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MARITIME

Keel Fatigue

Technical Background

Hasso Hoffmeister

08 April 2020

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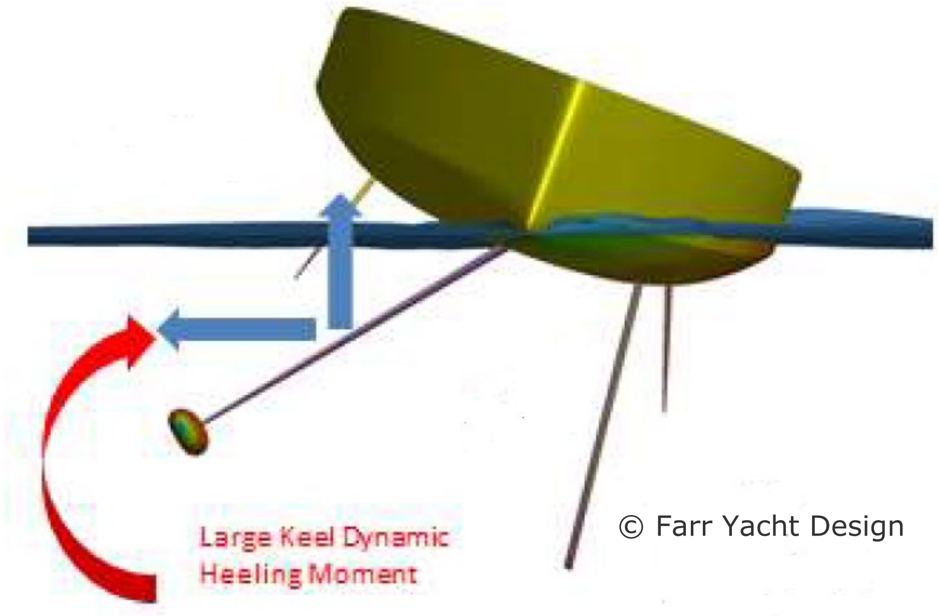
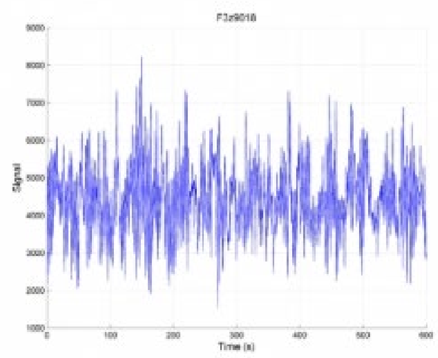
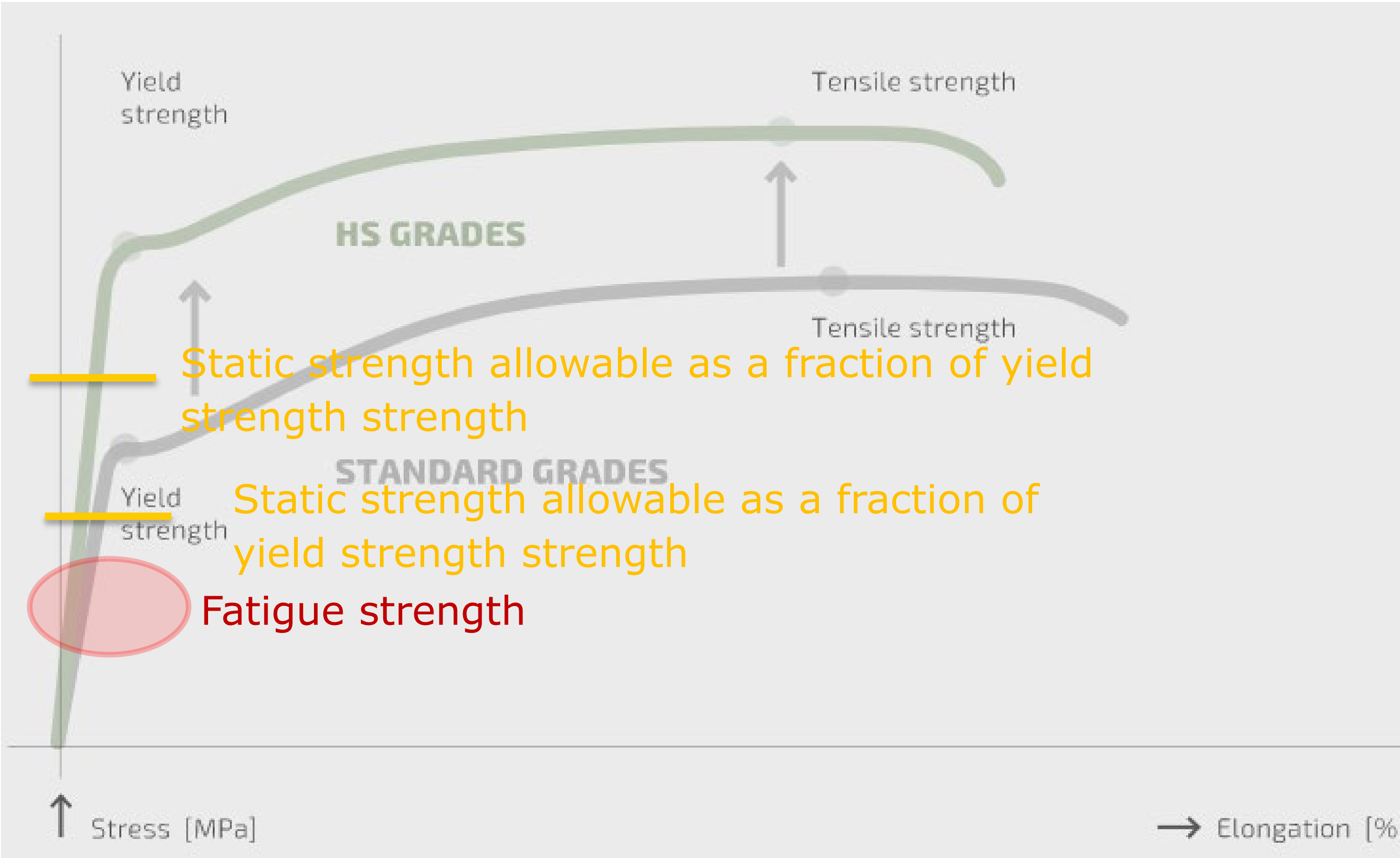
Yield/Ultimate strength in Quasi static applications







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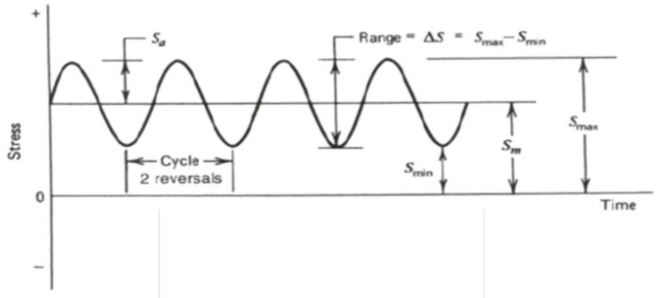
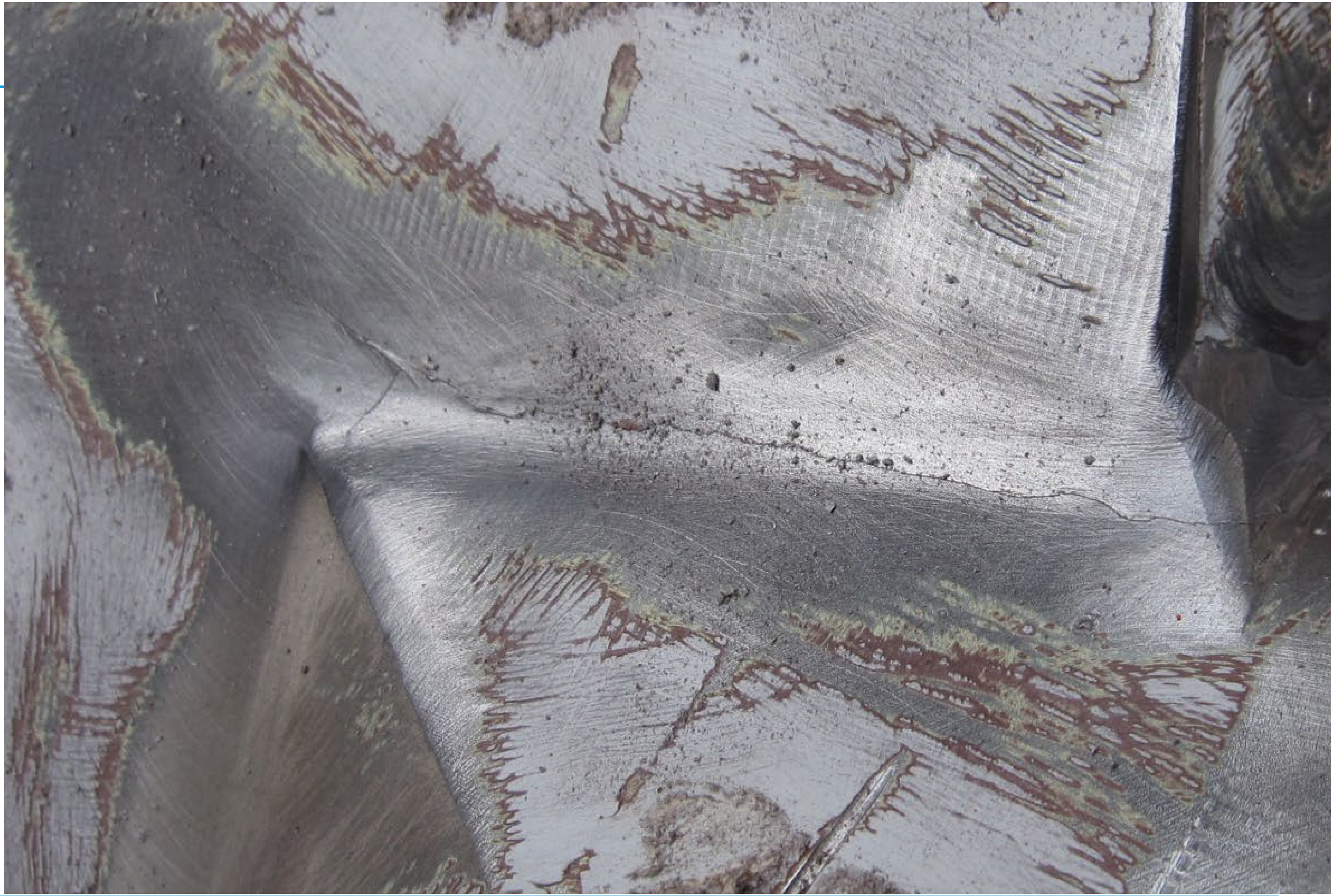
Metal Fatigue

- **Fatigue** is the weakening of a material caused by cyclic loading that results in progressive and **localized structural damage** and the **growth of cracks.**



- It occurs at **much lower stress levels** than the ultimate material strength.



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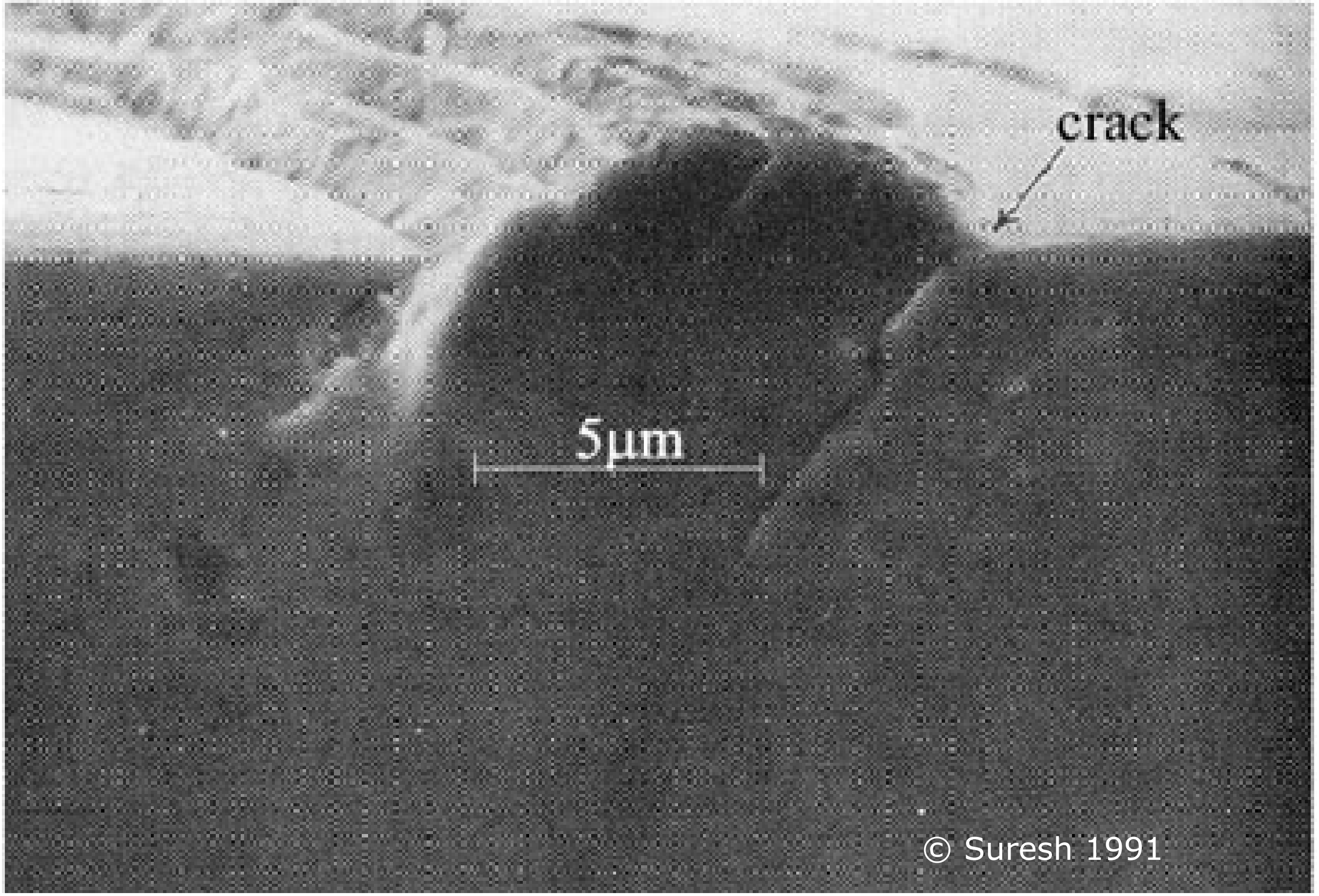
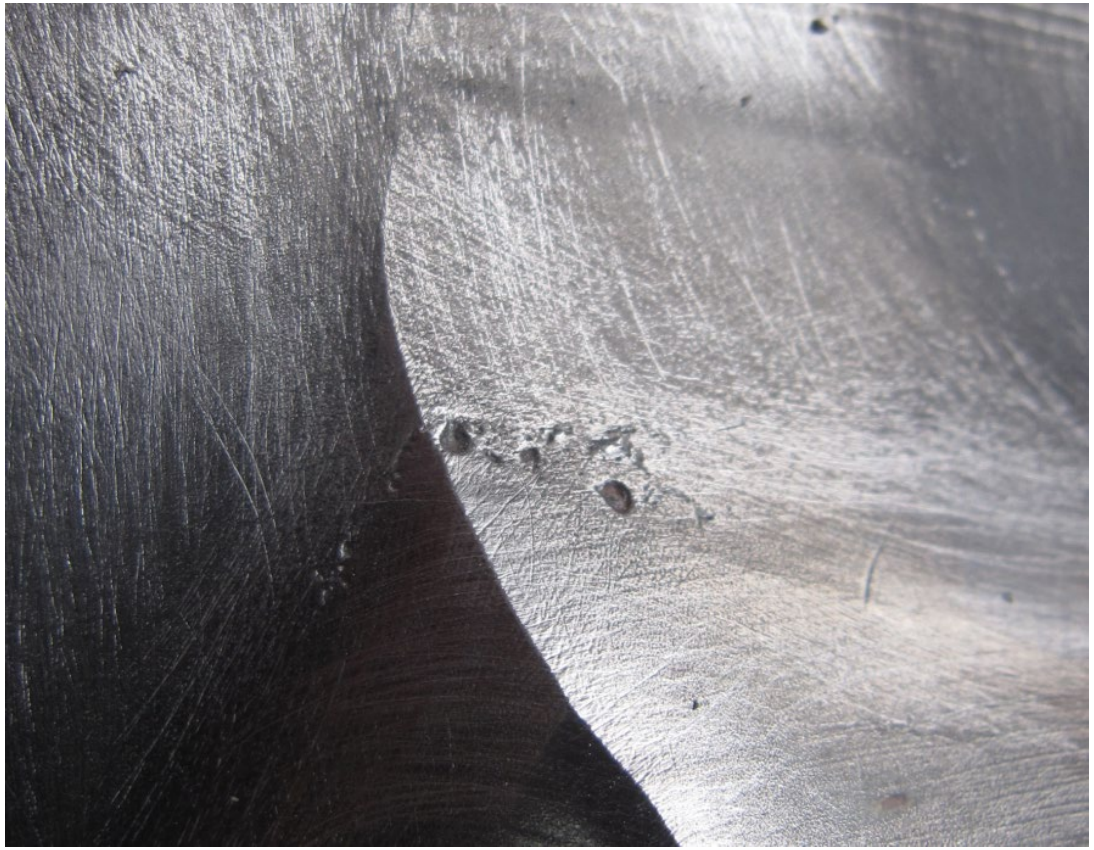
Initiation

- In metal alloys, the fatigue process starts with dislocation movements at the microscopic level, which eventually form persistent slip bands that become the basic origin of short cracks.



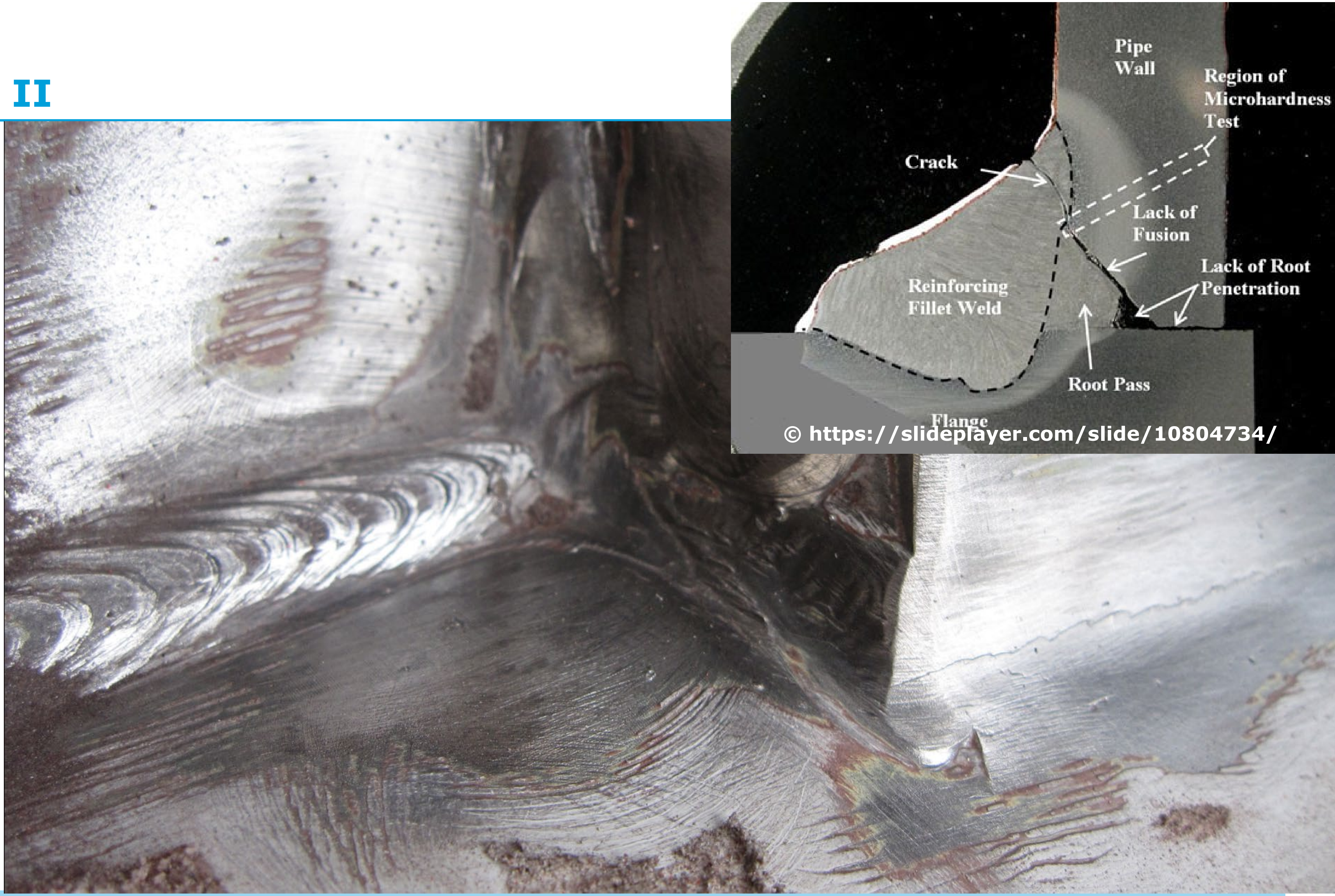
Detrimental effects

Microscopic (at the crystalline grain scale like on the previous slide) but also macroscopic discontinuities as well as production defects and component design features which cause stress concentrations, are common locations at which the fatigue process, the crack, begins.
You may anticipate even from these macroscopic photos, that not only air inclusions in a weld seam, or kinks from grinding can be critical, but also surface roughness.



Detrimental effects II

- This is also valid for other design and metallurgical discontinuities (holes, keyways, sharp changes of load direction etc.) and particularly welds, which further include metallurgical discontinuities.



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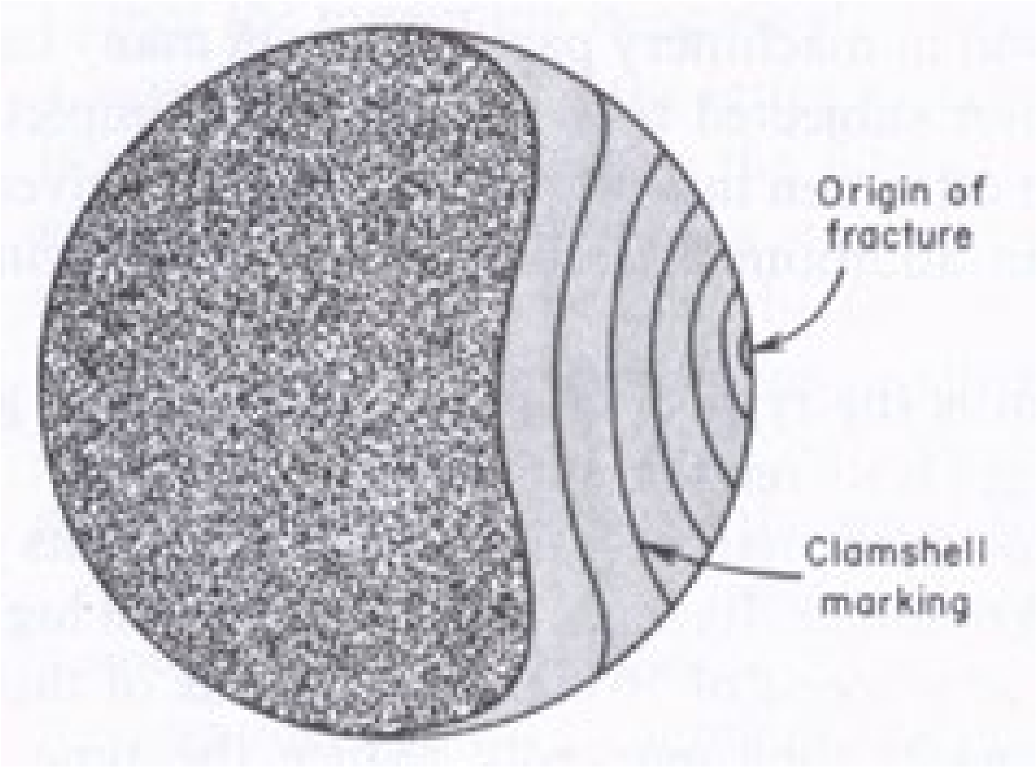
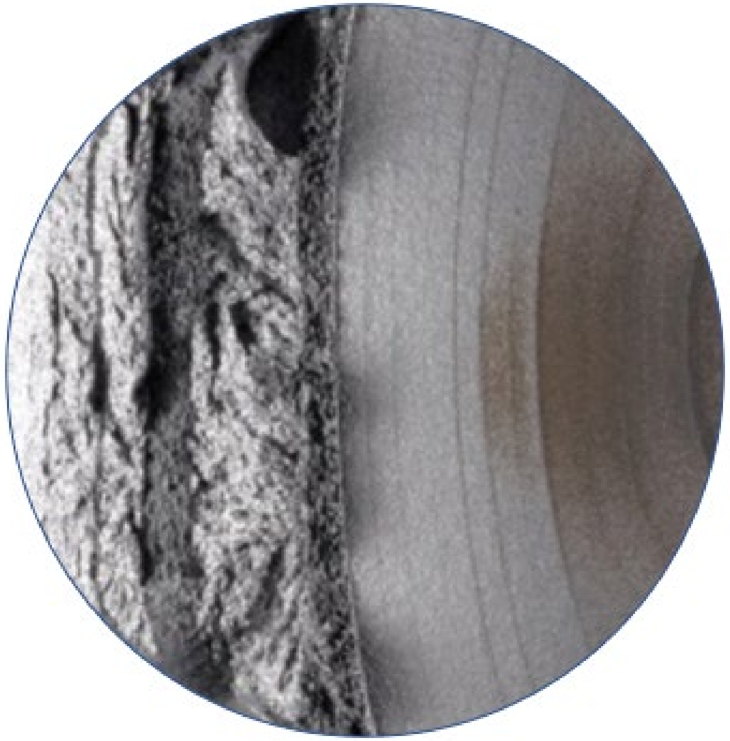
Growth of fatigue cracks

Upon repeated cyclic loading, the crack will continue to grow until it reaches a critical size, which occurs when the stress intensity factor of the crack exceeds the ultimate strength of the material, producing rapid propagation and typically complete fracture of the structure.
This is indeed what typically occurs on keels before they fail; cracks should be there before.





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© http://www.ux.uis.no/~hirpa/6KdB/ME/Fatigue.pdf

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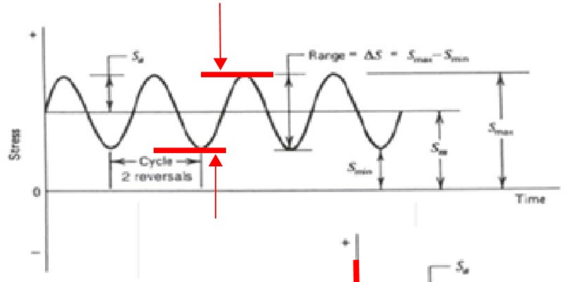
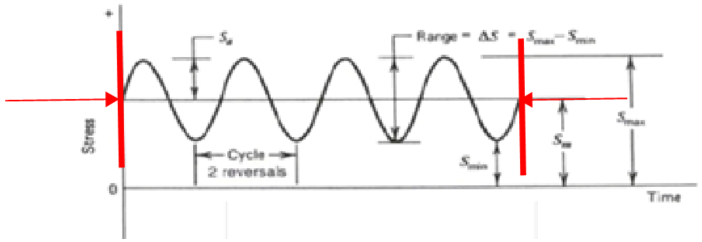
Summary of driving factors

- Magnitude of stress range (amplitude) →



- Number of (cumulated, irregular) load cycles →



- Stress discontinuities (stress concentration) →
  - Macroscopic imperfections (holes, edges, welds, surface finish)
  - Microscopic imperfections (metallurgical, voids)
- Residual stresses (from welding or production process)
- Presence of oxidizing chemicals
- Scuffing

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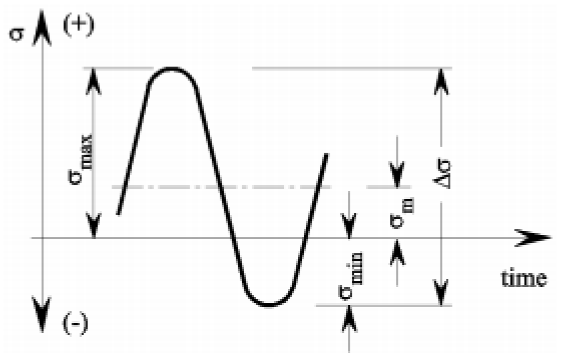
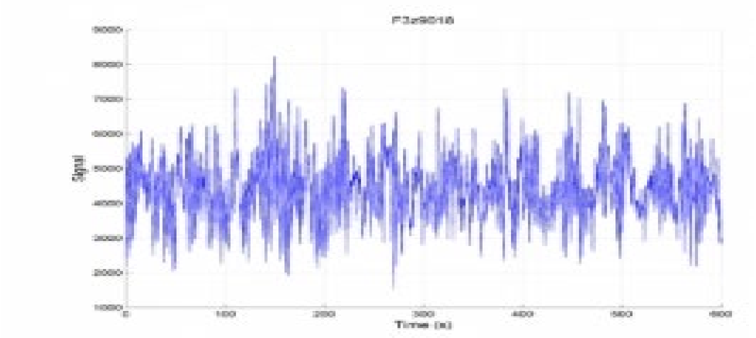
The greater the applied stress range, the shorter the life.

- A SN or Wöhler curve describes the resistance of metal (in this case a welded joint) to fatigue
- It describes the relationship of maximum stress range and tolerable number of cycles



Stress Range



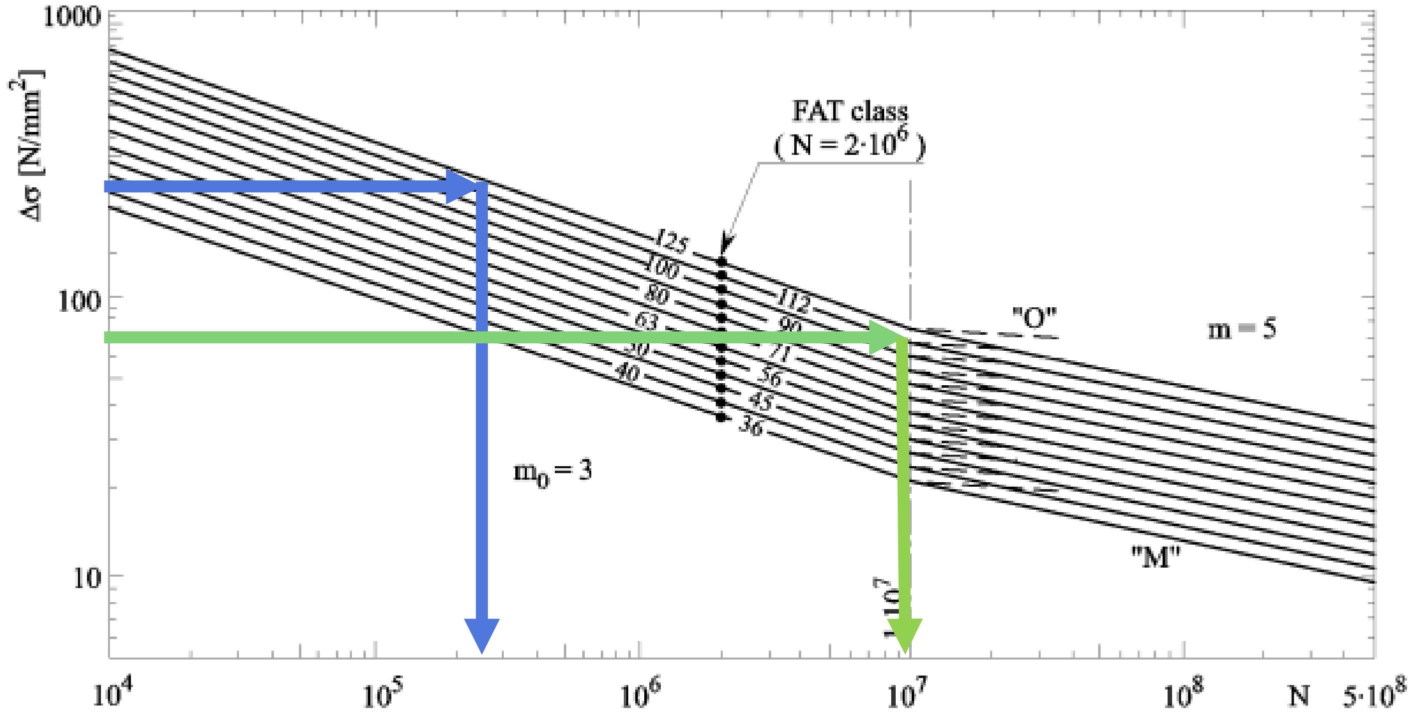
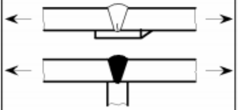
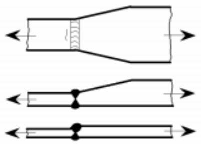
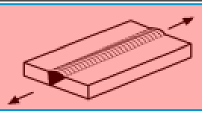
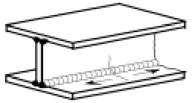
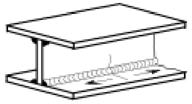
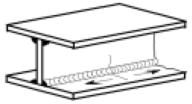
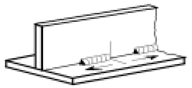
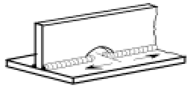
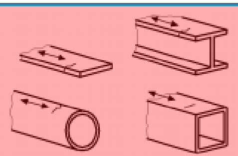
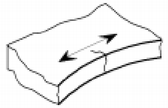
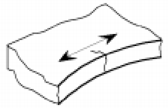
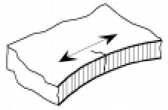


Figure 3 S-N curves for welded joints at steel

"FAT" Classes

A. Butt welds, transverse loaded				
Type No.	**Joint configuration showing mode of fatigue cracking and stress σ considered**	**Description of joint**	**FAT class $\Delta\sigma_R$ Steel**	**Al**
A1		Transverse butt weld ground flush to plate, 100 % NDT (Non-Destructive Testing)	112	45
A2		Transverse butt weld made in shop in flat position, max. weld reinforcement 1 mm + 0,1 × weld width, smooth transitions, NDT	90	36
A3		Transverse butt weld not satisfying conditions for joint type No. A2, NDT	80	32
A4		Transverse butt weld on backing strip or three-plate connection with unloaded branch Butt weld, welded on ceramic backing, root crack	71 80	25 28
A5		Transverse butt welds between plates of different widths or thickness, NDT as for joint type No. A2, slope 1 : 5 as for joint type No. A2, slope 1 : 3 as for joint type No. A2, slope 1 : 2 as for joint type No. A3, slope 1 : 5 as for joint type No. A3, slope 1 : 3 as for joint type No. A3, slope 1 : 2 For the third sketched case the slope results from the ratio of the difference in plate thicknesses to the breadth of the welded seam. Additional bending stress due to thickness change to be considered, see also B.1.3.	90 80 71 80 71 63	32 28 25 25 22 20
A6		Transverse butt welds welded from one side without backing bar, full penetration root controlled by NDT not NDT For tubular profiles $\Delta\sigma_R$ may be lifted to the next higher FAT class.	71 36	28 12
A7		Partial penetration butt weld; the stress is to be related to the weld throat sectional area, weld overfill not to be taken into account	36	12

B. Longitudinal load-carrying weld				
Type No.	**Joint configuration showing mode of fatigue cracking and stress σ considered**	**Description of joint**	**FAT class $\Delta\sigma_R$ Steel**	**Al**
B1		Longitudinal butt welds both sides ground flush parallel to load direction without start/stop positions, NDT with start/stop positions	 125 125 90	 50 50 36
B2		Continuous automatic longitudinal fully penetrated K-butt without stop/start positions (based on stress range in flange adjacent to weld)	125	50
B3		Continuous automatic longitudinal fillet weld penetrated K-butt weld without stop/start positions (based on stress range in flange adjacent to weld)	100	40
B4		Continuous manual longitudinal fillet or butt weld (based on stress range in flange adjacent to weld)	90	36
B5		Intermittent longitudinal fillet weld (based on stress range in flange at weld ends) In presence of shear τ in the web, the FAT class has to be reduced by the factor (1 – Δτ / Δσ), but not below 36 (steel) or 14 (Al).	80	32
B6		Longitudinal butt weld, fillet weld or intermittent fillet weld with cut outs (based on stress range in flange at weld ends) If cut out is higher than 40 % of web height In presence of shear τ in the web, the FAT class has to be reduced by the factor (1 – Δτ / Δσ), but not below 36 (steel) or 14 (Al). ***Note*** *For Ω-shaped scallops, an assessment based on local stresses in recommended.*	71 63	28 25

E. Unwelded base material				
Type No.	**Joint configuration showing mode of fatigue cracking and stress σ considered**	**Description of joint**	**FAT class $\Delta\sigma_R$ Steel**	**Al**
E1		Rolled or extruded plates and sections as well as seamless pipes, no surface or rolling defects	160 ($m_0 = 5$)	71 ($m_0 = 5$)
E2a		Plate edge sheared or machine-cut by any thermal process with surface free of cracks and notches, cutting edges chamfered or rounded by means of smooth grinding, groove direction parallel to the loading direction. Stress increase due to geometry of cut-outs to be considered by means of direct numerical calculation of the appertaining maximum notch stress range.	150 ($m_0 = 4$)	–
E2		Plate edge sheared or machine-cut by any thermal process with surface free of cracks and notches, cutting edges broken or rounded. Stress increase due to geometry of cut-outs to be considered. [1]	140 ($m_0 = 4$)	40 ($m_0 = 4$)
E3		Plate edge not meeting the requirements of type E2, but free from cracks and severe notches. Machine cut or sheared edge: Manually thermally cut: Stress increase due to geometry of cut-outs to be considered. [1]	 125 ($m_0 = 3{,}5$) 100 ($m_0 = 3{,}5$)	 36 ($m_0 = 3{,}5$) 32 ($m_0 = 3{,}5$)

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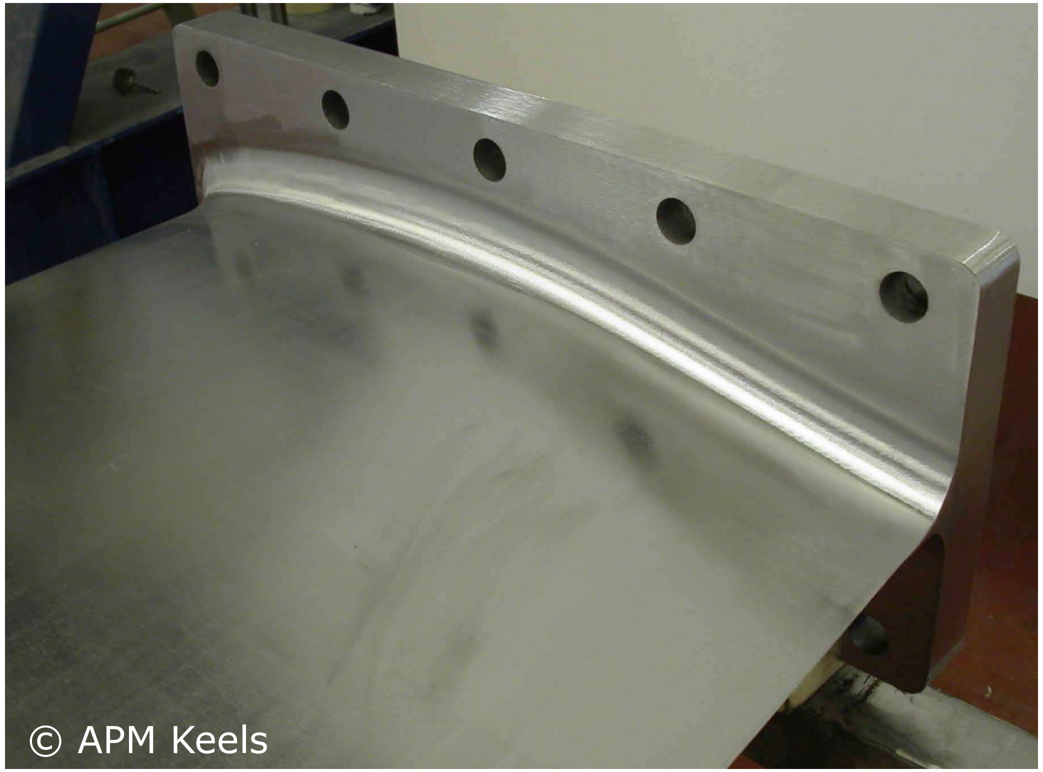
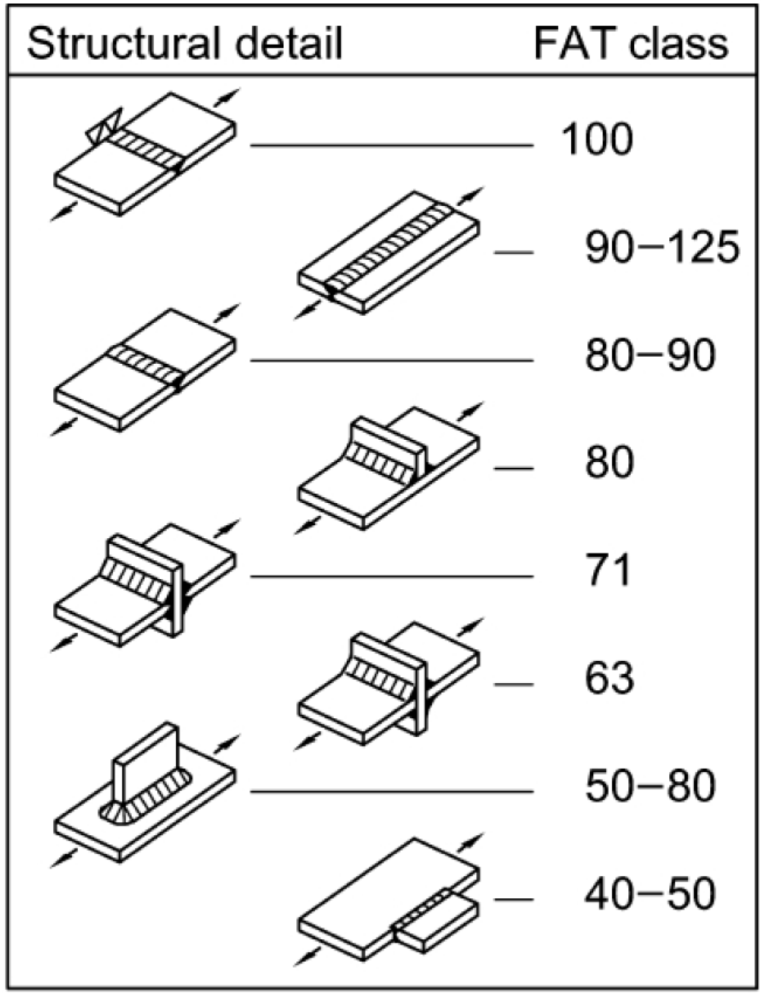
“FAT” Classes





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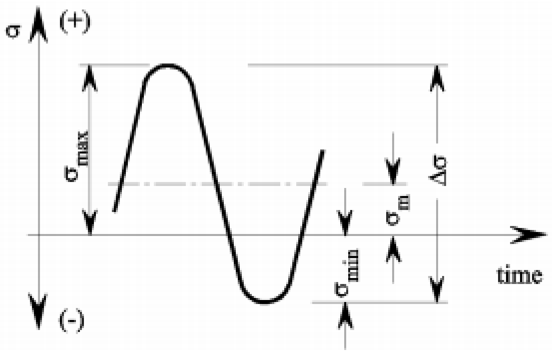
The higher the weld category, the higher the bearable stress range (for a given life time).

- A SN or Wöhler describes the resistance of metal (in this case a welded joint) to fatigue
- It describes the relationship of maximum stress range and tolerable number of cycles



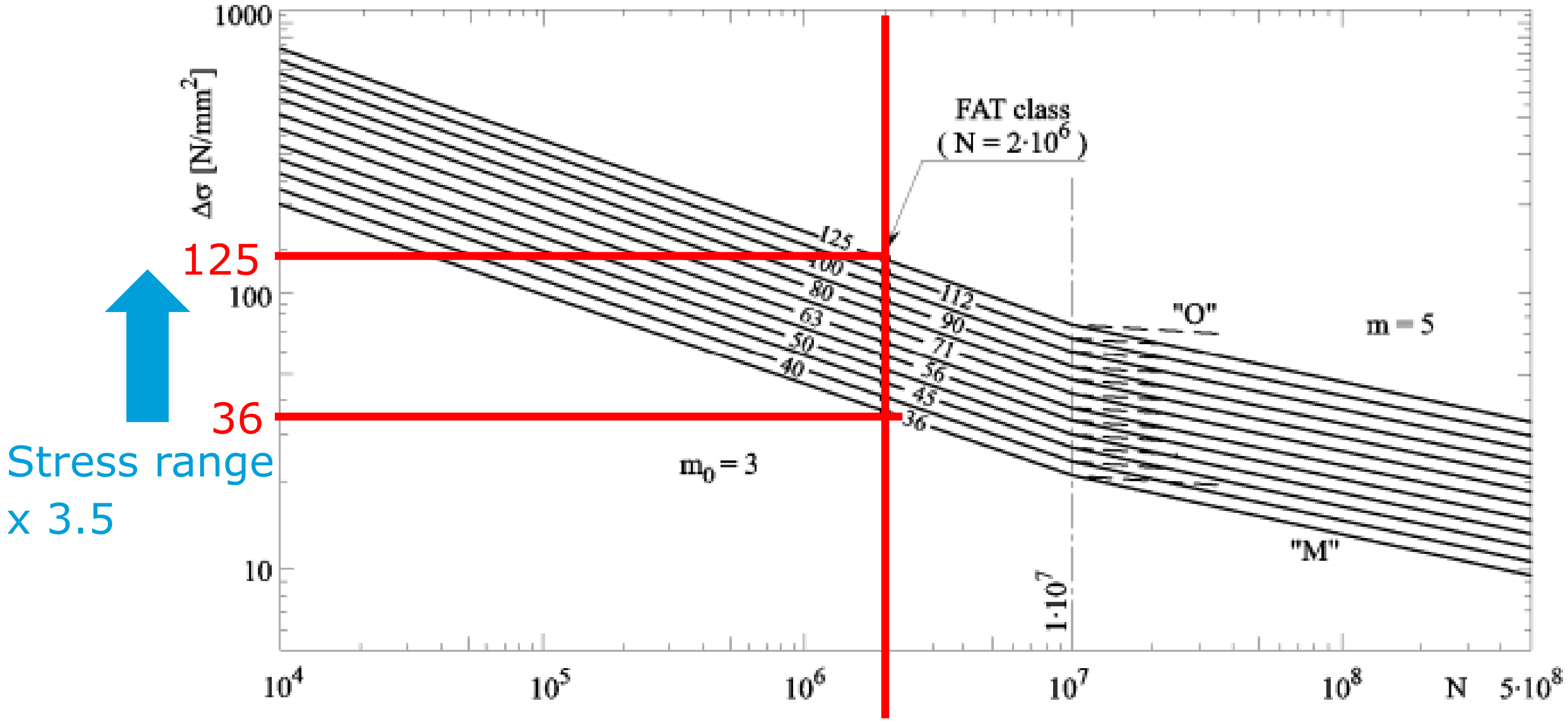
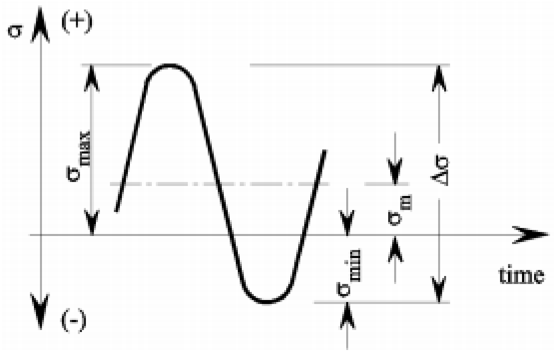


Figure 3 S-N curves for welded joints at steel

The higher the weld category, the higher the life time (for a given stress range).

- A SN or Wöhler describes the resistance of metal (in this case a welded joint) to fatigue
- It describes the relationship of maximum stress range and tolerable number of cycles



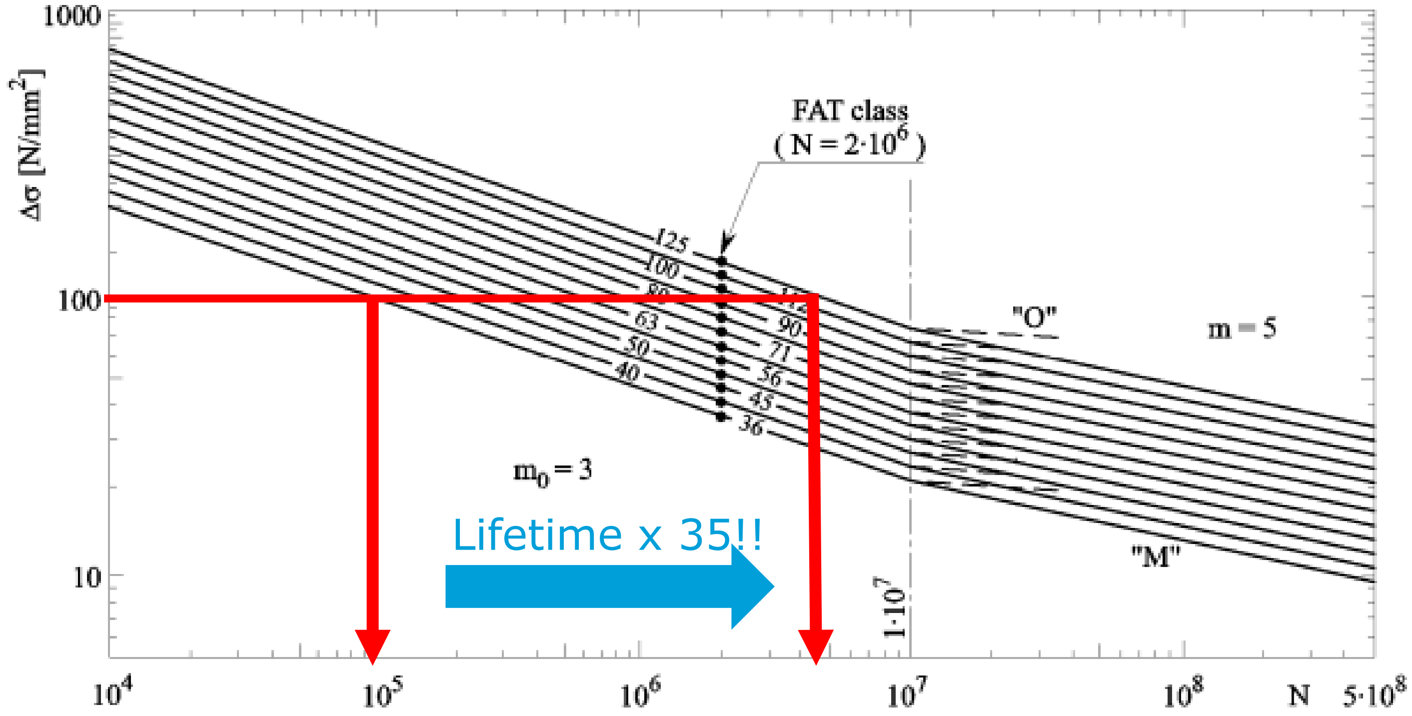
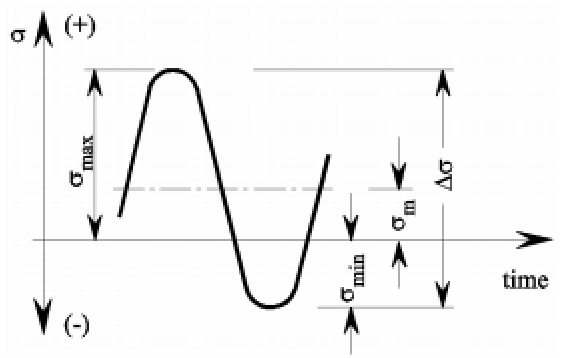


Figure 3 S-N curves for welded joints at steel

The higher the weld category, the higher the life time (for a given stress range)

- A SN or Wöhler describes the resistance of metal (in this case a welded joint) to fatigue
- It describes the relationship of maximum stress range and tolerable number of cycles



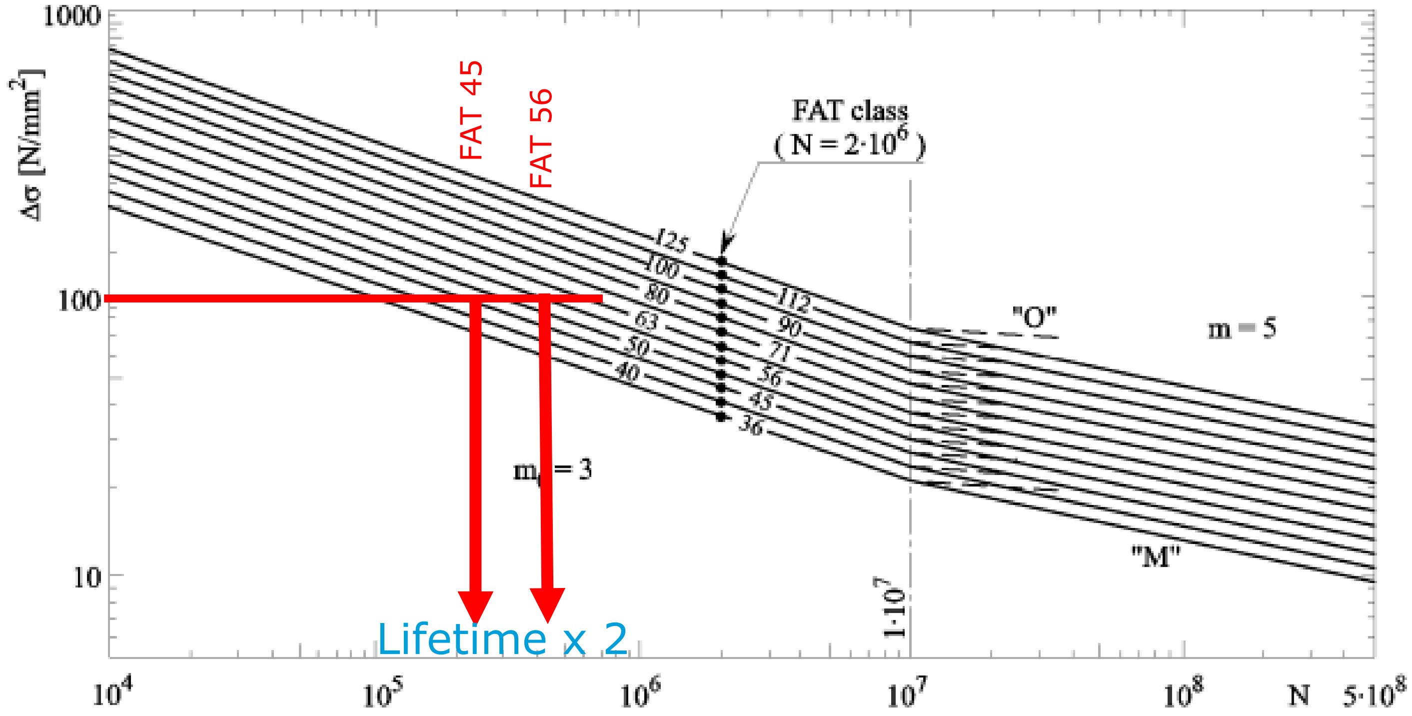
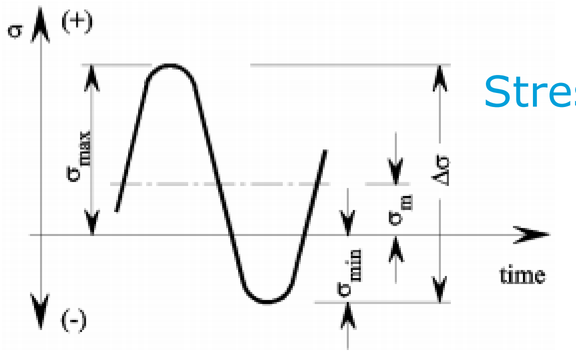


Figure 3 S-N curves for welded joints at steel

Life time doubles with 25% lower stress range

- A SN or Wöhler describes the resistance of metal (in this case a welded joint) to fatigue
- It describes the relationship of maximum stress range and tolerable number of cycles



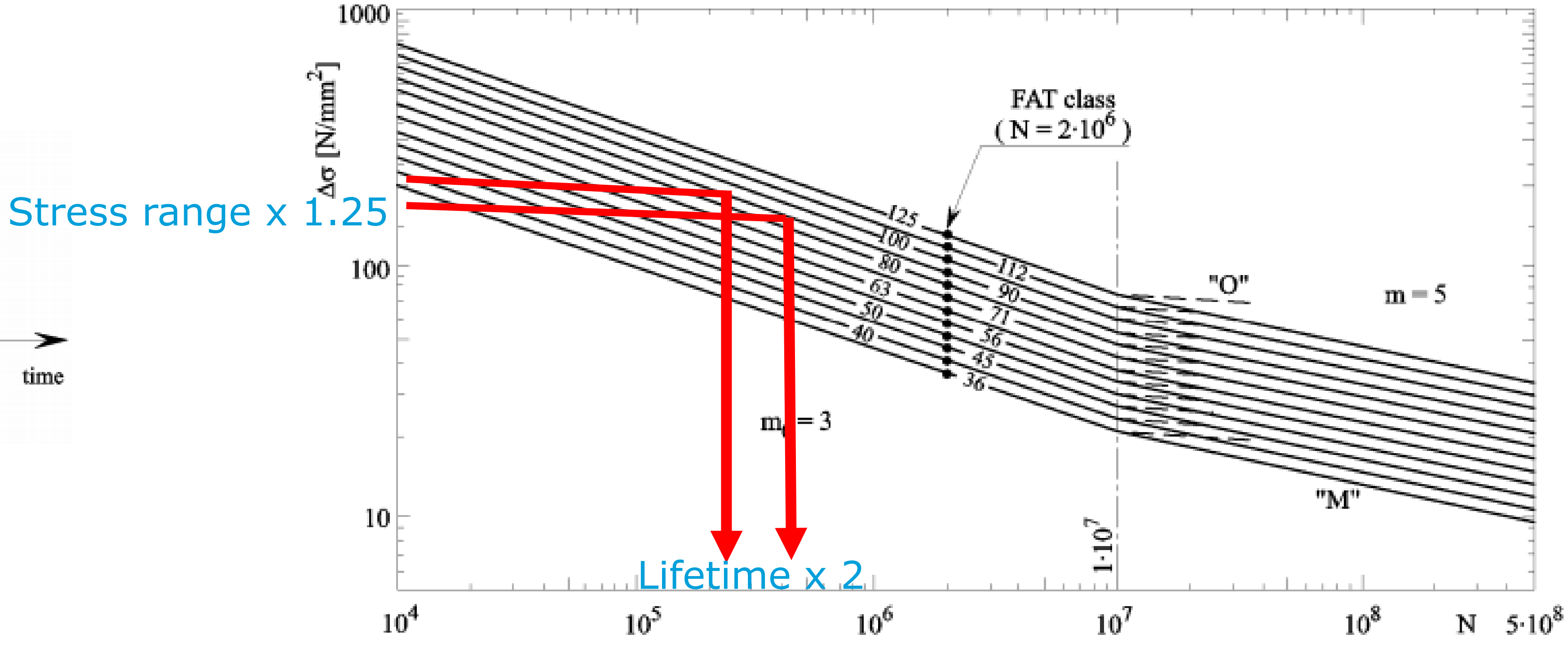


Figure 3 S-N curves for welded joints at steel

Summary

- 25% lower stress range extends life by a factor of 2
- 25% better FAT class (quality) extends life by a factor of 2

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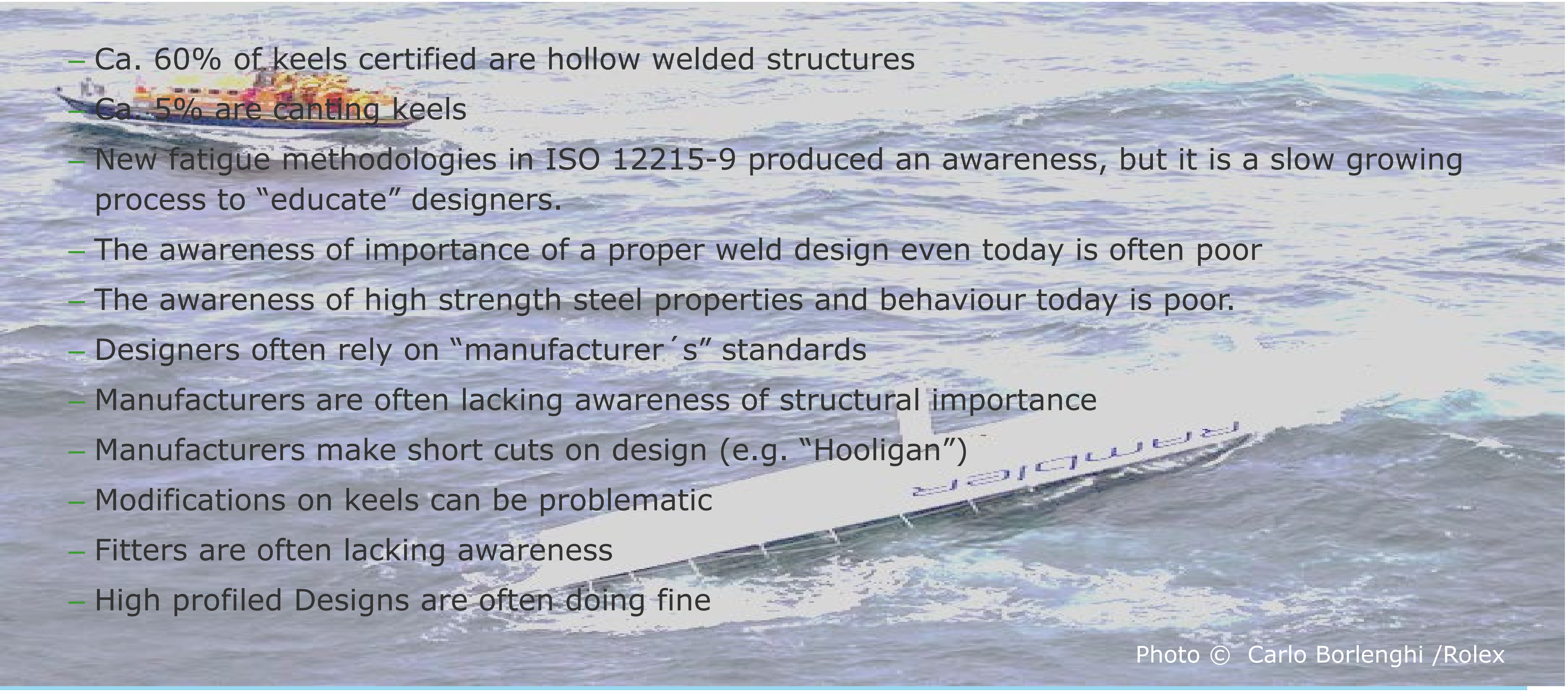
ISAF/WS OSR Plan Review;
Observations since 2010



- Ca. 60% of keels certified are hollow welded structures
- Ca. 5% are canting keels
- New fatigue methodologies in ISO 12215-9 produced an awareness, but it is a slow growing process to "educate" designers.
- The awareness of importance of a proper weld design even today is often poor
- The awareness of high strength steel properties and behaviour today is poor.
- Designers often rely on "manufacturer´s" standards
- Manufacturers are often lacking awareness of structural importance
- Manufacturers make short cuts on design (e.g. "Hooligan")
- Modifications on keels can be problematic
- Fitters are often lacking awareness
- High profiled Designs are often doing fine

Photo © Carlo Borlenghi /Rolex

Failures

- Hooligan V 2009

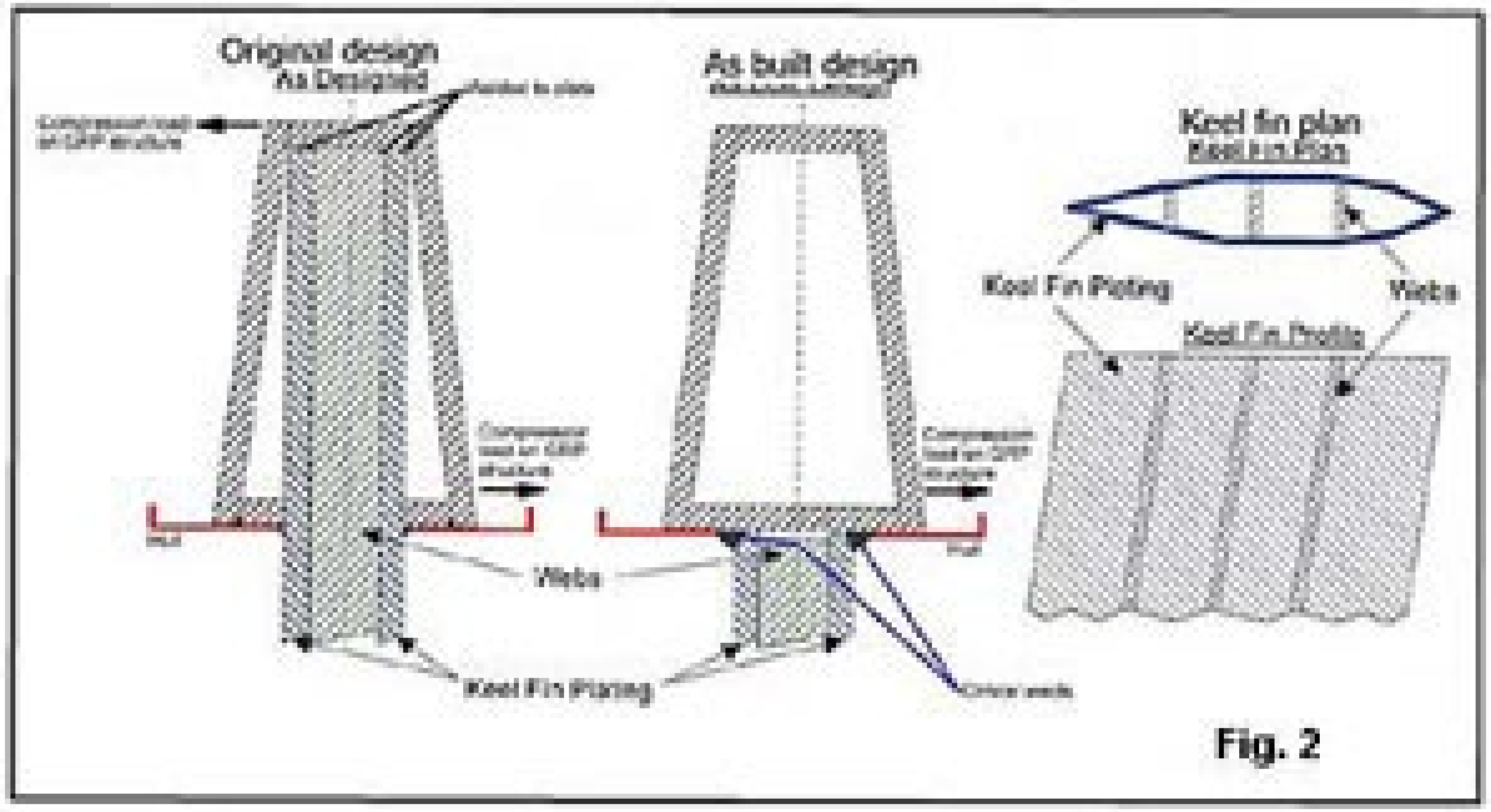


Fig. 2

Image ©: https://www.gov.uk/maib-reports/keel-failure-and-capsize-of-sailing-yacht-hooligan-v-off-prawle-point-devon-england-with-loss-of-1-life

Failures

- Canting Keel

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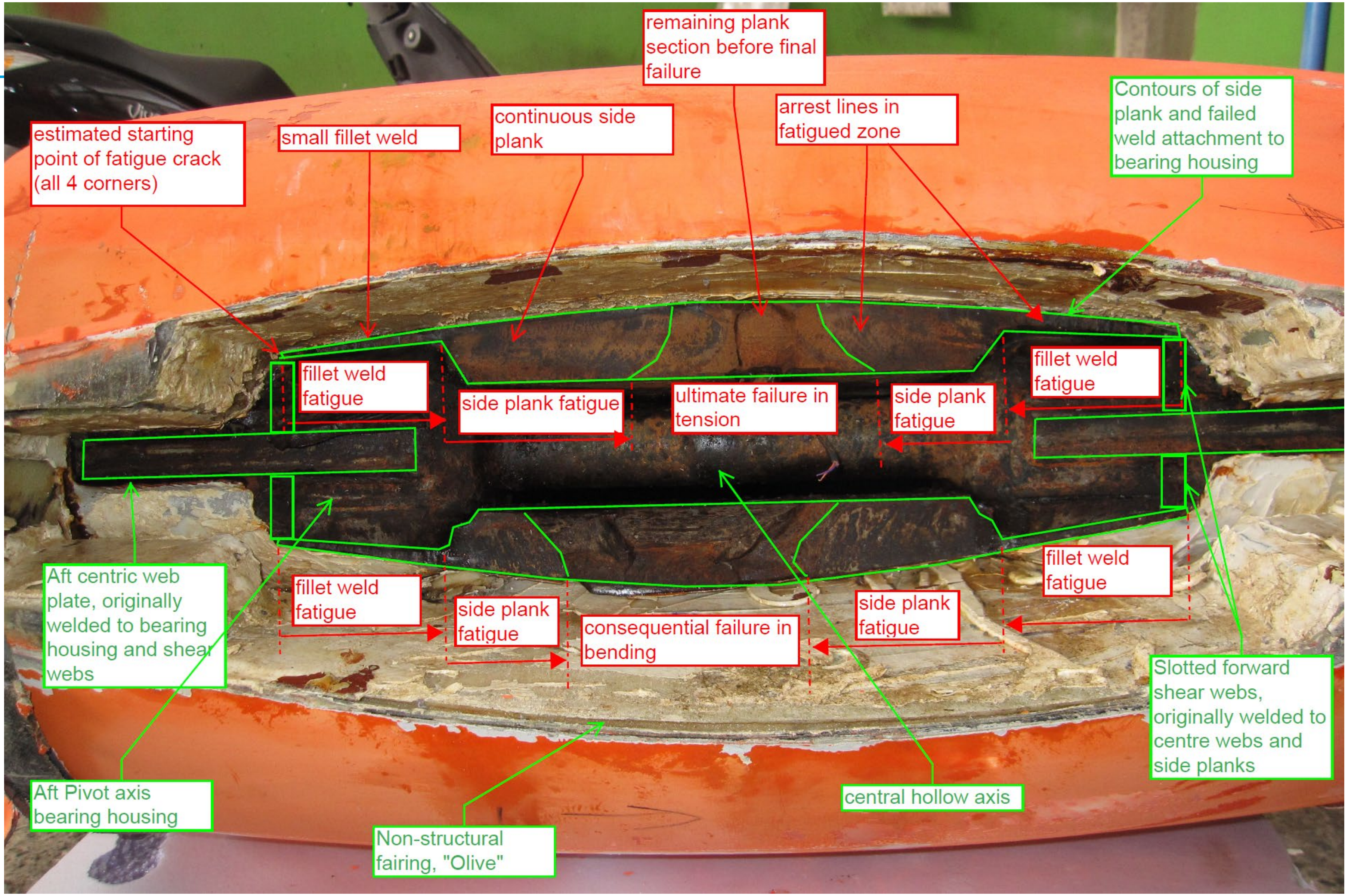
Failures

- Oyster 825 with deficient continuity in structural FRP bottom structures

Failures

- The surface of the failed piece had shown signs of stirations typical only for fatigue progressing failure, accompanied with an ultimate break surface. You can even find the place where the crack started rather easily.
- In this case, the crack origin was from a non-structural, cosmetic weld , which progressed into the previously sound and structural planc.



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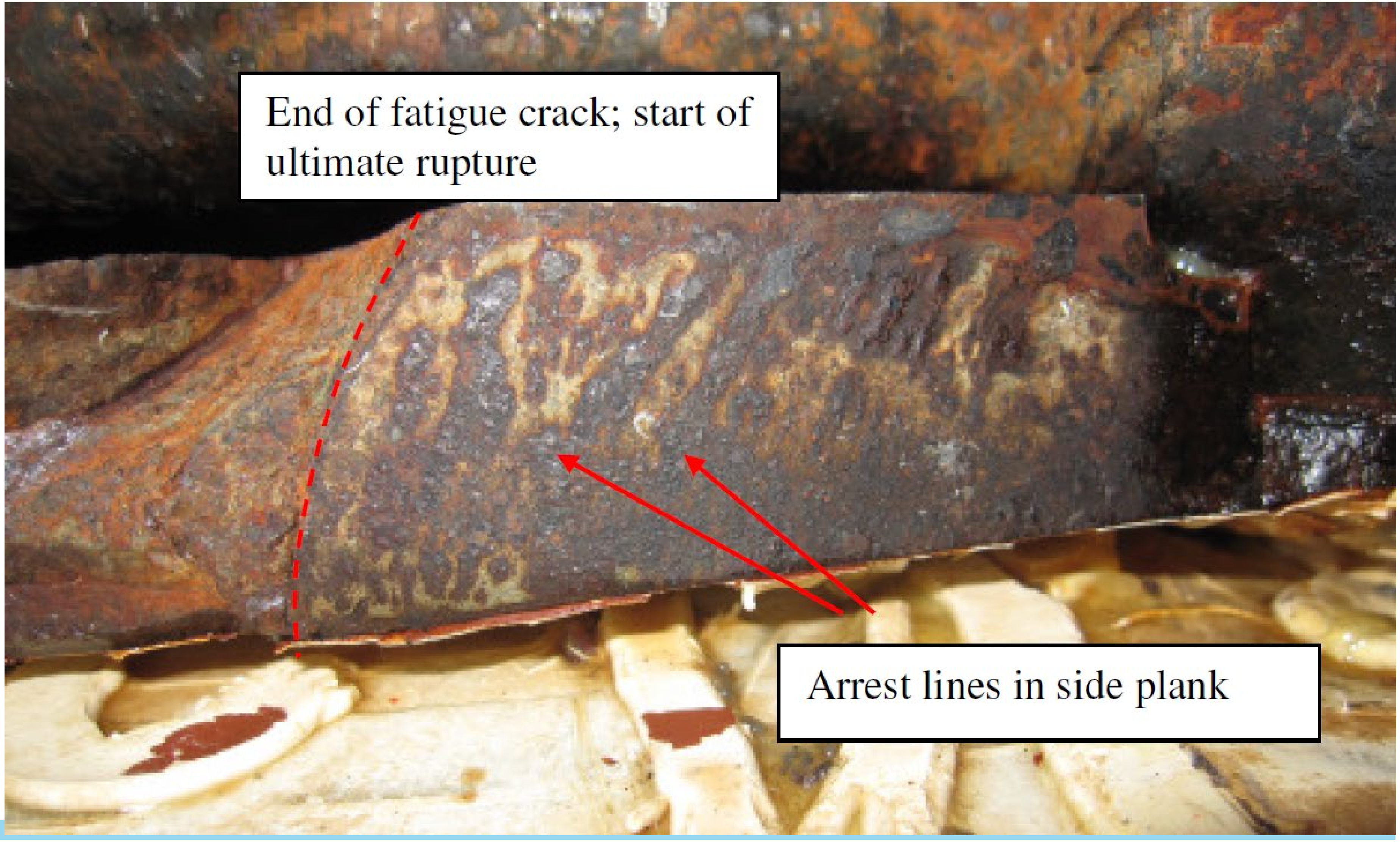
Failures

- Detail of fatigue in keel plank



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Scantling Standard Discussion

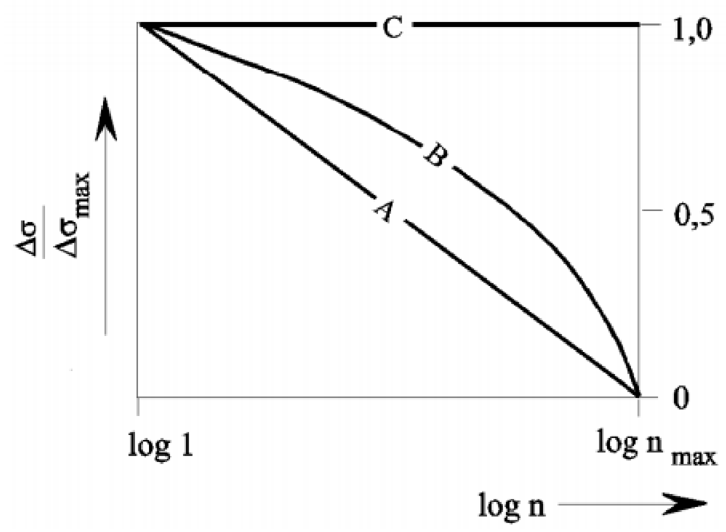
ISO 12215-9 for <24m

The operational life of the craft is assumed to be 8 million stress cycles. This is based on an assumed operational envelope — various times on different points of sail, average tacking times for beating, average rolling periods for downwind, typical wave encounter periods, estimated heel angles — and is only intended to be representative.

This corresponds to about 25–30 years of moderate-to-high usage recreational sailing or about five years of very extensive ocean racing (one, 30 000 NM, competition plus associated training and preparation annually). This is 15 % of the figure of the number of cycles normally used in ship fatigue assessment.

DNVGL Ship Rules:

In general the fatigue analysis has to be performed for a number of cycles $n_{max} = 5 \cdot 10^7$ for seaway induced stresses with the stress range spectrum A. This considers a lifetime of 25 years with 230 days per year at sea in the North Atlantic.



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Scantling Standard Discussion

- ISO 12215-9 Fatigue Design Criteria

If MSF < 0,5:

The calculated fatigue life will exceed the design life with an effective safety factor of 2 or more. This is the desired result. However, it is important to include the effect of stress concentration and welding, since otherwise the simplified procedure is meaningless.

If 0,5 ≤ MSF ≤ 1:

The calculated fatigue life will exceed the design life with an effective safety factor of between 1 and 2. As MSF approaches 0,7 and beyond, the uncertainties in the simplified method become increasingly critical and further investigation using more advanced engineering methods is strongly recommended.

If MSF > 1:

The calculated fatigue life will be less than the design life. The fatigue life is unsatisfactory according to the simplified method. Further analyses and/or redesign are essential.

- Life time behaves linear to these value

Essences

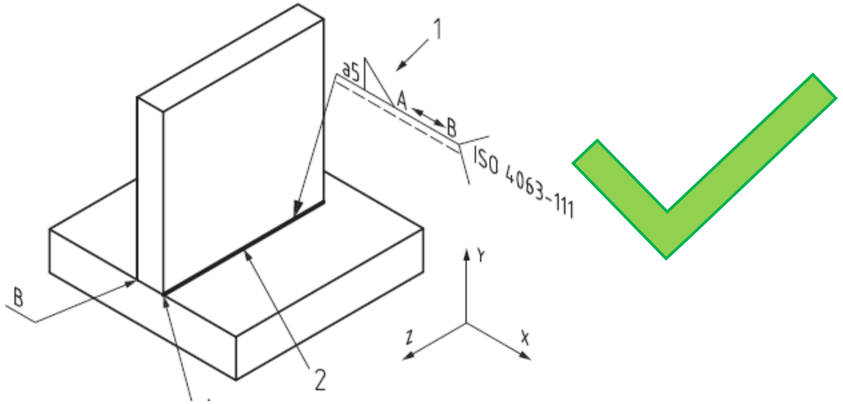
- Fatigue Design is essential for metal keels
  - Provisions are existing for proper design
- Particularly, Designers need to have awareness and capabilities
- Production can be “common” marine standard, if instructions given on design drawings are appropriate

Possible Solutions

- Increase required fatigue life by decreasing Total Damage Ratio “MSF” value in **ISO 12215-9**

The problem seems to also be that sometimes the designers don´t know the “language” of the builders; proposed solution:

- Involve **ISO 12215-6** Annex C “Good Practice Welding Procedure”, to be detailed
- Involve a proper common “language”: **ISO 2553**



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List of existingWelding Standards

Qualitätsanforderungen für das Schmelzschweißen

DIN EN ISO 3834-1 bis -5,
DIN FB CEN ISO/TR 3834-6

Lichtbogenschweißen

	Stahl	Aluminium
Einteilung der Werkstoffe	ISO/TR 15608, 20173, 20174; CEN ISO/TR 20172	
Empfehlungen zum Schweißen	DIN EN 1011-1 (ISO/TR 17671-1)	
	DIN EN 1011-2, -3	DIN EN 1011-4
Temperaturmessung	DIN EN ISO 13916	
Schweißerprüfung	DIN EN ISO 9606-1, -2, -4; DIN SPEC 35234	
Bedienerprüfung	DIN EN ISO 14732	
Schweißaufsicht	DIN EN ISO 14731	
Schweißanweisung	DIN EN ISO 15609-1, -2, -6	
Qualifizierung von Verfahren	DIN EN ISO 15607, 15610, 15611, 15612, 15613	
	DIN EN ISO 15614-1	DIN EN ISO 15614-2, -4
Kalibrieren, Validieren, Verifizieren	DIN EN ISO 17662; ISO/TR 18491	
Wärmebehandlung	DIN EN ISO 17663, DIN EN 10052, ISO/TR 14745	

Unregelmäßigkeiten, Schweißnahtvorbereitung

Gruppen Schmelzschweißen	DIN EN ISO 5817	DIN EN ISO 10042
Gruppen Strahlschweißen	DIN EN ISO 13919-1	DIN EN ISO 13919-2
Thermisches Trennen	DIN EN ISO 9013	
Nahtvorbereitung	DIN EN ISO 9692-1, -2, -4	DIN EN ISO 9692-3
Verbindungselemente Druckbeanspruchte und Nicht innendruck-beanspruchte Bauteile	DIN EN 1708-1, DIN EN 1708-2, DIN EN 1708-3 DIN 2559-2, DIN 2559-3, DIN 2559-4	
Geometrische Unregelmäßigkeiten Schmelz-, Preßschweißen	DIN EN ISO 6520-1,- 2	
Geometrische Unregelmäßigkeiten Thermische Schnitte	DIN EN ISO 17658	
Bez.-System Unregelmäßigkeiten	DIN ISO/TS 17845	
Schweißbarkeit	DIN FB ISO/TR 581	

Lichtbogenschweißeinrichtungen, Arbeitsschutz

Schweißstromquellen	DIN EN 60974-1, -2, -3, -4
Drahtvorschubgeräte, Brenner, Stabelektrodenhalter, Steckverbinder für Schweißleitungen	DIN EN 60974-5, -6, -7, -8, -9, -11, -12,- 13
Rohrleitungen, Gasschläuche, Anschlüsse, Manometer	DIN 2403; DIN EN 560, 561, 1256; DIN EN ISO 2503, 3821, 5171, 7291, 14113, 10462
Gebrauchsstellenvorlagen, Brenner	DIN EN ISO 5175-1, -2; DIN EN ISO 9012
Schutzkleidung, -handschuhe	DIN EN ISO 11611, DIN EN 12477
Augenschutz	DIN EN 169, 175, 379
Schweißvorhänge	DIN EN ISO 25980
Umwelt-Checkliste	DIN EN 14717
Luftreinigungssysteme	DIN EN ISO 15012-1, -2
Schweißrauche Laborverfahren	DIN EN ISO 15011-1 bis -5; DIN CEN ISO/TS 15011-6
Schweißrauche Probennahme	DIN EN ISO 10882-1, -2

Zerstörungsfreie Prüfungen

Qualifizierung Personal	DIN EN ISO 9712
Regeln für ZfP	DIN EN ISO 17635
Sichtprüfung	DIN EN ISO 17637
Durchstrahlungsprüfung	DIN EN ISO 17636-1, -2
Ultraschallprüfung	DIN EN ISO 17640
Eindringprüfung	DIN EN ISO 3452-1, -2, -5, -6
Magnetpulverprüfung	DIN EN ISO 17638
Wirbelstromprüfung	DIN EN ISO 17643
Härteprüfung	DIN EN ISO 9015-1, -2
Beugungslaufzeitprüfung (TOFD-Verfahren)	DIN EN ISO 10863, 16827
Phased Array	DIN EN ISO 13588, DIN EN 16018

Zerstörende Prüfungen

Querzugversuch	DIN EN ISO 4136
Längszugversuch SG	DIN EN ISO 5178
Kreuzzugprüfung	DIN EN ISO 9018
Biegeprüfung	DIN EN ISO 5173
Bruchprüfung	DIN EN ISO 9017
Kerbschlagbiegeversuch	DIN EN ISO 148-1, DIN EN 875, DIN EN ISO 9016
Härteprüfung	DIN EN ISO 9015-1, -2
Mikro- und makroskopische Untersuchung	DIN EN ISO 17639
Ätzungen für Mikro- u. makroskopische Unters.	DIN CEN ISO/TR 16060; DIN SPEC 8548
Heißrissprüfverfahren	DIN EN ISO 17641-1, -2, -3
Kaltrissprüfverfahren	DIN EN ISO 17642-1, -2, -3, DIN FB ISO/TR 17844
Bestimmung Ferritanteil	DIN EN ISO 8249

Annahmekriterien für ZfP

	Stahl	Aluminium
VT	DIN EN ISO 5817	DIN EN ISO 10042
RT	DIN EN ISO 10675-1	DIN EN ISO 10675-2
UT	DIN EN ISO 11666, DIN EN ISO 23279, DIN EN ISO 22825, DIN EN ISO 15626	
PT	DIN EN ISO 23277	
MT	DIN EN ISO 23278	
HT	DIN EN ISO 18265	

Schweißzusätze

Allg. Produktnorm	DIN EN 13479
QS-Anforderung für Herstellung	DIN EN 12074
Techn. Lieferbed.	DIN EN ISO 544
Richtlinien zur Beschaffung	DIN EN ISO 14344
Prüfverfahren & QS	DIN EN 14532-1, -2, -3 DIN EN ISO 15792-1, -2, -3
Prüfmethoden	DIN EN ISO 15792-1,-2,-3, DIN EN ISO 6847, 14372, 8249, 3690, DIN EN ISO 2401
Wolframelektroden	DIN EN ISO 6848
Zusätze zum Hartauftragen	DIN EN 14700
Zusätze für Gusseisen	DIN EN ISO 1071

Begriffe, Definitionen

Symbolische Darstellung	DIN EN ISO 2553
Verfahren und Nr.	DIN EN ISO 4063
Begriffe Metallschweißen	DIN EN 14610; DIN 1910-100; ISO 857-2
Begriffe & Definitionen	DIN FB CEN/TR 14599, DIN FB ISO/TR 25901
Mehrsprachige Benennung mit Bildern	DIN EN 1792, DIN EN ISO 17659
Schweißpositionen	DIN EN ISO 6947 CEN/TR 14633
Schweißtoleranzen	DIN EN ISO 13920

Weitere Normen

Schweißerprüfung Kupfer	DIN EN ISO 9606-3
Schweißerprüfung Nickel	DIN EN ISO 9606-4
Schweißerprüfung Titan	DIN EN ISO 9606-5
Schweißerprüfung Gußeisen	DIN EN 287-6
Bewertungsgruppen Hybrid	DIN EN ISO 12932
Verfahrensprüfung Kupfer	DIN EN ISO 15614-6
Verfahrensprüfung Nickel	DIN EN ISO 15614-1
Verfahrensprüfung Titan	DIN EN ISO 15614-5
VP Gusseisen	DIN EN ISO 15614-3
VP Auftragschweißen	DIN EN ISO 15614-7
VP Rohre in Rohrböden	DIN EN ISO 15614-8
VP Hybrid-Prozess	DIN EN ISO 15614-14
VP Schw. von Stahlguss	DIN EN ISO 11970
Schweißen von Gusseisen	DIN EN 1011-8
Schweißen v. Plattierungen	DIN EN 1011-5
Schweißen von Betonstahl	DIN EN ISO 17660
Verfahren zur Beurteilung von Unregelmäßigkeiten bei metallischen Bauteilen	DIN FB CEN/TR 15235

Schweißzusätze nach Werkstoff

	unleg. + FK-Stähle	hochfeste Stähle	warmfeste Stähle	nichtrostende Stähle	Nickel und Nickellegierungen	Kupfer und Kupferlegierungen	Aluminium und Al-Legierungen	Titan und Titanlegierungen
Stabelektroden (E)	DIN EN ISO 2560	DIN EN ISO 18275	DIN EN ISO 3580	DIN EN ISO 3581	DIN EN ISO 14172			
Drahtelektrode (MSG)	DIN EN ISO 14341	DIN EN ISO 16834	DIN EN ISO 21952	DIN EN ISO 14343	DIN EN ISO 18274	DIN EN ISO 24373	DIN EN ISO 18273	DIN EN ISO 24034
Stab/Draht (WIG)	DIN EN ISO 636							
Draht (UP)	DIN EN ISO 14171	DIN EN ISO 26304	DIN EN ISO 24598					
Pulver (UP)	DIN EN ISO 14174							
Fülldraht (MSG)	DIN EN ISO 17632	DIN EN ISO 18276	DIN EN ISO 17634	DIN EN ISO 17633	DIN EN ISO 12153			
Autogenstab (G)	DIN EN ISO 20378		DIN EN ISO 20378					
Schutzgas	DIN EN ISO 14175, DIN EN 1089-3							

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Thank you.

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