occurs with an upward grounding or a dry dock situation when a boat is put down hard on its keel.

This is a little less common but significant damage can occur to the hull shell and keel grid if the impact is severe enough.

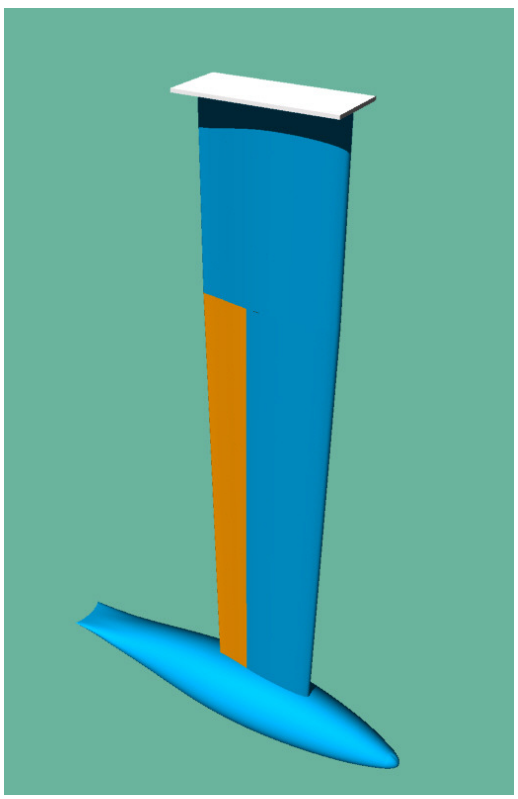
Common types of keels and keel attachments



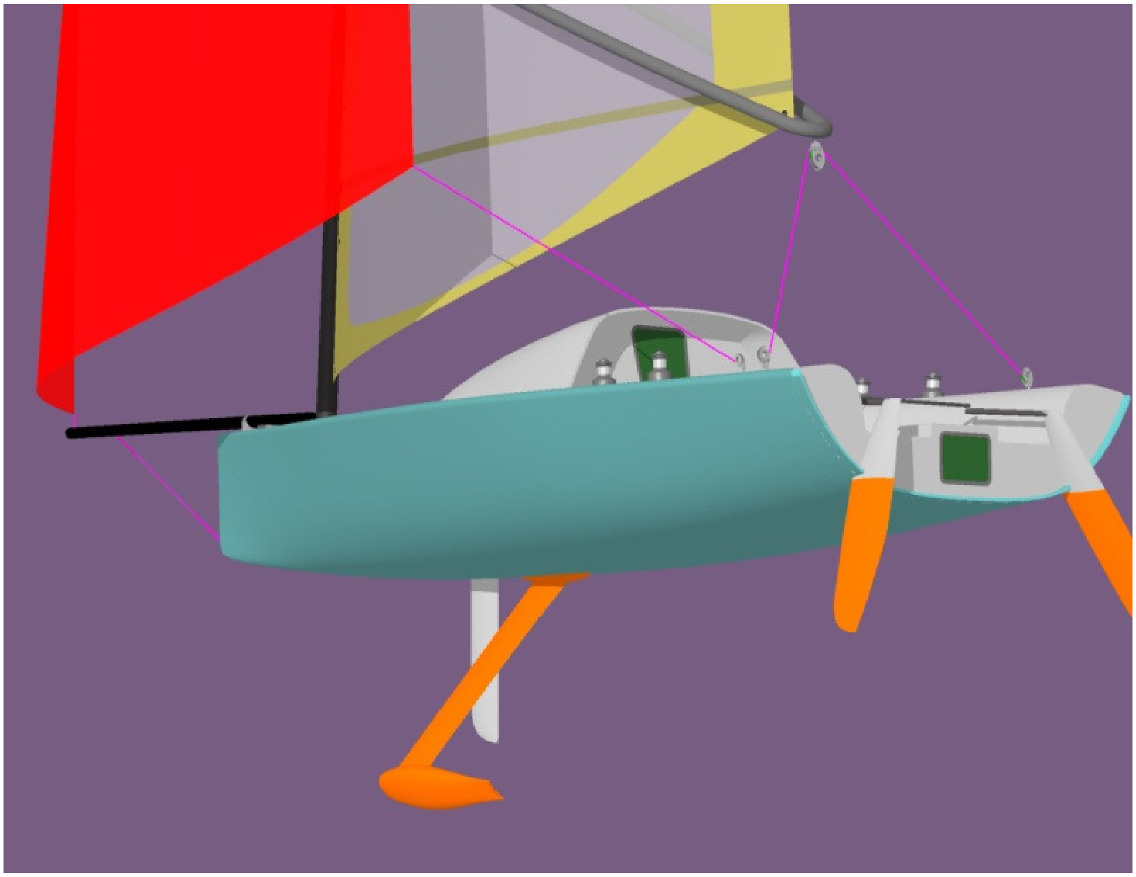
Conventional trapezoidal-type keels have ample space for keel bolt attachment. Bolts are typically welded together in a cage configuration and set into the keel casting and the molten lead poured in around it. The bolt specification (material, diameters, and pattern) must be able to withstand the bending moment imposed by a 90^{o} knockdown. Loads are transferred into hull structure via the reinforced shell, floors and longitudinal stringers.



Modern fin keels with bulbs can have integral flanges with keel bolts solidly attached. The flange fits into a rebate in the hull making for a fair extremity. The fixity of the bolts is critical, as is the geometry of the flange. The effective transference of loads into the keel grid is imperative in maintaining structural integrity. Fin and flange can be machined from a corrosive resistant metal such as stainless steel or bronze, fabricated from stainless steel plate, or cast in high strength ductile iron.



Lifting or demountable fin and bulb keels are becoming a lot more common on race boats these days as owners prefer to road-transport their yachts from venue to venue. The attachment point to the boat is usually in the sole of the cockpit (for smaller boats), or in the head of a keel trunk inside the boat (for larger yachts). A significant point load is imposed on the fin where it exits the hull. That load is transferred into the hull shell and keel trunk as a bearing load. The locking pin or fasteners will be typically in shear. Fabrication of the fin can be in metal, carbon fiber, or a combination of both.



VG-Open 30

With the advent of canting keels came a whole new set of structural concerns and considerations for the engineer. In fact, there is a specific loading case for this type of keel in the ISO scantling rule (12215-9).

The primary function of a canting keel is to provide added righting moment and that force is transmitted into the boat at essentially three points: the fore and aft attachment of the keel pin, about which the keel rotates; and the head of the keel attached to some type of mechanical device that controls the rotation – either a block and tackle arrangement (usually on small boats), or a hydraulically driven ram or screw system on larger yachts.

The device is in turn attached to the hull structure which is subject to extremely high loads. Recently, there has been a spate of failures on board performance ocean racers such as IMOCA 60s and Volvo 70s, which has lead to calls for a tightening of class rules and the standardization of equipment and structures.

One need only look at the statistics to appreciate the scale of the problem. Since the 1996/7 Vendee Globe when Thierry Dubois, Tony Bullimore and Raphael Dinelli were rescued from their keelless, capsized boats in the Southern Ocean, there have been 17 keel failures in the class.

ii) There are a number of tools available to naval architects and engineers that can assist them in designing structures for keels and their attachments. First principles engineering (i.e. beam and stress equations) should always be the fall back and used as a reality check for other methods. If the budget allows, finite element analysis (FEA) is an extremely powerful software device capable of defining every aspect of a structural member under load.

However, in the world of conformity and safer products, particularly in the production boat world, regulatory standards in design and construction must now be adhered to. These standards are written into scantling rules which give the engineer or builder a clear explanation and definition of the minimum structural requirements they need to achieve in their calculations. The most frequently used of these scantling rules come from the American Bureau of Shipping (ABS), and the International Organization for Standardization (ISO).

History - Back in 2007, the growing number of keel failures prompted the International Sailing Federation (ISAF) to investigate and propose amendments to the Offshore Special Regulations to help improve safety standards. This investigation highlighted the need for a universal structural standard to ensure that keels and keel attachments, and boat structures in general, be designed and built to an accepted benchmark.

Up to this point in time, other regulatory standards had been used by naval architects and boat builders to check their yacht structures. The most commonly being used were:

- Det Norske Veritas (DNV) – used more in northern European countries
- Lloyd’s Scantling Rules – relatively conservative and does not cover modern building materials
- American Bureau of Shipping (ABS) Guide for Building and Classing Offshore Racing Yachts – a good comprehensive rule but it has not been administered since the late 90’s
- ISO 12215 Structural Standard for Boats – work on the writing of this rule began back in 1989 and has been continually reworked and updated so that it has become the accepted standard

ISAF have now adopted the ISO 12215 rule for the design and construction of sailing yachts for all categories of intended use (A, B, C & D).

Side Note - CE Certification is required for all recreational boats entering or being sold in the European Union. Manufacturers must conduct various tests and provide extensive documentation to ensure conformity to all applicable International Organization for Standardization (ISO) directives and requirements.

The National Marine Manufacturer’s Association (NMMA) works closely with the International Marine Certification Institute (IMCI), a notified body in Europe that issues conformity certificates, to assist U.S. boat builders in the certification process. Certification by a notified body enables you to display the CE mark on your products and allows you free and open access to the European Union market.

The specifics of how ABS and ISO address the scantling requirements for keels and their attachment to the hull along with provisions for internal structural members designed to carry keel loads will not be addressed in this paper. That's up to the reader to explore, although examples will be given of actual boats that were built, some of which where the guidelines were not followed and problems ensued.

b) One of the leading causes of catastrophic failure in keel related structures is over-optimization to reduce weight, typically associated with high performance racing boats. The more weight you push through the water, the more energy is required, so keeping the overall weight of the boat down is desirable and something for which designers and builders will go to extraordinary lengths to achieve in their quest for better performance.

Sometimes this philosophy can be taken too far when designers and builders discount the fact that sailing yachts are subject to ever higher levels of stress even under sustained conditions, let alone extreme conditions. The shock loads they experience are violent and repetitive and can often exceed the estimates used by the engineers. Therefore, anticipating material fatigue and cyclic loadings with appropriate factors of safety is imperative when designing a structure that is meant to hold together in a dynamic environment.

Unfortunately there are many examples of what happens when people don't get it right. This was the case with Marc Guillemot's IMOCA 60 SAFRAN which was forced to retire from the 2012 Vendee Globe after its hollow Titanium canting keel failed. The investigation showed that the damage to the keel fin was due to metal fatigue caused by repeated shock loads from wave action. While titanium is much stronger and lighter than steel it is a more brittle material with a lower elongation rate.

Fortunately, this failure happened shortly after the start of the race and did not result in the loss of the keel so Marc was able to return safely to port.

2) Sub-standard building practices

a) What can happen when construction plans aren't followed? The consequences can be dire.

Example 1 - On the 2nd February 2007, the owner and four crew of the Max Fun 35 yacht *Hooligan V* sailed from Plymouth towards Southampton following out of season repairs and maintenance. At about 0320 on the 3rd, the boat's keel became detached and the boat suddenly capsized causing the loss of life of one crew member.

Investigations found that the fabricated steel keel had failed just below the fillet weld connecting the fin to the taper box. Laboratory metallurgical analysis confirmed that the keel had suffered fatigue failure in the fillet weld area, which had been subjected to high bending stresses. Defects were also found in the keel taper box welds, and two of the three keel bolts had also failed.

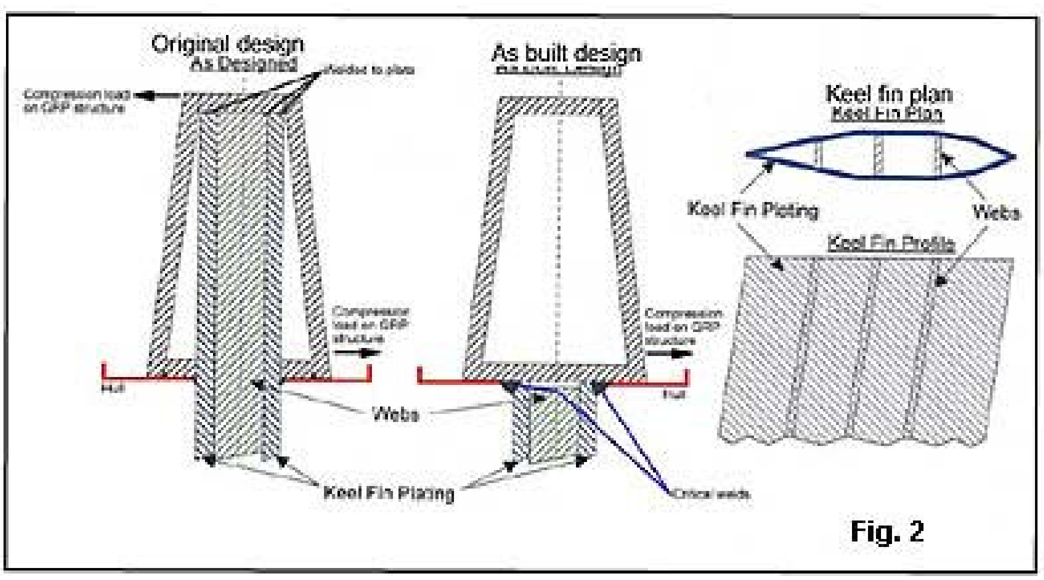


Fig. 2

It was further discovered that the builder had sub-contracted the hollow keel construction to a steel fabricator who had no marine experience. The fabricator changed the original design, and incorporated a fillet weld in a critical area, to ease manufacture and reduce costs, but without the supporting calculations to assess the stresses to which the keel would be subjected (Figure 2). He did not consult on the changes with the designer.

Although the designer was made aware of the keel changes by the boat builder, he did not validate them. In 2005 the owner contracted a UK yacht designer to optimize the yacht for IRM and IRC racing purposes. This involved adding 160kg of lead to the keel bulb.

Once again, there were no supporting calculations, nor were checks made against the “original” or “as built” design drawings to ensure that the modification would not adversely affect the design to cope with the “in service“ loads. Analysis of the “original” design calculations confirmed that they did not achieve the required Safety Factor of 2. The “as built” keel safety calculations were worse, and these were exacerbated by the addition of the extra bulb weight. The fabricated keel was unable to withstand the “in service” bending stresses and this led to the conditions of failure.

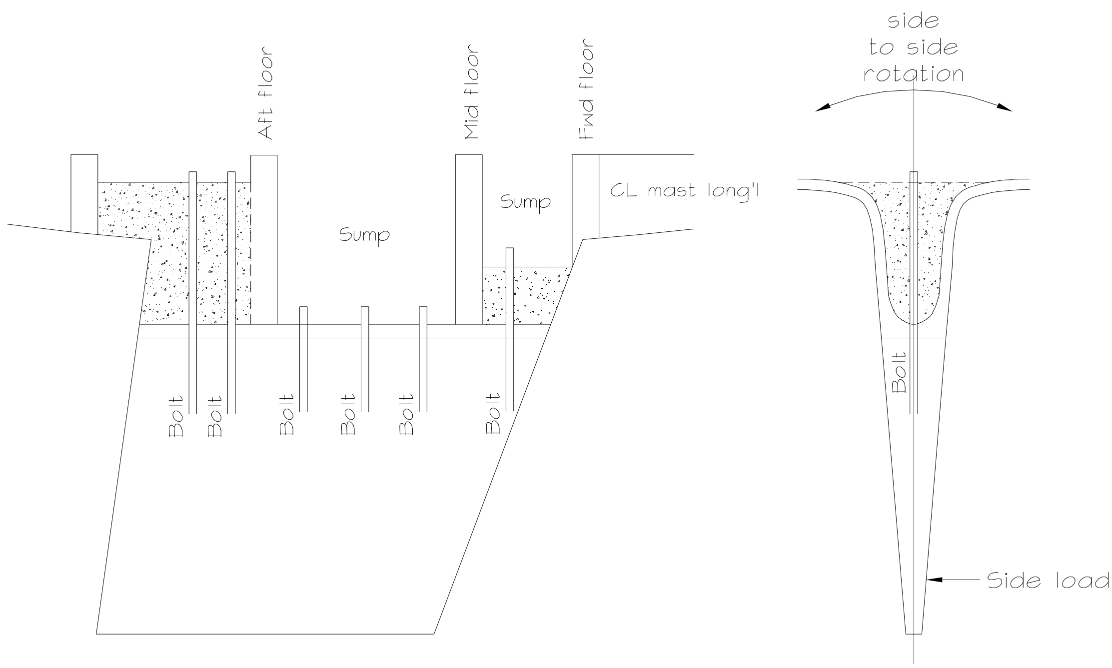
Despite a statement by the designer that the Max Fun 35 was built to ABS standards for yacht design, the minimum Safety Factor of 2 was not achieved. The reason for this is that he used the keel steel ultimate tensile strength instead of yield strength in his calculations.

(Segments taken from the report by the UK Marine Accident Investigation Board)

Example 2 - Van Gorkom Yacht Design was asked to get involved in the repair of a 40 foot cruiser/racer that went aground in Long Island Sound, damaging the keel (there was movement from side to side), the hull shell and the internal keel grid of the yacht. After a thorough investigation of the structure, which included thermal imaging, it was concluded that the besides the grounding damage there were significant flaws in the original construction of the boat.

This included dry spots in the hull laminate, under-building of the floor and girder structure (we were privy to the laminate schedule), and almost zero support for the aft two centerline keel bolts.

This boat has a deep sump so access to the nuts on the keel bolts is difficult. The forward bolts were manageable but the after centerline bolts were made longer and brought up through the sump which was filled in with high-density syntactic foam and glassed over. Backing plates went over the bolts and the nuts were torqued down.



What wasn't fully appreciated by the builder was that these aft bolts were relatively unsupported which placed a disproportional load on the remaining bolts leading an over stressing of the supporting structure and contributed to a "wagging" keel.

VGYD recommended grinding out all the high-density syntactic foam in the after sump and exposing the aft face of the aft floor. Then glue in sister plates on the front and back faces of this floor, making sure they went down to the bottom of the sump. These would then be tabbed in all around the hull and over the cap of the floor. We then recommended pouring an epoxy and chopped fiber mix into the aft sump area with G-10 compression tubes over the keel bolts. This was followed by glassing over the area, making sure there was a good bond with the tubes. Stainless steel backing plates were fabricated to span from longitudinal stringer to longitudinal stringer in order to distribute the load.

While the grounding of this boat greatly exacerbated the failure of the keel structure, subsequent surveys of sisterships showed that they too were having problems with their keel grids which was attributable to the builder cutting corners during the original construction.

b) The cost of fixing mistakes……. just do it right the first time!
I can't tell how many times I have inspected boats that have had previous "band-aid" like fixes to their keels and/or keel related structures only to have them fail again and be back in the boat yard. Repairs to these areas are usually complicated, involved and expensive. There's no way getting around it.

The extent of the damage needs to be thoroughly inspected and documented by a qualified surveyor or engineer, experienced in keel repairs and structures. The situation may also require the use of thermal imaging or the testing of material samples.

When the keel grid and sump area of this 41 foot production boat was found to be severely compromised, Steve Burke of Burke Design recommended the entire bottom of the hull in way of the keel be cut out of the boat and a new section be laminated up and put in its place. He jokingly yet appropriately calls this a "sumpectomy".

The boatyard where the work was done was lucky enough to have access to the hull tooling. Otherwise they would have had to splash a mould from the existing hull or a sistership.

Once the new section was ready and the existing hull prepared, it was carefully set in place and supported from underneath while being tabbed in from above and below. Next, the new floor and stringer structure was built in which was scarfed and tabbed to the existing structural members.

3) **Inadequate maintenance**

a) Putting a band aid on a gushing wound almost always leads to significant structural problems in the long run, and sometimes with fatal implications.

On 6th June 2008, the Cape Fear 38 “Cynthia Woods” was competing in the Regatta de Amigos from Galveston, Texas, to Veracruz, Mexico, with four Texas A&M students and two safety officers onboard. At approximately 23:00 the yacht suddenly and unexpectedly began taking on water at a very rapid rate and capsized and sank after its 5,000-pound keel fell off. 53 year old safety officer Roger Stone perished after he managed to push two students out of the cabin to safety. The four students and another safety officer drifted in the Gulf of Mexico for 26 hours before being rescued.

Cynthia Woods was raised and the keel was recovered to be brought ashore for a thorough investigation into the cause of the accident.

This is a case where I was involved as an expert witness for the lawyers representing the Stone Family. The reasons for this tragic accident were systematic with mistakes made at the design level, during construction by not following the structural specifications, and with the maintenance of the vessel. The latter of these was perhaps the most troublesome and was ultimately the catalyst for this disaster.

It appears there were multiple groundings of this boat on the ever shifting sand bars in the Gulf. In fact, the boat was reported to have been dragged for some distance to deep water after going aground in the waters off Galveston Bay. A tow like this would have exerted massive torsional loads on the keel and structure of the hull. Yet the boat was not taken out of the water and surveyed for damage even though there was evidence of structural damage to the keel grid. The only repairs that were done were by students who laid up several layers of bi-directional glass onto the faces of floors with very little surface preparation.

The fact that there was movement in the keel grid so as to have caused cracking in the fiberglass should have been enough of an indicator that the boat had a problem and that there was shear failure occurring in the laminate. What wasn't immediately evident was the unusually thin hull shell in way of the keel which eventually failed and ripped out of the bottom of the boat along with the keel still attached.

View looking up at where the keel should be

Keel with hull laminate still attached

4) Coming in contact with an immovable object

Here's an uncomfortable fact. Approximately 160 million shipping containers cross the oceans each year and 99.9 percent of them complete their journey without incident. But accidents do occur and cargos shift due to adverse weather and some are lost overboard. Most of these sink, but a few, filled with light cargo and packing material, stay afloat.

A 20-foot container can float for up to 57 days while a 40-foot container will float more than three times as long. That's plenty enough time to collide with something, especially since a fully-loaded container will generally float only 18 inches above water. Additionally, they don't always show up on radar and can be especially hard to spot at night.

Since containerization has been around now for forty years, you would think the cumulative effect would be staggering. Yet there do not seem to be that many incidents with yachts and containers. However, colliding with a water-logged shipping container in the middle of a gale is a sailor's worst nightmare, does happen and appendages are damaged or lost completely. Whales and basking sharks have also been credited with blue water collisions and damage to yachts.

Bad weather caused this shipping container stack to topple

A shipping container afloat ….a potentially lethal hazard