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Avoiding Failures: It's All About the Interfaces

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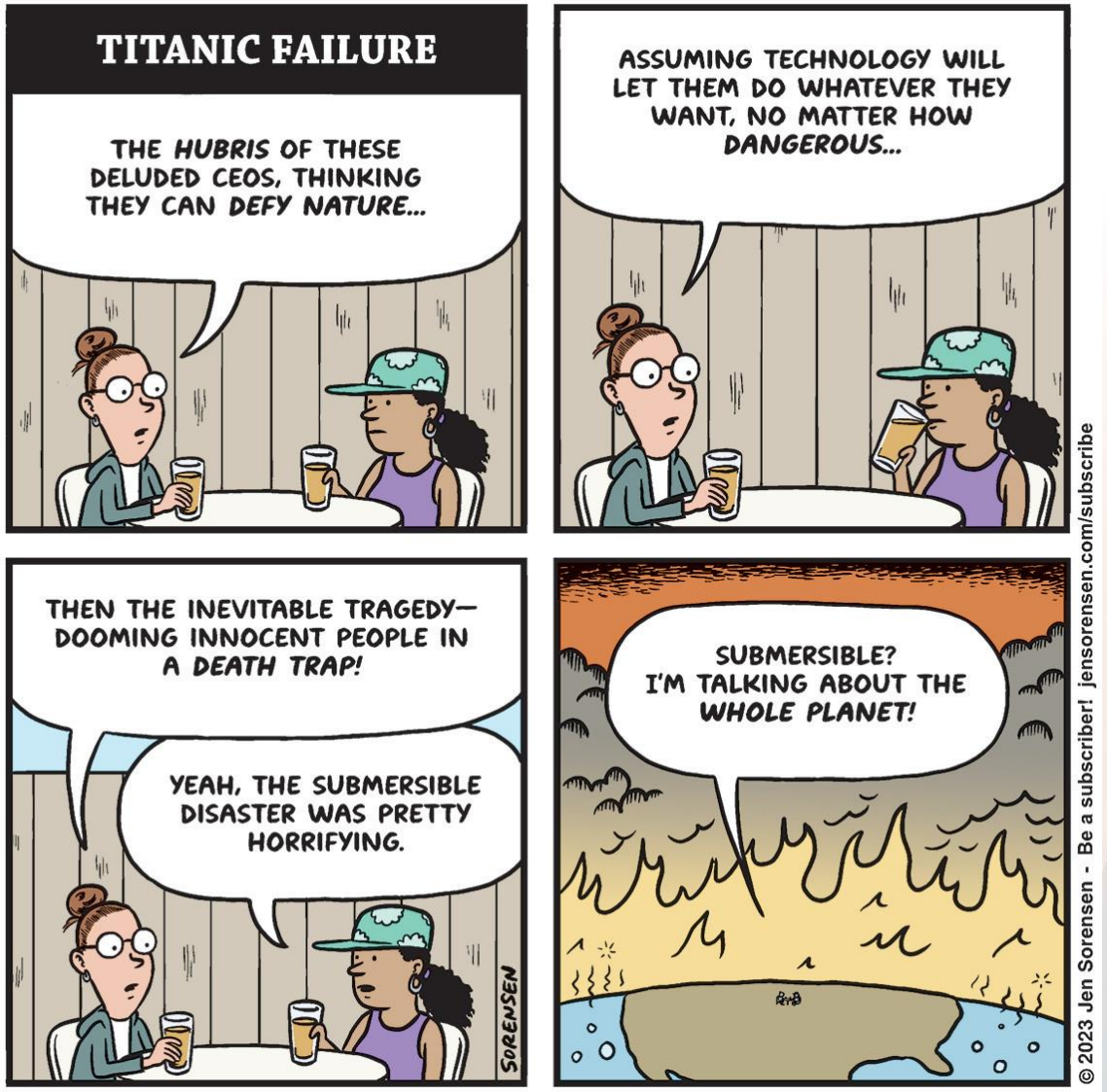
What Everyone Thinks about Titan



Interfaces?

Meriam-Webster

"a surface forming a common boundary of two bodies, spaces, or phases"

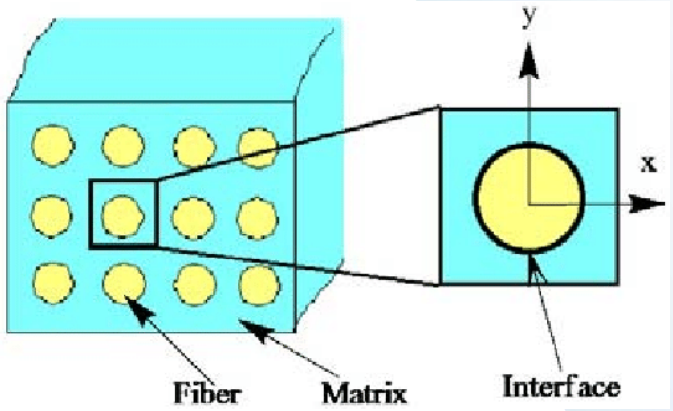
In Composites:

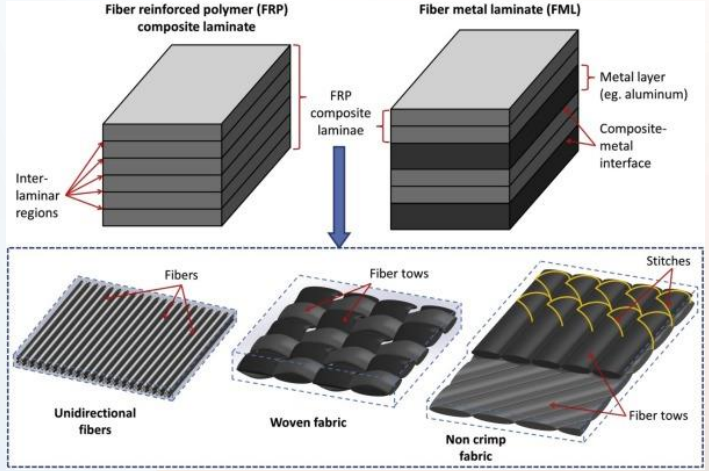
Fiber/matrix

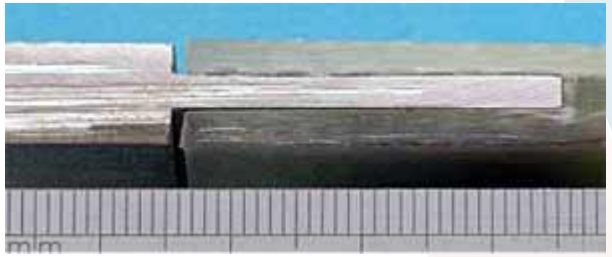
Composite/metal

Bonded or bolted joints

Composite/composite

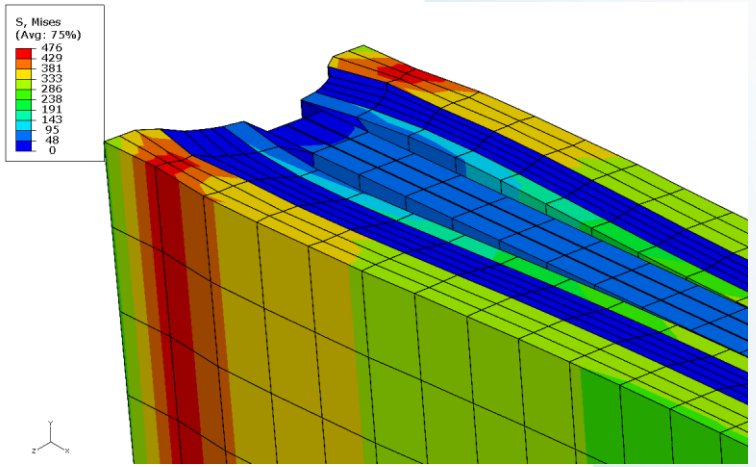


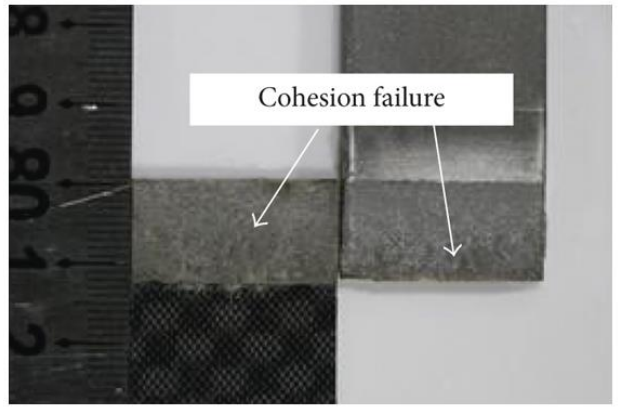


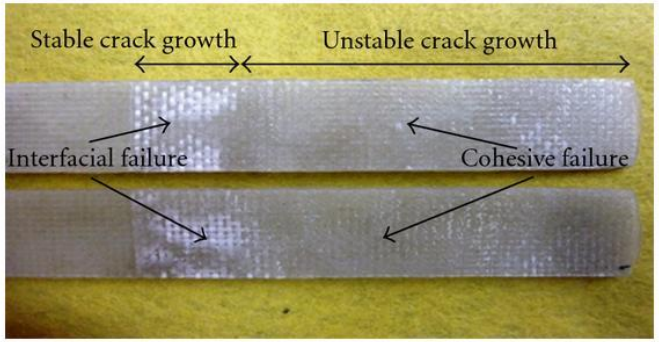


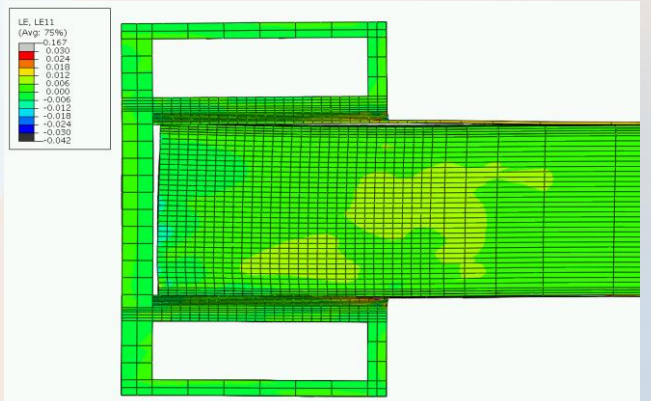
Composite Failure – Almost Always at an Interface

- Most common at Metal – Composite interface
  - Bonded, bolted, captured, overlayed, lapped, …..
- Failure starts in high strain areas
  - Metal and composite have different stiffnesses/strains
  - Strain mismatch causes disbonds or delamination
- Critical to get the design and fabrication process right and **test, test, test**









Critical Pressure Hull Interfaces

- Composite/metal – cylinder to end metallic ring connection
  - Stiffness / strain mismatch between cylinder and metal end attachment
  - Potential imperfections in bonding of joint
  - Potential of seawater intrusion to soften adhesives
- Interlaminar – layer by layer in initial winding process
  - Avoiding stress buildup from winding process and buckling of inner layers
  - Avoiding any voids or inclusions that can cause local loss of stiffness
- Fiber/Matrix – within a layer
  - Potential seawater intrusion damaging fiber/matrix bond or softening matrix
  - Potential lack of adhesion or embedded inclusions/voids during fabrication and cure

Composite/Metal Joint Most Critical

- Metals are isotropic, composites are not
  - External pressure causes strain mismatch between composite and metal
  - Strain mismatch – high interlaminar shear and tensile stress
- Results in:
  - Carbon fiber cylinder compressing more than metal attachment ring
  - High interlaminar tension and shear leading to bending in region of metal ring
- Composite delamination likely result

What does this Mean for Deep Submersibles

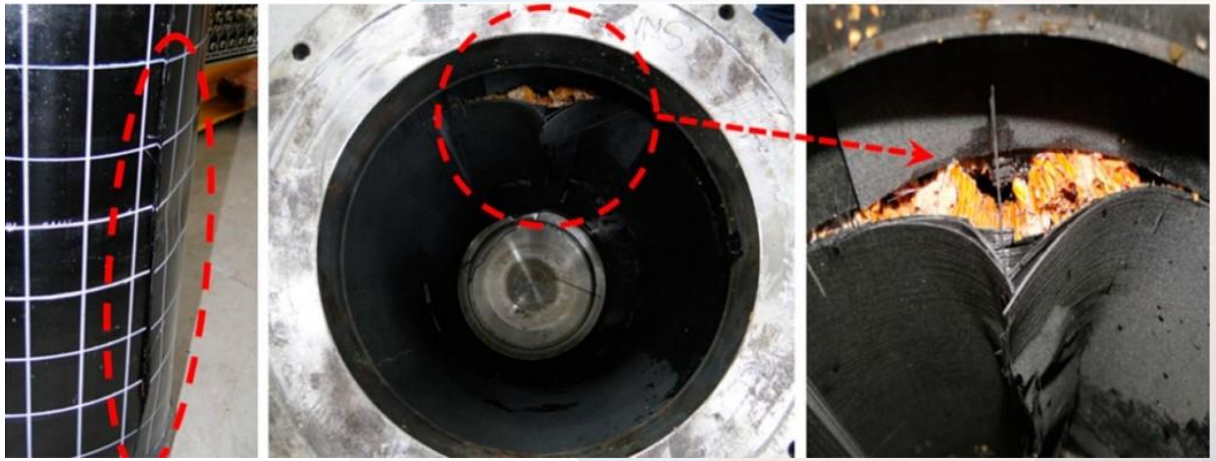
- Composite to metal joints hard to get right,

AND

- The deep ocean is unforgiving,

SO

- Designing these joints best left to experts
- Attention to detail in design and process control critical, and
- Rigorous testing with trial and error prototyping required

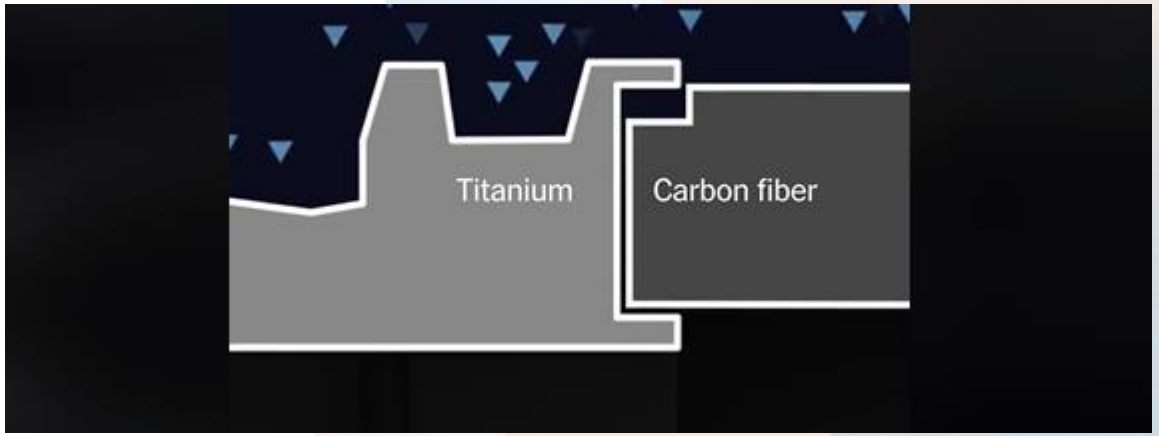


Other Things to Consider to Get it Right

- Cyclic damage from repeated dives
- Fabrication process and fabrication imperfections must be part of design process
- Structural modeling of real world imperfections – how to take into account
- Inspection during and after fabrication – who will inspect and how
- Testing after fabrication – cyclic testing, overpressure testing
- Structural health monitoring
- **Thorough inspection after every dive**

Titan Carbon Fiber to Titanium Hull Joint

- Captured composite joint design
- Titanium stiffness ~17 MSI
- Carbon/Epoxy
  - Through thickness ~1-2 MSI
  - Hoop ~10-20 MSI
- Were material coupon tests performed?
- Was joint design tested to failure?
- Was cyclic damage assessment made?
- Structural health monitor?



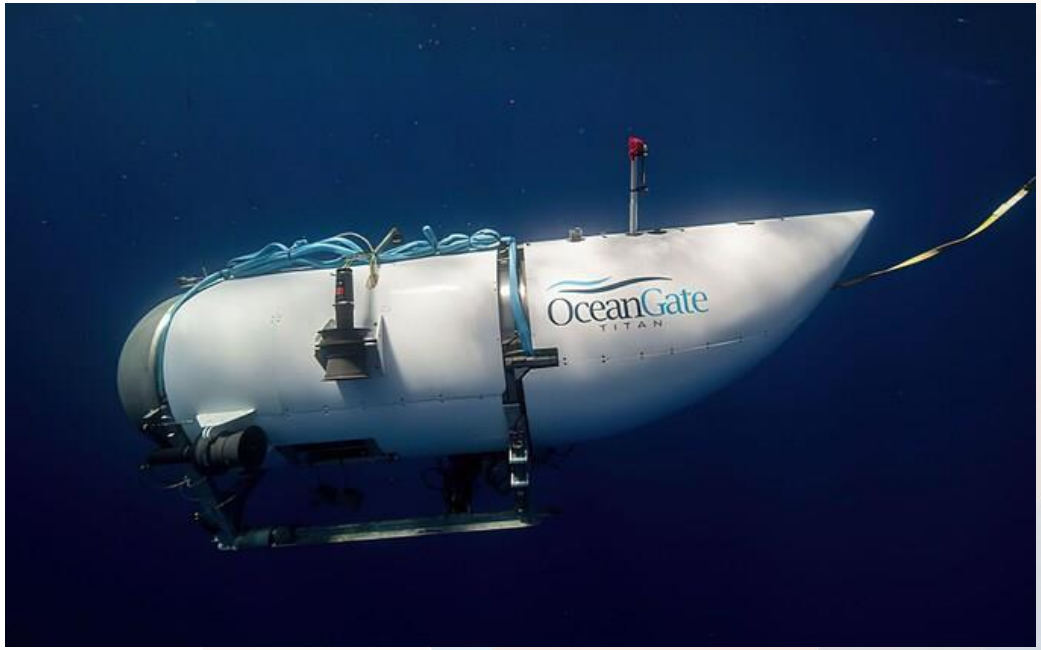
What Mistakes Eventually Led to Disaster?

- ✓ Failure to have design and fabrication reviewed outside the company
- ✓ Probable failure to adequately control raw materials
- ✓ Probable failure to take into account composite exposed to seawater
- ✓ Probable failure to adequately control fabrication process
- ✓ Failure to build and test sub-scale prototypes of at least critical components (e.g. Titanium to Carbon Fiber joint)
- ✓ Failure to perform adequate testing of final pressure hull
- ✓ Failure to get DNV or ABS inspection and certification
- ✓ **Failure to pay sufficient attention to the Interfaces**

Bottom Line

Interface Failures Likely Led to Collapse

Disaster was Avoidable



Thanks for Listening

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