Transformation et comportement des matériaux

Materials behaviour and processing

Fractures Mechanics

Mécanique de la Rupture

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23 mars 2010

Outline

Some exemples of ruptures mechanics

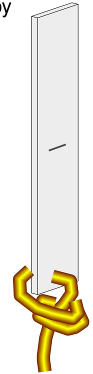
The material and the design of RMS Titanic

Fracture of the glass

Brittle material| Problem

A noted philanthropist offers you the chance to earn £ 50 000 by simply hanging from a rope for just one minute. The rope is attached to a sheet of glass which is 300 cm long by 10 cm wide and 0.127 cm thick.
Complicating the situation are :

1. The glass sheet contains a central crack with a length of 1.62 cm that is orientated parallel to the ground and perpendicular to the longest side of the glass sheet. The fracture toughness of the glass is known to be 0.83 MPa.m$^{1/2}$.
2. The rope is suspended over a deep pit containing rather annoyed green mamba snakes.



Would you try for the pot of gold at the end of the rainbow ?
The stress intensity factor for a through-thickness crack is given by :

$$K = Y\sigma\sqrt{\pi a} \text{ where } Y = 1 + 0.256\left(\frac{a}{W}\right) - 1.152\left(\frac{a}{W}\right)^2 + 12.2\left(\frac{a}{W}\right)^3$$

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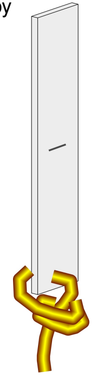

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Fracture of the glass

Brittle material| Solution

The size of the glass sheet is necessary to calculate the stress in the sheet due to your weight hanging on the rope. Remember that this stress is calculated on the full cross-sectional area of the sheet, i.e. as though the crack is absent. This is clearly a finite sheet of glass, so we need to correct the stress intensity equation for this.
Essentially :

$$K = Y\sigma\sqrt{\pi a}$$

where the finite geometry correction function Y is given by :

$$Y = 1 + 0.256\left(\frac{a}{W}\right) - 1.152\left(\frac{a}{W}\right)^2 + 12.2\left(\frac{a}{W}\right)^3$$

Hence as $2a$ = 16.2 mm, a = 8.1 mm and W = 100 mm, which gives Y = 1.0196. The applied stress is simply obtained from :

$$\sigma = \frac{F}{A} \text{ where } F = \text{load and } A = \text{cross-sectional aera}$$

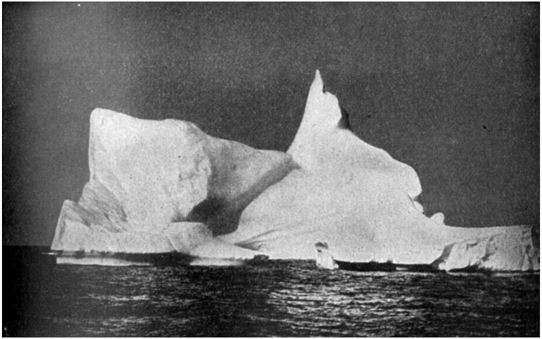
$$\text{i.e. } \sigma = \frac{60 \times 9.81}{100 \times 1.27} \text{ MPa for a 60 kg person} \rightarrow \sigma = 4.63 \text{ MPa}$$

$$\text{Hence } K = 1.0196 \times 4.63\sqrt{\pi \times 8.1 \times 10^{-3}} = 0.75 < 0.83 \text{ MPa.m}^{1/2}$$

This calculation is not based on my own weight and, if I was feeling brave, I might try for the money. In general terms, the margin of safety is somewhat low - it might be better to let a younger and lighter sibling earn the money for you !

The material and the design of RMS Titanic

The raison of sinking

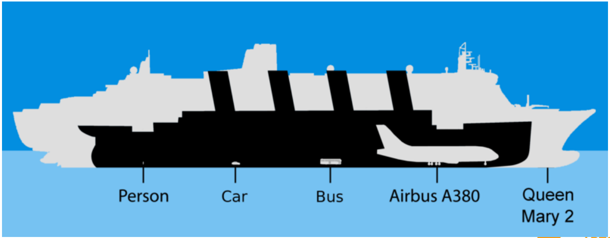


RMS Titanic before this first voyage – Iceberg

Titanic

Size

- Length 269 m
- Width 30 m
- Draft (from waterline to bottom of the hul) $\approx$ 11 m
- Depth (from waterline to deck) 45.5 m
- Weight 52250 t
- Power 33.1 MW
- Speed 42-45 km.h^{-1}



Comparison of Titanic size with Queen Mary II and Airbus A380

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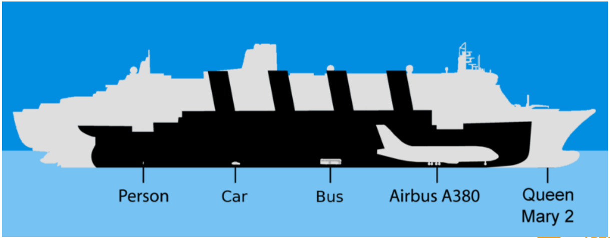

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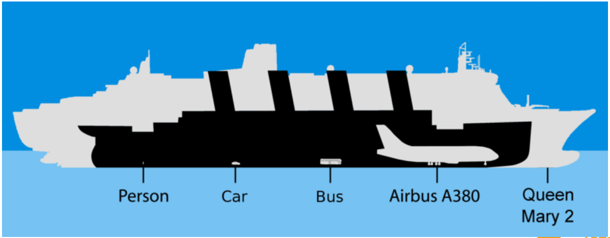

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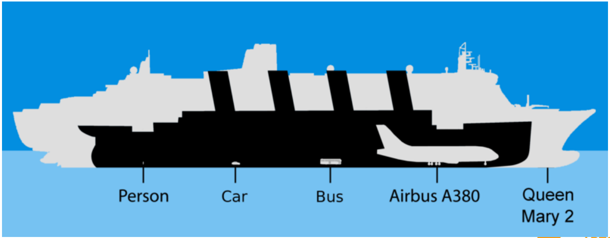

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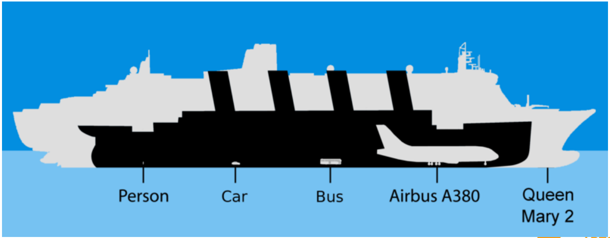

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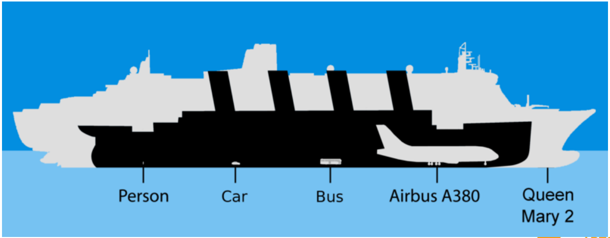

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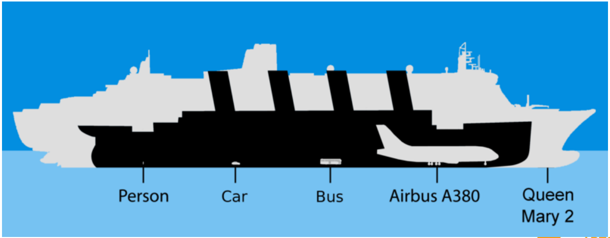
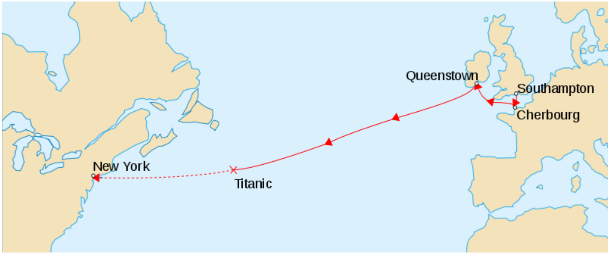


Comparison of Titanic size with Queen Mary II and Airbus A380

Titanic

First voyage

- On April 10, 1912, RMS Titanic began her voyage from Southampton
- On April 14 @ 11 :20 PM RMS Titanic struck an iceberg on her right hand side of the front section facing while traveling at a speed of 20.5 knots (38 km.$^{-1}$)
- @ 2 :20 AM Titanic sank (within 2 h 40 min)



Titanic route

What caused Titanic to sink ?

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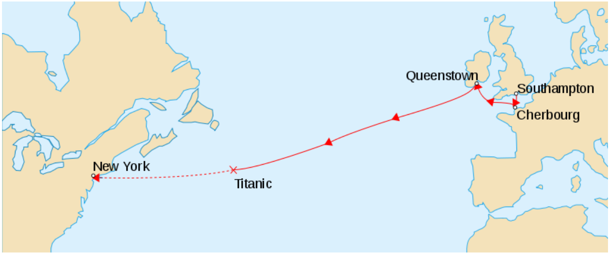

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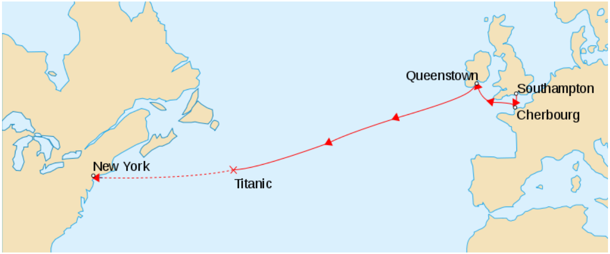

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What caused Titanic to sink ?

Titanic

Reasons for sinking

1. Material issues
   - Composition
   - Microstructure
   - Mechanical Properties
2. Design issues

Titanic at the bottom of the Atlantic ocean

Titanic

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Titanic

Material composition | Hull steels

TABLE: composition in weight percent [K. Felkins, H. P. Leighly, and A. Jankovic. JOM, 50(1), 1998, 12-18]

	Titanic hull plate	A36 modern structural steel
C	0.21	0.20
Mn	0.47	0.55
P	0.045	0.012
S	0.069	0.01 to 0.04
Si	0.017	0.007
Cu	0.024	0.01
O	0.013	-
N	0.0035	0.0032
Mn :S Ratio	7 :1	15 :1 (typical)

- Presence of relatively high amounts of P and S embrittles the steel at low temperature
- The lower Mn :S ratio increases the ductile-brittle transition temperature

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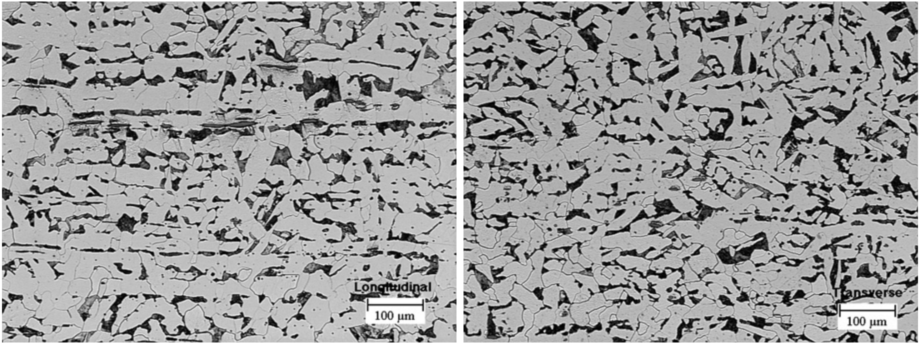
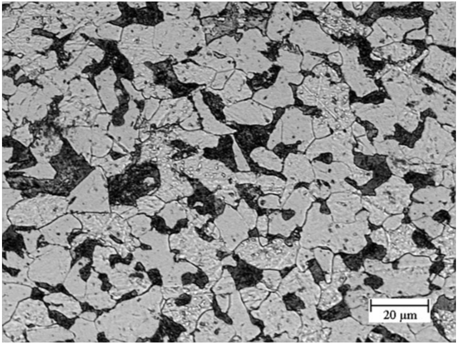
Hull steel microstructure



Longitudinal direction (average grain diameter $\approx$ 60 μm – Transversal direction (average grain diameter $\approx$ 42 μm

Titanic

Modern A36 microstructure



Longitudinal direction (average grain diameter ≈ 26 μm)

Titanic

Effect of grain size

- How does the grain size affect strength ?
  - Hall-Petch equation : $\sigma_{ys} = a + bd^{-1/2}$
  - Yield strength of steel with 26 μm grain size is about 27 % higher than that of a steel with 42 μm grain size if the value of a is small
  - N.A. : $\frac{\sigma_{ys}^{\text{Titanic}}}{\sigma_{ys}^{\text{A36}}} = \frac{a+b.42^{-1/2}}{a+b.26^{-1/2}} = \frac{a+6.5b}{a+5.1b}$ if $a \ll b$ then $\frac{\sigma_{ys}^{\text{Titanic}}}{\sigma_{ys}^{\text{A36}}} = \frac{6.5}{5.1} = 1.27$
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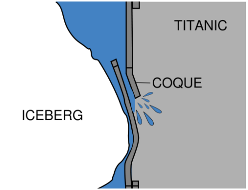
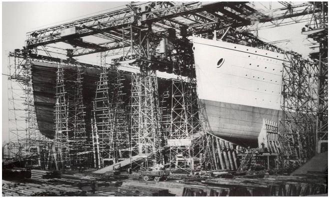
Titanic
Material failure

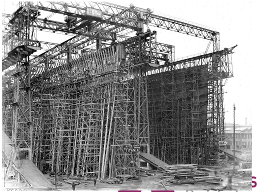
- When the Titanic collited with iceberg, the hull steel and the wrought iron rivets failed



Collision with iceberg – The number of rivets for Titanic assembly is about 3 000 000

- The steel and the wrought iron rivets failed by brittle fracture
- Brittle facture
  is a failure of a metal by rapid crack propagation and without any significant deformation





Titanic structure was assembled using plates riveting

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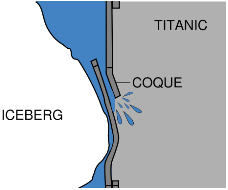

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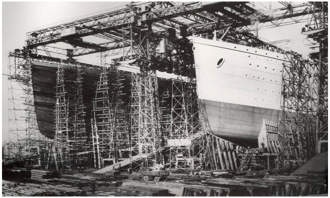

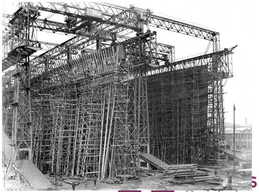

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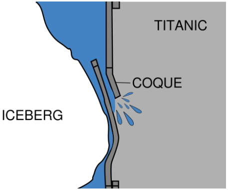

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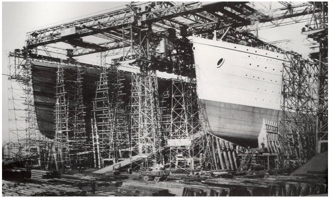

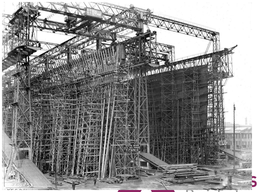

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Brittle fracture

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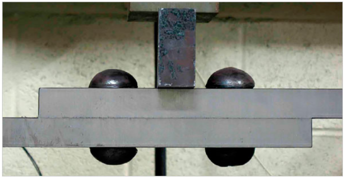
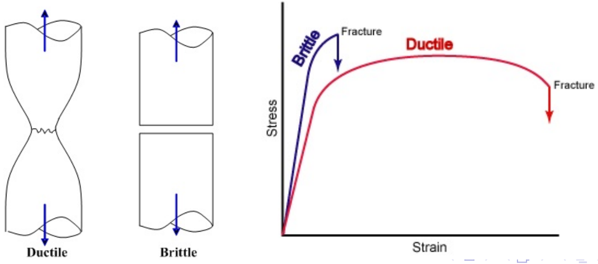



Plate riveting – Brittle crack of rivet

- Schematic representations of tensile stress-strain behavior for brittle and ductile materials loaded to fracture



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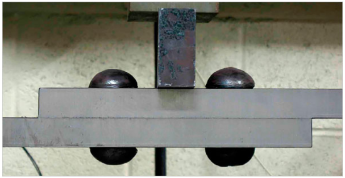


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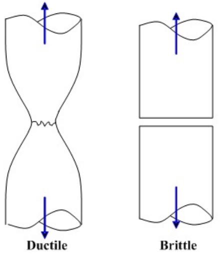

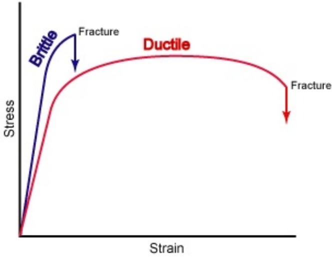

Titanic

Cause of the brittle fracture

- What was the effect of the impact with the iceberg ?
- Did the sulphur content play a role in the failure ?
- What was the ductile to brittle transition temperature for the steel used to construct the hull of Titanic ?
- Did the sea water temperature experienced by the Titanic (-2˚C) play a role ?

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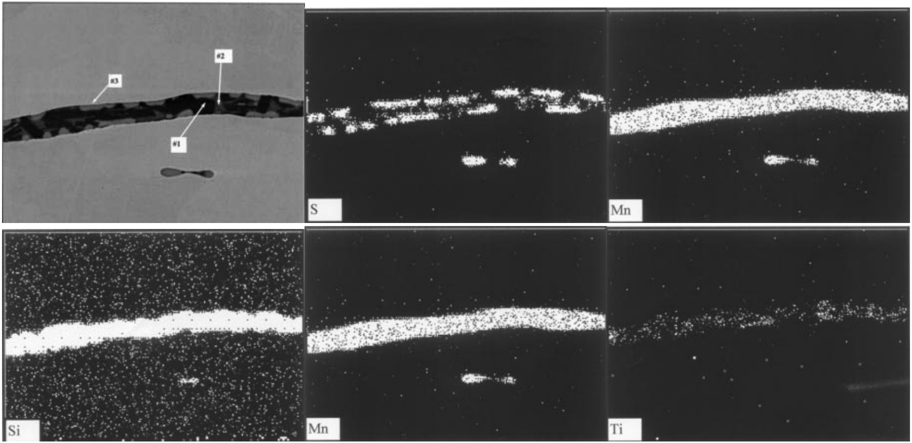
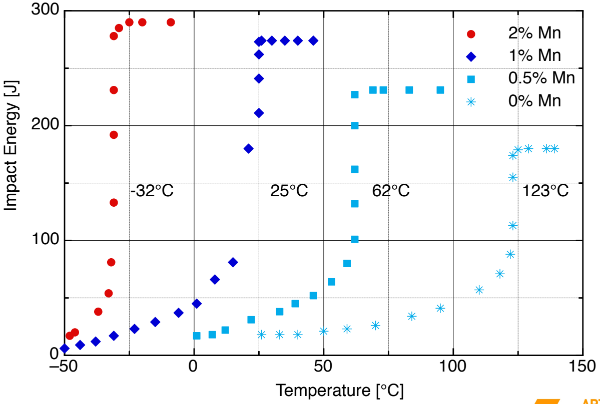
Cause of the brittle fracture| Sulphur



Titanic

Cause of the brittle fracture| Effect of steel composition

- Higher %Mn is beneficial to prevent ductile to brittle transition because Mn prevents formation of brittle iron sulfides

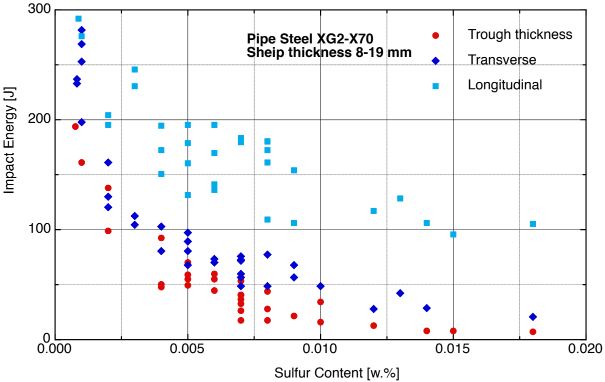


Effect of Mn composition on ductile/brittle temperature

Titanic

Cause of the brittle fracture| Sulphur Effect

- Lower %S is beneficial to prevent ductile to brittle transition because S prevents formation of brittle iron sulfides



Effect of S composition on ductile/brittle temperature

Titanic

Material | Tensile properties

TABLE: [H. P. Leighly, B. L. Bramfitt, and S. J. Lawrence. Practical Failure Analysis, 1(2), 2001]

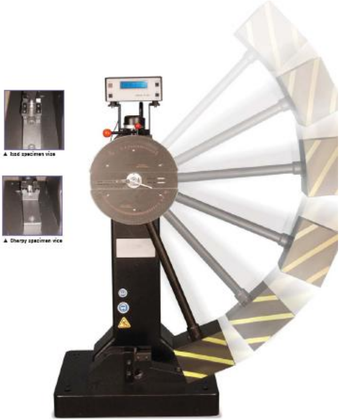
	Titanic Steel	A36 modern steel
Yield Strength [MPa]	193	338
Tensile Strength [MPa]	417	441
Total Elongation [%]	29.0	27.0
Reduction in Aera [%]	57.1	66.0

- Presence of relatively high amounts of P and S embrittles the steel at low temperature

Titanic

Material | Charpy Impact Test

- The energy absorption is a measure of the impact energy
- The results are qualitative in nature and are useful in making comparisons
- Determine whether or not a material experiences a ductile/brittle transition with decreasing temperature and, if so, the range of temperatures over which it occurs



Charpy Tester and Sample

Titanic

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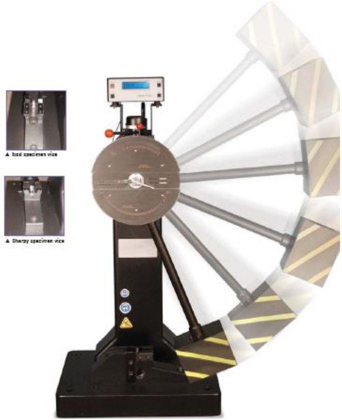

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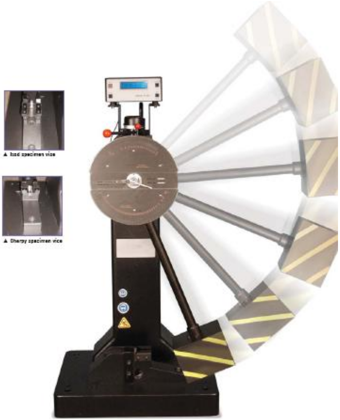
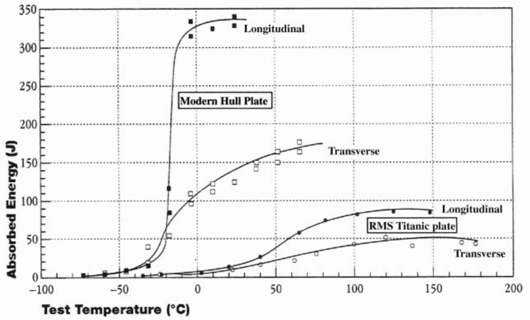


Charpy Tester and Sample

Titanic

Material | Effect of Temperature on Toughness



Effect on Temperature on Modern and Titanic Steel

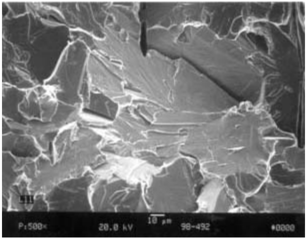
TABLE: [H.P. Leighly, B.L. Bramfitt and S.J. Lawrence, RMS Titanic : A metallurgical problem, Journal of Failure Analysis and Prevention, Volume 1, Number 2 / avril 2001, 10-37]

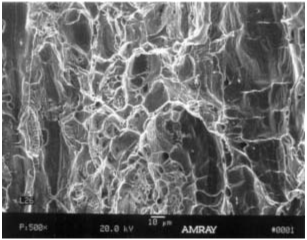
	Titanic Steel		A36 modern steel	
	Longitudinal Direction	Transverse Direction	Longitudinal Direction	Transverse Direction
Impact Energy @ -2˚C [J]	4	4	325	100
Ductile-brittle Transition Temperature	30˚C	42˚C	-42˚C	-42˚C

Titanic

Material | Fracture Surface

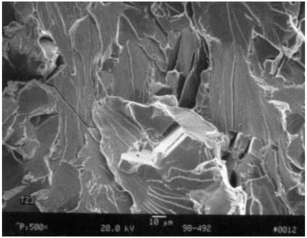
Longitudinal Direction

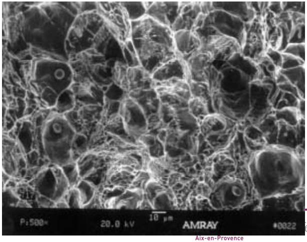




Brittle fracture @ -32˚C – Ductil fracture @ 120˚C

Transversal Direction



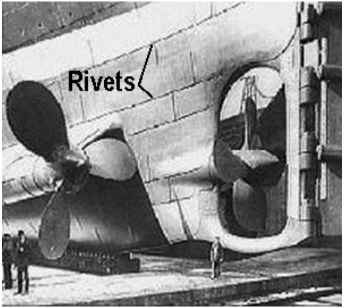


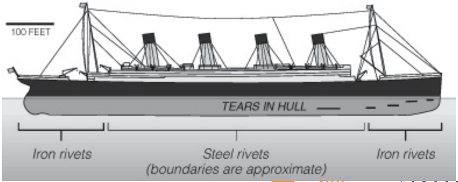
Brittle fracture @ -34˚C – Ductil fracture @ 148˚C

Titanic

Rivet | Failure

- Tremendous forces were created on impact with the iceberg
- Rivets failed either in shear or by elongation
- Rivet heads in the areas of contactcwere simply popped off
- More seams opened up.
- Water was flooded the hull of the ship





Rivets were made from wrought iron – Rivets repartition

Titanic

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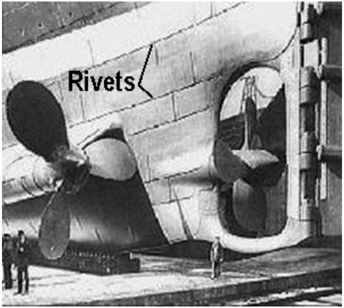

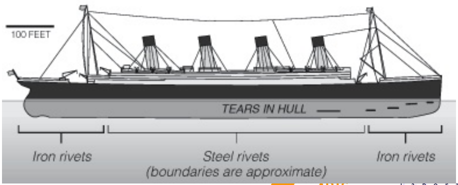

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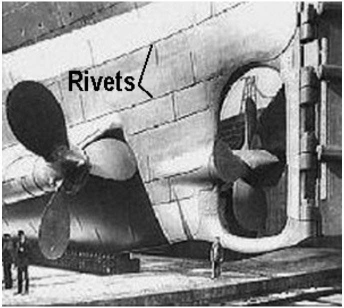

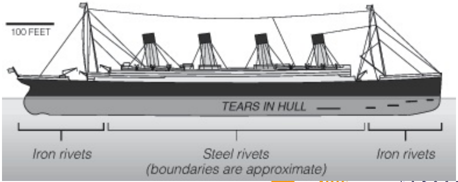

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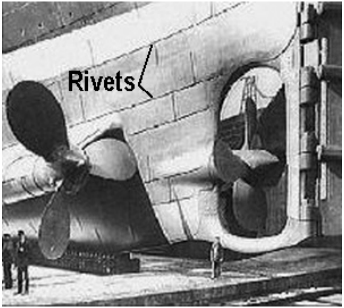

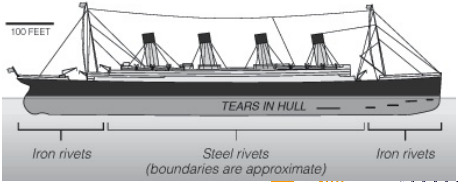

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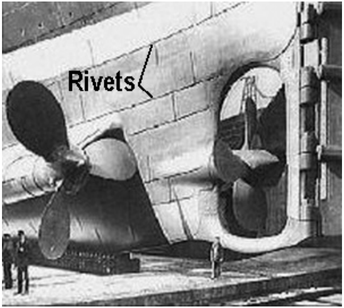
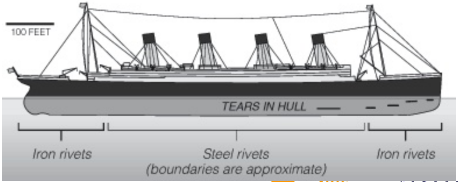


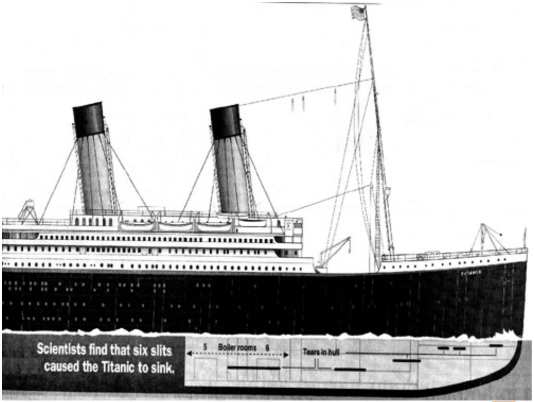


Rivets were made from wrought iron – Rivets repartition

Titanic

Design flaws

- Along with the material failures, poor design of the watertight compartments in the Titanic's lower section was a factor in the disaster.
- The transverse bulkheads of the watertight compartments should have been raised.



Layout of watertight compartments

Titanic

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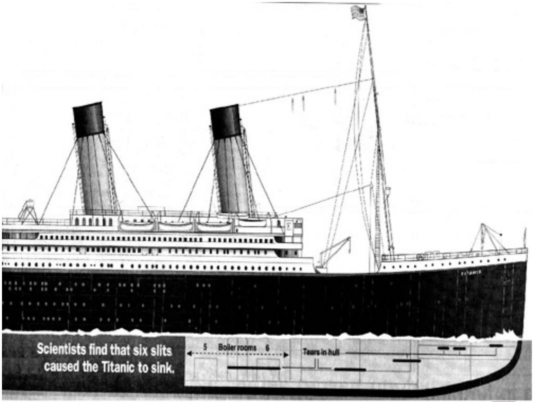

Layout of watertight compartments

Titanic

What caused Titanic sink ? | Main reason of sinking

- The failure of the hull steel resulted from brittle fractures caused by
  - High impact loading of the collision with the iceberg
  - Low temperature water on the night of the disaster
  - High sulphur content of the steel
- The rapid sinking of the Titanic was worsened by the poor design of the transverse bulkheads of the watertight compartments

Artist view of Titanic wreck exploration

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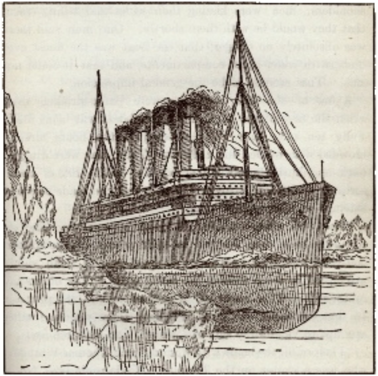
Artist view of Titanic wreck exploration

Titanic

Lesson from the disaster | Safety regulations

- **Mandatory use of the wireless**
  - Able to receive weather reports, check their positions, and call for help in emergencies
- **Increased lifeboat capacity**
  - Increased the required number of lifeboats to a number that would accommodate all passengers and crew aboard the ship
- **Implementation of the ice patrol**



Artist view of Titanic collision with iceberg

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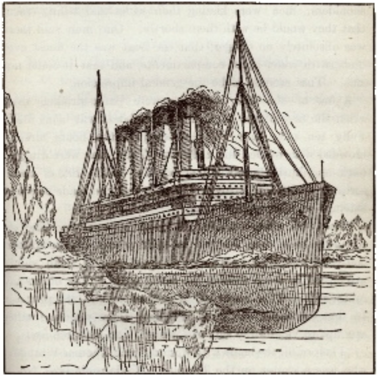

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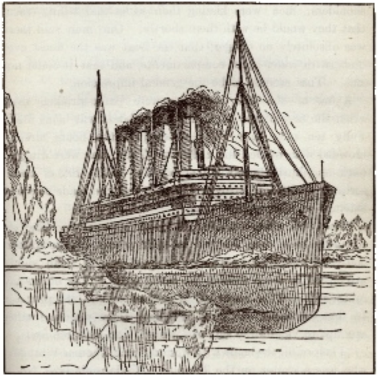

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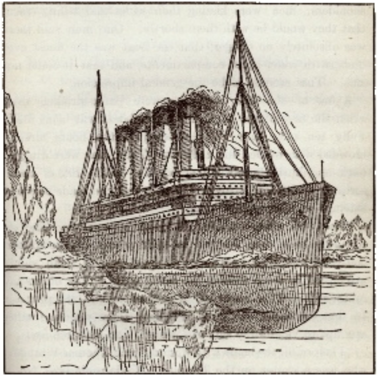

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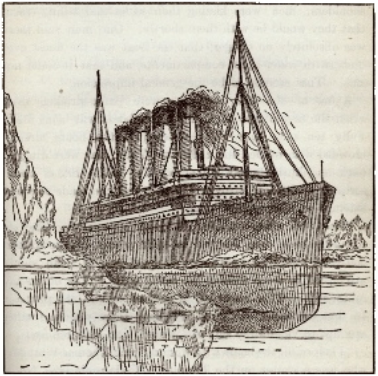

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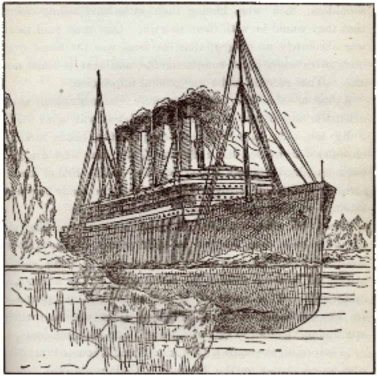

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