Grounding

With results from the first investigations

An important challenge to the boat's design is the ability to sustain a hard grounding. Ideally, a 8-knot grounding should not compromise the integrity of the boat, nor lead to highly difficult repairs.

Ready to hit a wall?

First of all, let's reflect on what happens when we hit a rock.

Here, the way we dissipate energy is crucial: 8 knots of boat speed is the energy equivalent of a 80 centimeter high freefall. Now,

- let the boat fall into water from 80 centimeters, and no damage will be made: all the energy will be dissipated in water or transferred to waves.
- let the boat fall from the same height to some hard ground: it's hard (ouch) to imagine that no damage will be made.

We can start with a short calculation of how the energy is dissipated in a grounding. In this simplified sketch, the boat arrives with horizontal momentum, then a "perfectly inelastic collision" happens at the bottom-front point of the keel, after which the boat has a rotation movement around that point, which drives the hull into water, and the water ends stopping the boat and dissipates what was still left of the initial energy. In other terms, we have first something that falls in the same category as the boat falling onto hard ground, then something of the same kind as the boat falling into water. What we want to know is, given the geometry of how all this happens, if the initial energy will be dissipated the hard or the gentle way.

The "striking" result of this calculation is that at least two-thirds of the initial energy is dissipated in the initial collision. In short, this is because the vertical distance between the boat's center of gravity and the point of impact is shorter than the "characteristic distance of pitching inertia" (d such as $I = md^2$, where I is the boat's moment of inertia and m its mass). In other words, the rock strikes the boat relatively close to its center of inertia, so that the linear initial movement is not easily transformed into a rotational movement. Thus, any mental image of the boat going past the rock as it hits it, somewhat reducing the violence of the thing, is a fallacy. Basically, we must think of hitting a rock, be it with the lowest point of the keel, as the equivalent of hitting a wall.

8 knots rather than 3?

We are lucky enough that the sailing school where we used to teach experiences… hum… several hard groundings per year. So we went to the experts.

Their "expert opinion" is that on most fibreglass production boats today, the threshold in terms of grounding speed is around 3 knots: under that speed, there generally is no structural damage, above it, we can assume that there will be some damage. This means we have almost a factor 3 in grounding speed, and a factor 7 in terms of grounding energy, to achieve. Wow.

Oversizing won't be enough

We could go like, "let's make everything 7 times beefier". Would that work?

Well, first, 7 times beefier is a lot.

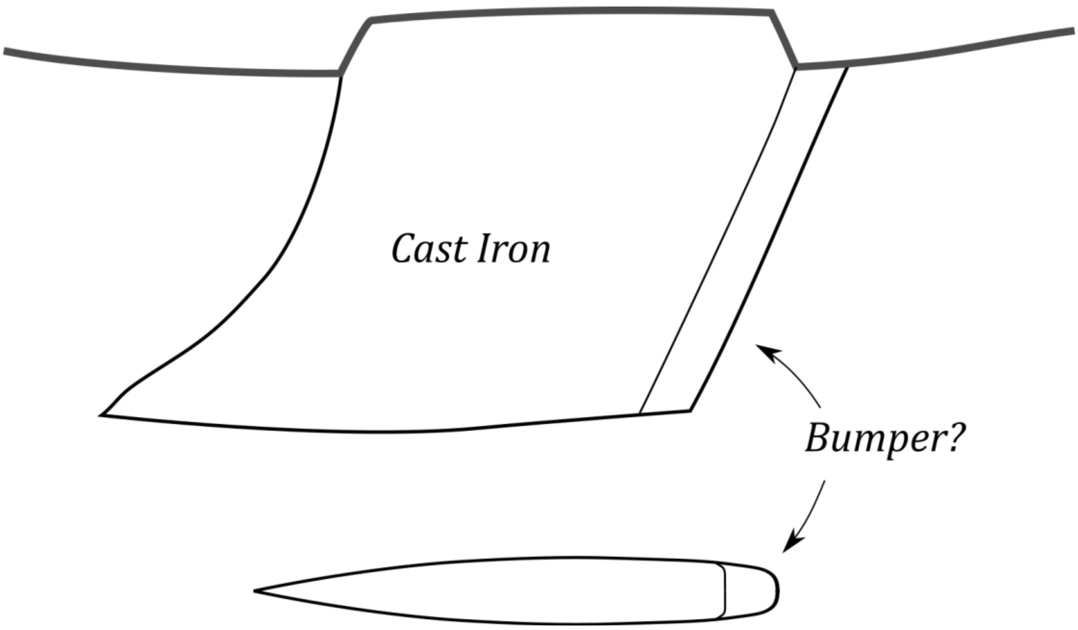
But more importantly, this approach would not properly address the issue. What we want to deal with is a shock, and we have to ensure that shock absorption happens, without shock loads going too high. In that regard, structural rigidity is not a good thing: the more rigid the structure, the more violent the shock loads - because the shock will happen in an even shorter timeframe. This has to do with the time-old story of the oak and the reed in a storm.

Looking for an absorber

Hence we tried to investigate how to build some kind of fuse, for instance between the keel and the hull, that could break and absorb the energy in a predictable manner. Long story short : apart from a lifting keel with a hydraulic ram (or, for that matter, with a massive spring…), which for other missions can be an excellent solution, but for our purposes would likely be over-complex and costly, we could think of no credible system - hey, having something break in the middle of the boat's structure is not going to be easy to organise and to deal with.

However, our field experts in grounding, apart from the usual thing with the aft edge of the keel going up and the leading edge going down, and the repairs being horribly complex, gave us a useful hint: when there is lead ballast, the lead generally goes significantly distorted.

This made us realise that the fuse doesn't need to be inside the structure of the boat: the fuse can be on the leading edge of the keel! Here, the question becomes how to engineer some sort of sacrificial absorber, or "bumper", integrated to the front edge of the keel.



Other than representing the absorber hypothesis, this drawing features a cast-iron keel with a serious keel-to-hull joint, which is the base solution for our purpose, because it is reliable and affordable.

The strategy

So here we have our strategy: make the structure beefy, but, also, protect it with a shock absorber.

The material and shape of the shock absorber will have to be carefully determined. It must be able to absorb, by deformation, a sufficient amount of energy.

Think of a comparison: we have a (drinking) glass fall from a table to the floor, and we want it to stay intact. Obviously, if it is too thin, it will break. If we make it thicker, the probability that it breaks will decrease. But relying on thickness only to make the glass unbreakable probably requires going too far. The way to go is to make the glass thick, AND protect it with a layer of rubber or other non-super-rigid material.

This is where we stood when Vincent entered the stage. With him, we reviewed this whole issue - as we did on all the main design points.

Are keel bumpers a thing?

First, Vincent told us that a “keel bumper” has already been done on one of his boats (!). This was on the Paroa 34, and the bumper was in wood. In this case, it was added after the fact more than integrated to the initial design, and it was not the subject of detailed engineering. Moreover, Vincent and the builder are now replicating the general idea on a bluewater design: in this other case, which relies on a welded-steel keel, the structure supporting the steel skins will be absent in the forward sections of the keel.

All this sounded like we were not totally wrong-headed! And of course, we will be glad to learn whether others, somewhere else, have gone the same way.

The Paroa 34’s backwards-lifting cast-iron keel, with its bumper

Let’s talk speed of impact…

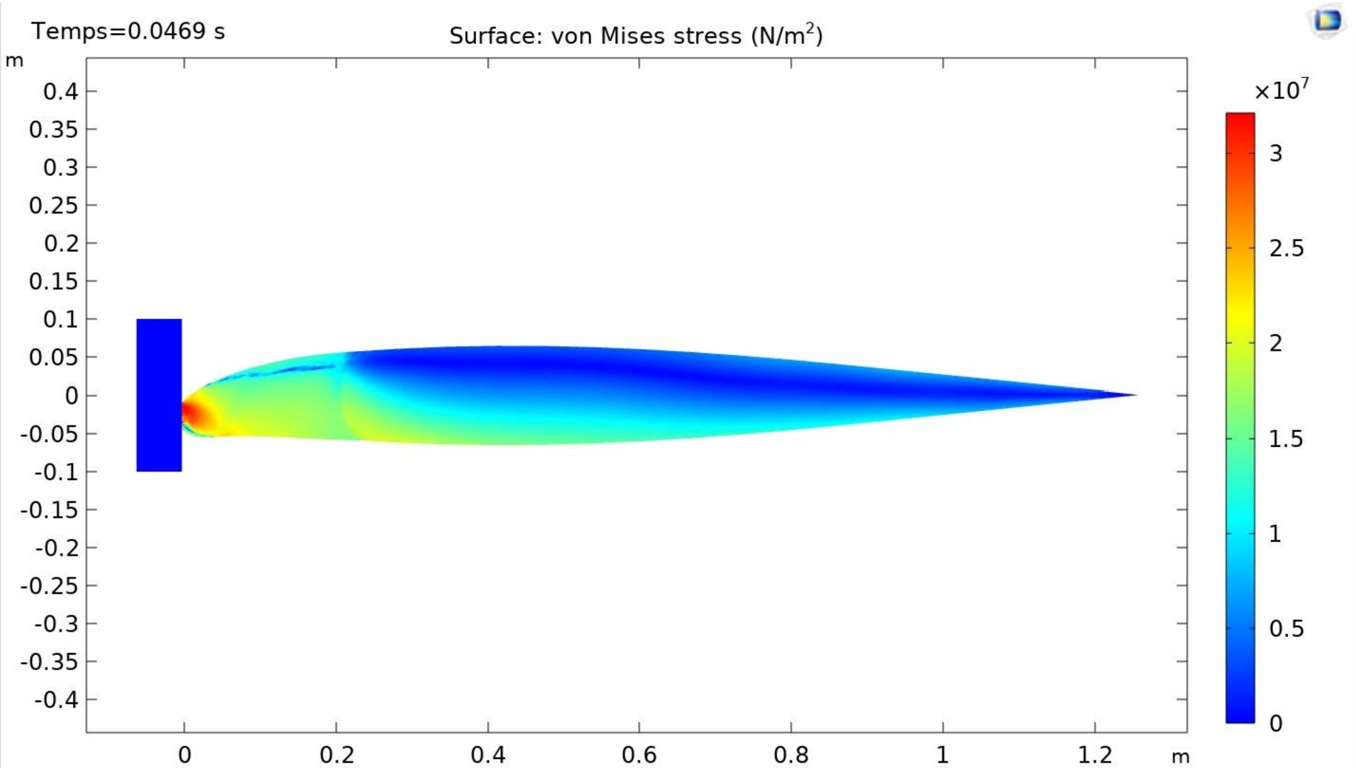
However, we still have to quantify things - to write down, in the specifications, what we want the boat to sustain. Ideally, this is a speed of impact, and the related outcome.

Here, Vincent confirmed this is not usually done. In fact, he has already been asked by several of his clients *"well, we're doing the engineering of the boat's structure as required by the relevant ISO standard - but what does this mean in terms of the grounding speed I can likely sustain?"*. It happens that to date, and at least for most builds, no one really knows, because the usual calculation, as mandated by the ISO standard, only simulates a static load, and not a shock load.

… and finite element analysis

We had an opportunity to have some numerical computations carried out by engineering students. We started with simple 2D simulations, and, given what we had learned, with lead at the leading edge.

Here are the results, for a 3-knot impact:



Here we assumed that:

- the boat weighs 9 metric tons with its load,
- the vertical offset between the point of impact and the center of gravity has an effect equivalent to removing one quarter of the boat's mass – with the assumptions we made on the geometry and mass characteristics of the boat, this figure would even be approximately one third if the impact hits at the lowest point of the leading edge, but only one tenth for an unlikely impact with a fixed object at the highest point,
- the impact happens along a 20-cm-high fraction of the leading edge.

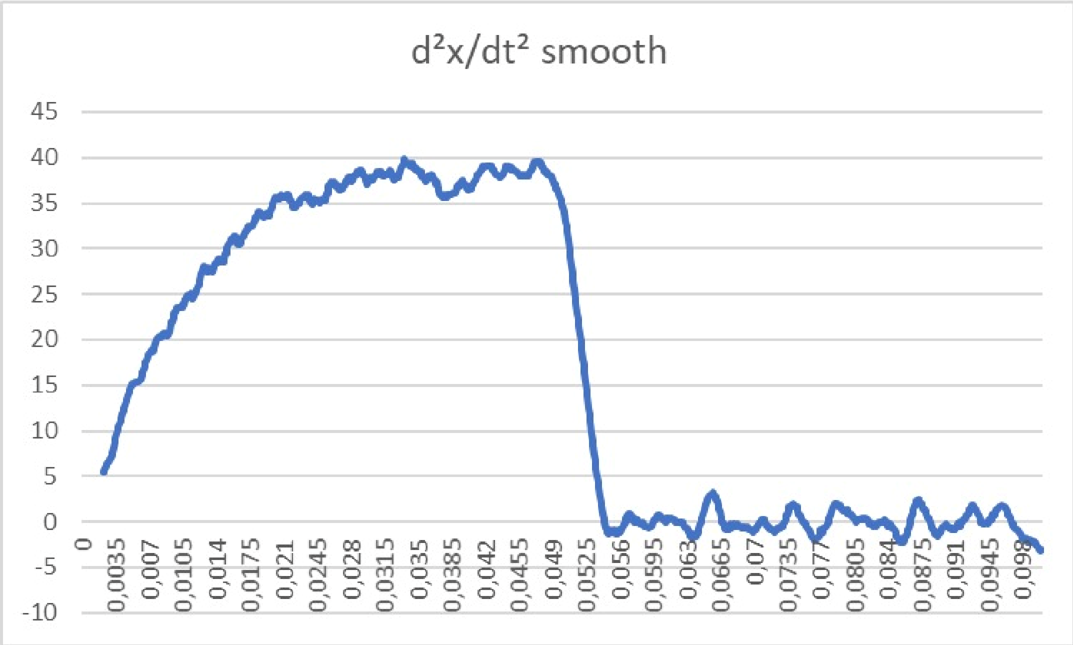
In relation to the last assumption, it's important to note that the real-world behaviour will strongly depend on the geometry of the rock. These 20 cms are just an hypothesis, that ideally would have to be adjusted to the actual local geometry of the rock.

Another hypothesis is that the lead used here is not alloyed with antimony in order to harden it, as is the usual for manufacturing keels, but is close to pure lead.

The above represents the keel as deformed by an impact at 3 knots – assuming all the forementioned hypotheses. And below is the deceleration that the keel experiences.

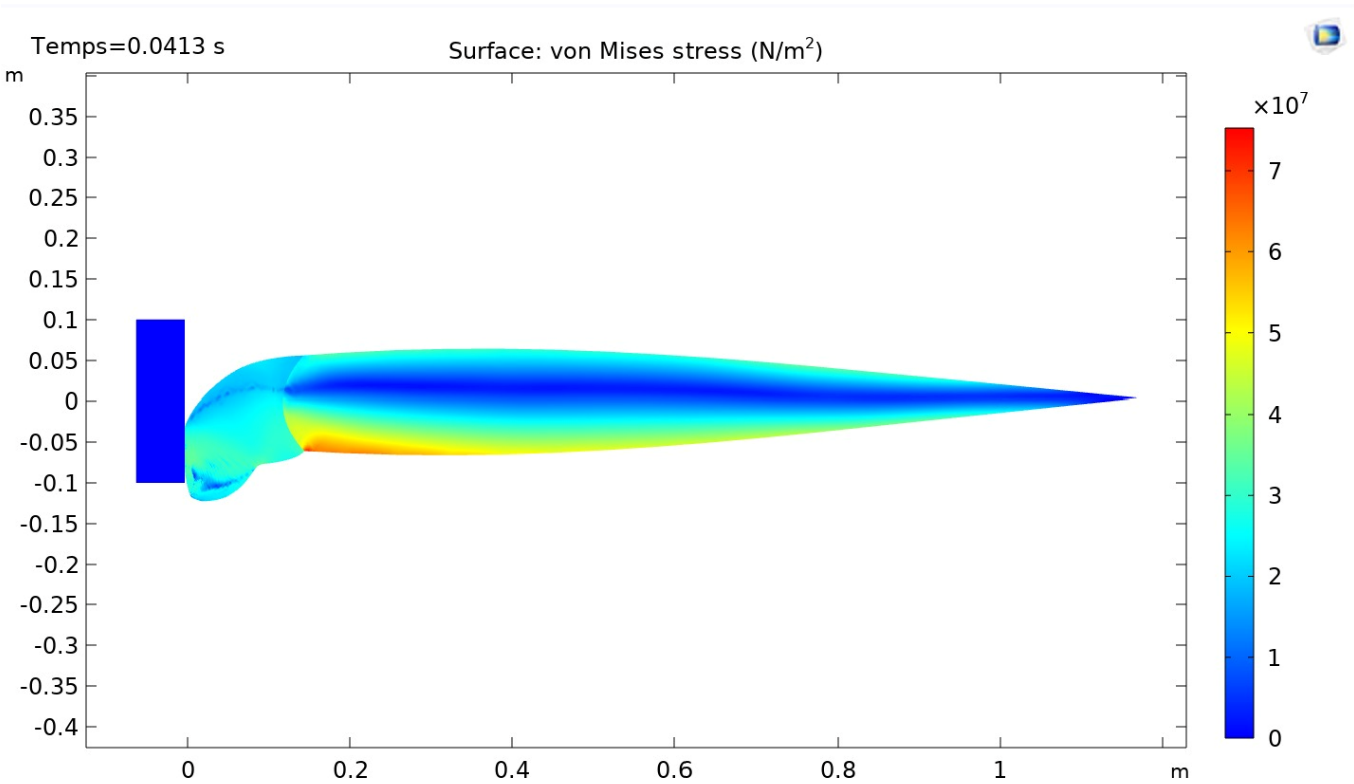
Grounding

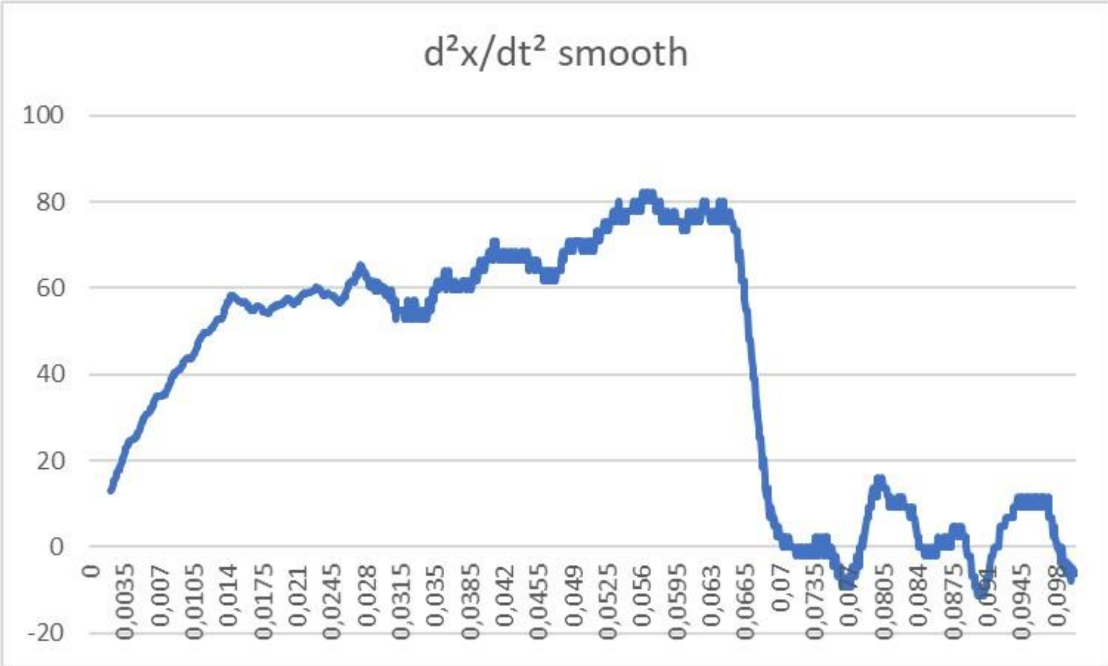
With results from the first investigations



Deceleration, with our assumptions and 3 knots initial speed. Note: the horizontal scale is in seconds, and 10 $m.s^{-2}$ on the vertical scale amount to a deceleration of 1 G.

And below are the results, with an initial speed of 8 knots:





What can we learn from these?

Well, first, it appears that unalloyed lead is soft enough to go significantly distorted, but not as soft as to be totally pushed away by a violent shock. This is good news. Too strong a material wouldn't distort much, which wouldn't allow for much absorption. Conversely, too soft a material would collapse even in the face of a comparatively minor collision, leaving the main body of the keel to hit the rock when not much of the initial speed of the boat has been removed, and this we don't want. Here we seem to reach a good trade-off.

To interpret the deceleration curves, let's recall what we're trying to achieve: we're trying to stop the boat in a given limited distance – we cannot realistically have a 1-meter deep absorber –, while limiting the loads on the keel-to-hull structure. These loads are directly proportional to the deceleration we're applying to the keel. So we need to cap deceleration. And we also need to bring deceleration (ie, the braking force) close to this cap as soon as the braking process starts – if we don't, we will spoil some part of the "braking distance" to no use. The excellent news from the deceleration graphs is that our very crude absorber design does exactly that: the deceleration is capped, at 4 Gs for the 3-knot case and 8 Gs for the 8-knot case, and the "braking profile" is in fact relatively close to the rectangle (constant-force braking) that we would ideally dream of! As opposed to a curve that would take off slowly (insufficient initial braking) and then climb to a super-high peak-load (brutal braking).

Caveats:

- there are a variety of possible impact configurations, and these simulations only represent a geometrical case that we think represents some "average" of the possible likely configurations;
- for the sake of simplicity, these simulations were made in 2D, which obscures the fact that the vertical length of contact between the rock and the keel will likely increase along the impact process. Accounting for this would probably take the deceleration curves further away from the ideal rectangle, but not (unless we meet some exceptionally weird-shaped rock) change the nice result that the bumpers "caps" the maximum deceleration.

Isn't 8 Gs a lot?

This may sound like a lot. But it's actually a lot lot less than the deceleration we would experience if directly hitting the rock with a rigid keel. In fact, 8 Gs is a deceleration not totally unknown to us humans: above, we said that 8 knots is the equivalent of a 80-cm high freefall. 4 Gs is what we experience if we stop this fall by flexing our legs on a 20-cm distance (not enjoyable, but quite common experience), and 8 Gs come with flexing the legs along 10 cms only (not advisable, but not deadly).

Assuming we go with this solution, how do we engineer the keel-to-hull joint?

As usually done! Have the architect devise a structure that, according to his experience, feels sufficient, send it to the engineering office to perform the static loading computation and see if something breaks. If it breaks, beef up the structure and restart the process until everything is fine.

However, the big difference here is that, since the absorber caps the maximum force, we can safely rely on a static loading computation, even if the initial problem is a shock. And the bumper engineering gives us an estimate of the force that must be applied in this computation. By the way, assuming this force is around 8 Gs (this will have to be thought through after the keel is designed for real), it would still be many times the force required by the ISO standard!

Let's sum up.

Our core solution

In the end, to date, the core of our solution is to:

- stick to the "bumper" solution, ie design an absorbing feature at the leading edge of the keel.
- oversize the boat's structure, perform the static load calculus mandated by the ISO standard (it's compulsory anyway), and altogether perform the shock load calculus (probably on the "bumper" only) that will yield an estimated maximum speed of no-failure grounding. For now, we don't define this speed in advance, because it may be a trade-off and we need to go further into the design to understand the parameters of this trade-off. But this speed will for sure be well above the approx. 3 knots threshold.

Caveats to the core solution

However, two important caveats must be made:

First, hitting a rock at speed with the keel is not the only way a grounding can happen. Another type of grounding to be feared is hitting the ground vertically in a repeated way - for instance, over a sand bank with even a minimal amount of swell. This can be extremely destructive, even to the strongest keels and hull structures. There is no way our absorber will do anything to ameliorate this situation.

Second, a grounding with the keel at high speed endangers the crew in two ways:

- if applicable, by compromising the structural integrity of the boat. This is what our absorbers seeks to minimize;
- but also, before that, by direct wounds, when the crew falls unexpectedly, if not overboard, onto whatever is there to hit a head or anything else. The absorber will do little to this.

Further investigations

We've seen that unalloyed lead is a very good candidate for a bumper – but this by no way means that it is the only solution. Any other design that is affordable to build and can live in seawater for decades could be considered!

If we go the lead way, the perspective of placing lead at the leading edge increases the point of making the whole keel out of lead (with some bit of steel structure inside). While the better performance (density) of lead and its easier long-term maintenance over cast-iron (no rust) were initially, we felt, not enough to justify its higher cost, adding the benefit of a "built-in" bumper arguably reverses the equation.

For the lead bumper to work, the leading edge of the keel shouldn't be wider than what we computed. This means that any ballast "torpedo" shouldn't hit the rock head-first. A relatively narrow leading edge should come first, and the torpedo "head" be further aft.

There remains a fun still-to-be-investigated engineering question: is it possible to cast a lead keel with the main parts alloyed with antimony, and the absorbing part in pure lead, and have no fragility at the border between the two, and stay affordable?

Anyway, we seem to be on the path to some low-tech solution that will be effective while keeping things simple!