Topics in Ship Structures

01 Fatigue Strength

Reference : 선박해양구조역학 by 고대은 장범선
Fatigue Strength of Welded Stricutres
DNV 30.7 and DNV RP-C 203

2017.09

Naval Architecture and Ocean Engineering
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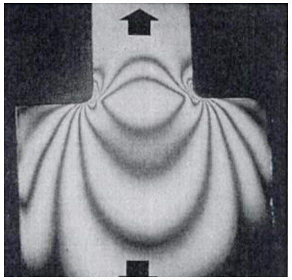
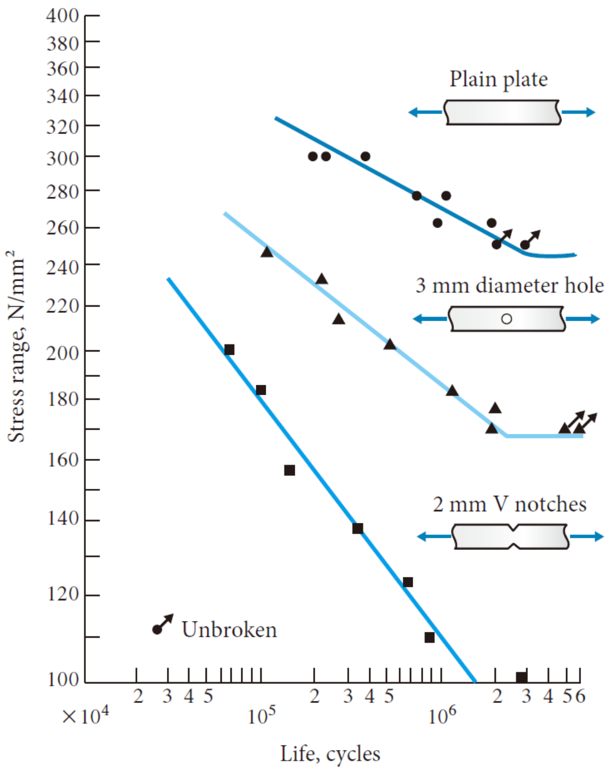
Stress Concentration

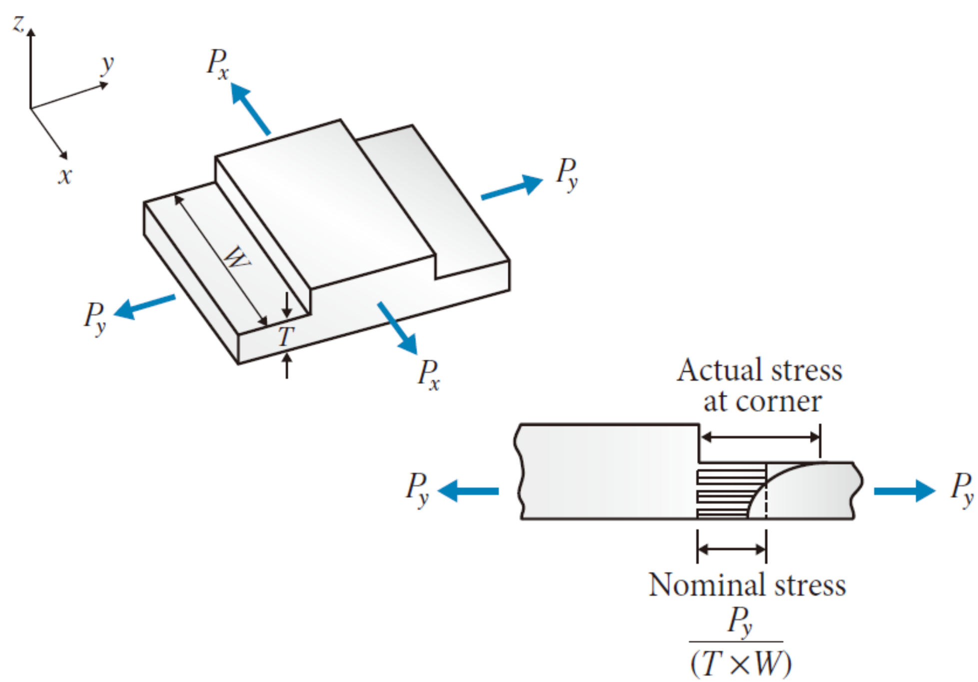
- Different S-N curves for different stress concentrations.



- Stress concentration due to discontinuity or change of shape.
- Under static loading, a stress concentration in a ductile material has no effect on the strength.



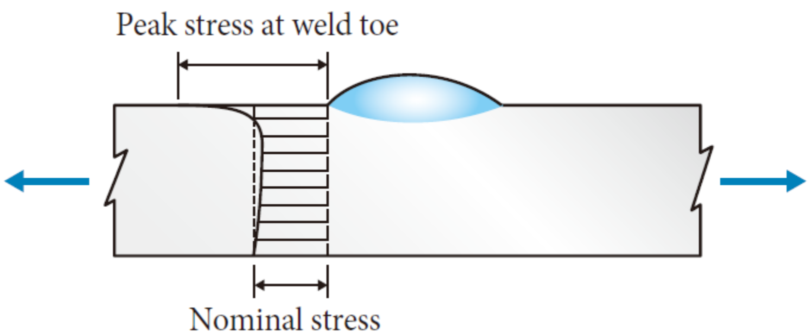
Effect of stress concentration on fatigue strength



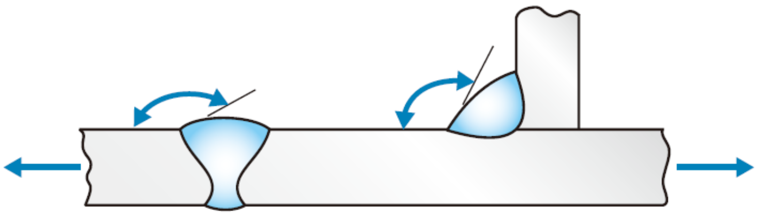
Stress concentration at increase of section

Stress concentration caused by weld shape

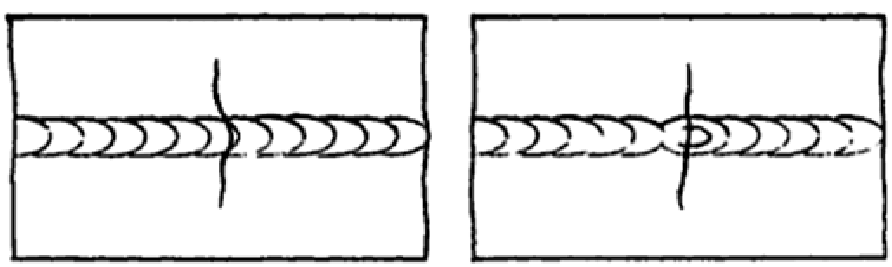
- Stress concentration level depending on geometric transition, smooth transition vs. abrupt change
- Concentration at the 'toes' of weld is the most likely site.
- Weld surface irregularities, like weld ripples, and lumps.



Stress concentration at toe of weld bead



Comparison of butt and fillet weld shape



Fatigue cracking from weld ripples, and stop/start positions

Alternate Stress and Mean Stress

- Stress range $\Delta\sigma = \sigma_{\max} - \sigma_{\min}$

- Stress amplitude $\sigma_a = \dfrac{\sigma_{\max} - \sigma_{\min}}{2}$

- Mean stress $\sigma_m = \dfrac{\sigma_{\max} + \sigma_{\min}}{2}$

- Stress Ratio $R = \dfrac{\sigma_{\min}}{\sigma_{\max}}$

- For Example

✓ Fully reversed

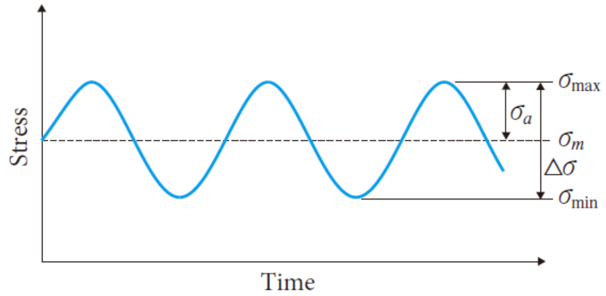
$$\sigma_{\min} = -\sigma_{\max},\ R = -1,\ \Delta\sigma = 2\sigma_{\max},\ \sigma_{mean} = 0$$

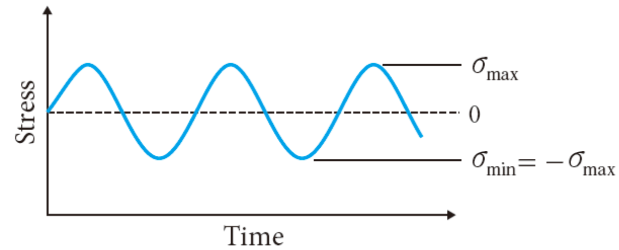
✓ Zero to max

$$\sigma_{\min} = 0,\ R = 0,\ \Delta\sigma = \sigma_{\max},\ \sigma_{mean} = \sigma_{\max}/2$$

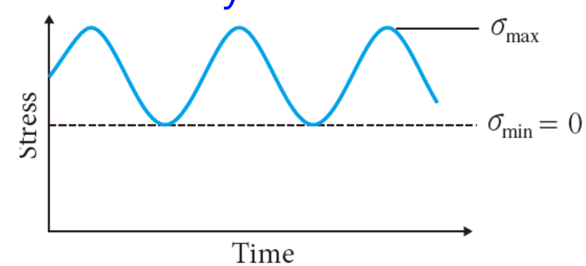
✓ Zero to min

$$\sigma_{\max} = 0,\ R = \infty,\ \Delta\sigma = -\sigma_{\min},\ \sigma_{mean} = -\sigma_{\min}/2$$

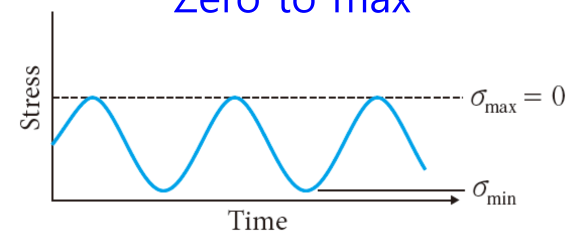




Fully reversed



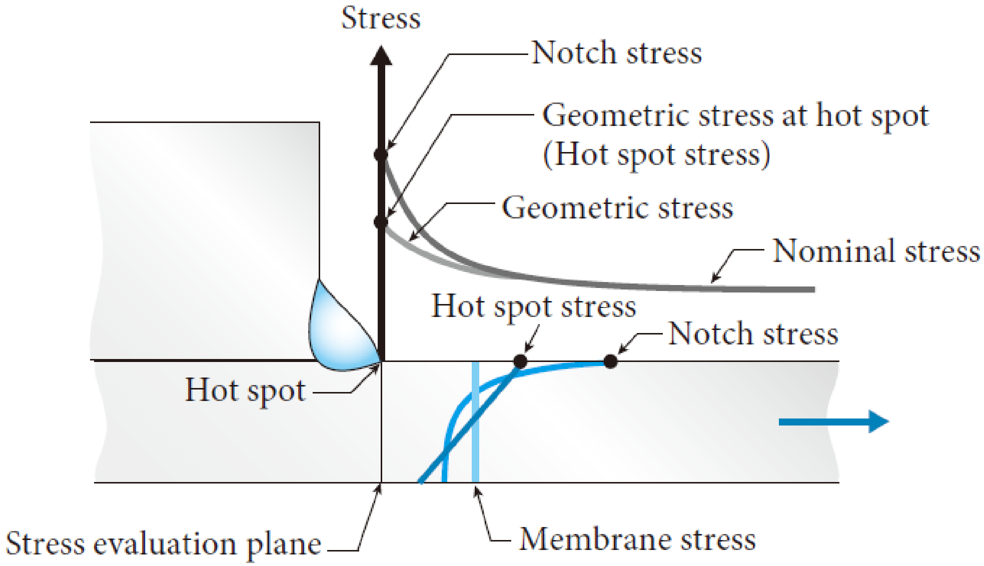
Zero to max



Zero to min

Definition of Three Kinds of Stresses

- **Nominal stress**
  - ✓ A stress to be calculated using general theories such as beam theory.
  - ✓ It is difficult to consider stress concentration caused by geometric discontinuity.
- **Hotspot stress (Geometric stress**)
  - ✓ A stress on the surface at hot spot. Not real stress.
  - ✓ The effect of structural details are taken into account but, the effect of weld bead is not included.
  - ✓ To be calculated from shell FE model where weld bead is not included.
- **Notch stress**
  - ✓ Total stress taking into account the stress concentration caused by the weld bead and geometric discontinuity.



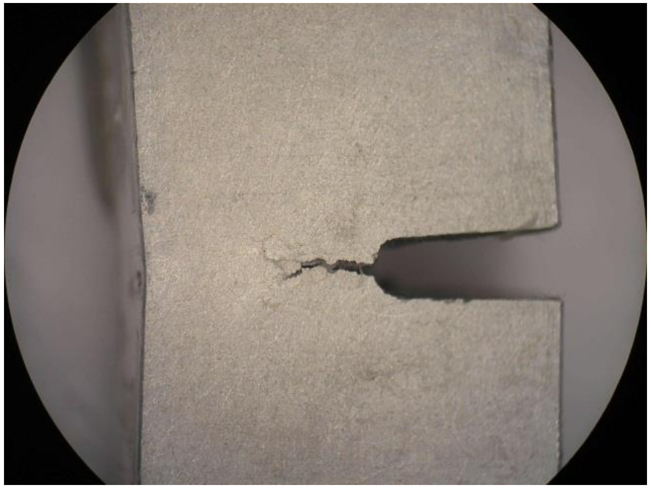
Fatigue Fracture

- Three stages of fatigue failure

1) Crack Initiation :
   - ✓ plastic deformation is accumulated at the toe of weld bead or notch
   - ✓ Fatigue crack initiates from crack-like flaws and crack growth phase accounts for 90% of entire fatigue life for welded joint.

2) Crack growth :
   - ✓ Crack grows perpendicular to principal stress direction.
   - ✓ Crack growth at crack tip depends on the stress level of crack tip. Crack always grows under cyclic tensile load.
   - ✓ Under compressive load, two faces contact and crack tip is closed

3) Final failure : brittle facture, ductile fracture, plastic collapse



Notch crack propagation under tensile load

S-N curve

- S-N Curve : Relationship curve between stress range ($\Delta\sigma$) and number of stress cycles (N) in log-log scale graph.
- Mean S-N curve

$$\log\Delta\sigma = -\frac{1}{m}\log N + \frac{1}{m}\log a$$

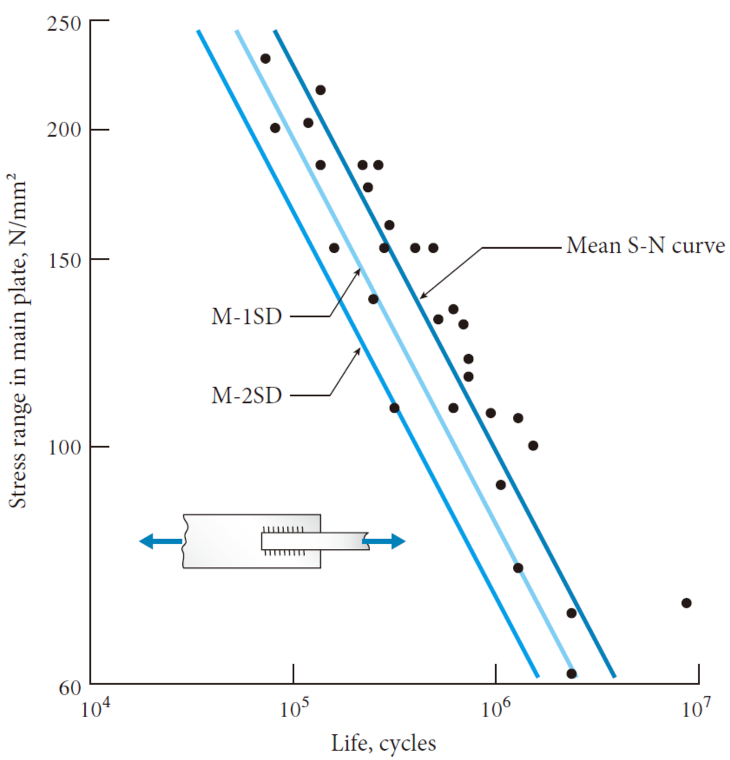
- Design S-N curve
  - ✓ Survival limit of 97.7% and failure probability of 2.3%

$$\log\Delta\sigma = -\frac{1}{m}\log N + \frac{1}{m}(\log a - 2\log s)$$

$$= -\frac{1}{m}\log N + \frac{1}{m}\log\bar{a}, \quad \bar{a} = \frac{a}{s^2}$$

s : standard deviation of log N

$-\frac{1}{m}$: slope of S-N curve, m=3,4,5



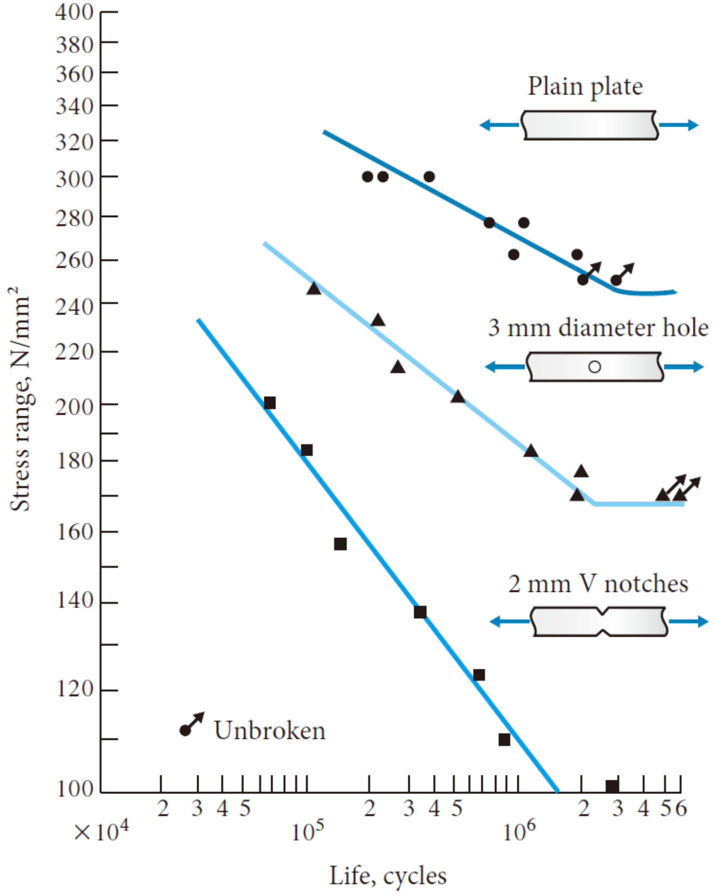
S-N curve

S-N curve

- S-N curve depends on the level of stress concentration
- S-N curve is inversely proportional to cubic of stress range.

$$\log \Delta\sigma = -\frac{1}{m}\log N + \frac{1}{m}\log \bar{a}$$

$$N = \bar{a}\ \Delta\sigma^{-m}$$



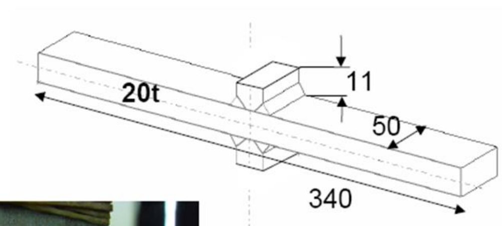
Example of S-N Curve for three types

Fatigue Test

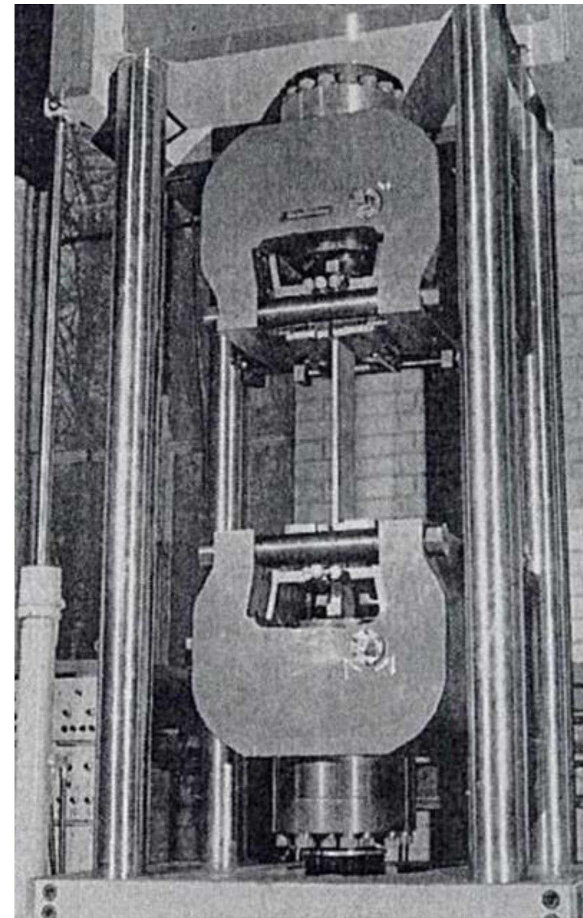
- Cyclic load of 5-15Hz under mean tensile stress to avoid buckling failure if possible.
- 8-24 days for 10^7 cycles.
- Variations due different weld bead shape.

Setting Figure

Fractured Figure



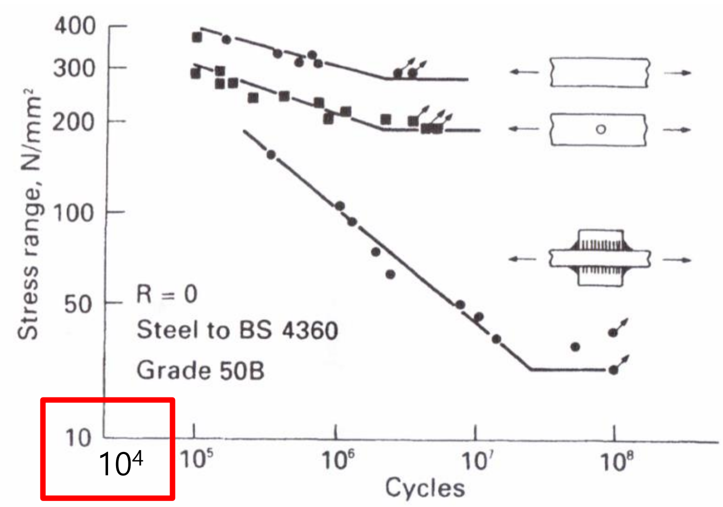
Geometry of Specimen



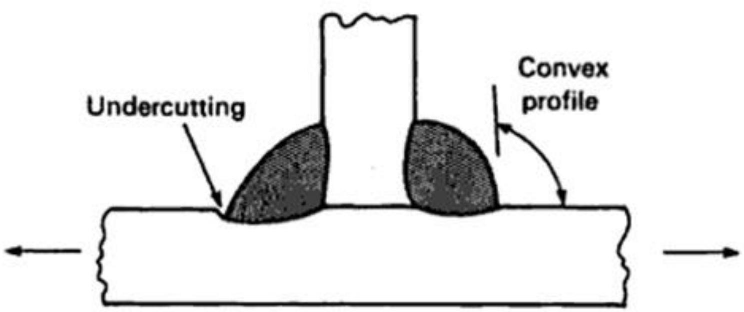
Stress concentration caused by discontinuity

- Stress concentration at the edge of a hole ≈ that of Weld toe, but, geometry of weld toe is different.
- Features of weld toe
  - Undercutting or abrupt & convex profile,
  - very small crack-like discontinuities, termed " intrusions".
  - Variations along welding length

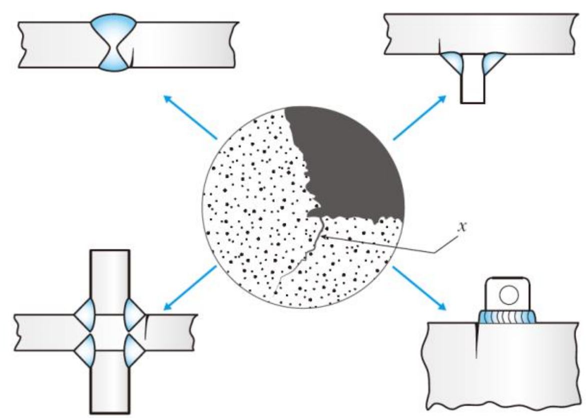
  → K_t calculation or experimental technique are meaningless.



Comparison of fatigue strengths



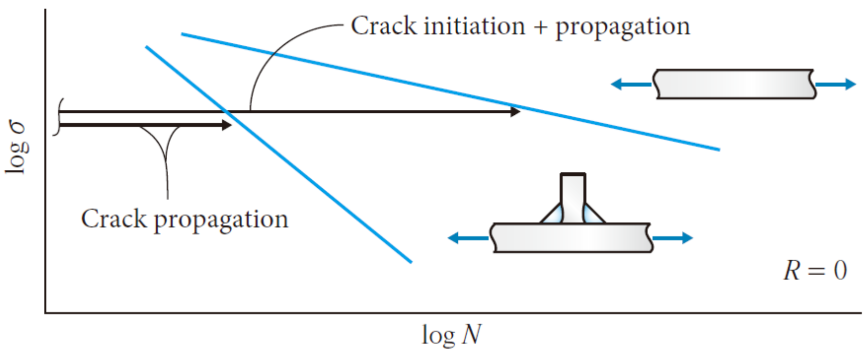
Unfavourable characteristics of weld profiles

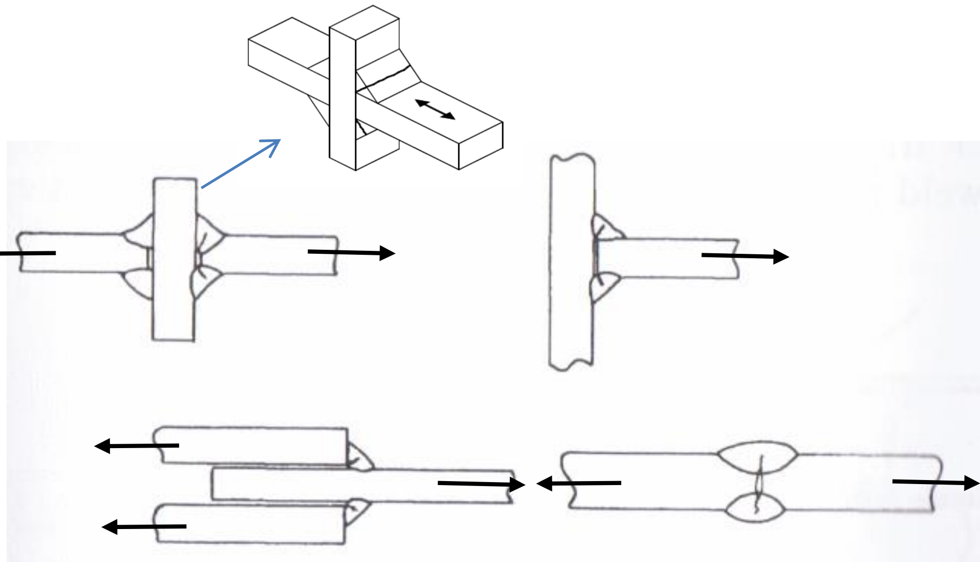


Fatigue cracking from pre-existing crack-like flaw

Stress concentration caused by discontinuity

- Welded details : Smaller portion of fatigue crack initiation time than unwelded details. Crack propagation time is dominant.
- It is essential that welds are made in accordance with strict procedure.
- Weld root fatigue : more severe than weld toe since it is hard to be detected.





Difference between plate and welded joint

Fatigue cracking from the root

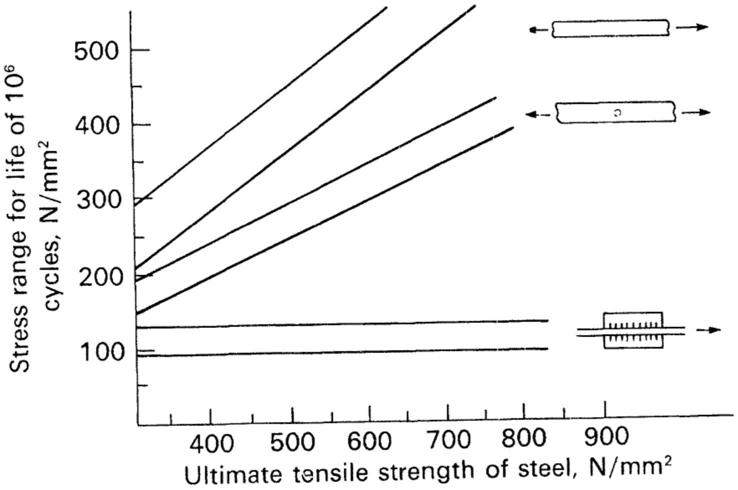
MATERIAL PROPERTY

- The fatigue strength of unwelded components increases with material strength.
- However, this is not the case with welded material. ← crack propagation of crack-life flaws is dominant and the rate of crack growth is little affected by material strength

  ► Use of high-tensile steel ('70~'80)→ high applied stress → fatigue crack → high repair cost → cap on the use

  → the same S-N curve as that for mild steel

- Brittle material (fracture failure with small crack) : little affected. ← fatigue crack growth rate increases exponentially and the crack size at final failure doesn't not have a large influence on fatigue life.



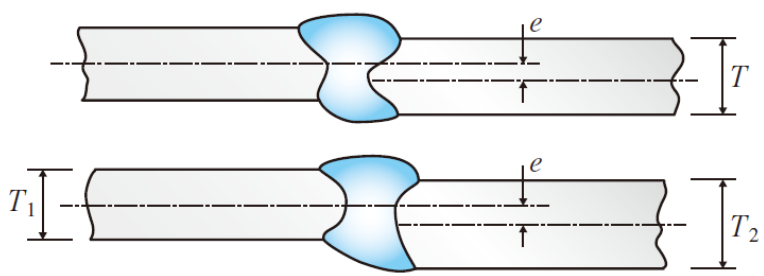
Effect of steel strength on fatigue strength

Weld quality

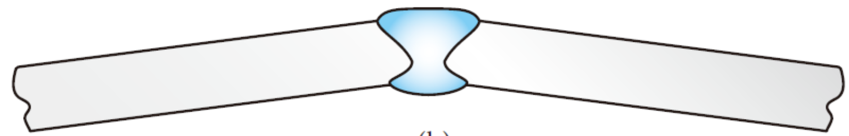
- Welding flaws like porosity(다공성), slag, intrusions, lack of fusion, or incomplete weld root penetration reduces fatigue strength.
- Alternative sites for fatigue crack initiation.
- Misalignment like axial eccentricity or angular distortion subjected to perpendicular load. → local secondary bending → stress increases.
- Strict welding procedure

- Fitness-for-purpose : estimation of effect of welding flaws and welding imperfection

  → establishment of acceptance limit



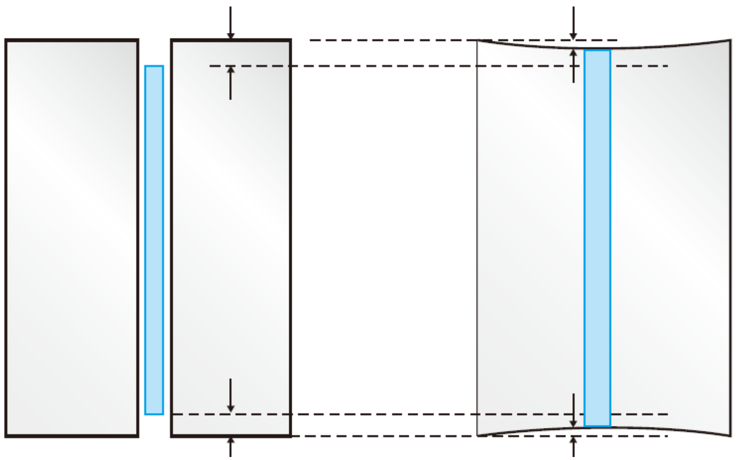
(a) Axial eccentricity



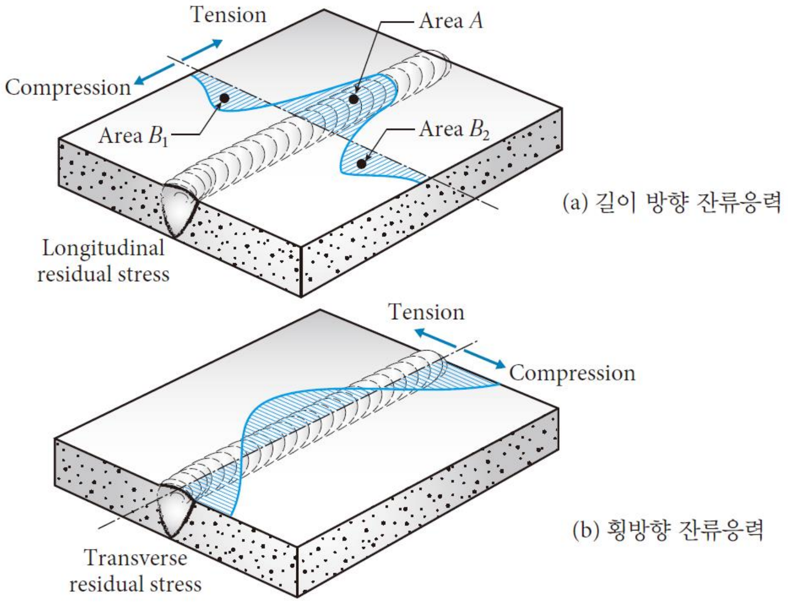
(b) Angular distortion

Residual Stress

- Two systems of stress in welded stresses
  1)Reaction stress : from assembly conditions, affecting the various members as whole.
  2) Residual stresses : from weld heating and cooling, affecting localized area, along welding line.
- During cooling stage the longitudinal shrinkage of the weld metal is resisted. → high residual tensile stress acting along the welding line remains at weld joint.



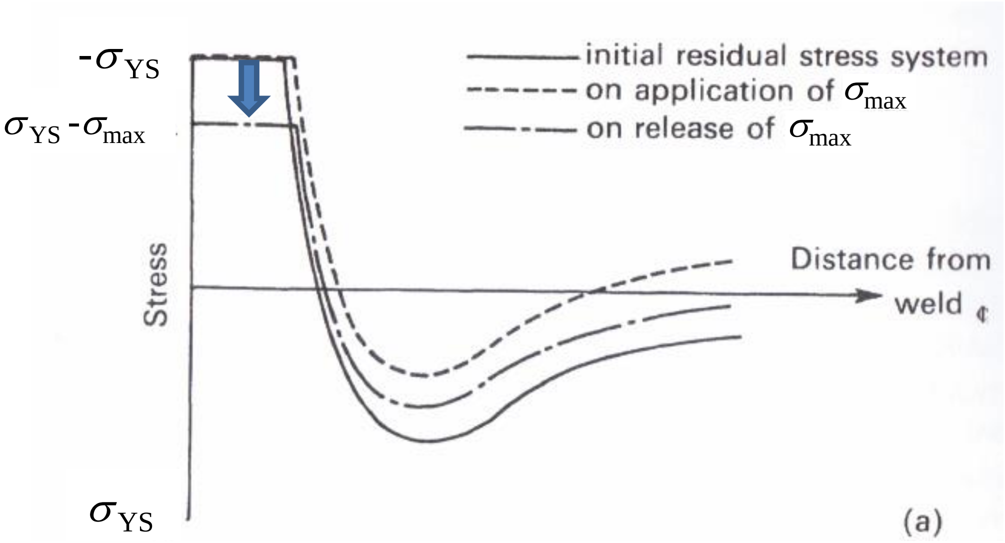
Formation of residual stress
(a) Shrinkage of unrestrained weld
(b) Shrinkage of restrained weld



Typical residual stress distribution

Residual Stress

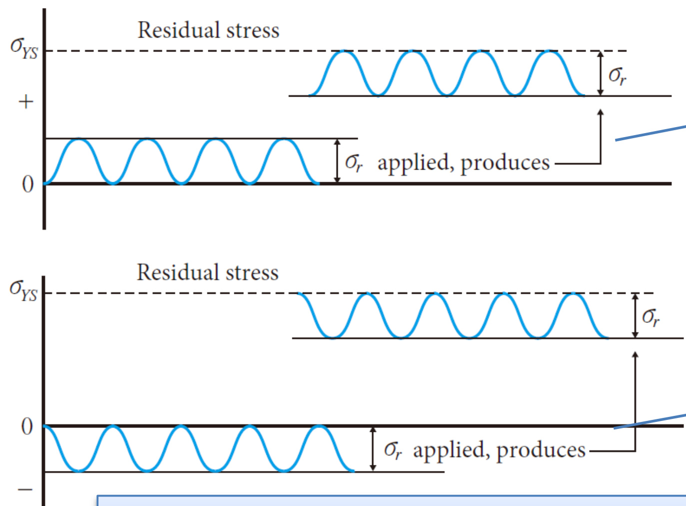
- Behavior of longitudinal residual stresses subjected to a nominal tensile stress σ_{max} in the welding direction
- Local plastic straining occurs and the stress in the weld remains at σ_{YS} .When load is removed, the stress at the weld becomes σ_{YS} -σ_{max} .



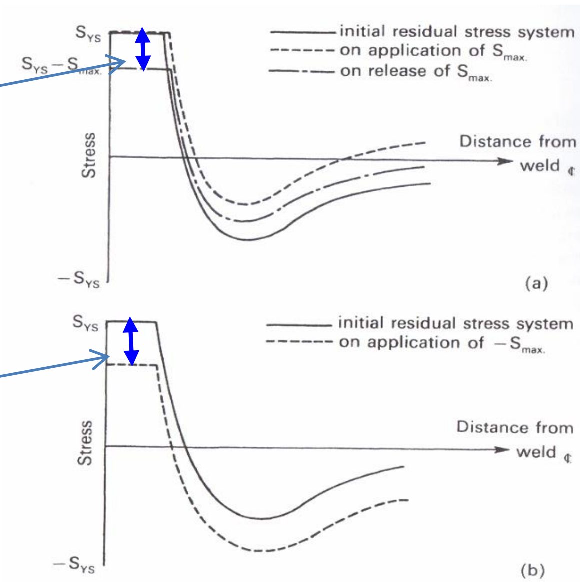
- Mechanism of shake down :
  - Residual stress at weld toe is usually in the level of yield stress.
  - Residual stress at weld toe changes during cyclic loading.

Residual Stress

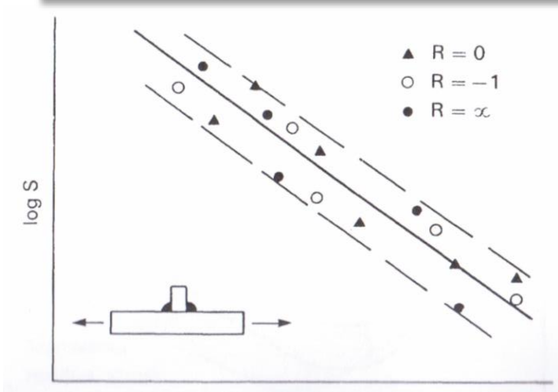
- Tensile residual stresses can lead to a reduction of fatigue life.
- Tensile cyclic load 0~ $\sigma_{max} \rightarrow$ shifted to σ_{YS} - σ_{max} ~ σ_{YS} (Tensile)
- Compressive cyclic load - σ_{YS} ~0→shifted to σ_{YS} -σ_{max} ~ σ_{YS}(Tensile).



Effective stress from superposition of applied and residual stress



Superposition of applied stress and residual stress



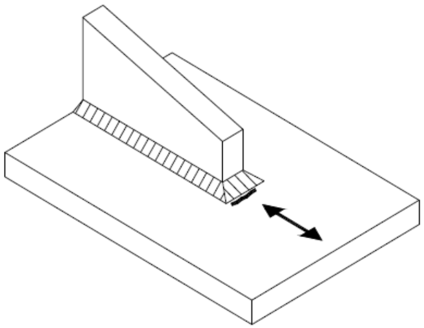
Fatigue test results for fillet joints containing high tensile residual stress

In Practical Engineering in Ship and offshore field

- Residual stress effect in marine & offshore field?
  - Varying stress amplitude
  - High stress beyond yield stress due to stress concentration
  - Shake down effect
  - Quite complicated especially at bracket toe end

→ Residual stress disappears soon after operation

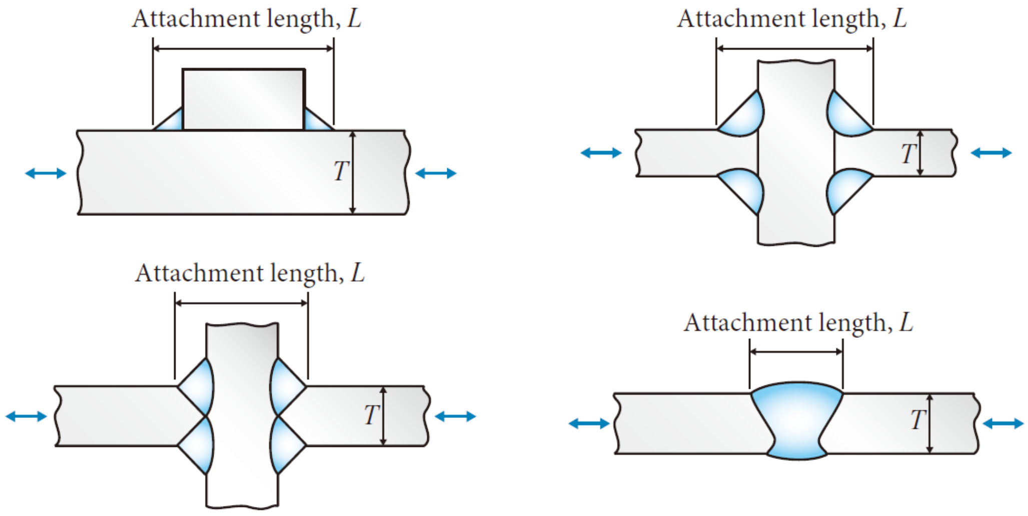
→ Usually not considered



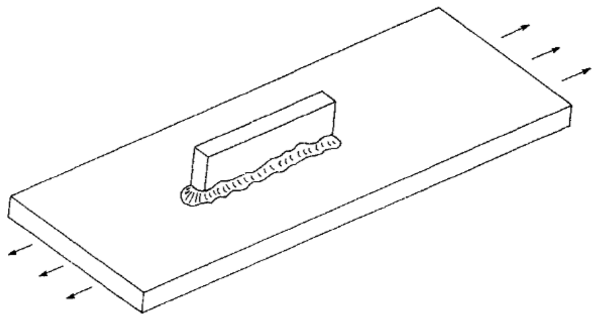
- Mean stress effect in marine & offshore field?
  - Beneficial effect due to compressive mean stress is included.
  - Some offshore regulations neglects it in a conservative way.
  - Mean stress is calculated in static loading condition.

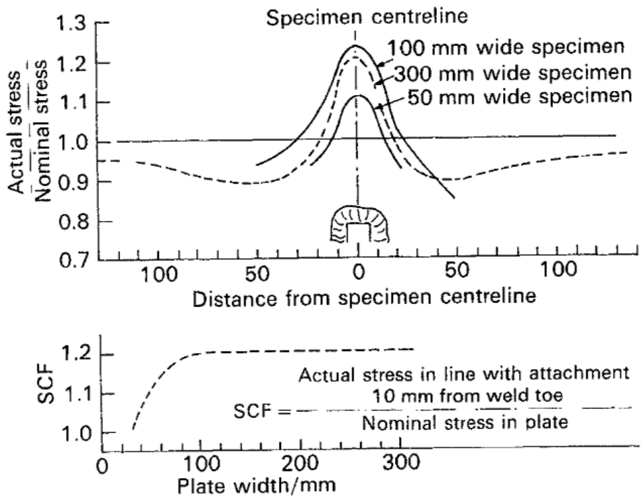
Size effects

- The effect of weld bead width is analogous to attachment length.
- The effect of plate width is also significant.
- An appropriate correction factors to experiment data relevant to other dimensions.



Dimensions relevant to size effects in fillet and butt weld joints

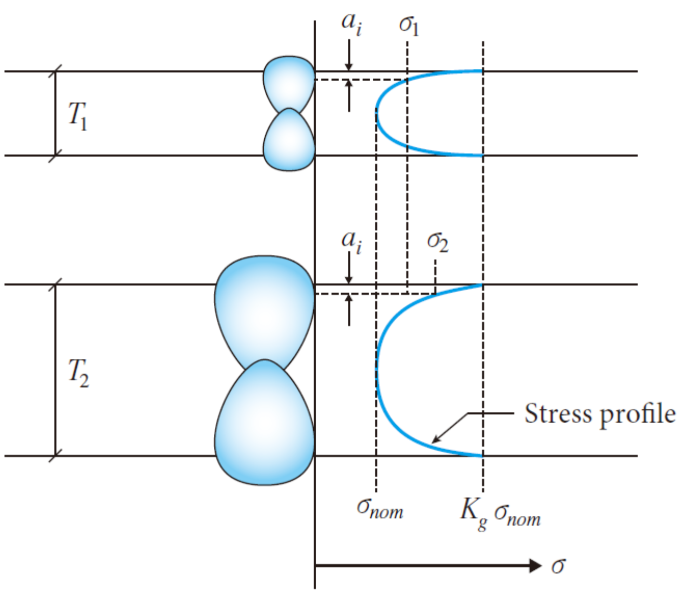




Influence of plate width on stress concentration factor

Thickness effects

- Fatigue strength decreases with plate thickness.
- There exists larger probability of weld flaws in thicker plate.
- The number and severity of flaws is likely increase with size.
- More restriction on thick plate during the fabrication process
- Smaller stress gradient over plate thickness in thicker plate ⇒ larger high stress zone.

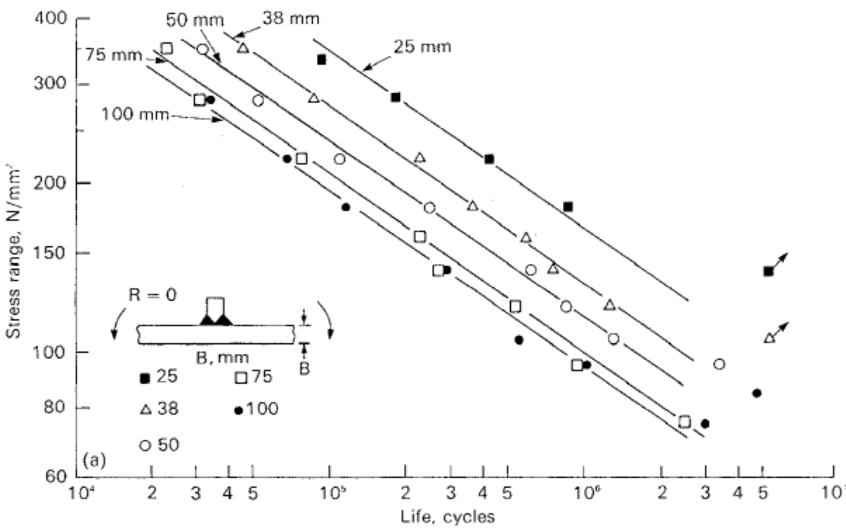


$\sigma_1 < \sigma_2$
for
$T_1 < T_2$
and
a_i constant

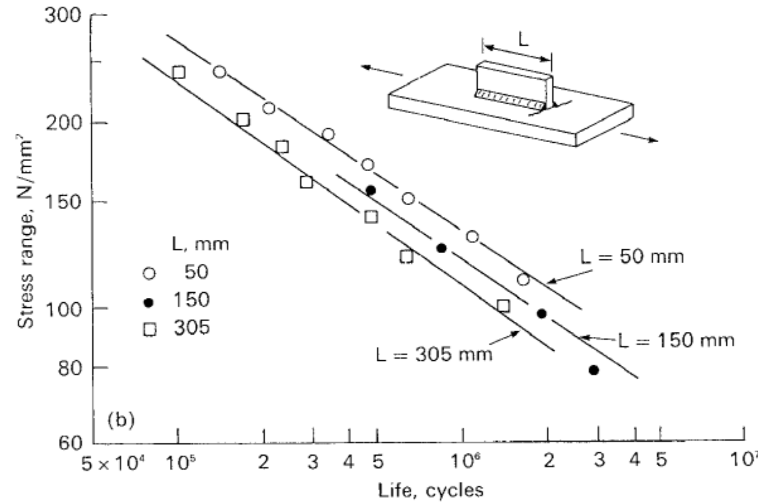
Thickness effect due to the stress gradient over plate thickness

Size effects

- S-N curve representing size effect



Influence of plate thickness

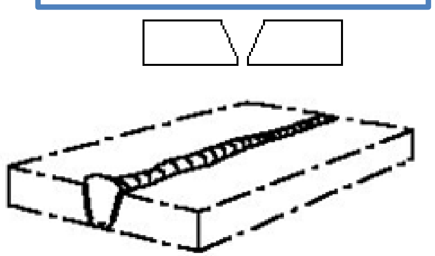


Influence of attachment length

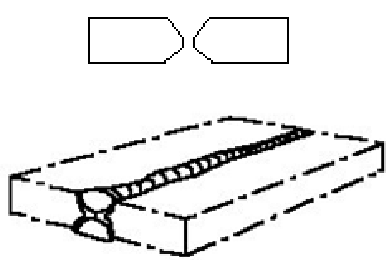
Transverse butt welds

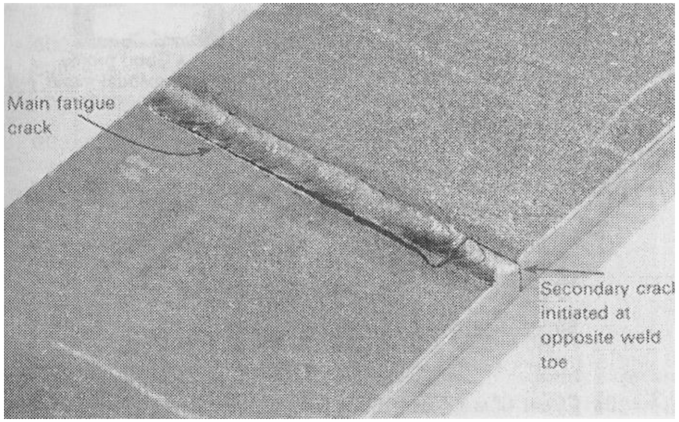
- Ductile failure occurs in the parent material. No reduction in strength caused by the weld
- Under fatigue loading, stress concentration associated weld reduces fatigue strength, the effect of stress concentration and weld toe intrusions.
- Complete removal of the excess weld metal and weld toe instructions by machining or grinding.
- Variations in shape of weld profiles → Large variation of fatigue life.
- Welds which have a minimum of excess metal and a smooth transition at the weld gives the highest fatigue strengths.

Single sided
Butt welding



Double sided
Butt welding





Fatigue failure from the toe of a transverse butt weld

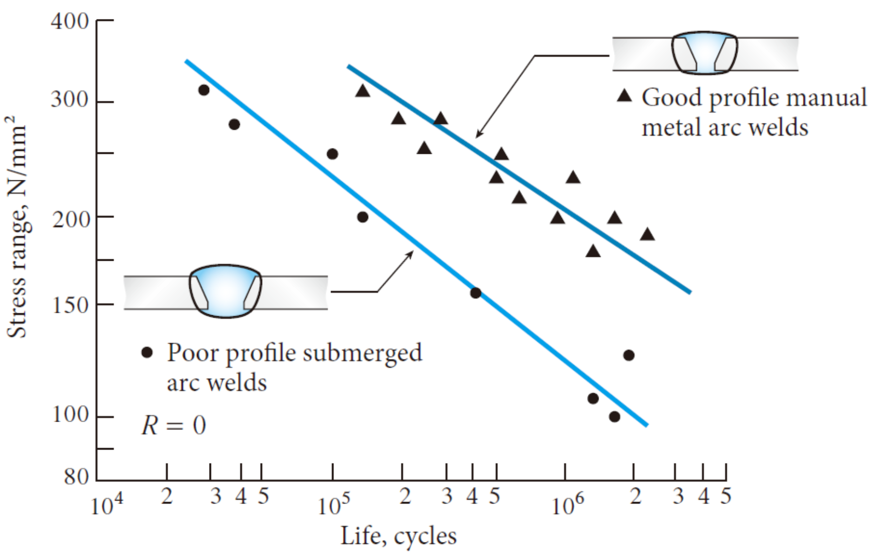
Transverse butt welds (Both sides)- Misalignment

- Axial misalignment
- Local bending stress, σ_a = nominal applied axial stress

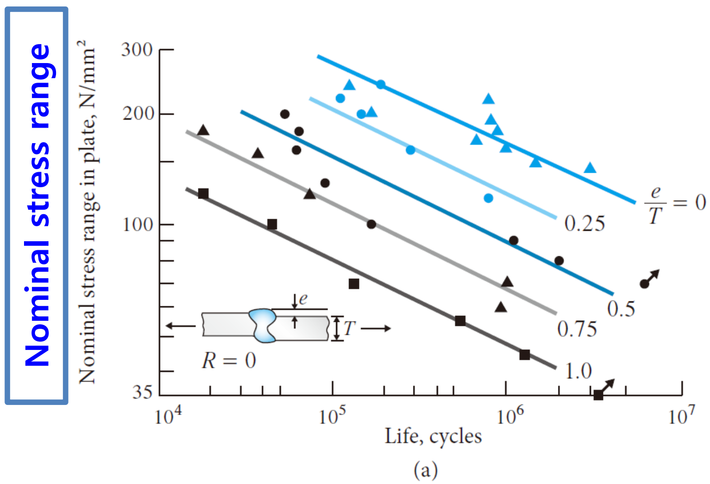
$$\sigma_b = \frac{3e}{T} \times \sigma_a \qquad \sigma_a + \sigma_b = \sigma_a(1+\frac{3e}{T}),\ K_g = (1+\frac{3e}{T})$$

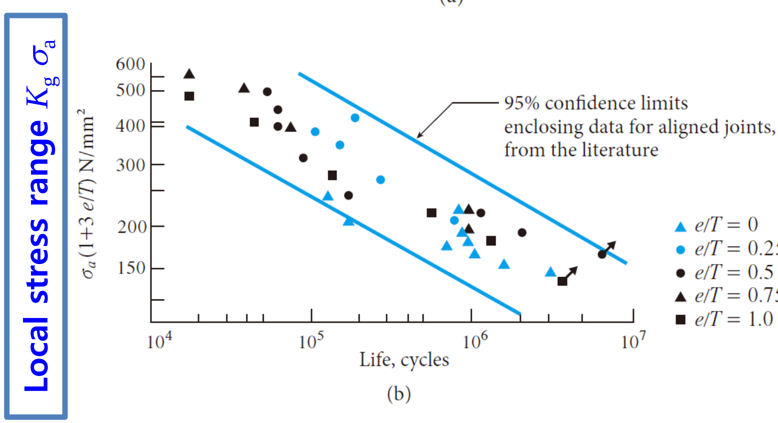
K_g=Stress concentration factor

- Angular misalignment 1° , K_g= 0.3



Effect of weld profile on fatigue strength of transverse butt welds

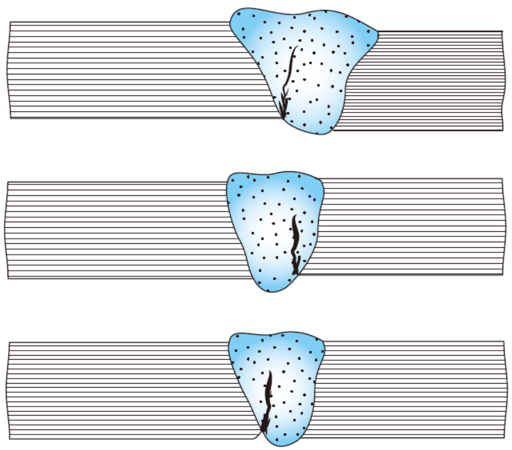




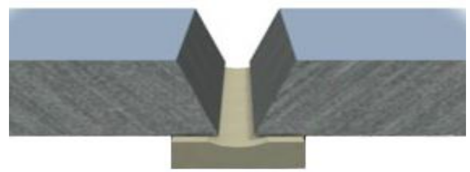
Fatigue test results from axially misaligned butt welds

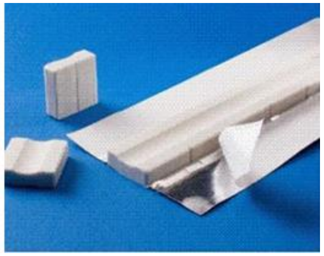
Transverse butt welds – Single Sided butt welds

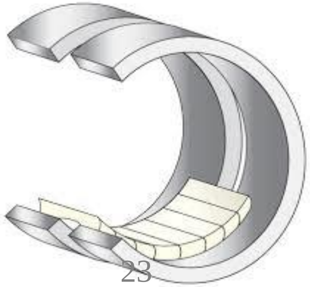
- Single sided welds : pipes or rectangular or circular hollow section.
- Lack of penetration or unfavorable bead shape with a bad profile → low fatigue strength
- Backing strip is effective.



Root cracks of butt welds





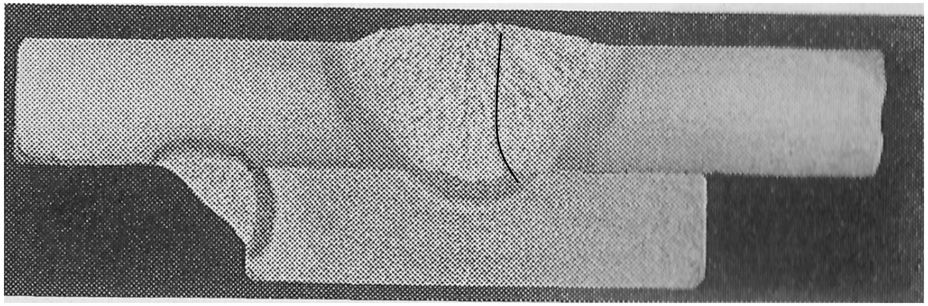


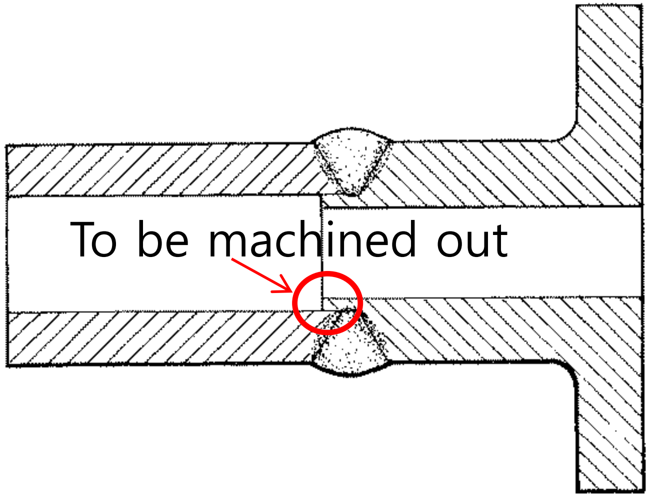
Use of ceramic backing strip

Transverse butt welds – Single Sided butt welds

❖ Permanent backing :

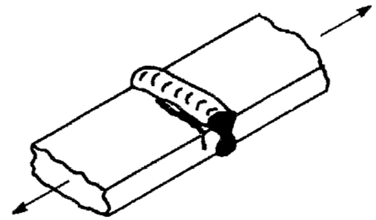
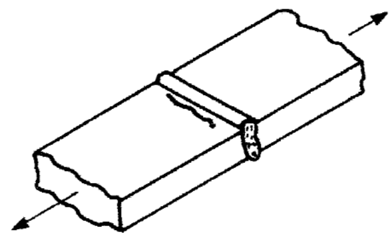
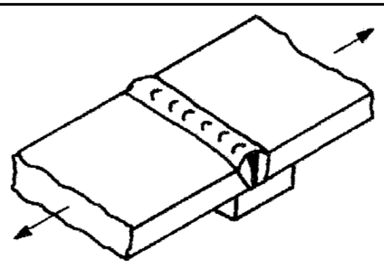
- integral with one of the members.
- crack initiation at the junction of the weld metal and backing strip.
- useful to tubular component.





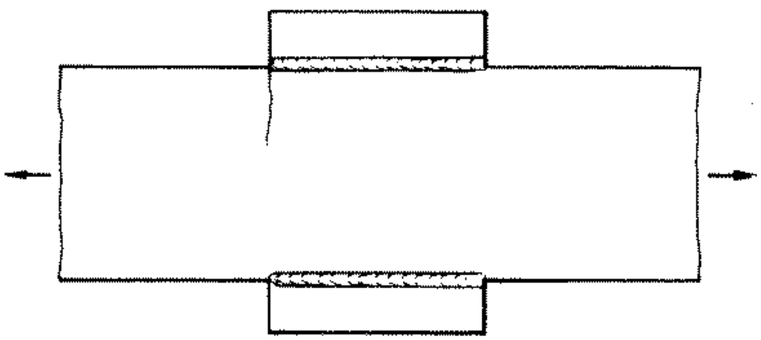
Fatigue failure in transverse butt weld made on backing strip

Transverse butt welds – S-N Curve

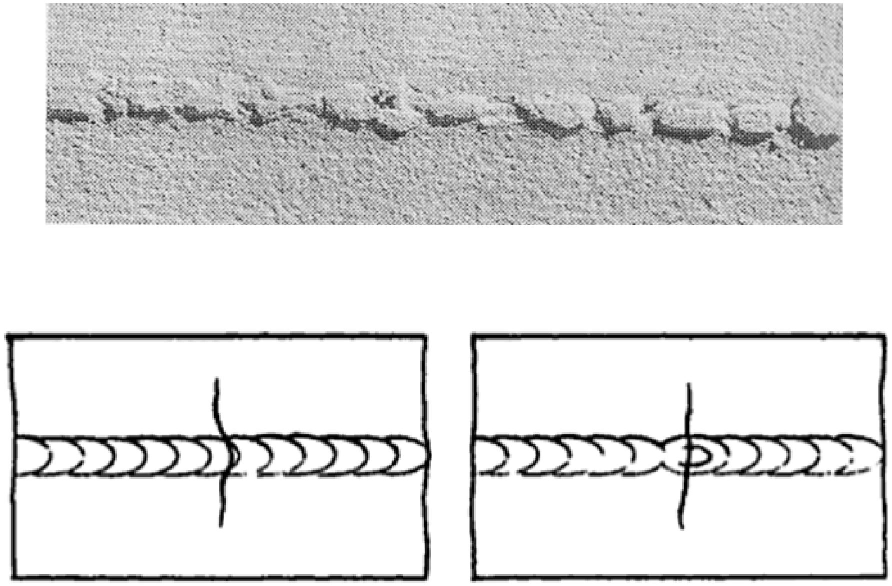
Detail	Sketch of detail	10^5 cycles	$2x10^6$
Transverse butt welds with good profile		355 MPa	155 MPa
Transverse electron beam butt weld		310 MPa	155 MPa
Transverse butt weld with poorer profile (including submerged arc)		260 MPa	116 MPa
Transverse butt weld on a permanent backing strip		260 MPa	115 MPa

Longitudinal butt Welds

- The excess weld metal lies parallel to the direction of applied load → no stress concentration.
- Stop/start positions, where the electrode is changed in manual welds, the ripples on the surface.
- Far less severe than that at the edge of the excess weld metal in transverse direction.
- Side plates produce severe stress concentration.

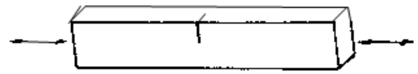
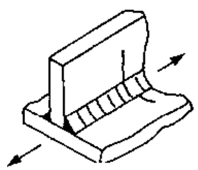
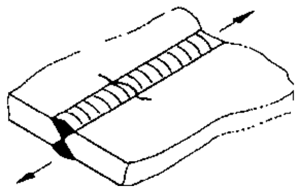
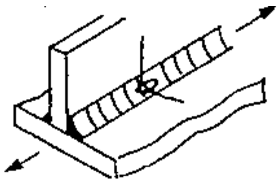
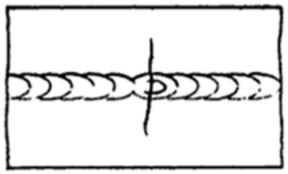
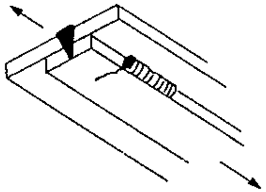
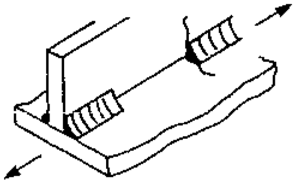


Fatigue cracking at the attachment butt welded to edge of stressed plate

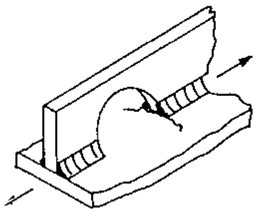
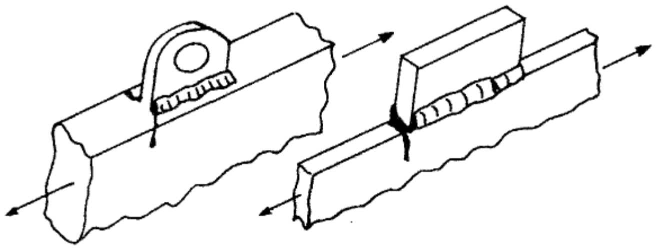
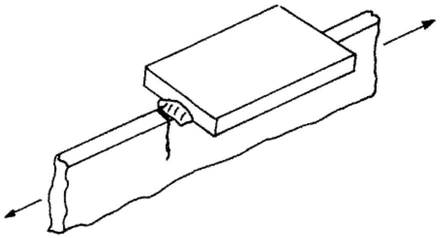


Fatigue cracking from weld ripples, (b) Stop/start positions

Longitudinal butt Welds – S-N Curve

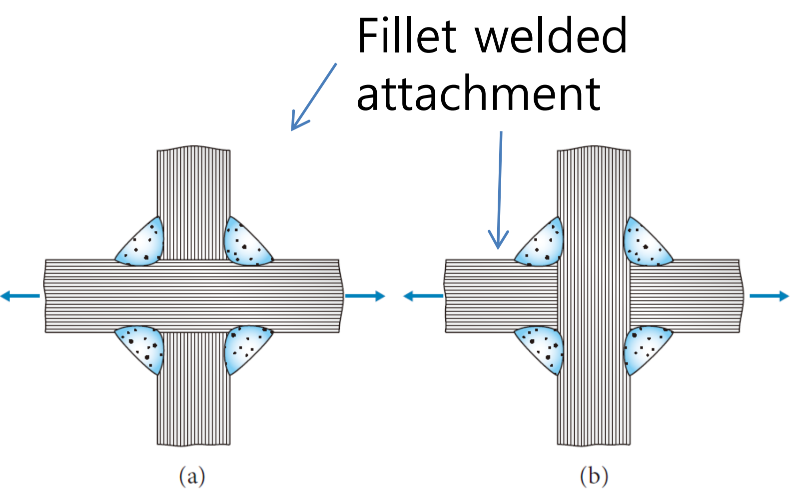
Detail	Sketch of detail	10^5 cycles	$2x10^6$
Plain as-rolled steel plate		300 MPa	200 MPa
Continuous automatic longitudinal weld	 	350 MPa	160 MPa
Continuous manual longitudinal weld	 	325 MPa	140 MPa
Longitudinal butt weld on tack welded backing strip		280 MPa	125 MPa
Intermittent longi. Fillet weld		260 MPa	120 MPa

Longitudinal butt Welds – S-N Curve

Detail	Sketch of detail	10^5 cycles	$2x10^6$
Web/flange weld at cope hole		230 MPa	95 MPa
Fillet attachment to edges of stresses members		180 MPa	70 MPa
Butt attachment to edges of stresses members		180 MPa	70 MPa

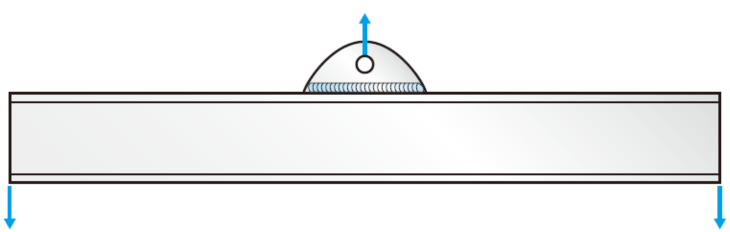
Fillet Welded Connections

- Attachments give rise to a general stress concentration in addition to local effect of the weld.
- Non-load-carrying fillet weld : attachment welds not designed to transmit the loads.
- Load-carrying fillet weld : transmits load from one member to another.
- Some loads will be transmitted through non-load carrying joint.



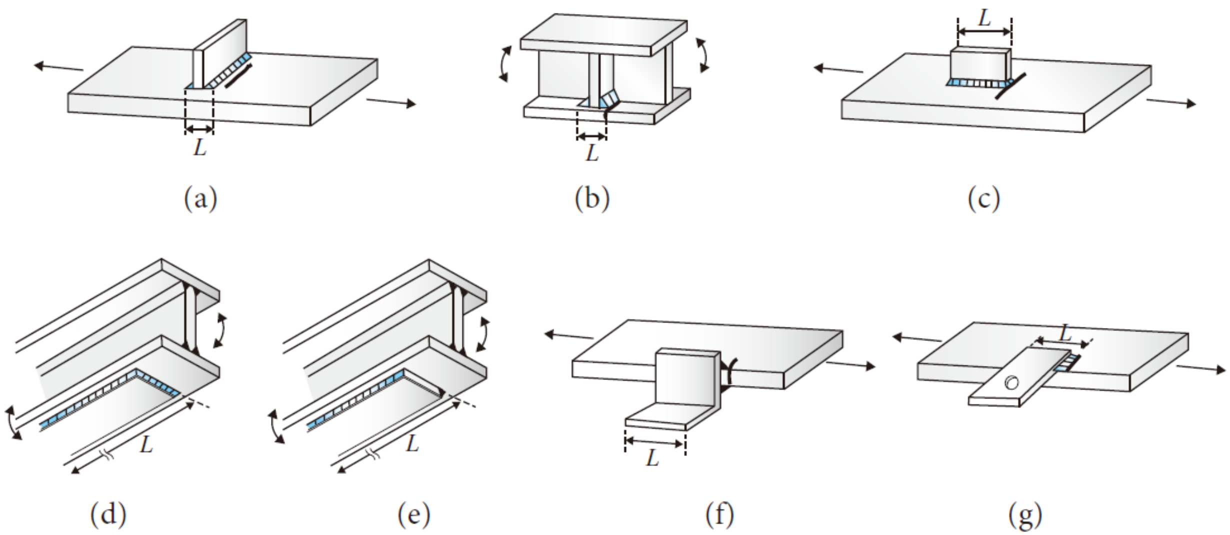
Non-load carrying Fillet weld | **Load carrying Fillet weld**

Lug : load carrying member to lifting load, but non-load carrying member to bending stress



Fillet Welded Connection – Non load carrying

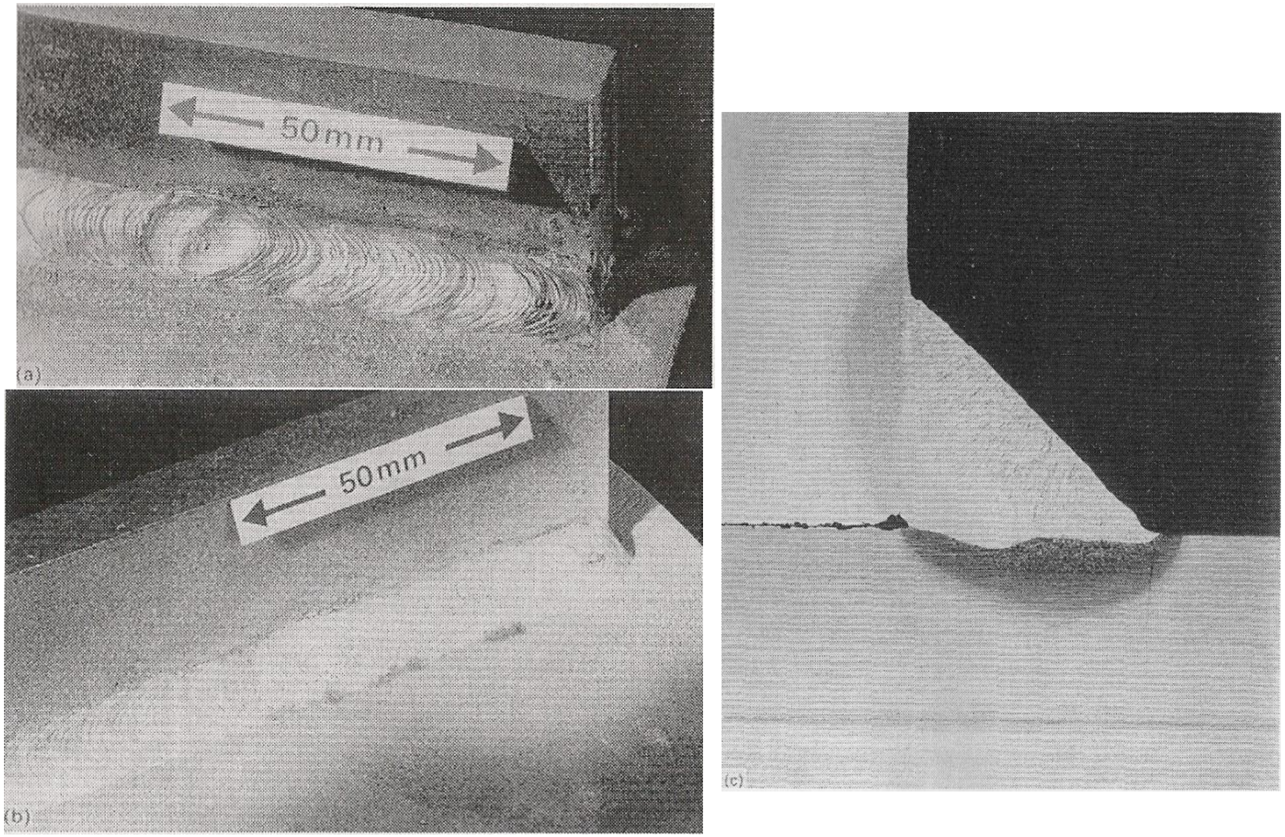
- Stress concentration increases with increase in attachment length, 'L', the thickness of longitudinal attachment or the width of doubling plate.
- Increase in main plate thickness can lead to a reduction in fatigue strength.
- Crack initiates at weld toe end and propagate through the plate.



Examples of non-load carrying fillet welded attachment

Fillet Welded Connection – Non load carrying

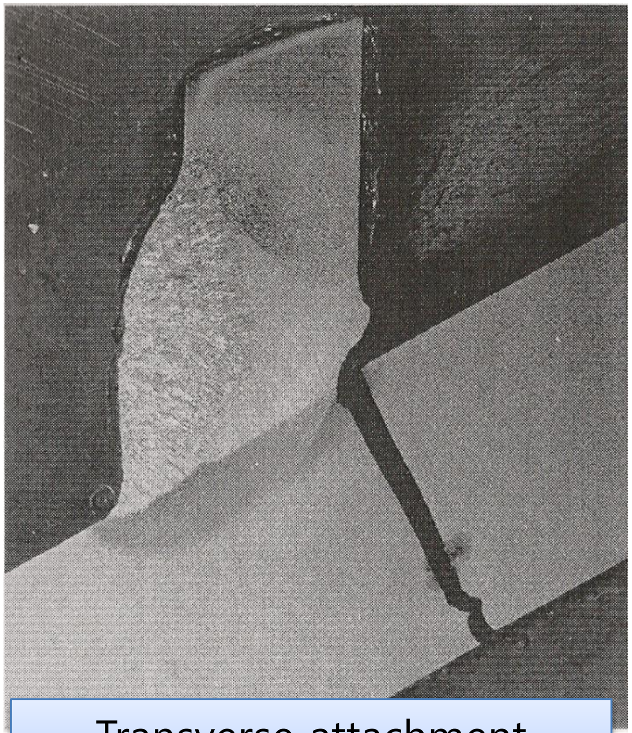
- Hard to detect through visual inspection, dye penetrant is used.



Fatigue cracking at toe of transverse fillet weld (5.5 mm crack depth)

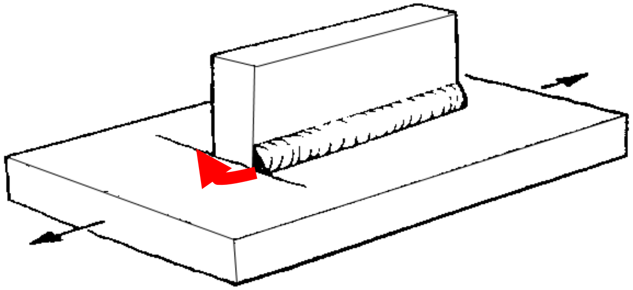
Fillet Welded Connection – Non load carrying

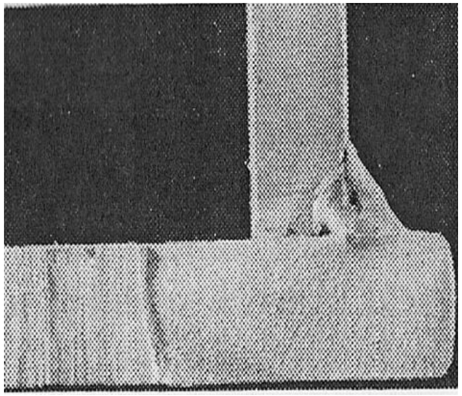
- Attachment with single fillet weld : fatigue crack initiation at crack root.
- Weld root crack is unlikely to be detected before final failure. No measures to improve the fatigue strength by treating the weld toe.



Transverse attachment welded from one side

- To return the ends of the weld around the edge of the attachment → little improvement of fatigue strength but, sealing against corrosion.





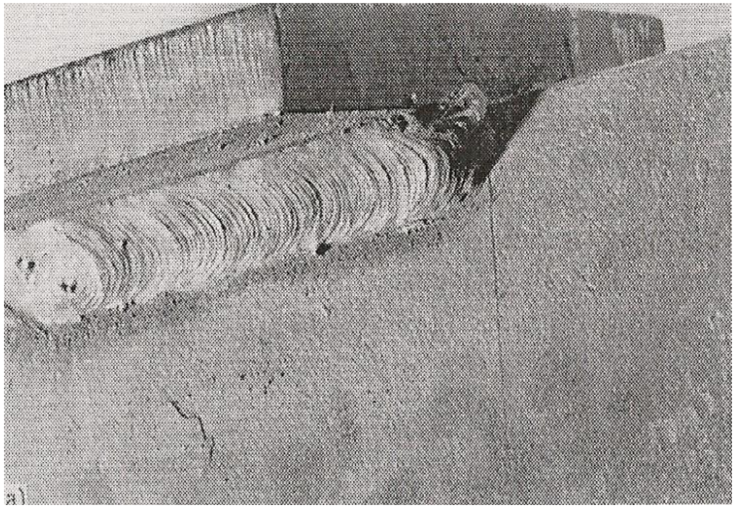
Fatigue failure from end of longitudinal fillet weld

Fillet Welded Connection – Non load carrying

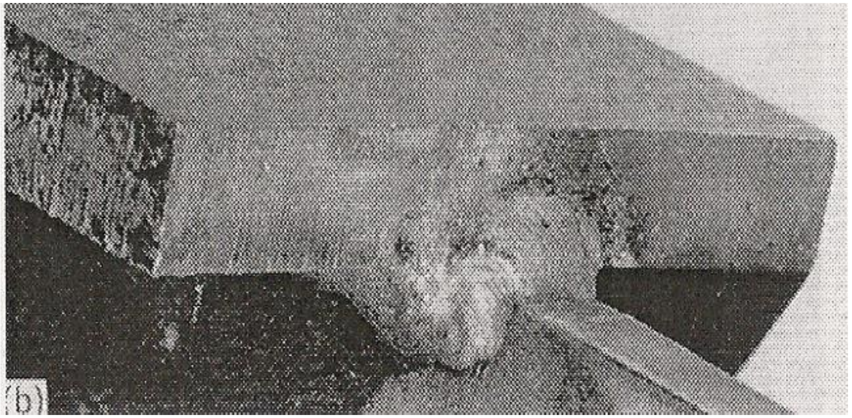
- Continuation of the weld around the ends of the edge type of attachment and across the edge of the main plate.

→ adversely reduce fatigue strength due to larger geometric discontinuity.

Fatigue strength = 70 MPa at $2X10^6$ cycle

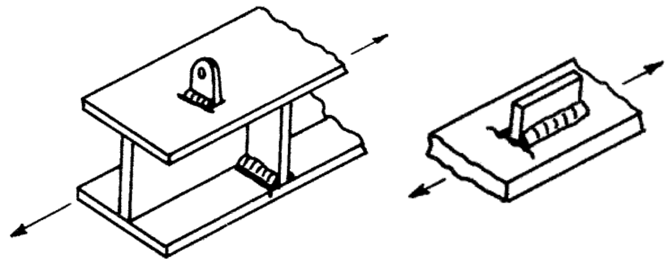
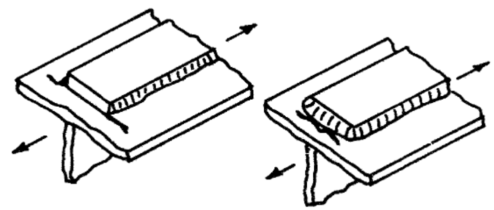
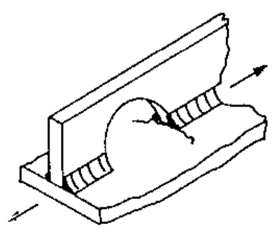
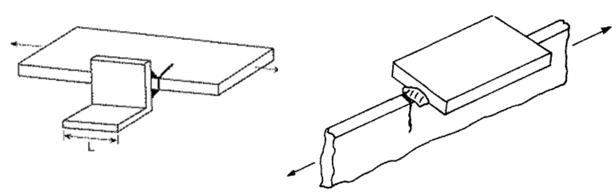


Fatigue strength = 52 MPa at $2X10^6$ cycle



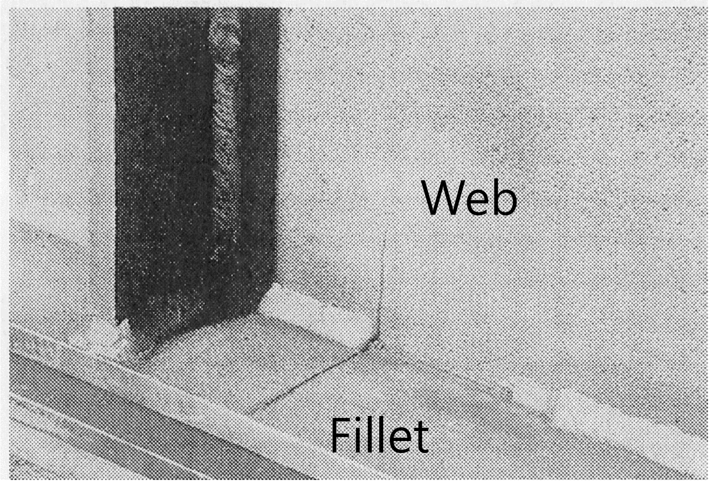
Fatigue cracking from end of fillet welded attachment to edge of stressed plate

Fillet Welded Connection – Non load carrying

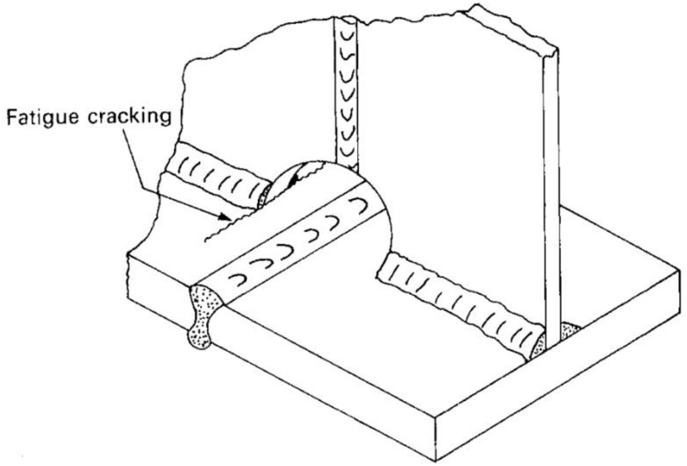
Detail	Sketch of detail	10^5 cycles	$2x10^6$
Fillet or butt welded stiffeners or attachments to the surfaces of stresses member		250	95
Cover plates on beam flanges		160	65
Web/flange weld at cope hole		230	95
Butt welded attachments to the edges of stressed member		180	70

Fillet Welded Connection – Non load carrying

- Intermittent fillet welds joining web to a flange in a beam : the geometric stress concentration, fatigue strength is slightly high. = 120 MPa at $2X10^6$ cycle.
- Web/flange fillet weld at cope hole : stress concentration is increased.



Fatigue cracking from the end of a longi. intermittent web/flange fillet weld.



Fatigue cracking from the end of a web/flange fillet weld at cope hole.

Fillet Welded Connection – Load carrying fillet welds

- Design of load carrying fillet welded joints for static loads
  - Weld length H is determined such that $P/2A_W <$ allowable design stress
  - Fig (a) : $2A_W/A_P = 1$, the same stress in both the plate and the weld < allowable tensile stress (H =0.7B)
  - Fig (b) : P/(total weld length X 4 throat thickness) < allowable shear stress
- However, behavior under Fatigue loading condition is more complicated.
  Fatigue strengths are dependent on weld configurations and joint forms

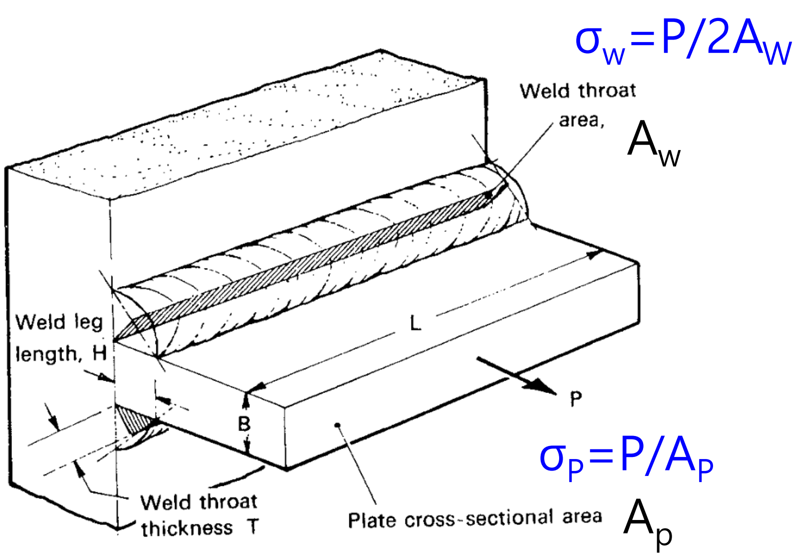


Fig (a) Transverse load-carrying fillet weld

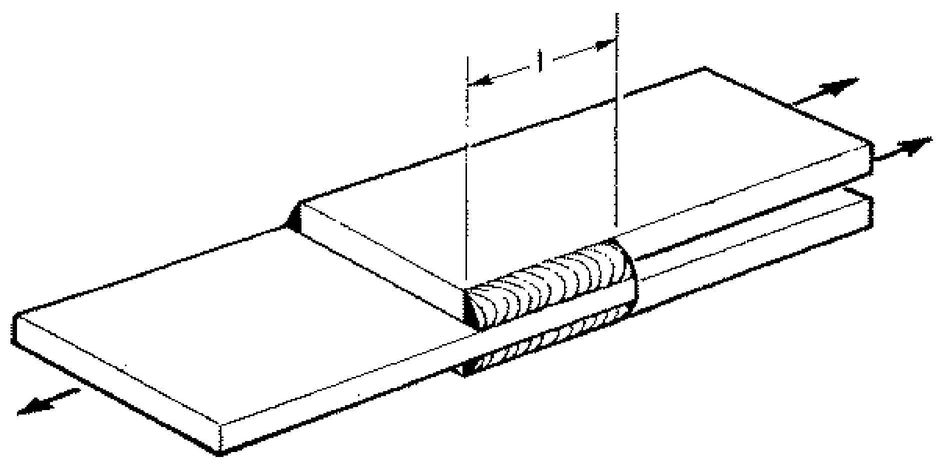


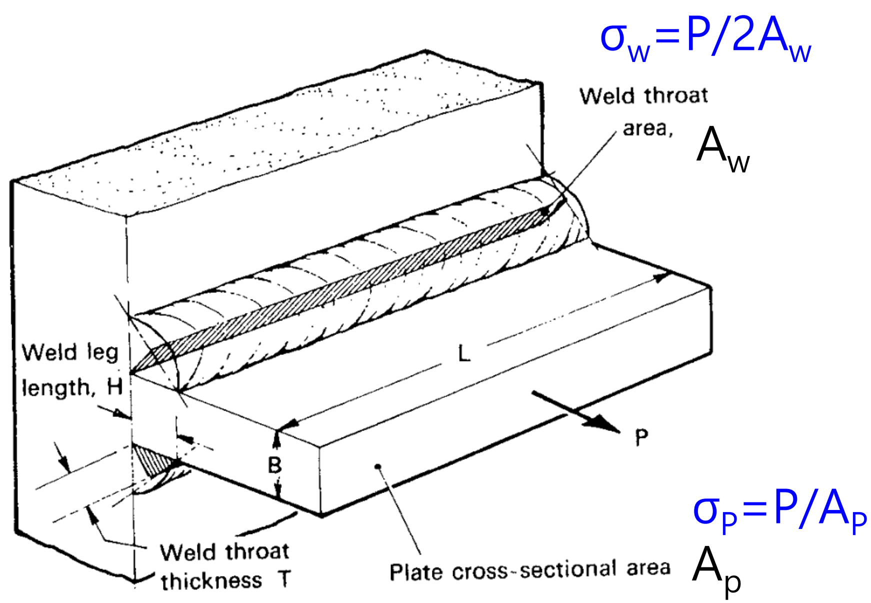
Fig (b) Longitudinal load-carrying fillet weld

Fillet Welded Connection – Load carrying fillet welds

- The location of failure depends on the ratio leg length/plate thickness (H/B) .
- Fatigue strength at weld toe = 85 MPa at $2X10^6$
  at weld root = 57 MPa at $2X10^6$
- For the same fatigue life at weld toe and weld root,

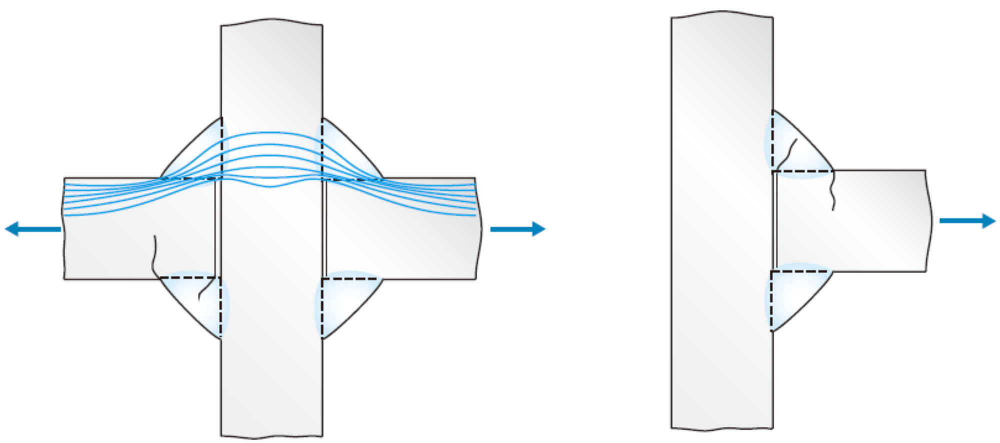
$$\frac{\sigma_{p(toe)}}{\sigma_{w(root)}} = \frac{2A_w}{A_P} = \frac{\sqrt{2}H}{B} = \frac{85}{57} = 1.5 \qquad H = \frac{1.5B}{\sqrt{2}} \approx 1.06B$$

- Optimum performance : enough weld metal to ensure that failure would be form the weld toe rather than weld root.



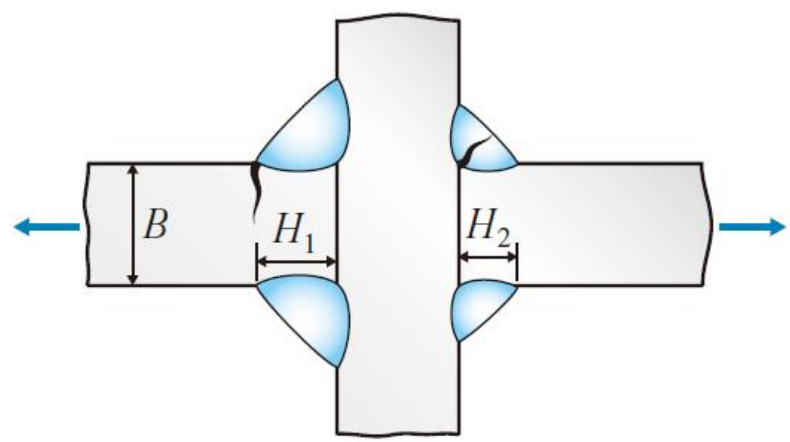
Fillet Welded Connection – Load carrying fillet welds

- Cruciform joint : two basic stress concentrations : at weld root and at weld toes.
- Large fillet leg length (H_1) : Larger notch stress at weld toes and smaller stress on weld throat → crack initiation at weld toe.
- Small fillet leg length (H_2) : Larger stress on the weld throat and smaller stress at weld toe → crack initiation at weld root.



(a) (b)

Two possible sites for fatigue cracking

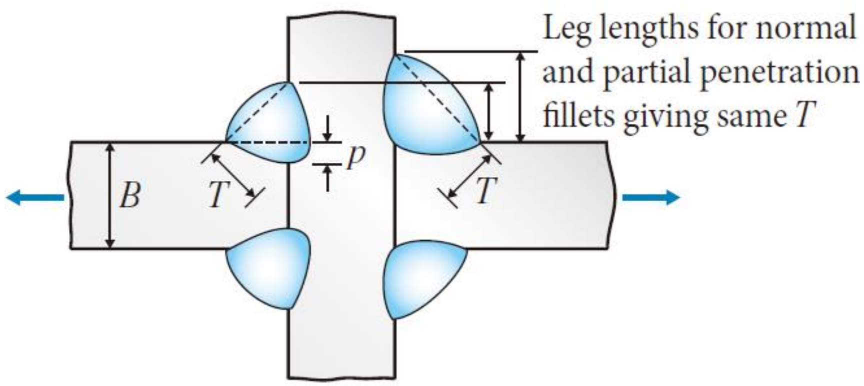


(a)

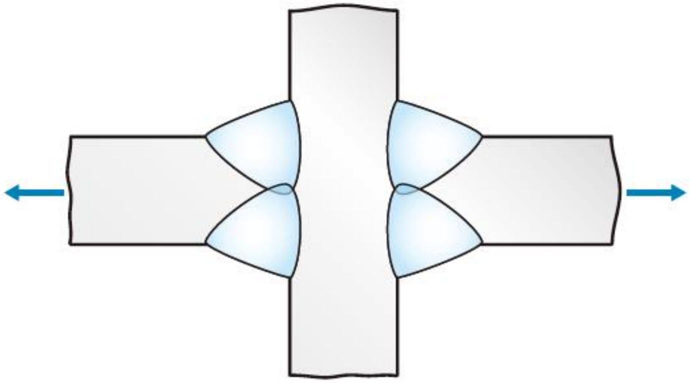
Fatigue cracking for different leg length

Fillet Welded Connection – Load carrying fillet welds

- Partial penetration welds can achieve a given throat dimension with a leg length smaller than would be required in normal fillet weld.
  → efficient way of improving fatigue performance.
- Full penetration weld eliminates stress concentration at the weld root and reduce stress concentration at the toes.
  → However, the improvement is limited, increase of 10 MPa at $2X10^6$



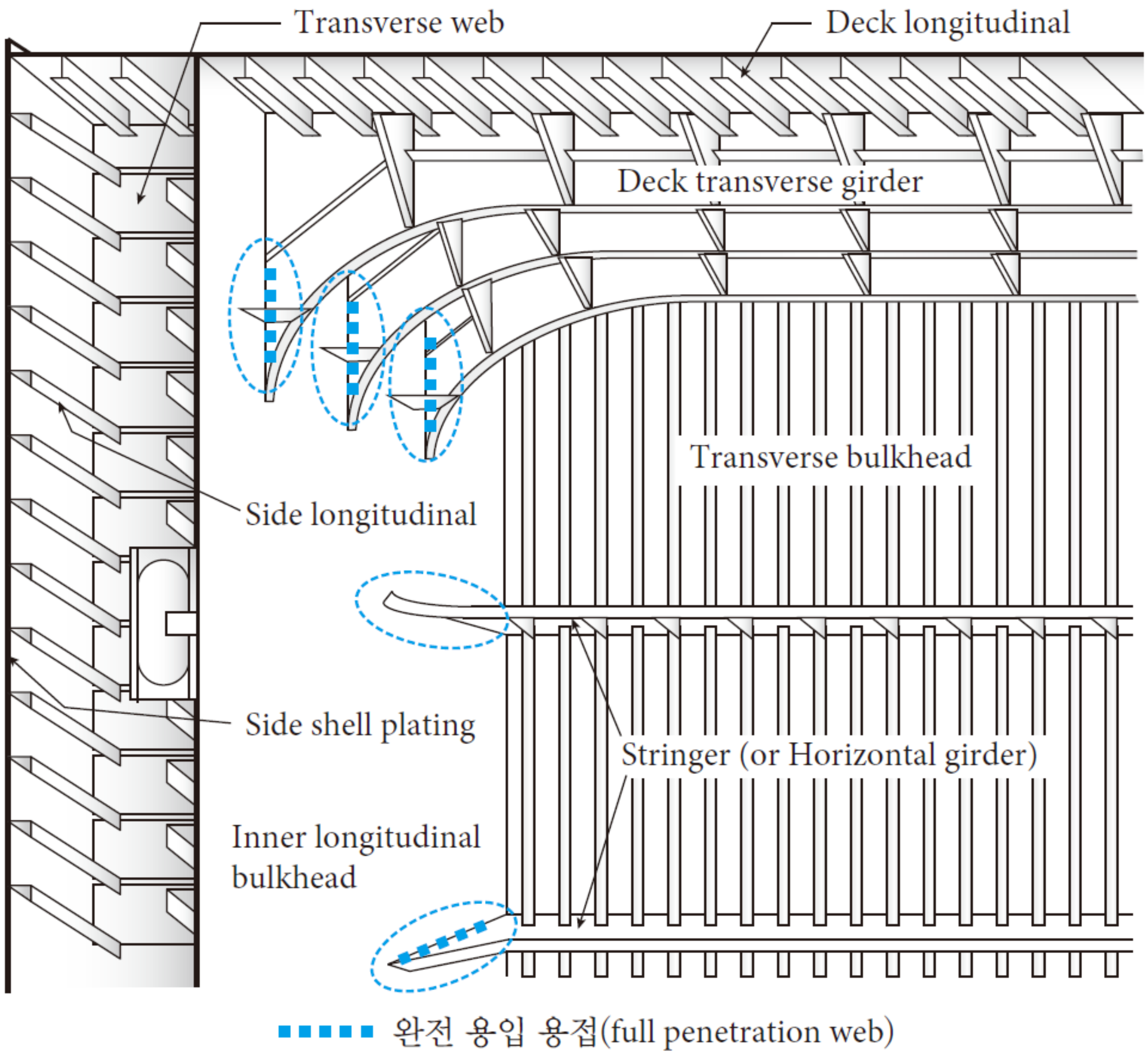
Partial penetration fillet weld



Full penetration butt welded cruciform joint

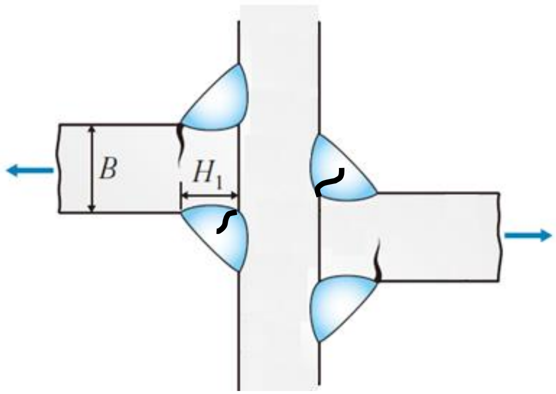
Fillet Welded Connection – Load carrying fillet welds

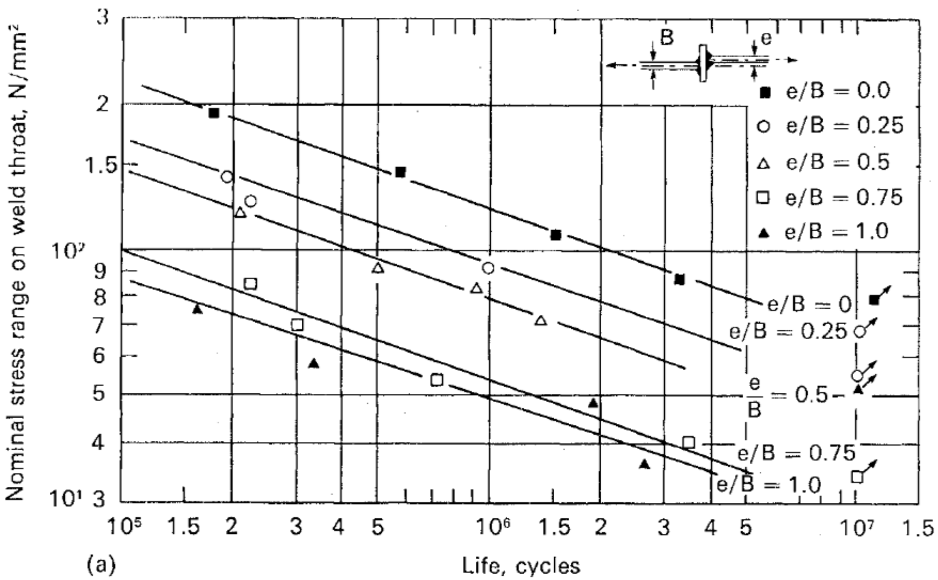
- Example of full penetration welds in ship structures



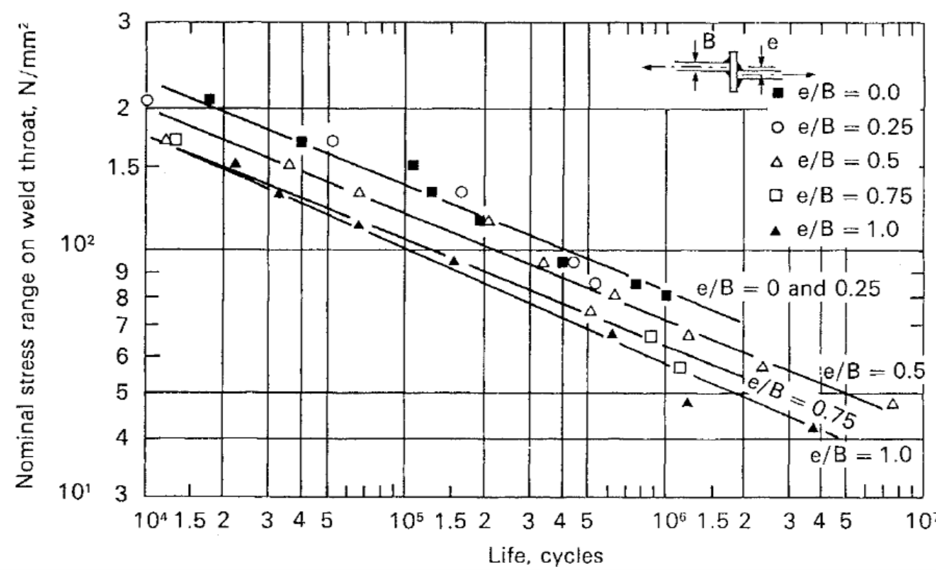
Fillet Welded Connection – Load carrying fillet welds

- Misalignment of cruciform joint introduces secondary bending stress and increases the stress range at the weld toe and weld root.
- Less effect for weld root crack since it is closer to neutral axis of the section w.r.t. the induced bending moment.
- In real structure, the restraint of cross plate inhibits bending due to misalignment. (no restraint in test)





Joints failing from the weld toe in the plate



Joints failing from the weld root in weld throat

Transverse butt welds (Both sides)- Misalignment

- Stress concentration factors for butt welds (DNV –RP-C203,2010,Section 3.1.2)

$$K_g = 1 + \frac{6(\delta_m + \delta_t - \delta_0)}{T_1\left[1 + \frac{T_1^{1.5}}{T_2^{1.5}}\right]}$$

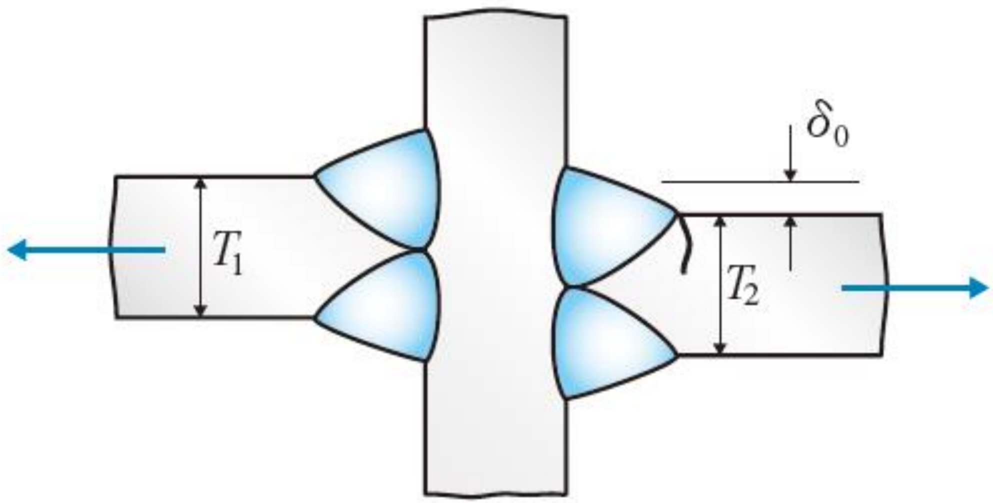
δ_m = maximum misalignment

δ_t = $1/2(T_2 - T_1)$ eccentricity due to change in thickness.

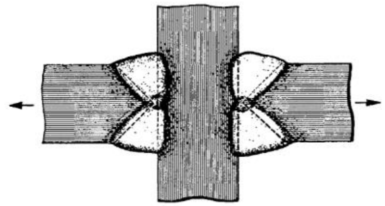
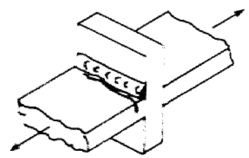
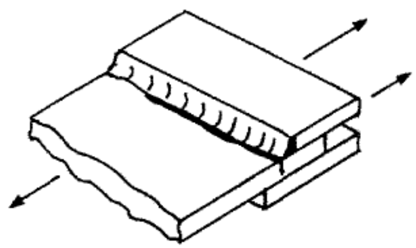
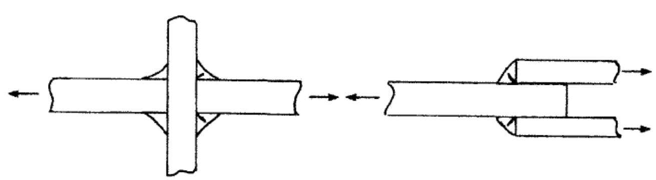
δ_0 = $0.1T_1$ is misalignment inherent in the S-N data for butt welds.

T_2 = thickness of thicker plate

T_1 = thickness of thinner plate

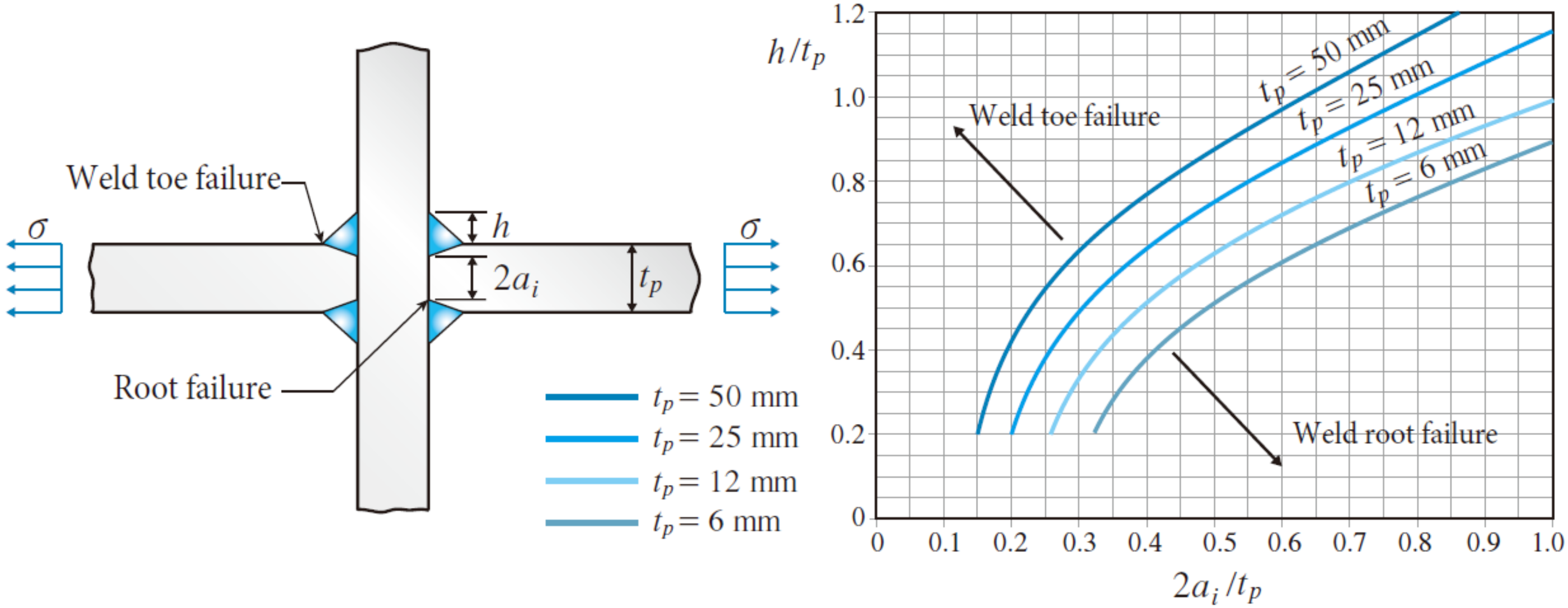


Fillet Welded Connection – Load carrying

Detail	Sketch of detail	10^5 cycles	$2x10^6$
Full penetration T or cruciform joints		360	95
Fillet welded T or cruciform joints		250	85
Lap joint with transverse fillets		250	85
Weld throat failure in transverse weld (based on stress on weld throat)		154	57

Fillet Welded Connection – Root Crack

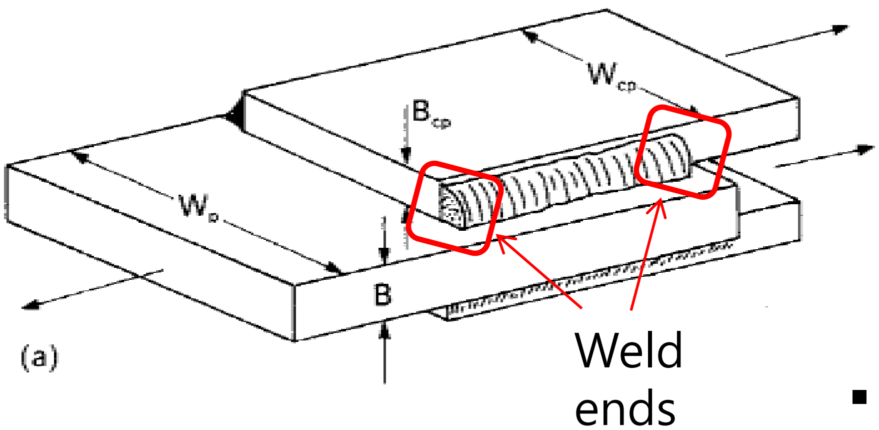
- Design Chart for fillet and partial penetration welds(DNV –RP-C203,2010,Section 2.8)
- Design should be performed such that fatigue cracking from the root is less likely than from the toe.



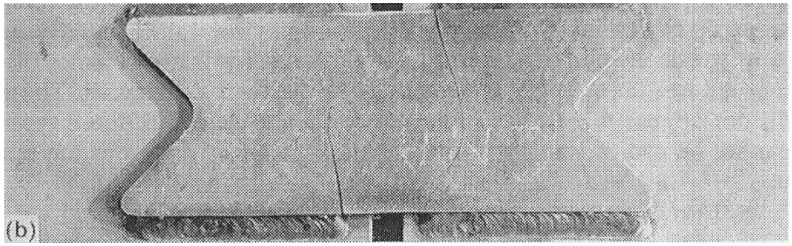
Design chart for partial penetration fillet weld (DNV-RP-C203)

Fillet Welded Connection – Load carrying fillet welds

- Lap joint using longitudinal fillet weld : less sensitive to weld size since the changes of section at the weld toe and weld root are parallel with the direction of applied stress.
- Weld ends induce stress concentration in both the main and cover plates.
- Weld on the edge is more damaging than weld on surface.
- Under the same nominal stress ($BXW_P=2B_{CP}W_{CP}$), failure will initiate from a weld end and propagate into the cover plate.

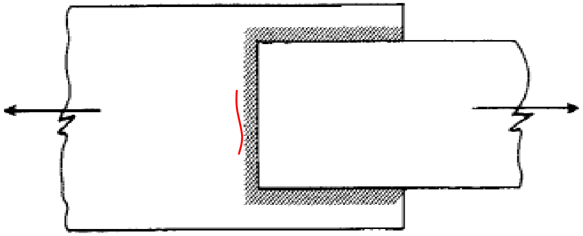


Lap joint made using longi. fillet joint



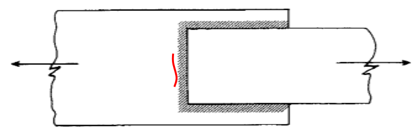
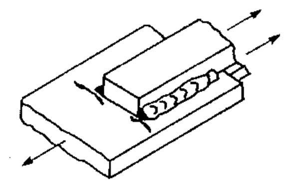
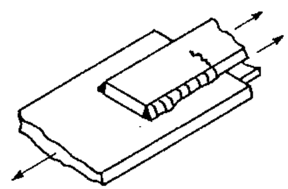
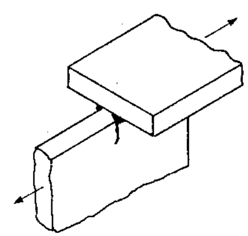
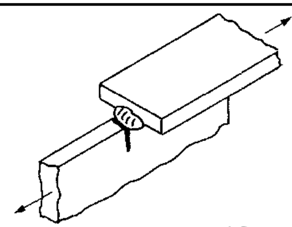
Fatigue failure from weld ends in cover plate

- Designed $BW_P<2B_{CP}W_{CP}$
- Continued weld around the end



Joint with weld continued around end of cover plate

Fillet Welded Connection – Load carrying

Detail	Sketch of detail	10^5 cycles	2x10^6
Lap Joint with weld continued around end of cover plate		235	85
Lap joint with longi. fillet welds – crack initiates on surface		230	80
Lap joint with longi. fillet welds – crack initiates on edge of cover plate		200	66
Load carrying weld on plate edge – not welded around end		150	50
Load carrying weld on plate edge – welded around end		125	44

What is fatigue failure?

- Before 70's, fatigue strength is not a critical issue to be treated in ship design stage.
- Remarkable increase in use of high tensile steel ('70~'80) → high applied stress → frequent occurrence of fatigue crack → high repair cost
- The fatigue strength of unwelded components (base material) increases with material yield strength but this is not the case with welded joints ← crack propagation of crack-like flaws is dominant and the rate of crack growth is little affected by material strength
- During 80'~90s, lots of research in fatigue strength → fatigue strength assessment is mandatory, cap on the use of high tensile steel is placed by ship owner.
- The most common and important failure mode together with buckling.

Demand of fatigue strength assessment based on wave load analysis is increasing, especially for high risk vessel like LNG carrier. (Required fatigue life of LNG carrier is 40 years)

- Offshore structure requires higher fatigue life than commercial ship due to no inspection after re-docking (Commercial vessel : 25 years. Offshore structure : 40 ~ 200 years depending on the accessibility)

Fatigue strength assessment

- Assessment of fatigue life under one cyclic load is simple since it can be predicted from S-N curve.

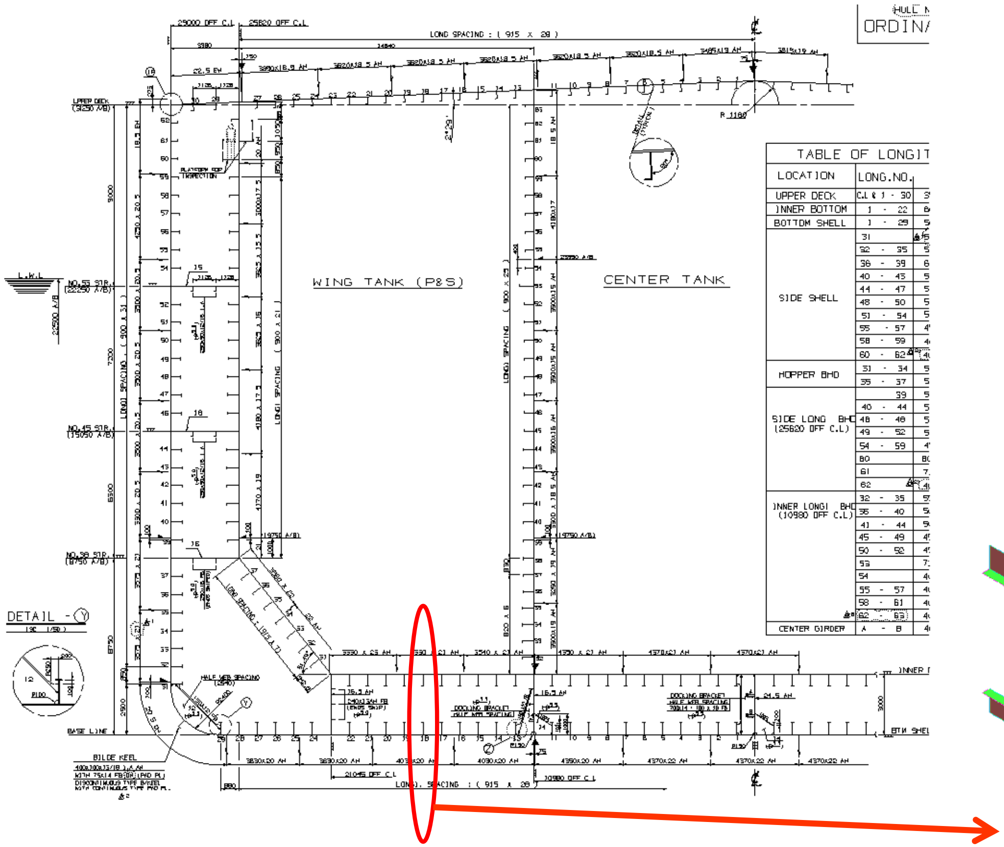
- However, fatigue damage is accumulated over the entire lifetime of a vessel, it is hard to analyze the load and stress history.

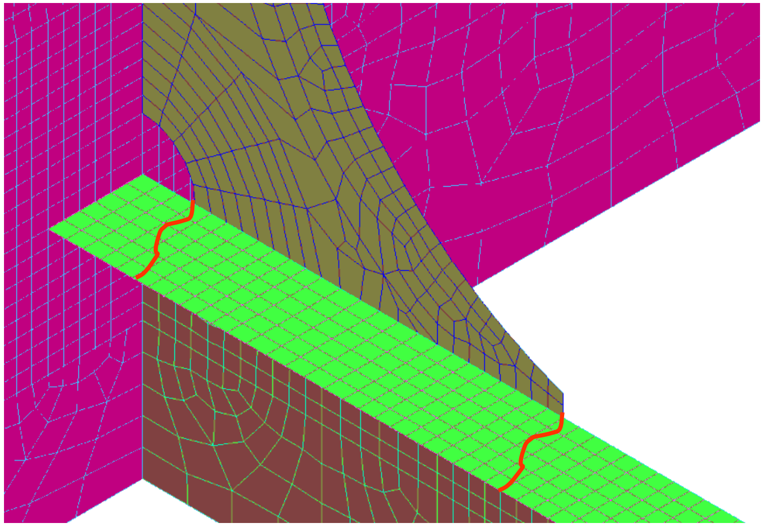
- Due to a huge number of welded joints in a vessel, an engineering sense to screen critical joints which are prone to fatigue crack is important.

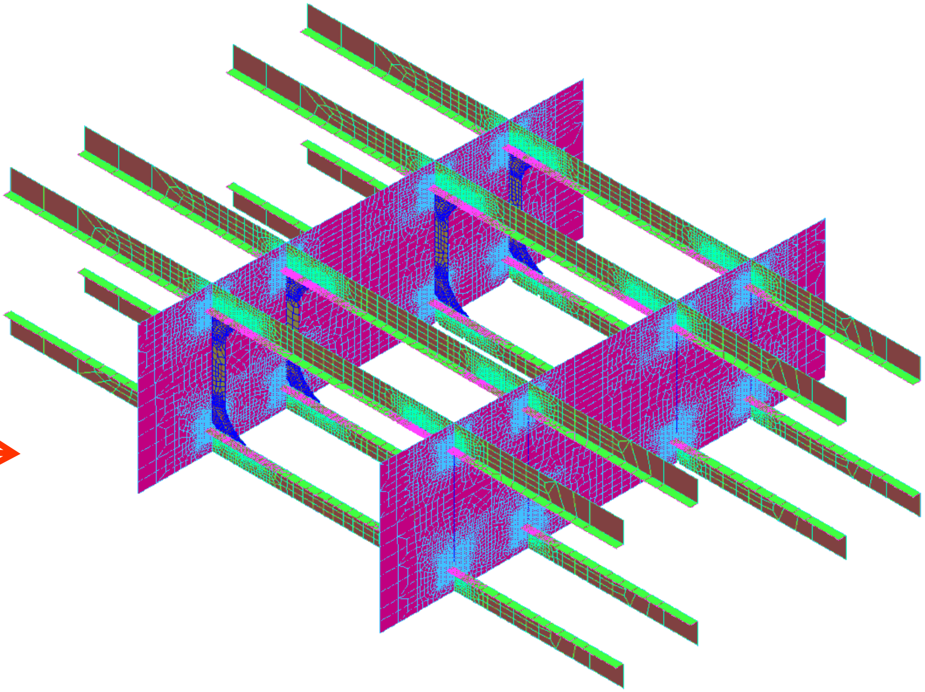
- Fatigue analysis using finite element method : construction of detailed fine mesh model and hot spot stress evaluation under random wave load are sophisticated work.

Design Regulations

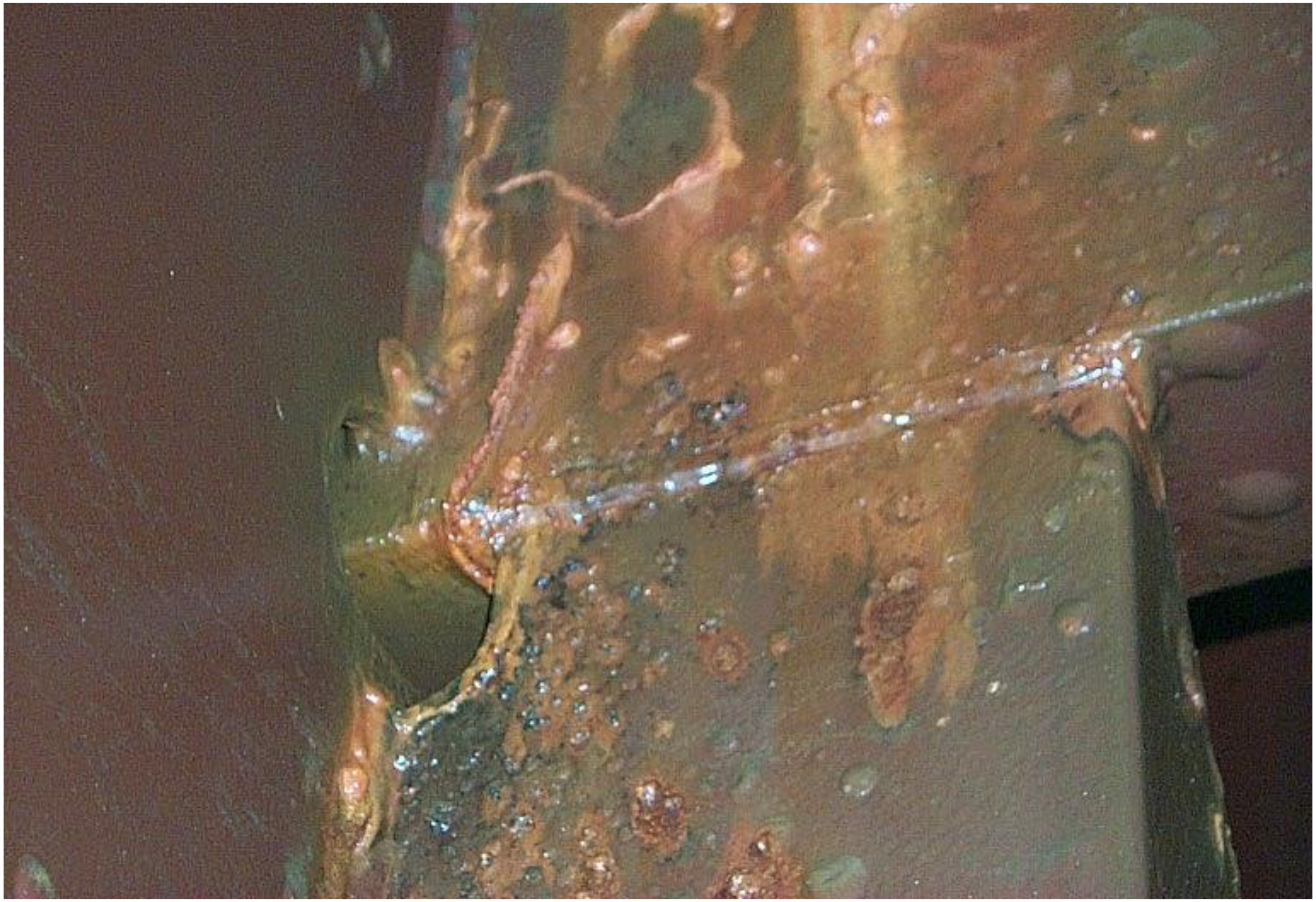
Fatigue Critical Area







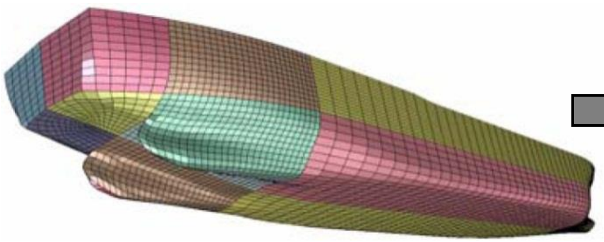
Fatigue Critical Area



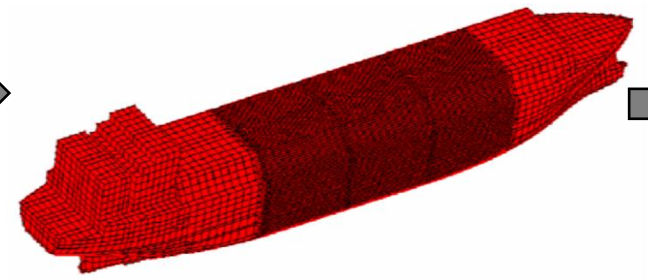
Fatigue Critical Area

Fatigue Critical Area

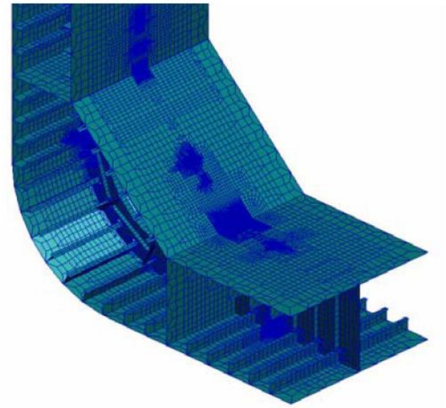
Fatigue strength assessment : LNG Carrier



Hydrodynamic Analysis



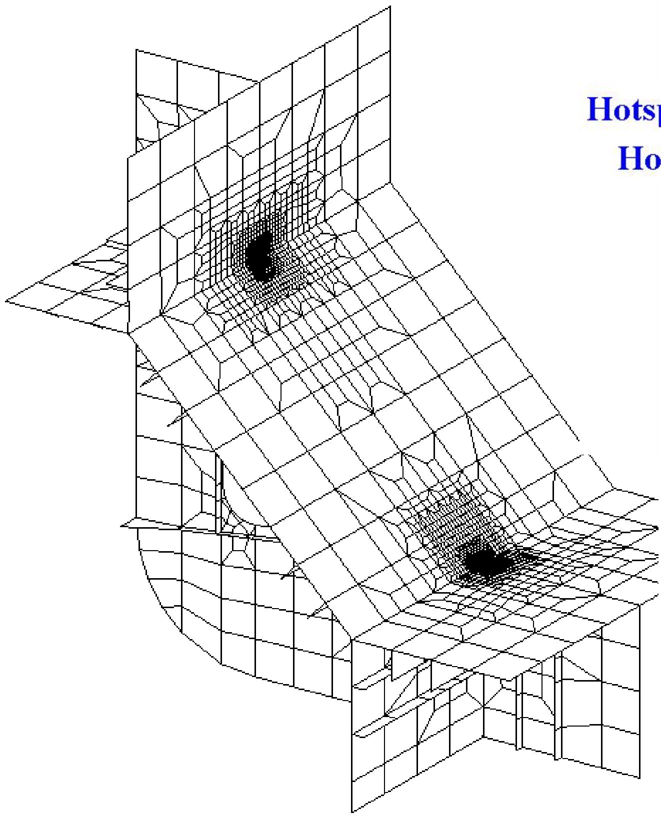
Full Stochastic FE analysis

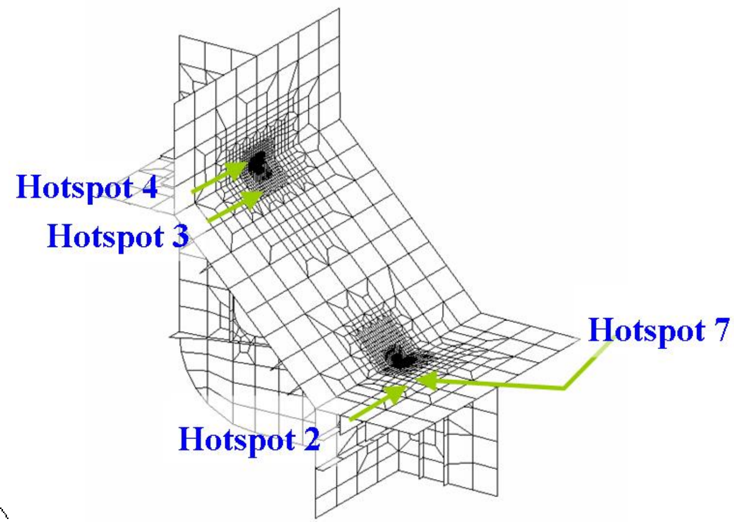


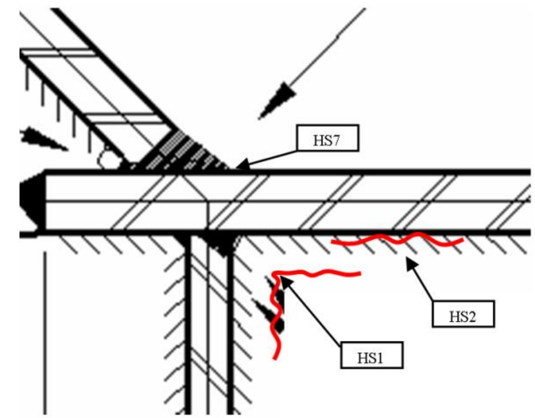
Local Zoom Model

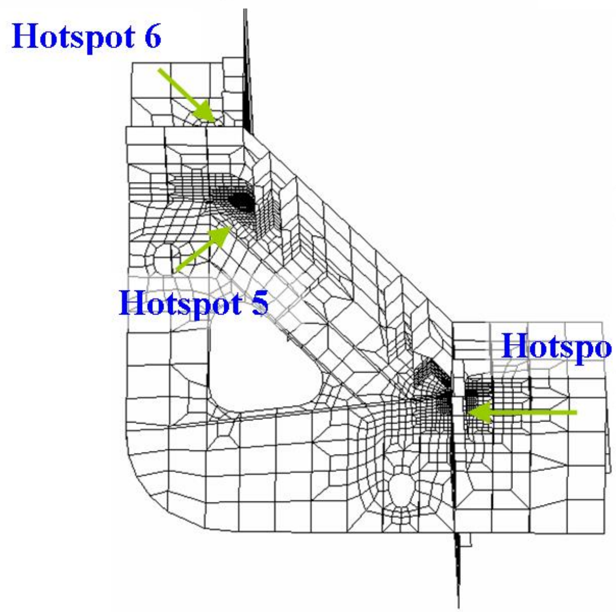
Fatigue strength assessment : LNG Carrier

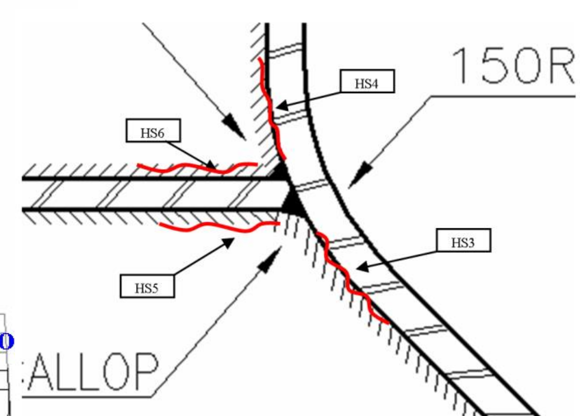
Hopper



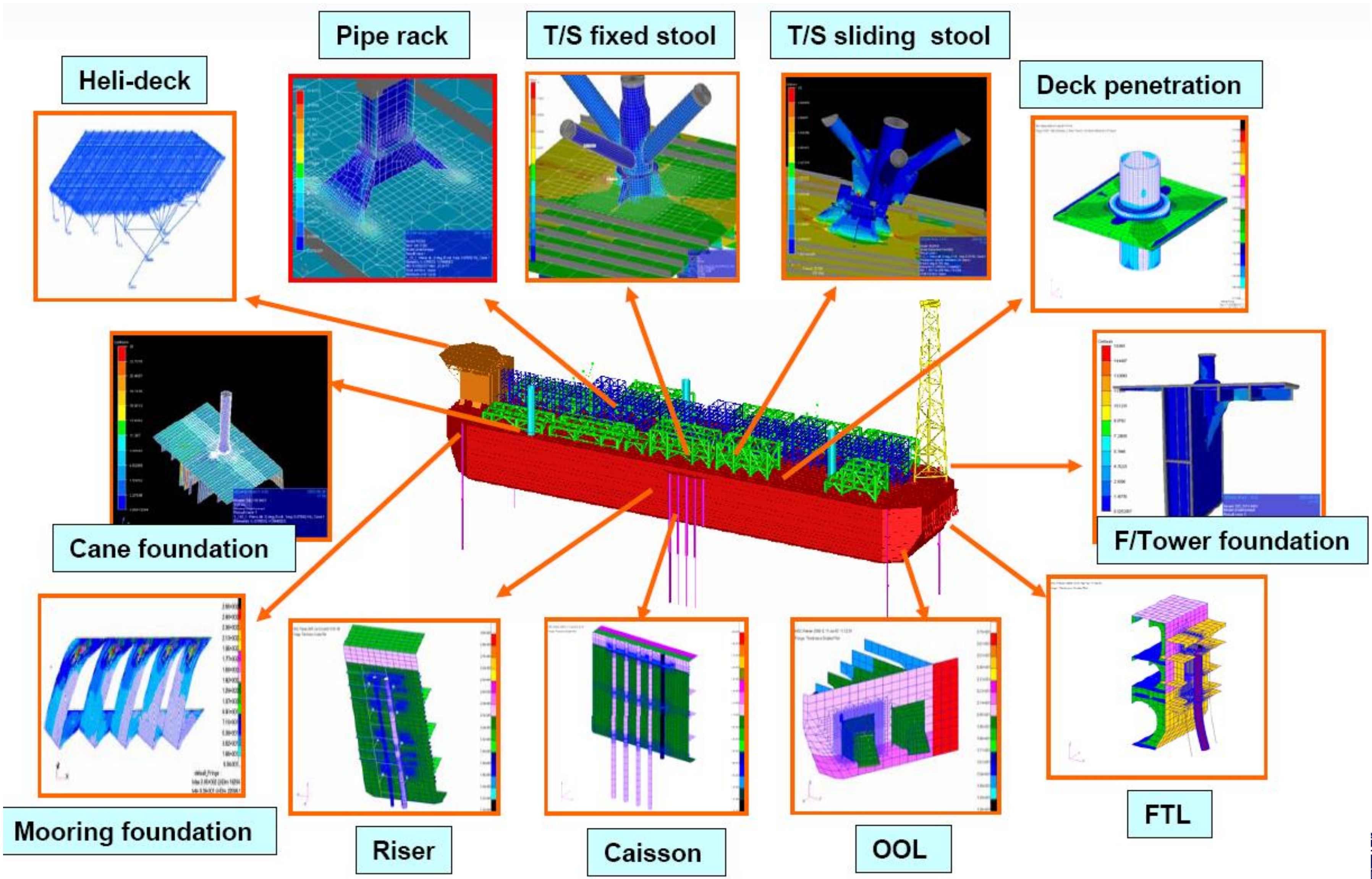








Fatigue strength assessment : FPSO



S-N Curve – DNV RP –C203 vs DNV 30.7 Ship

RECOMMENDED PRACTICE
DNV-RP-C203

FATIGUE DESIGN OF OFFSHORE STEEL STRUCTURES

APRIL 2010

DET NORSKE VERITAS

CLASSIFICATION NOTES
No. 30.7

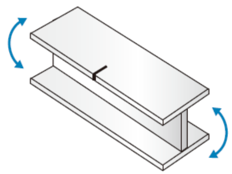
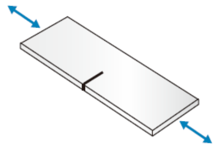
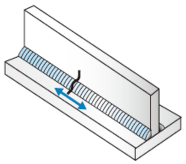
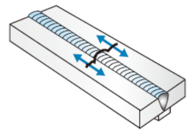
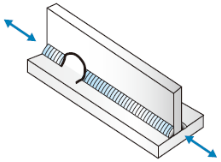
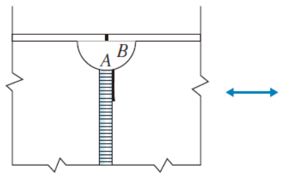
FATIGUE ASSESSMENT OF SHIP STRUCTURES

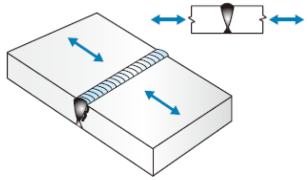
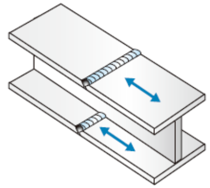
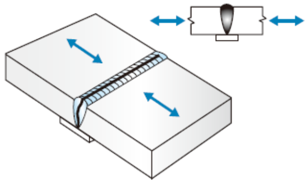
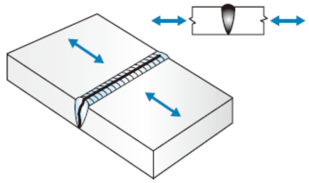
JUNE 2010

DET NORSKE VERITAS

Veritasveien 1, NO-1322 Høvik, Norway Tel.: +47 67 57 99 00 Fax: +47 67 57 99 11

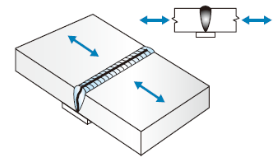
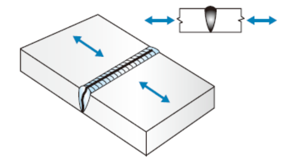
Nominal Stress based Approach : DNV RP –C203

Detail category	Constructional details	Detail category	Description
Type I : Non-welded details			
B1	 (I-1) Rolled sections	B2	 (I-2) Machine gas cut
		C	(I-3) Manually gas cut material
Type II : Continuous welds essentially parallel to the direction of applied stress			
C	 (II-1) Automatic welds carried out from both sides without start-stop position	C1	 (II-2) Automatic butt welds made from one side only, with a backing bar, but without start-stop positions
Type III : Intermittent welds and welds at cope holes			
F	 (III-1) Ends of continuous welds at cope holes	F	 (III-2) Cope hole and transverse butt weld

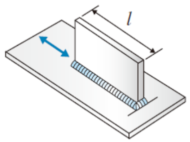
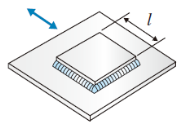
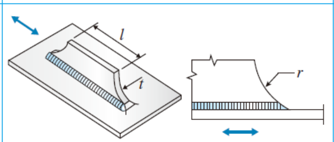
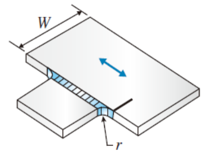
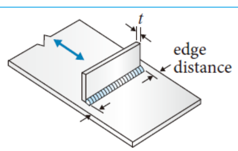
Type IV : Transverse butt welds, welded from both sides			
D	 (IV-1) Transverse splices in plates and flats	D	 (IV-2) Transverse splices in rolled sections or welded plate girders
Type V : Transverse butt welds, welded from one side			
F	 (V-1) Transverse butt weld on a temporary or a permanent backing strip without fillet welds	W3	 (V-2) Butt weld made from one side only and without backing strip

Nominal Stress based Approach : DNV RP –C203

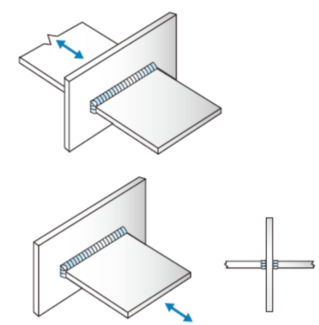
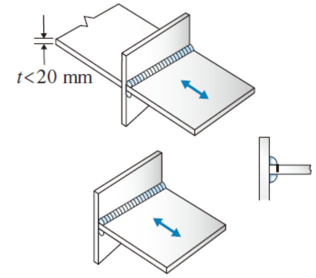
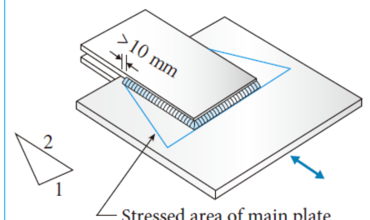
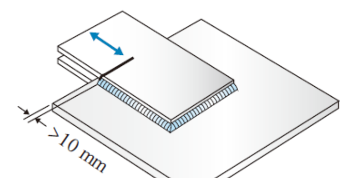
Type V : Transverse butt welds, welded from one side

F	 (V-1) Transverse butt weld on a temporary or a permanent backing strip without fillet welds	W3	 (V-2) Butt weld made from one side only and without backing strip

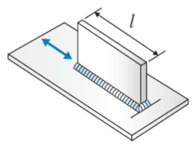
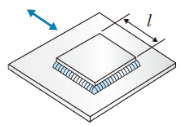
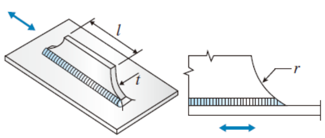
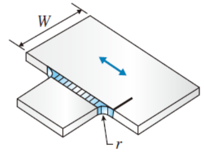
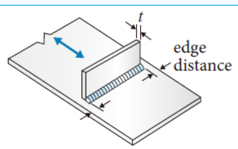
Type VI : Welded attachments on the surface or the edge of a stressed member

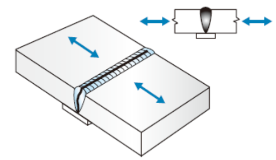
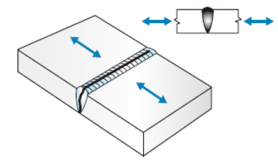
E	 (VI-1) Welded longitudinal Attachment $l \le 50$ mm	E	 (VI-2) Doubling plate welded to a plate. $l \le 50$ mm
F	$50 < l \le 120$ mm	F	$50 < l \le 120$ mm
F1	$120 < l \le 300$ mm	F1	$120 < l \le 300$ mm
F3	$l > 300$ mm	F3	$l > 300$ mm
E	 (VI-3)Longitudinal fillet welded gusset with radius transition to plate or tube $r > 150$ mm	E	 (VI-4) Gusset plate with a radius welded to the edge of a plate or beam flange $\frac{1}{3} \le \frac{r}{W}$, $r \ge 150$ mm
E	 (VI-5) Transverse attachments with edge distance ≥10 mm, $t \le 25$ mm	F	$\frac{1}{6} \le \frac{r}{W} < \frac{1}{3}$
		F1	$\frac{1}{10} \le \frac{r}{W} < \frac{1}{6}$
		F3	$\frac{1}{16} \le \frac{r}{W} < \frac{1}{10}$
F	$t \le 25$ mm	G	$\frac{1}{25} \le \frac{r}{W} < \frac{1}{16}$

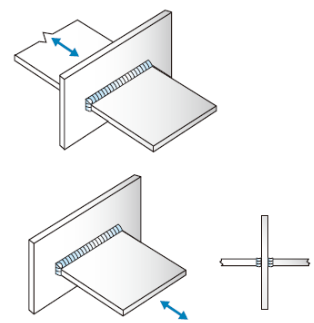
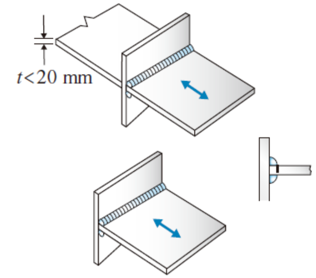
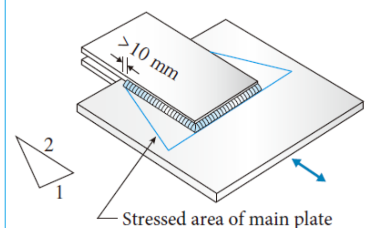
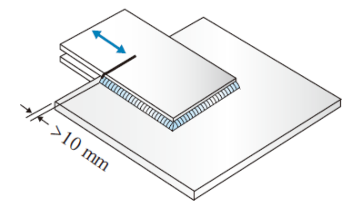
Type VII : Welded joints with load carrying welds

F	 (VII-1) Full penetration butt welded cruciform joint	W3	 (VII-2) Partial penetration tee butt joint or fillet welded joint and effective full penetration in tee-butt joint
F1	 (VII-3) Fillet welded overlap joint. Crack in main plate	W1	 (VII-4) Fillet welded overlap joint. Crack in overlapping plate

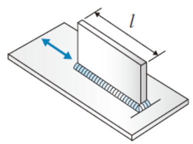
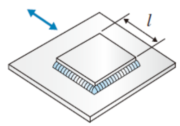
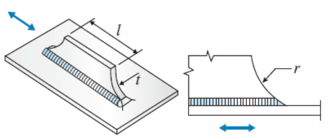
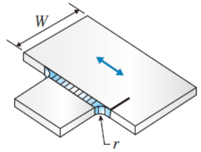
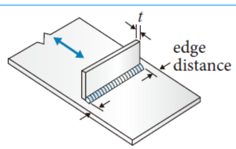
Nominal Stress based Approach : DNV RP –C203

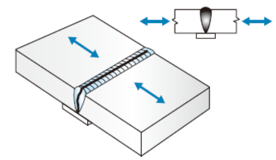
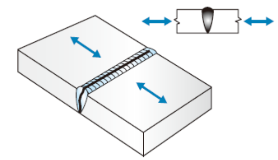
Type VI : Welded attachments on the surface or the edge of a stressed member			
E	 (VI-1) Welded longitudinal Attachment $l \le 50$ mm	E	 (VI-2) Doubling plate welded to a plate. $l \le 50$ mm
F	$50 < l \le 120$ mm	F	$50 < l \le 120$ mm
F1	$120 < l \le 300$ mm	F1	$120 < l \le 300$ mm
F3	$l > 300$ mm	F3	$l > 300$ mm
E	 (VI-3)Longitudinal fillet welded gusset with radius transition to plate or tube $r > 150$ mm	E	 (VI-4) Gusset plate with a radius welded to the edge of a plate or beam flange $\frac{1}{3} \le \frac{r}{W}$, $r \ge 150$ mm
E	 (VI-5) Transverse attachments with edge distance ≥10 mm, $t \le 25$ mm	F	$\frac{1}{6} \le \frac{r}{W} < \frac{1}{3}$
		F1	$\frac{1}{10} \le \frac{r}{W} < \frac{1}{6}$
		F3	$\frac{1}{16} \le \frac{r}{W} < \frac{1}{10}$
F	$t \le 25$ mm	G	$\frac{1}{25} \le \frac{r}{W} < \frac{1}{16}$

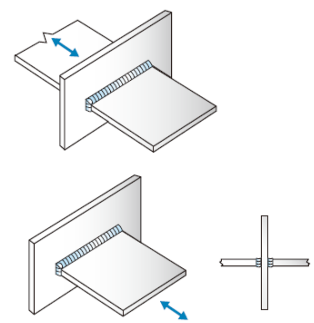
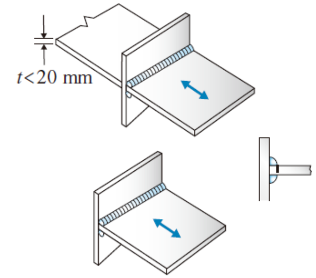
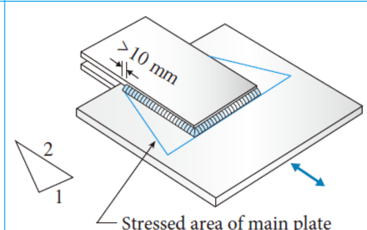
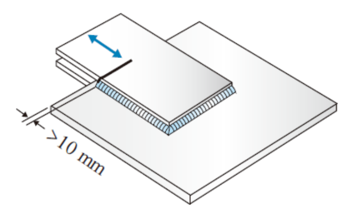
Type V : Transverse butt welds, welded from one side			
F	 (V-1) Transverse butt weld on a temporary or a permanent backing strip without fillet welds	W3	 (V-2) Butt weld made from one side only and without backing strip

Type VII : Welded joints with load carrying welds			
F	 (VII-1) Full penetration butt welded cruciform joint	W3	 (VII-2) Partial penetration tee butt joint or fillet welded joint and effective full penetration in tee-butt joint
F1	 (VII-3) Fillet welded overlap joint. Crack in main plate	W1	 (VII-4) Fillet welded overlap joint. Crack in overlapping plate

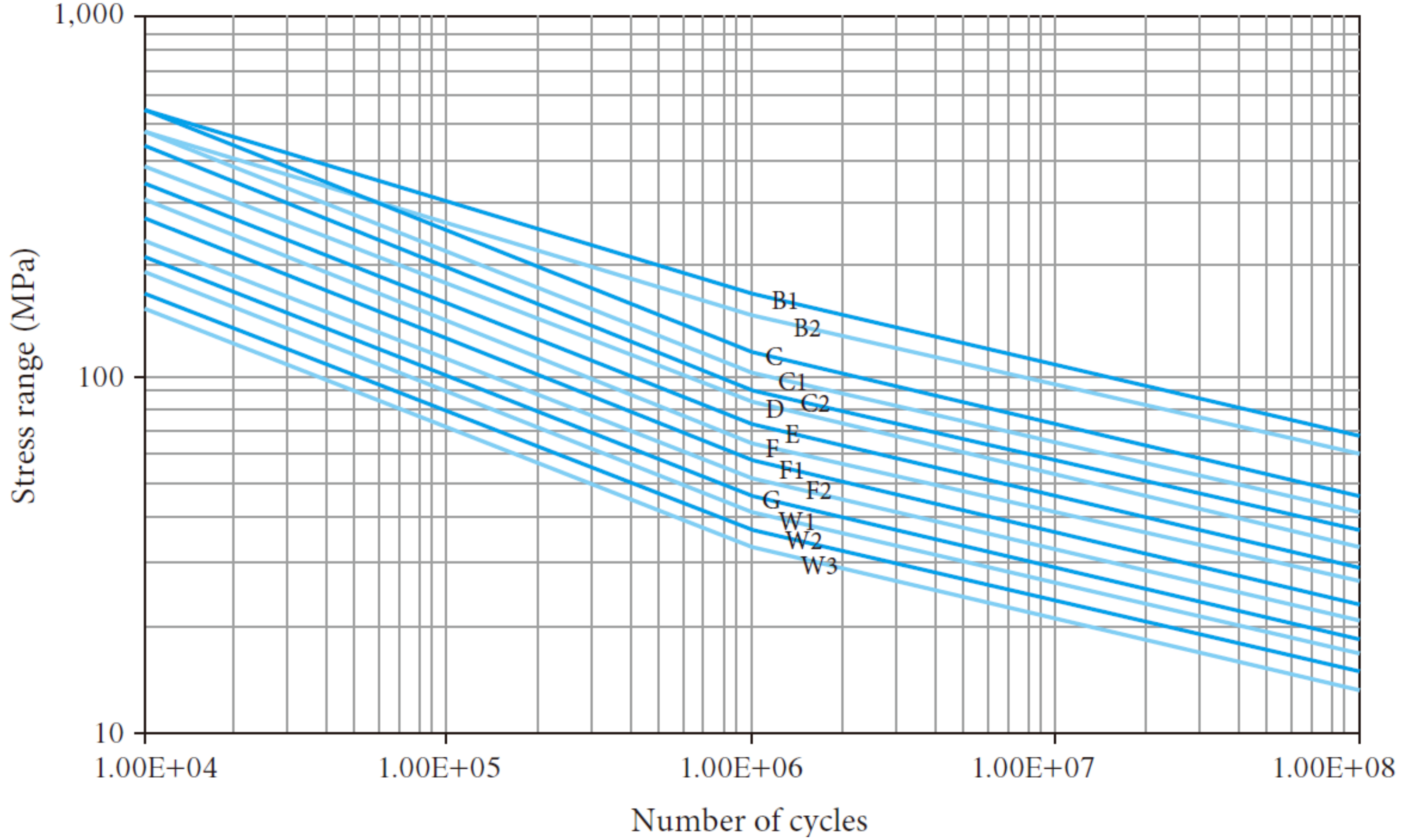
Nominal Stress based Approach : DNV RP –C203

Type VI : Welded attachments on the surface or the edge of a stressed member			
E	 (VI-1) Welded longitudinal Attachment $l \leq 50$ mm	E	 (VI-2) Doubling plate welded to a plate. $l \leq 50$ mm
F	$50 < l \leq 120$ mm	F	$50 < l \leq 120$ mm
F1	$120 < l \leq 300$ mm	F1	$120 < l \leq 300$ mm
F3	$l > 300$ mm	F3	$l > 300$ mm
E	 (VI-3)Longitudinal fillet welded gusset with radius transition to plate or tube $r > 150$ mm	E	 (VI-4) Gusset plate with a radius welded to the edge of a plate or beam flange $\frac{1}{3} \leq \frac{r}{W}$, $r \geq 150$ mm
E	 (VI-5) Transverse attachments with edge distance ≥10 mm, $t \leq 25$ mm	F	$\frac{1}{6} \leq \frac{r}{W} < \frac{1}{3}$
		F1	$\frac{1}{10} \leq \frac{r}{W} < \frac{1}{6}$
		F3	$\frac{1}{16} \leq \frac{r}{W} < \frac{1}{10}$
F	$t \leq 25$ mm	G	$\frac{1}{25} \leq \frac{r}{W} < \frac{1}{16}$

Type V : Transverse butt welds, welded from one side			
F	 (V-1) Transverse butt weld on a temporary or a permanent backing strip without fillet welds	W3	 (V-2) Butt weld made from one side only and without backing strip

Type VII : Welded joints with load carrying welds			
F	 (VII-1) Full penetration butt welded cruciform joint	W3	 (VII-2) Partial penetration tee butt joint or fillet welded joint and effective full penetration in tee-butt joint
F1	 (VII-3) Fillet welded overlap joint. Crack in main plate	W1	 (VII-4) Fillet welded overlap joint. Crack in overlapping plate

Nominal Stress based Approach : DNV RP –C203



Nominal stress approach – S-N Curve : DNV RP –C203

- S-N Curves in seawater with cathodic protection

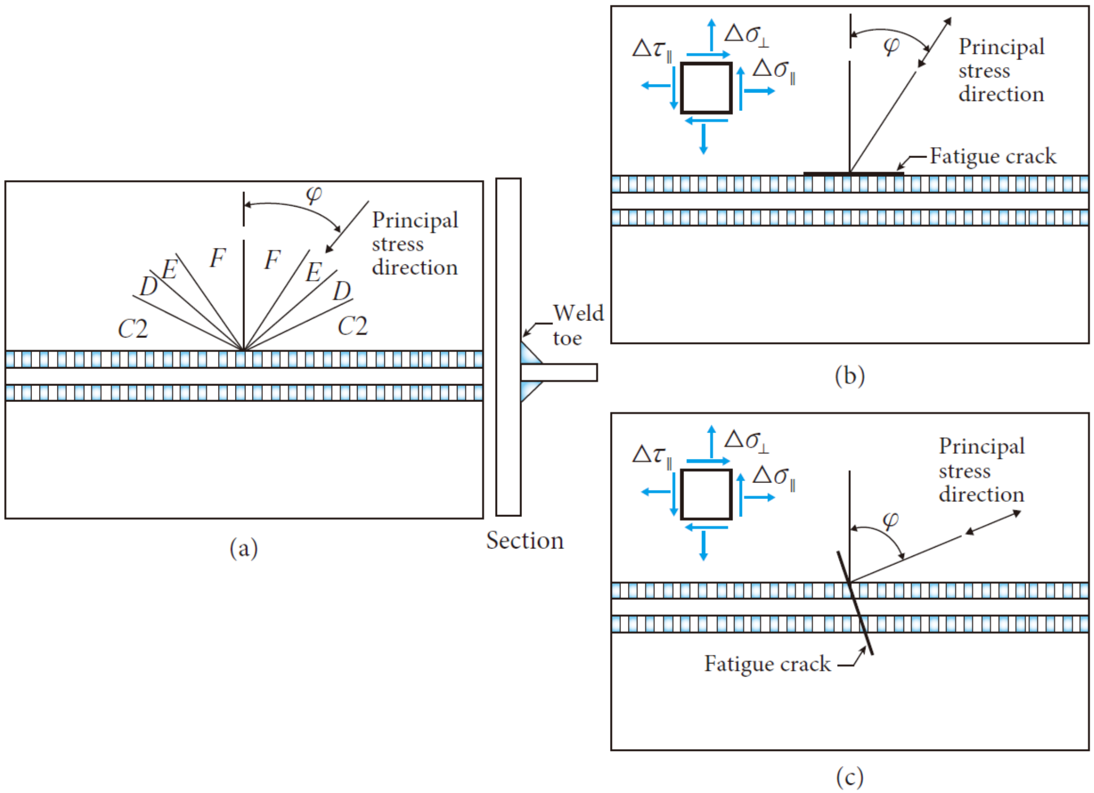
Table 2-2 S-N curves in seawater with cathodic protection

S-N curve	*$N \le 10^6$ cycles*		*$N > 10^6$ cycles*	*Fatigue limit at 10^7 cycles*)*	*Thickness exponent k*	*Stress concentration in the S-N detail as derived by the hot spot method*
	m_1	$\log \bar{a}_1$	$\log \bar{a}_2$ $m_2 = 5.0$			
B1	4.0	14.917	17.146	106.97	0	
B2	4.0	14.685	16.856	93.59	0	
C	3.0	12.192	16.320	73.10	0.15	
C1	3.0	12.049	16.081	65.50	0.15	
C2	3.0	11.901	15.835	58.48	0.15	
D	3.0	11.764	15.606	52.63	0.20	1.00
E	3.0	11.610	15.350	46.78	0.20	1.13
F	3.0	11.455	15.091	41.52	0.25	1.27
F1	3.0	11.299	14.832	36.84	0.25	1.43
F3	3.0	11.146	14.576	32.75	0.25	1.61
G	3.0	10.998	14.330	29.24	0.25	1.80
W1	3.0	10.861	14.101	26.32	0.25	2.00
W2	3.0	10.707	13.845	23.39	0.25	2.25
W3	3.0	10.570	13.617	21.05	0.25	2.50
T	3.0	11.764	15.606	52.63	0.25 for SCF ≤ 10.0 0.30 for SCF >10.0	1.00

*) see also 2.11

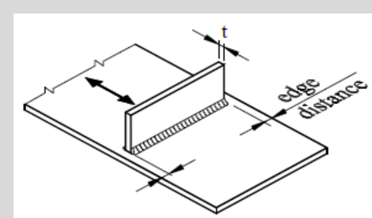
Nominal Stress Approach-Combined stress : DNV RP –C203

- Design Chart for fillet and partial penetration welds
- Depending on the angle between principal stress and welding line, different S-N curves are applied.

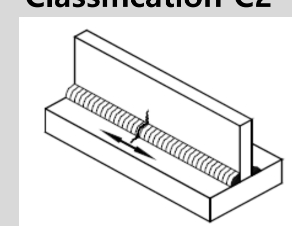


S-N curve depending on stress direction normal to the weld and crack propagation

Classification E or F

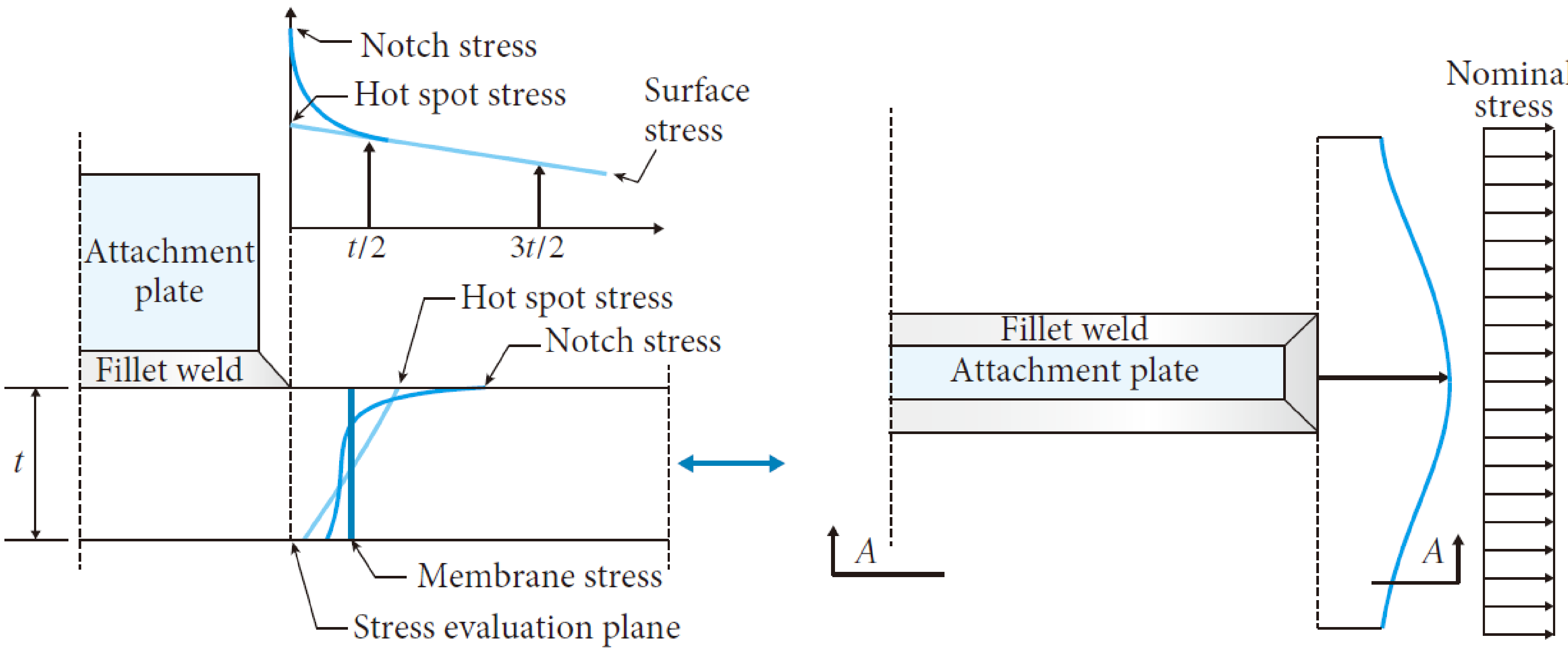


Classification C2



Hot Spot Stress Approach

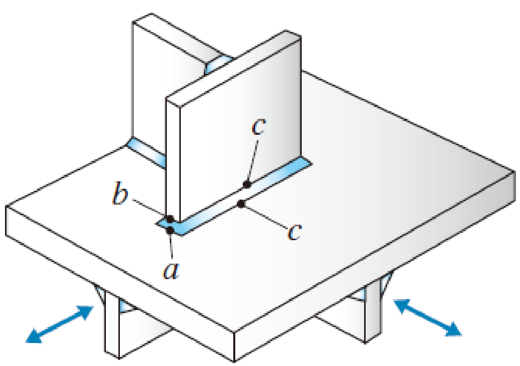
- Use of finite element analysis and difficulty in nominal stress → hot spot stress for fatigue life assessment.
- Linear interpolation from t/2 and 3t/2
- Or $\sigma_{\text{hot spot}} = K_g \cdot \sigma_{\text{nominal}}$, K_g : structural stress concentration factor.



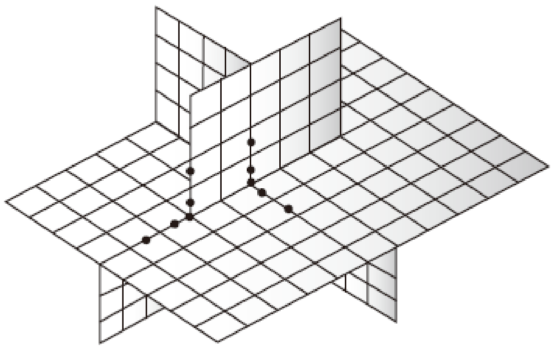
Schematic stress distribution at a hot spot

Hot Spot Stress Approach – Modeling

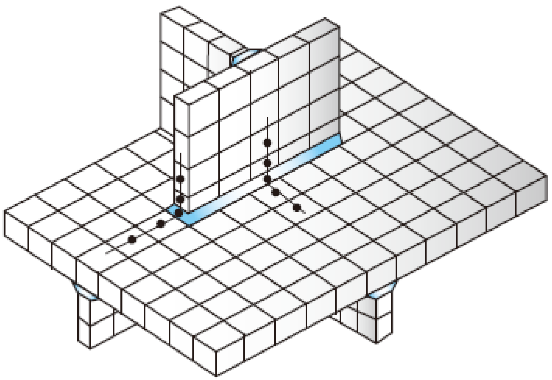
- Shell element modeling :
  - Modeling is easy but higher stress than the actual.
  - 8-noded element is more flexible than 4-noded → less stress
  - t x t mesh size
- Solid element modeling :
  - Modeling is quite difficult but close to the actual.
  - Fillet weld is modeled.
  - 20-noded element is more flexible than 8-noded, t x t mesh size



Different hot spots



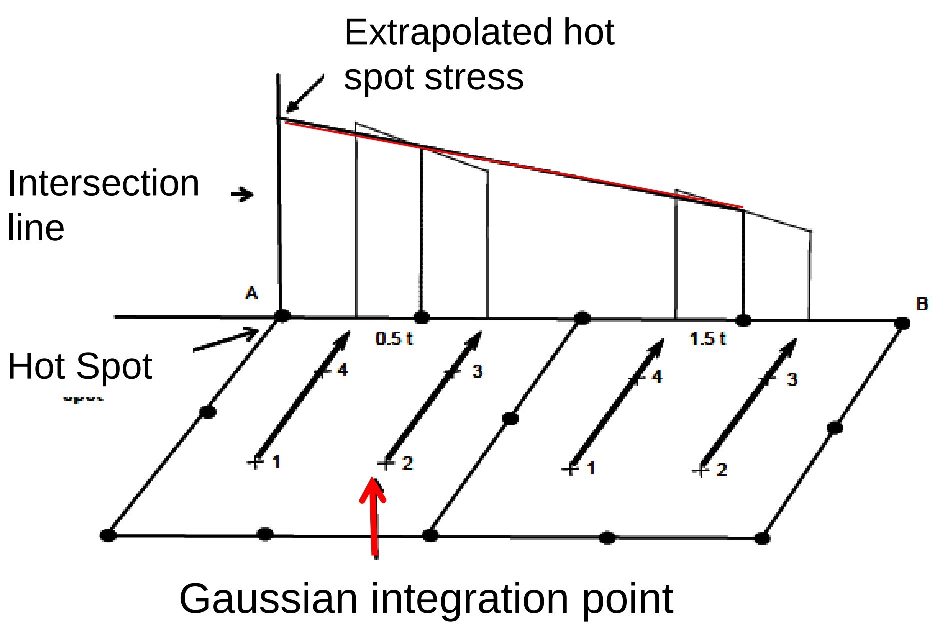
Extrapolation in FE Shell Element Model



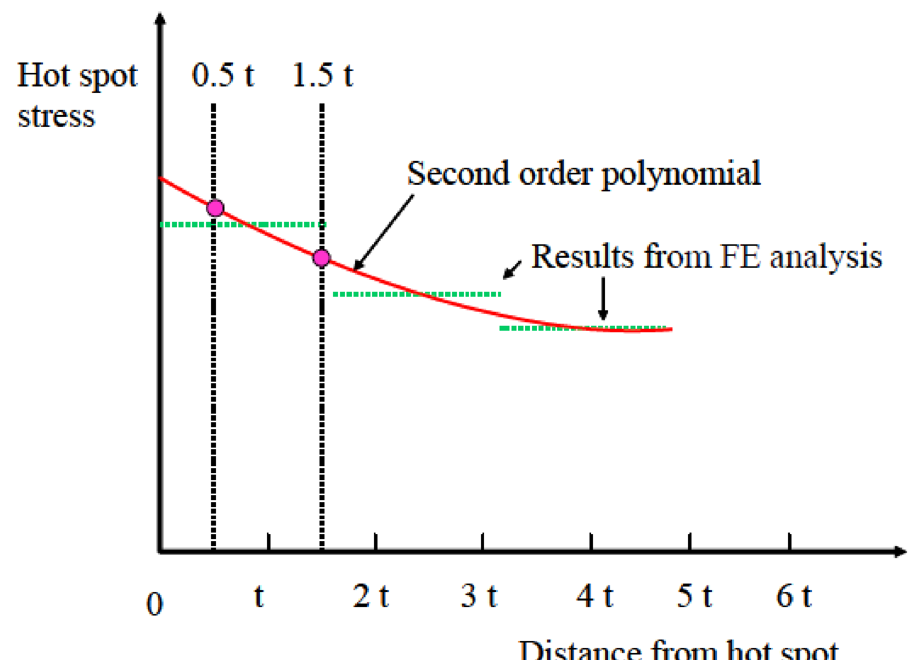
Extrapolation in FE Solid Element Model

Hot Spot Stress Approach–Hot Spot Stress

- Derivation of stress at read out points 0.5 t and 1.5 t
- If mesh size is t x t in shell element, top surface stress to be read at mid side nodes along A-B
- If solid element, stress to be extrapolated to the surface.
- If element size > t, fit a second order polynomial to the element stresses in the three first elements and derive 0.5t & 1.5t stresses.



Example of derivation of hot spot stress

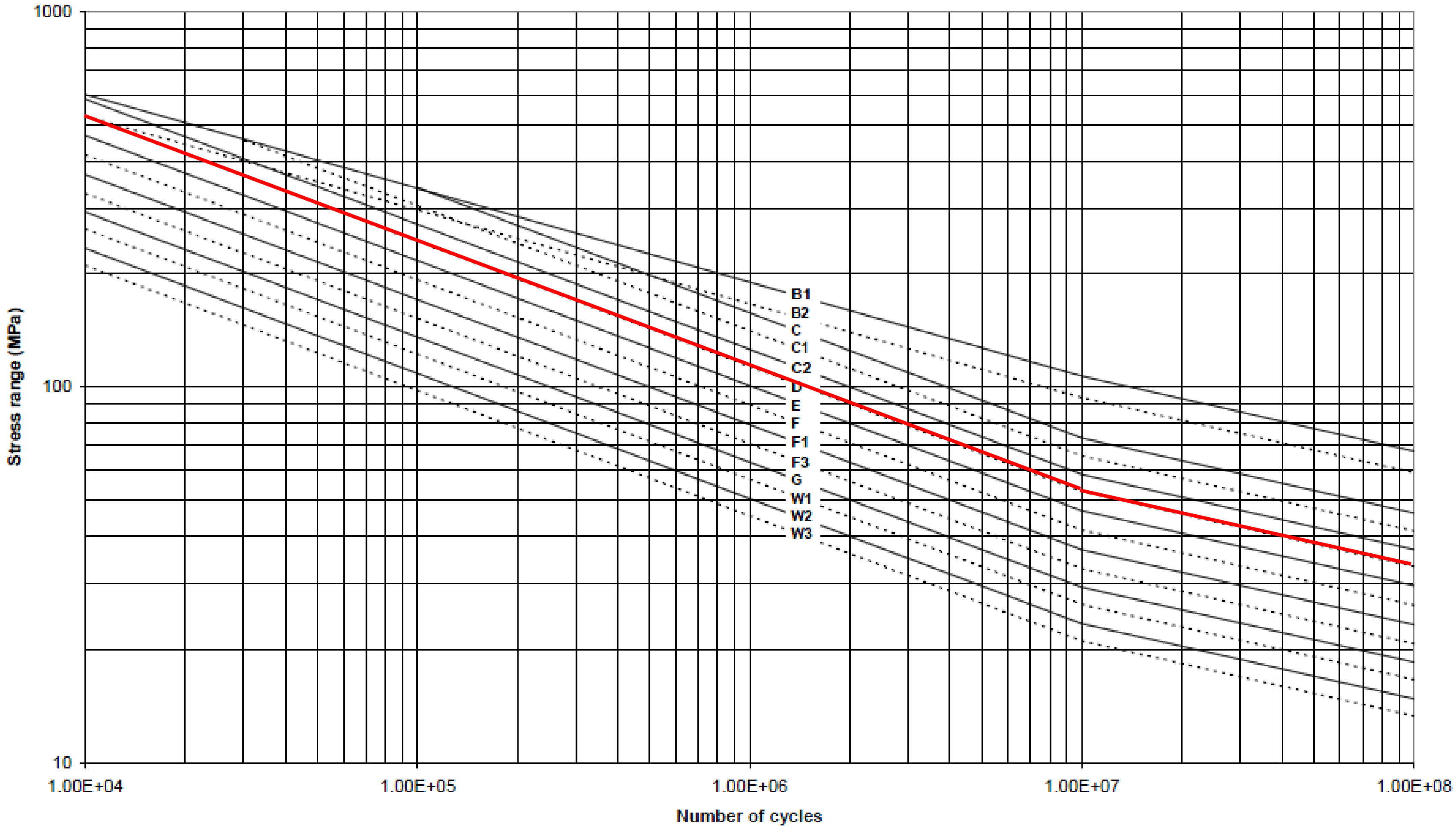


Derivation of hot spot stress for element size larger than t x t

Hot Spot Stress Approach – S-N Curve : DNV RP-C203

- D Curve in air

Stress range (MPa)



Number of cycles

S-N curves in air

Hot Spot Stress Approach – S-N Curve : DNV RP-C203

- Relationship between S-N Curves

S-N Curve	$N \le 10^7$ Cycles		$N > 10^7$ cycles $\log \overline{a_1}$ $m_2 = 5.0$	Fatigue limit at cycles	Thickness exponent k	Structural stress concentration embedded in the detail
	m_1	$\log \overline{a_1}$				
D	3.0	12.164	15.606	52.63	0.20	1.00
E	3.0	12.010	15.350	46.78	0.20	1.13
F	3.0	11.855	15.091	41.52	0.25	1.27
F1	3.0	11.699	14.832	36.84	0.25	1.43

D – curve, SCF=1.0

$$\log N = 12.164 - 3.0 \log \Delta\sigma$$

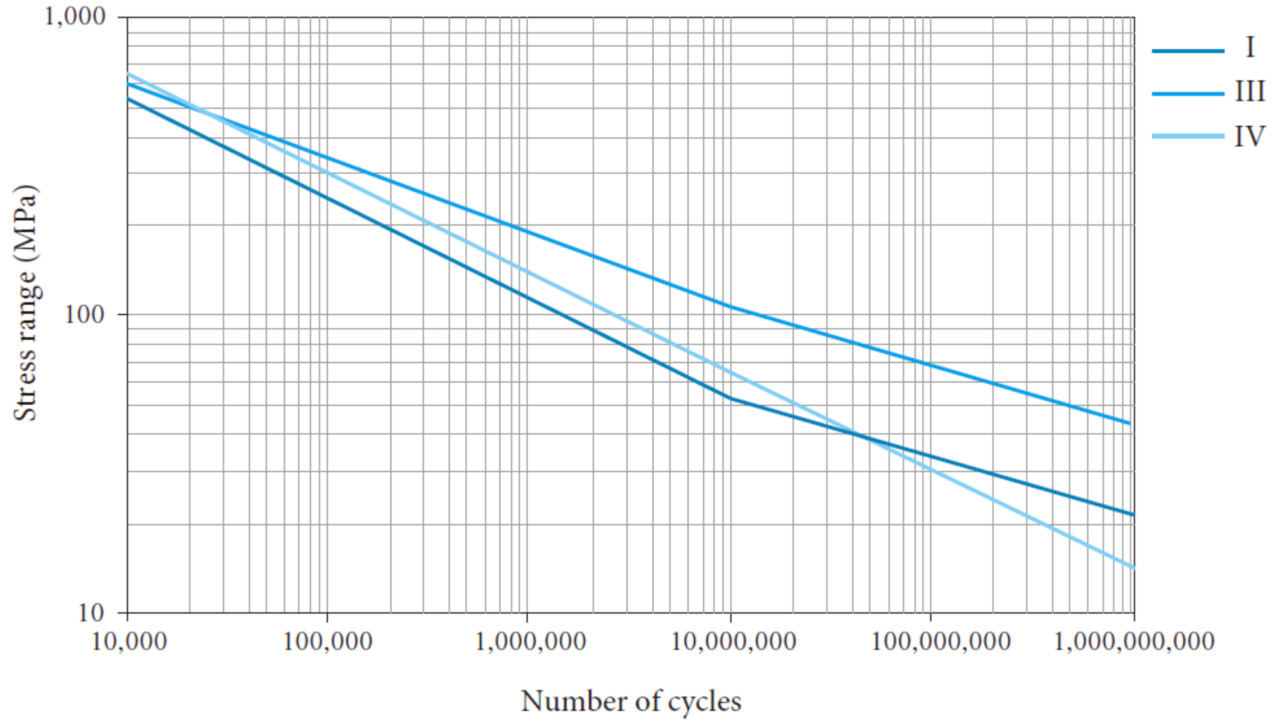
F1 curve, SCF=1.43

$$\log N = 12.164 - 3.0 \log(SCF(=1.43) \times \Delta\sigma)$$

$$= 11.699 - 3.0 \log \Delta\sigma$$

Hot Spot Stress Approach – S-N Curve : DNV CN.30.7

- Relationship between S-N Curves

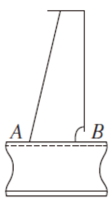
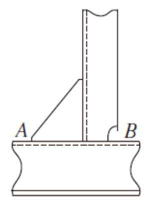
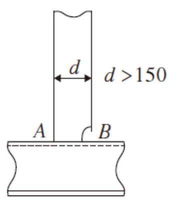
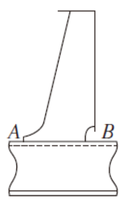
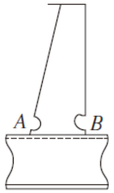
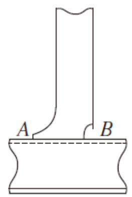
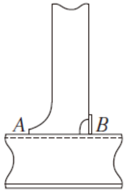
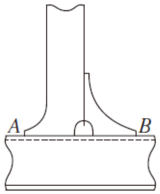


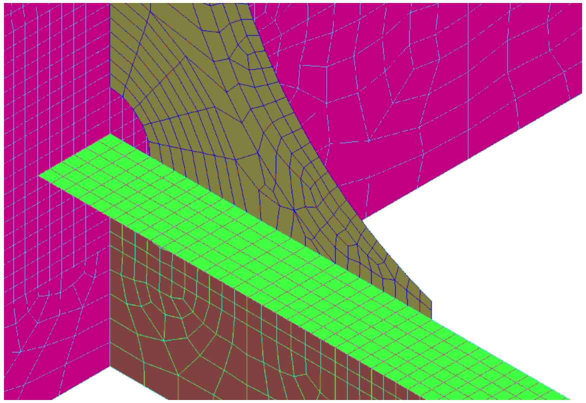
Environment	S-N Curve	Material	$\log \bar{a}$		m	
			$N \leq 10^7$	$N > 10^7$	$N \leq 10^7$	$N > 10^7$
Air or with cathodic protection	I	Welded joint	12.164	15.606	3.0	5.0
	III	Base Material	15.117	17.146	4.0	5.0
Corrosive environment	IV	Base Material	12.436		3.0	

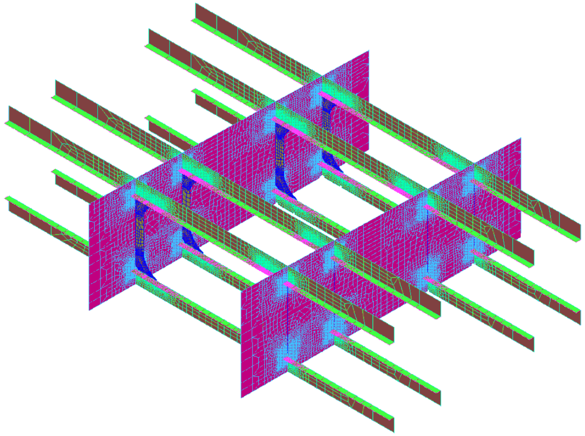
Hot Spot Stress Approach – S-N Curve : DNV CN.30.7

- Stiffener support is used to mitigate stress concentration at the intersection between stiffener flange and web section .

Type I : Stress concentration factors for stiffener supports

No	Geometry	Factors	No	Geometry	Factors
1		Point *A*	2		Point *A*
		K_g axial = 1.60 K_g bending = 1.80			K_g axial = 1.60 K_g bending = 1.80
		Point *B*			Point *B*
		K_g axial = 1.60 K_g bending = 1.80			K_g axial = 1.60 K_g bending = 1.73
3		Point *A*	4		Point *A*
		K_g axial = 1.40 K_g bending = 1.60			K_g axial = 1.47 K_g bending = 1.40
		Point *B*			Point *B*
		K_g axial = 1.60 K_g bending = 1.80			K_g axial = 1.40 K_g bending = 1.60
5		Point *A*	6		Point *A*
		K_g axial = 1.47 K_g bending = 1.40			K_g axial = 1.27 K_g bending = 1.27
		Point *B*			Point *B*
		K_g axial = 1.47 K_g bending = 1.60			K_g axial = 1.40 K_g bending = 1.73
7		Point *A*	8		Point *A*
		K_g axial = 1.27 K_g bending = 1.20			$K_g$axial = 1.27 K_g bending = 1.27
		Point *B*			Point *B*
		K_g axial = 1.47 K_g bending = 1.73			K_g axial = 1.27 K_g bending = 1.27

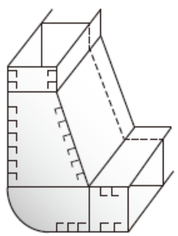
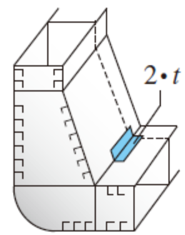
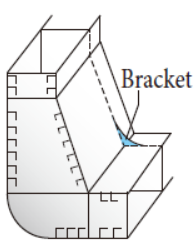




Hot Spot Stress Approach – S-N Curve : DNV CN.30.7

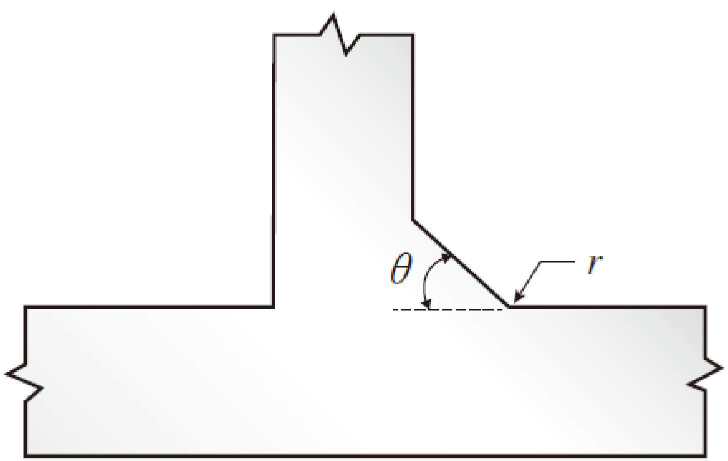
- Fatigue crack at lower hopper knuckles is caused by external dynamic pressure and internal dynamic pressure of ballast tank or cargo tank.
- Fatigue crack initiates on inner bottom plate and propagates along the welding line.

Type II : Stress concentration factors for lower hopper knuckles

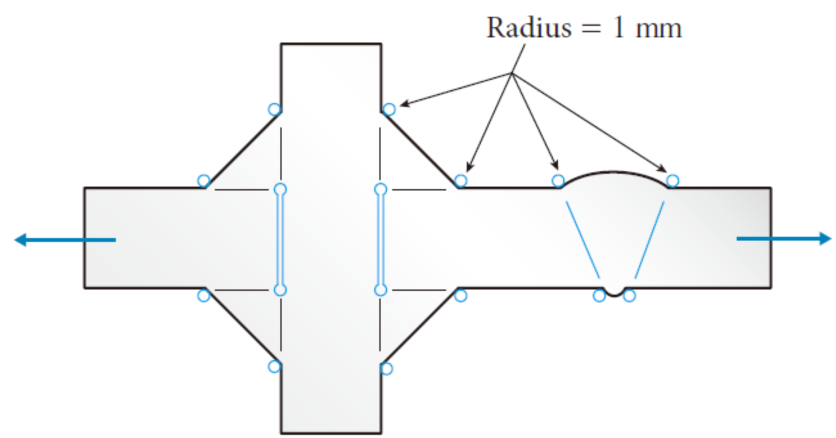
No	Geometry	Factors	No	Geometry	Factors
1		$K_g = 7.0$	2		Insert plate of 2.0 times the thickness normally required. Insert plates should be provided in inner bottom, hopper tank top, and web frame. $K_g = 4.5$
3		Bracket inside cargo tank. The bracket should extend approximately to the first longitudinals and the bracket toe should have a soft nose design. $K_g = 2.5$			

Notch Stress Approach

- Effective notch stress is the total stress at the root of a notch, obtained assuming linear-elastic material behaviour.
- For structural steels an effective notch root radius of r = 1.0 mm has been verified to give consistent results.
- The method is restricted to welded joints which are expected to fail from the weld toe or weld root and it is limited to thicknesses t ≥5 mm.
- Flank angles of 30° for butt welds and 45° for fillet welds are suggested.
- After certain post weld improvement procedures such as grinding, the actual geometrical radius may be used in the effective notch stress analysis.



Frank angle and notch radius



Analysis of effective notch stress

Notch Stress Approach

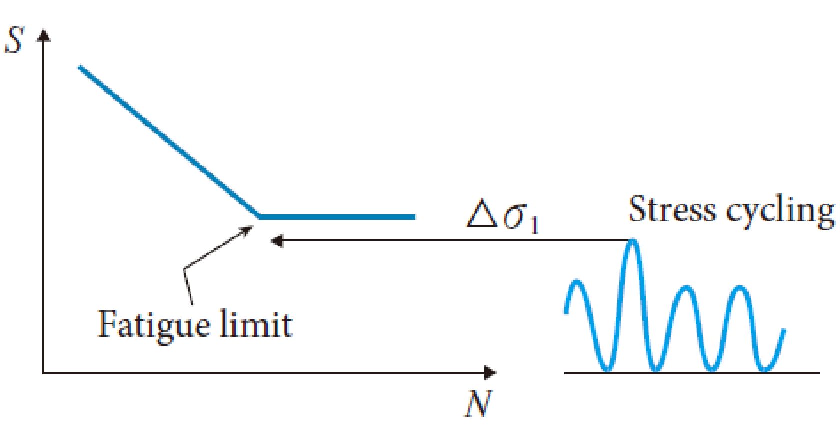
- Calculation of effective notch stress by the finite element method : a fine element mesh is used around the notch region.
- This maximum surface stress directly from the nodal stress calculated at the surface or from extrapolation of element stresses to the surface.
- The effective notch stress to be used together with the recommended S-N curve is the maximum calculated surface stress in the notch.

Environment	$\log \overline{a}$	
Air	$N \leq 10^7$ cycles $m_1 = 3.0$	$N > 10^7$ cycles $m_2 = 5.0$
	13.358	17.596
Seawater with cathodic protection	$N \leq 10^6$ cycles $m_1 = 3.0$	$N > 10^6$ cycles $m_2 = 5.0$
	12.958	17.596
Seawater with free corrosion	For all N $\log \overline{a} = 12.880$ and $m_1 = 3.0$	

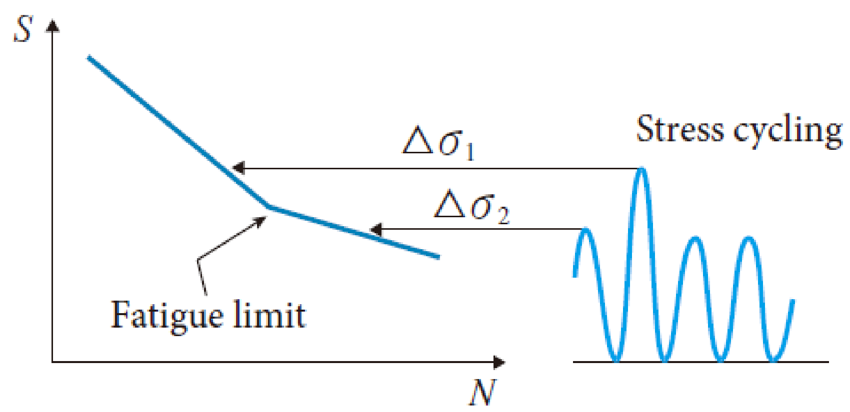
Notch stress based S-N 선도

Fatigue Limit

- Fatigue limit is the maximum stress range below which the fatigue strength is infinite.
- Permitted in design only when all stress range blocks are below the fatigue limit.
- Otherwise, the slop is reduced from (-1/3) to (-1/5).



(a)



(b)

Stress cycling where further fatigue assessment can be omitted

Stress cycling where a detailed fatigue assessment is required

Mean Stress Effect : DNV RP –C203

❖ Mean stress influence for non welded structure

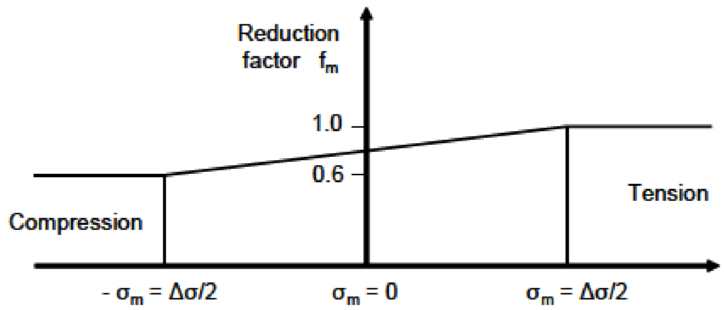
- For fatigue analysis of regions in the base material not significantly affected by residual stresses due to welding, the stress range may be reduced if part of the stress cycle is in compression.

$$f_m = \frac{\sigma_t + 0.6|\sigma_c|}{\sigma_t + |\sigma_c|}$$

$$\sigma_t = \text{tension stress} = \max\left(\sigma_{static} + \frac{\Delta\sigma}{2}, 0\right)$$

$$\sigma_c = \text{compressive stress} = \min\left(0, \sigma_{static} - \frac{\Delta\sigma}{2}\right)$$

$$\log N = \log \bar{a} - m \log(f_m \Delta\sigma)$$



Stress Range Reduction Factor (f_m)

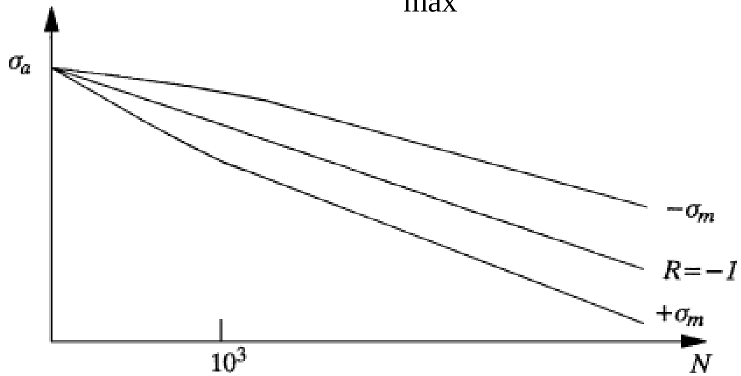
- The calculated stress range may be multiplied with the reduction factor f_m before entering the S-N curve

❖ For welded joint

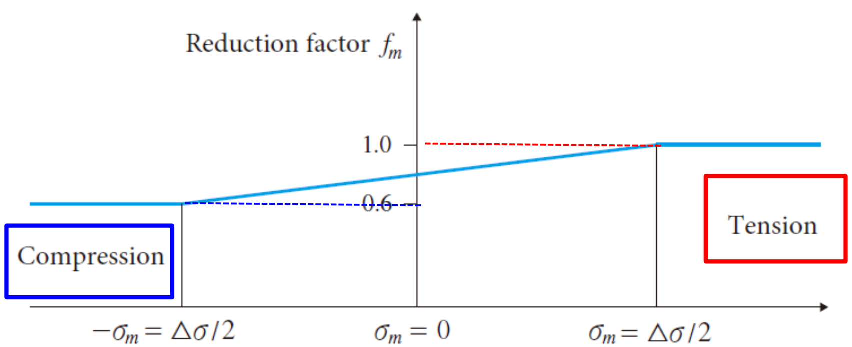
- Mean stress effect is neglected for fatigue assessment of welded connections due to tensile residual stress around welded joint.

Mean Stress Effect : DNV RP –C203

$$Load\ Ratio\ R = \frac{\sigma_{min}}{\sigma_{max}}$$



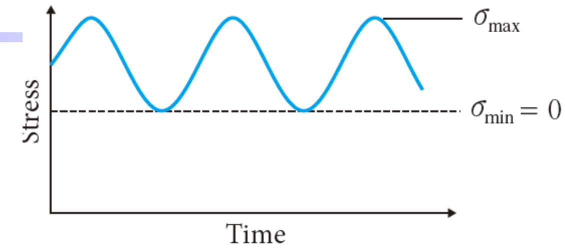
Mean stress effect on S-N Curve



$$\sigma_m = \frac{\sigma_{max} + \sigma_{min}}{2} \qquad \text{fatigue life} \propto \frac{1}{(f_m \Delta\sigma)^3}$$

Stress Range Reduction Factor (f_m)

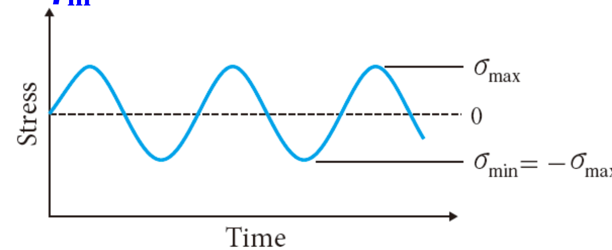
Zero to max



(b) 인장 교변응력

f_m =1.0

Fully reversed
R=-1

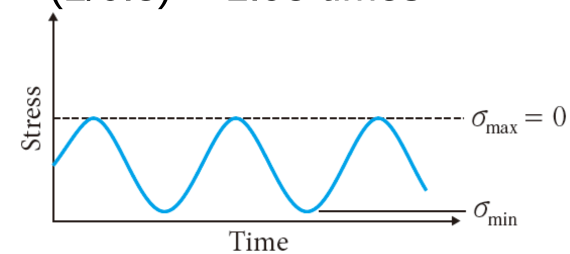


(a) 완전 교변응력

f_m =0.8

Fatigue life is increased by $(1/0.8)^3$= 1.95 times

Zero to min



(c) 압축 교변응력

f_m =0.6

Fatigue life is increased by $(1/0.6)^3$= 4.63 times

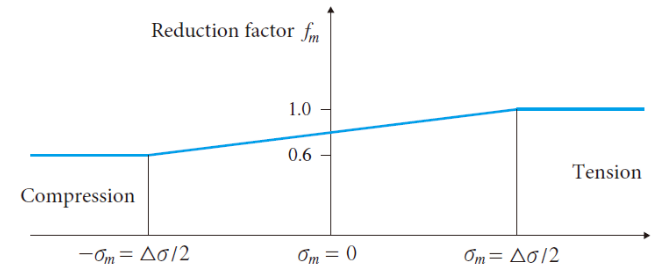
Mean Stress Effect : DNV 30.7 Ship Rule

❖ For Base material

$$f_m = \frac{\sigma_t + 0.6|\sigma_c|}{\sigma_t + |\sigma_c|}$$

$$\sigma_t = \text{tension stress} = \max\left(\sigma_{static} + \frac{\Delta\sigma}{2}, 0\right)$$

$$\sigma_c = \text{compressive stress} = \min\left(0, \sigma_{static} - \frac{\Delta\sigma}{2}\right)$$



Stress Range Reduction Factor (f_m)

- The calculated stress range may be multiplied with the reduction factor f_m before entering the S-N curve

❖ For welded joint

- A hot spot region is subjected to tensional residual stress.
- However, residual stresses due to welding and construction are reduced over time as the ship is subjected to external loading.
- The mean stress effect is applicable. (Slightly larger than Base material)

$$f_m = \frac{\sigma_t + 0.7|\sigma_c|}{\sigma_t + |\sigma_c|}$$

Thickness Effect

- Basic S-N curve
  Tested plate thickness =22mm (DNV 30.7 Ship Rule)
  Tested plate thickness =25mm (DNV RP-C203 Offshore Rule)

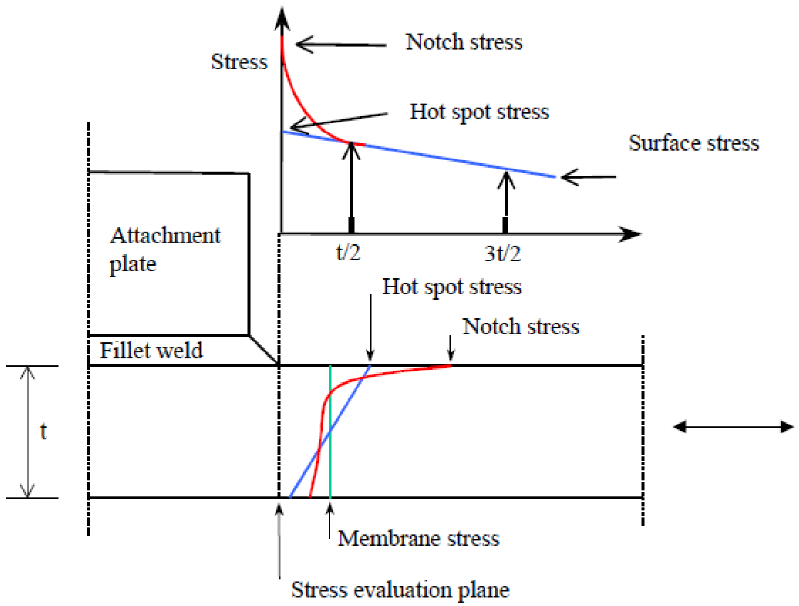
- Surface stress on the weld bead is increasing exponentially
- If plate thickness is beyond the reference thickness , modification of S-N curve is needed.

$$\log N = \log \bar{a} - m \log \Delta\sigma \left(\frac{t}{t_{ref}} \right)^k$$

- ✓ t : plate thickness
- ✓ k : thickness exponent

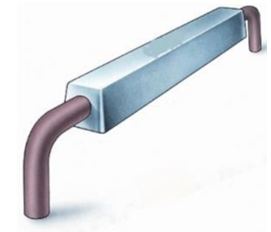
  DNV RP-C203 : k =0~0.3

  DNV CN 30.7 : k=0.25



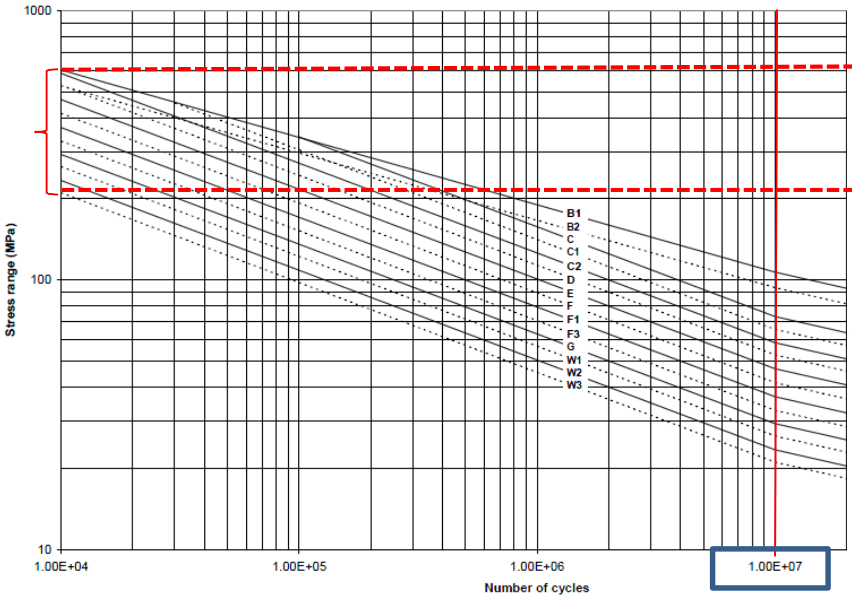
Stress distribution through thickness

Effect of corrosive environment : DNV RP –C203

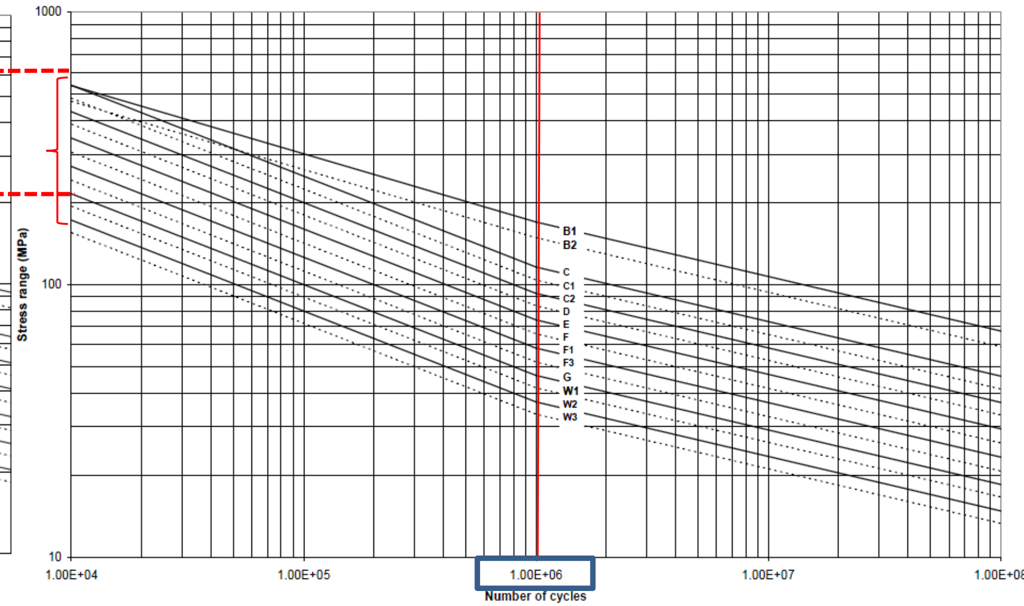


- Decrease in Fatigue Strength in Corrosive environment.
- Cathodic protection : to control the corrosion of a metal surface by connecting the metal to be protected with another more easily corroded "sacrificial metal" to act as the anode of the electrochemical cell.

S-N curves in air



S-N curves in seawater with cathodic protection



Nominal Stress based Approach : DNV RP –C203

- S-N Curves in air

Table 2-1 S-N curves in air

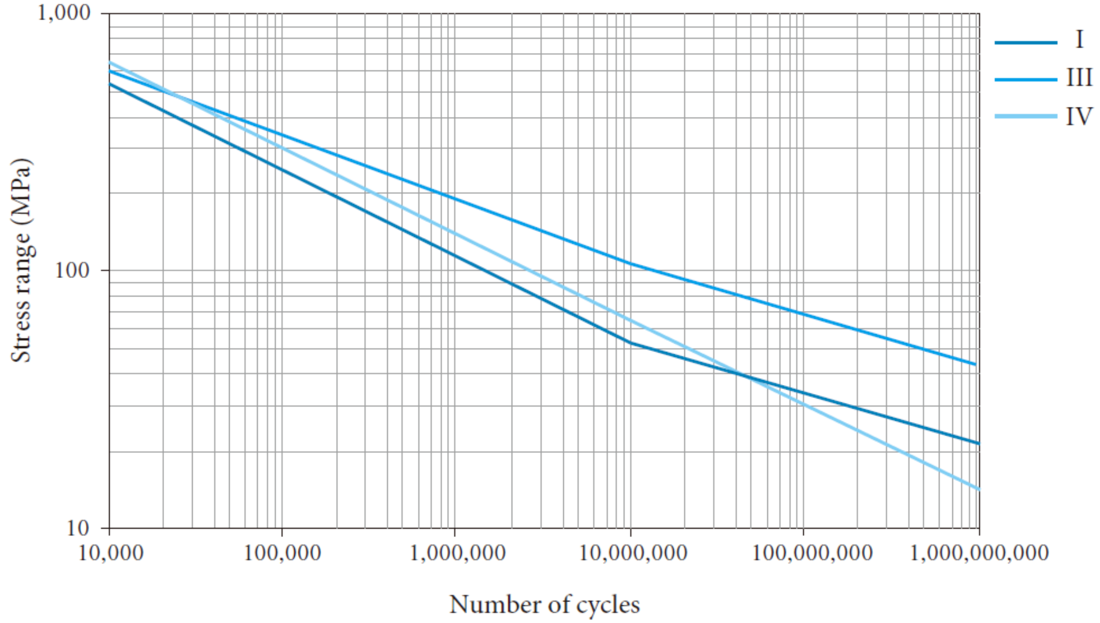
S-N curve	*N ≤ 10^7 cycles*		*N > 10^7 cycles* $\log \bar{a}_2$	*Fatigue limit at 10^7 cycles *)*	*Thickness exponent k*	*Structural stress concentration embedded in the detail (S-N class), ref. also equation (2.3.2)*
	m_1	$\log \bar{a}_1$	$m_2 = 5.0$			
B1	4.0	15.117	17.146	106.97	0	
B2	4.0	14.885	16.856	93.59	0	
C	3.0	12.592	16.320	73.10	0.15	
C1	3.0	12.449	16.081	65.50	0.15	
C2	3.0	12.301	15.835	58.48	0.15	
D	3.0	12.164	15.606	52.63	0.20	1.00
E	3.0	12.010	15.350	46.78	0.20	1.13
F	3.0	11.855	15.091	41.52	0.25	1.27
F1	3.0	11.699	14.832	36.84	0.25	1.43
F3	3.0	11.546	14.576	32.75	0.25	1.61
G	3.0	11.398	14.330	29.24	0.25	1.80
W1	3.0	11.261	14.101	26.32	0.25	2.00
W2	3.0	11.107	13.845	23.39	0.25	2.25
W3	3.0	10.970	13.617	21.05	0.25	2.50
T	3.0	12.164	15.606	52.63	0.25 for SCF ≤ 10.0 0.30 for SCF >10.0	1.00

D	3.0	11.764	15.606	52.63	0.20	1.00

S-N Curves in seawater with cathodic protection

Effect of corrosive environment : DNV CN 30.7

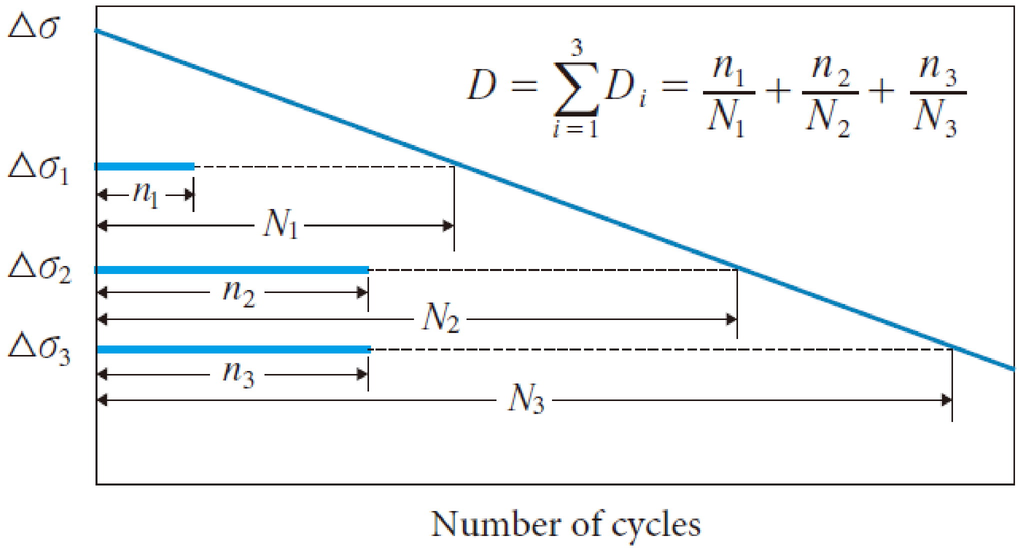
- Ship rule is not conservative.
- SN-Curve for air = SN-Curve for cathodic protection.



Environment	S-N Curve	Material	$\log \bar{a}$		m	
			$N \leq 10^7$	$N > 10^7$	$N \leq 10^7$	$N > 10^7$
Air or with cathodic protection	I	Welded joint	12.164	15.606	3.0	5.0
	III	Base Material	15.117	17.146	4.0	5.0
Corrosive environment	IV	Base Material	12.436		3.0	

Palmgren-Miner rule

- EX) During 10 years, $\Delta\sigma_1$: n_1 cycles
  $\Delta\sigma_2$: n_2 cycles
  $\Delta\sigma_3$: n_3 cycles
- Damage ratio $D = \sum_{i=1}^{k} \frac{n_i}{N_i}$



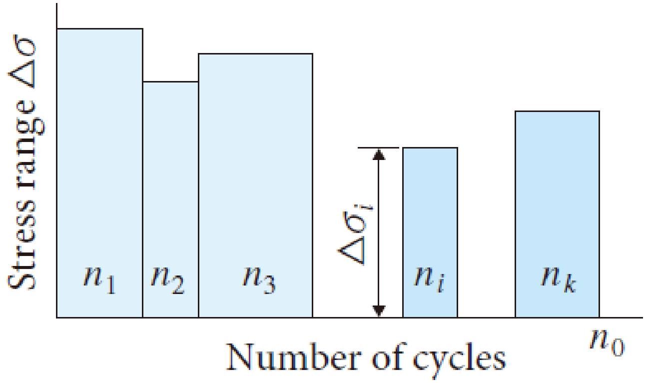
$D = n_1/N_1 + n_2/N_2 + n_3/N_3$

Fatigue Life= $(n_1 + n_2 + n_3)/D$ = 10 years/D

Palmgren-Miner rule

- Palmgren-Miner Rule

$$D = \sum_{i=1}^{k} D_i = \sum_{i=1}^{k} \frac{n_i}{N_i} = \frac{n_1}{N_1} + \frac{n_2}{N_2} + \cdots + \frac{n_k}{N_k}$$



Where,

k= number of stress blocks

n_i = number of stress cycles in stress block with constant stress range

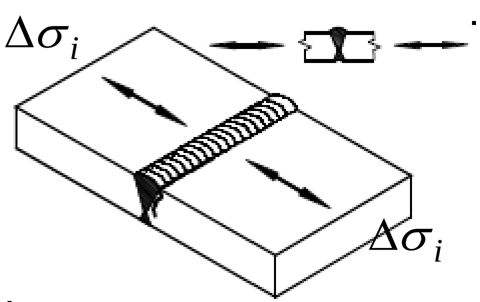
N_i = number of cycles to failure at constant stress range

L = fatigue life $L = \frac{L_0}{D}$

L_o = the time for the total number of stress cycles $n_0 = \sum_{i=1}^{k} n_i$

Example 1

- Calculate fatigue life of the following butt weld using E curve subjected to long term stress range in sea water in cathodic protection. Use DNV-RP-C203. Plate thickness = 40 mm. Mean stress is tensile stress.



Block	n_i	$\Delta\sigma_i$(MPa)
1	4	455
2	6	400
3	30	345
4	70	300
5	300	250
6	700	210
7	3,000	170
8	7,000	130
9	30,000	90
10	70,000	55
11	300,000	30

Example 1 : Solution

- It belongs to E class and thickness effect to be considered.
- E class

$$\log \bar{a} = 11.61, m = 3 \text{ for } N \le 10^6$$

$$\log \bar{a} = 15.35, m = 5 \text{ for } N \ge 10^6$$

for $N \le 10^6$

$$\log N = \log \bar{a} - m\log(\frac{t}{25})^{0.2} - m\log\Delta\sigma$$

$$= 11.61 - 3.0\log(\frac{40}{25})^{0.2} - 3.0\log\Delta\sigma$$

$$= 11.49 - 3.0\log\Delta\sigma$$

for $N \ge 10^6$

$$\log N = 15.35 - 5.0\log(\frac{40}{25})^{0.2} - 5.0\log\Delta\sigma$$

$$= 15.15 - 5.0\log\Delta\sigma$$

Block	n_i	$\Delta\sigma_i$(MPa)	N_i	$D_i = n_i / N_i$
1	4	455	3,281	0.00122
2	6	400	4,829	0.00124
3	30	345	7,526	0.00399
4	70	300	11,446	0.00612
5	300	250	19,778	0.01517
6	700	210	33,369	0.02098
7	3,000	170	62,900	0.04769
8	7,000	130	140,660	0.04977
9	30,000	90	423,909	0.07077
10	70,000	55	2,806,639	0.02494
11	300,000	30	58,129,117	0.00516

$$n_0 = \sum_{i=1}^{k} n_i = 411,110, \quad D = \sum_{i=1}^{k} \frac{n_i}{N_i} = 0.247$$

✓Damage ratio = 0.247

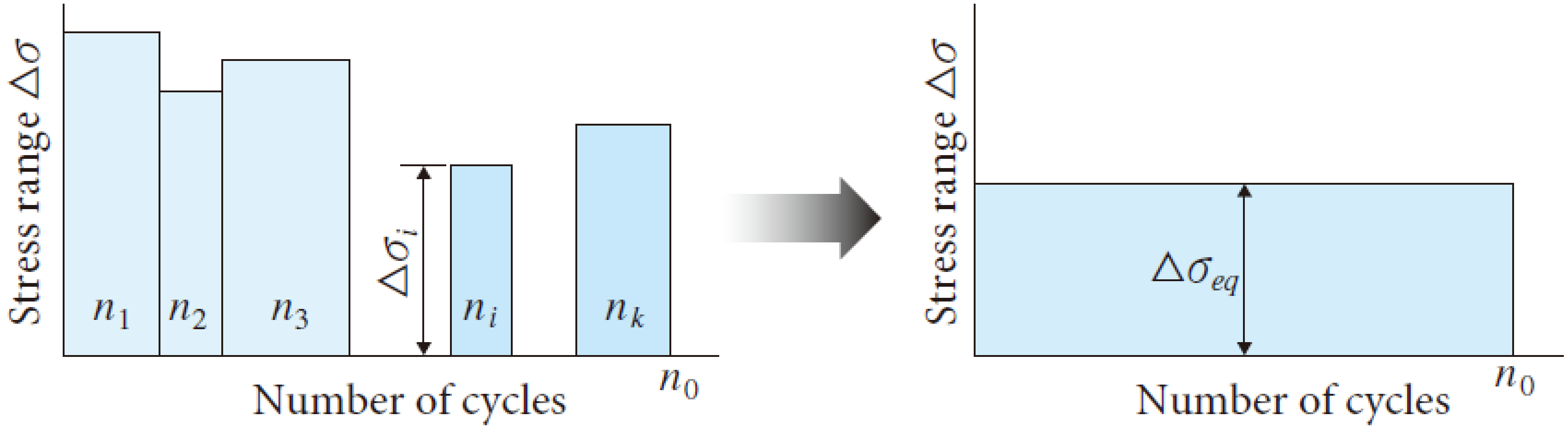
✓ Fatigue Life = $n_0/0.247$ =1,664,413

Equivalent Stress Range

- The same tress range is assumed to be applied across the entire life and it gives the same damage ratio subjected to variable stress ranges

$$D = \sum_{i=1}^{k} \frac{n_i}{N_i} = \sum_{i=1}^{k} \frac{n_i \Delta\sigma_i^m}{\bar{a}}, \quad N_i = \bar{a}\Delta\sigma_i^{-m}$$

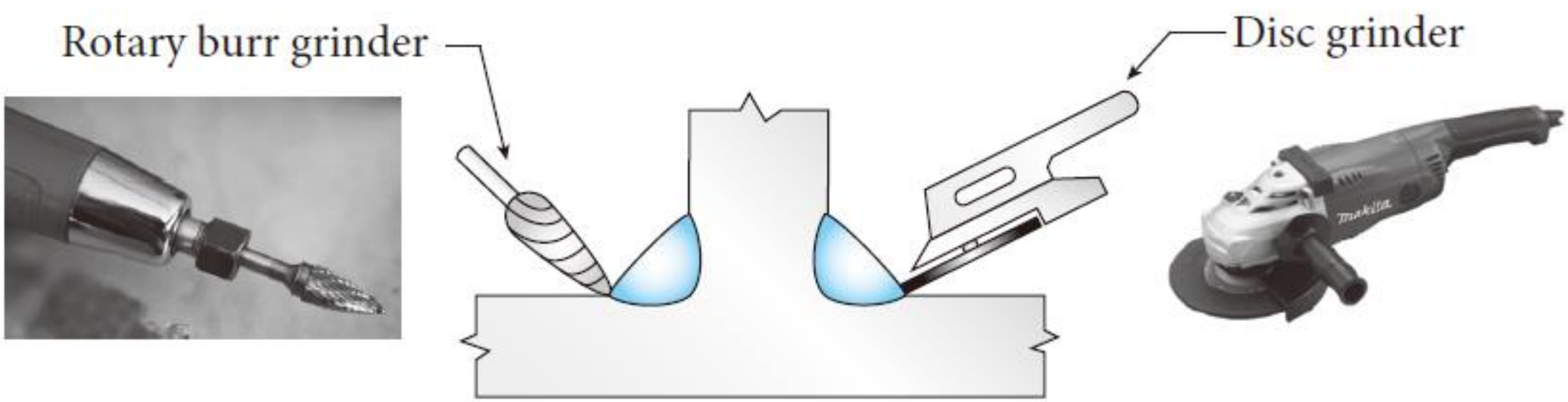
$$D = \frac{n_0 \Delta\sigma_{eq}^m}{\bar{a}}, \quad n_0 = \sum_{i=1}^{k} n_i$$



$$\Delta\sigma_{eq} = \left[\sum_{i=1}^{k} \frac{n_i \Delta\sigma_i^m}{n_0} \right]^{1/m}$$

Weld Toe grinding - mitigation of stress concentration

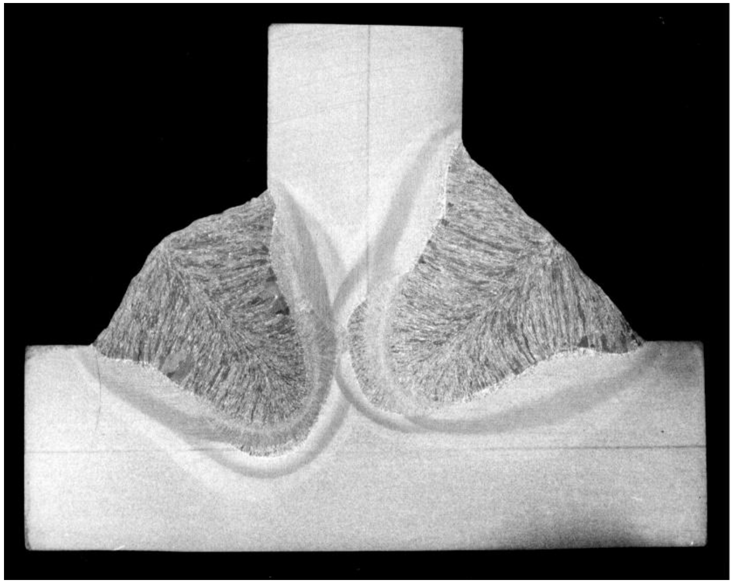
- A major cause of fatigue damage in welded structures : stress concentration at the toe + crack-like flaws.
- Machining and grinding to eliminate such flaws and give a smoother profile → improvement fatigue strength.
- Disc grinding is completely more quickly.
- Hand-held burr grinding is more effective.



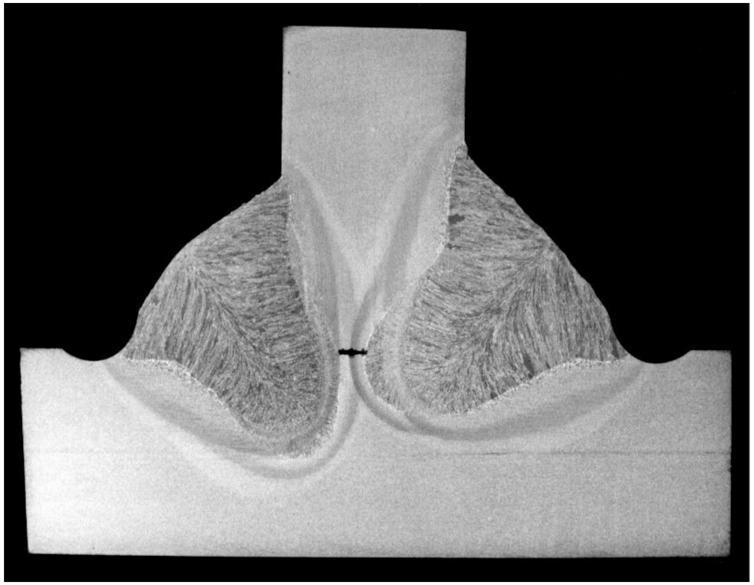
Burr machining and disc grinding

Weld Toe grinding – mitigation of stress concentration

- Fatigue life improvement is valid only when corrosion protection is effective
- After protection, corrosion induces notches.
- Adverse effect of strength reduction due to the decrease in area.



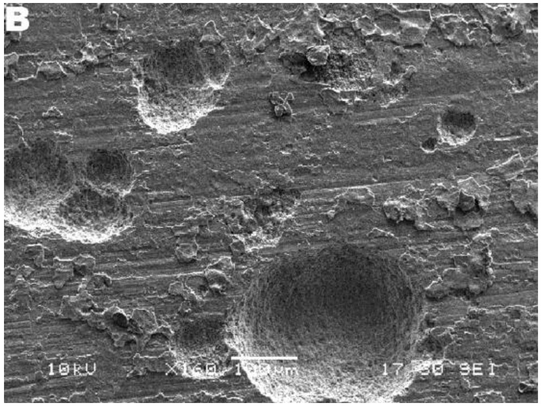
As Welded

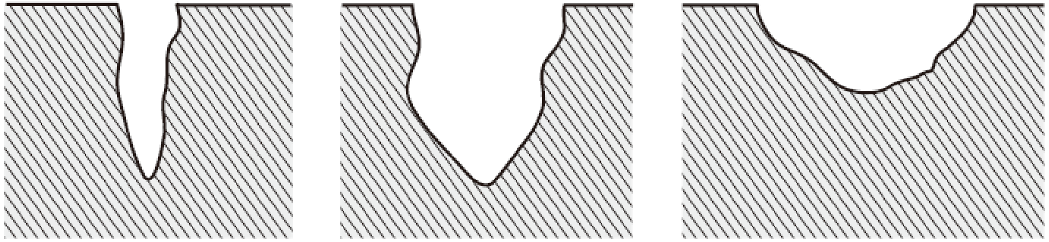


Burr Ground

Weld Toe grinding – side effect, corrosion

- Corrosion pitting of the ground metal surface virtually eliminates the benefit of burr grinding.
- The ground surface must be adequately protected by cathodic protection system or permanent protection means like a paint system.

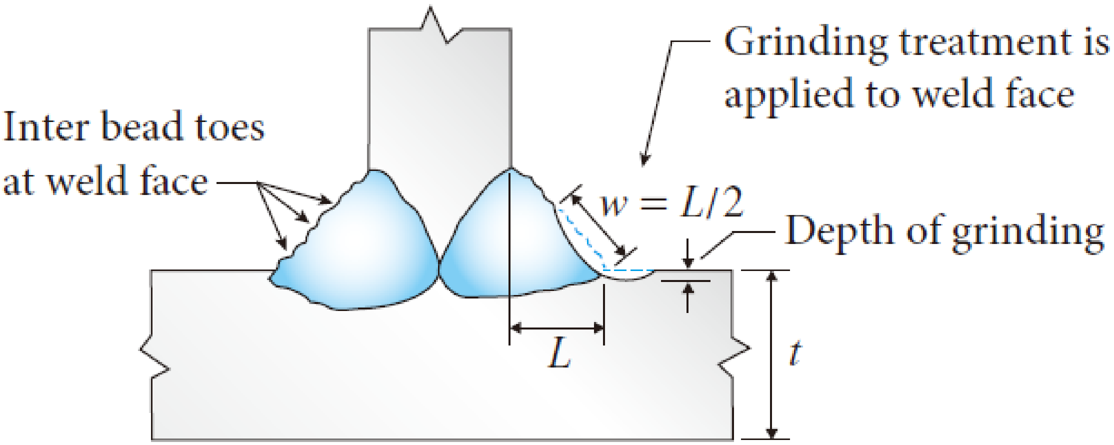




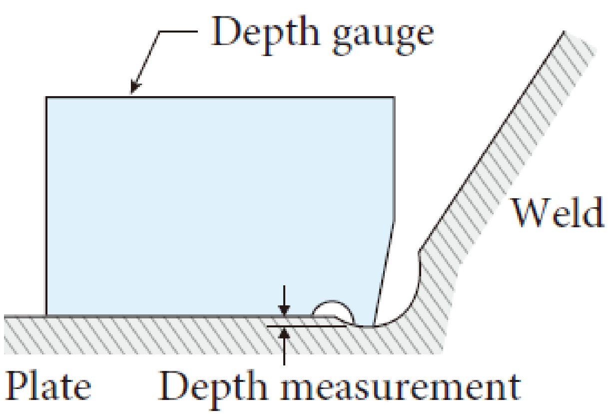
Corrosion pitting

Weld Toe grinding – mitigation of stress concentration

- Necessary to remove all traces of the original weld toe and material to a depth of 0.5~1.0 mm below any undercut.
- 0.5mm <Depth of grinding < 2mm or 7% of plate thickness



Depth of grinding

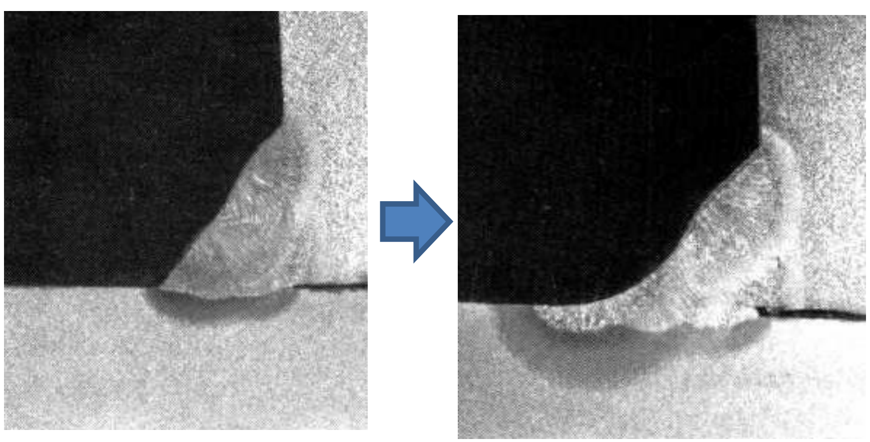


Depth measurement gauge

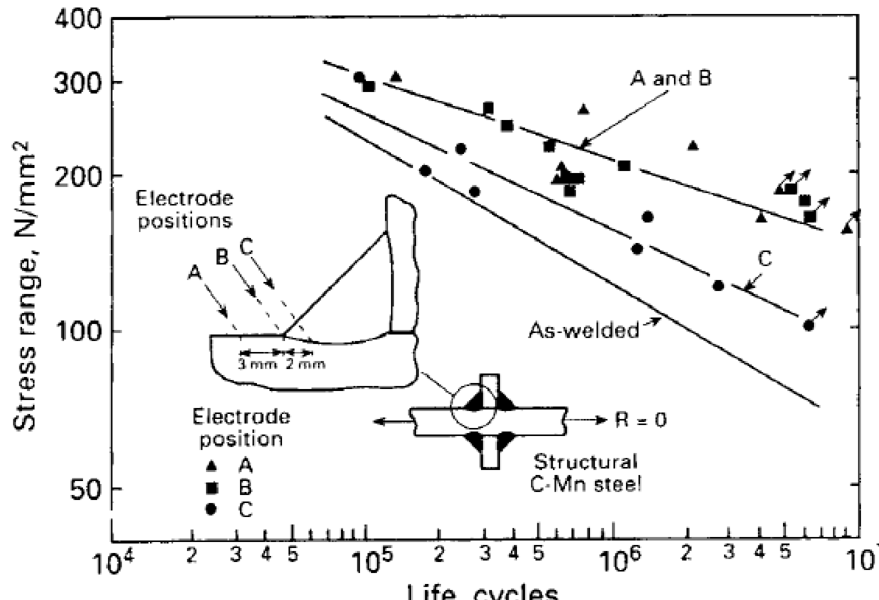
TIG dressing

❖ TIG and plasma dressing

- As effective as local grinding but considerably faster.
- To re-melt the weld toe and wash the weld pool into the plate surface as to produce a smoother weld profile and remove inherent flaws.
- TIG dressing calls for precise positioning of the arc
- Plasma technique gives a larger area of heating → less demanding



Weld cross section



Influence of electrode position fatigue strength of plasma dressed fillet welds

Weld Toe grinding - Burr Grinding

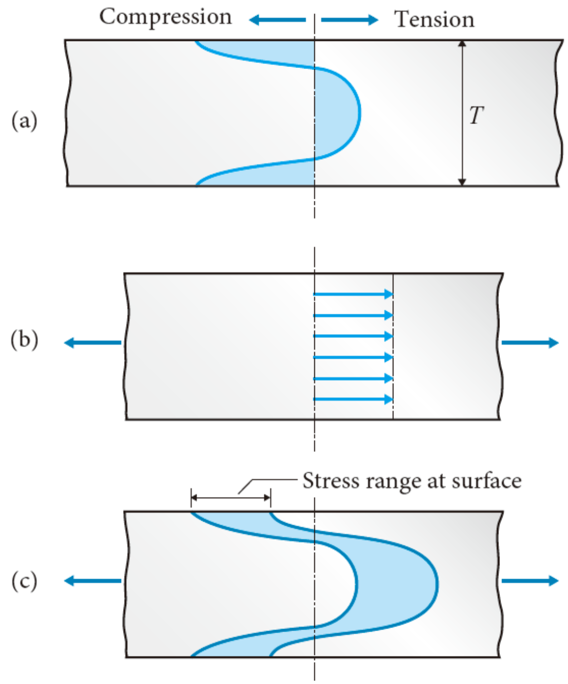
- A high speed pneumatic, hydraulic or electric grinder : rotational speed :15,000 ~ 40,000 rpm.
- The diameter :10 ~ 25 mm for 10t ~50t.
  root radius > 0.25t.
- The high-speed grinding tool removes material at a high rate.
- The cutting operation itself produces hot, sharp cuttings and some noise.
- Heavy protective clothing together with leather gloves, safety glasses and ear protection are mandatory

Pneumatic grinder and burrs

Example of protective clothing used during weld toe burr grinding.

Hammer peening - compressive residual stress

- Effective stress = applied stress + residual stress
- Tensile residual stress + compressive applied stress = no compressive mean stress effect
- Compressive residual stress + tensile applied stress = compressive mean stress effect



- High compressive stresses at the site of stress concentration leads to an improvement in fatigue strength.
- Cold working the material surface → compressive stress on surface which is balanced by a residual tensile stress within core.

Superimposition of applied and residual stresses

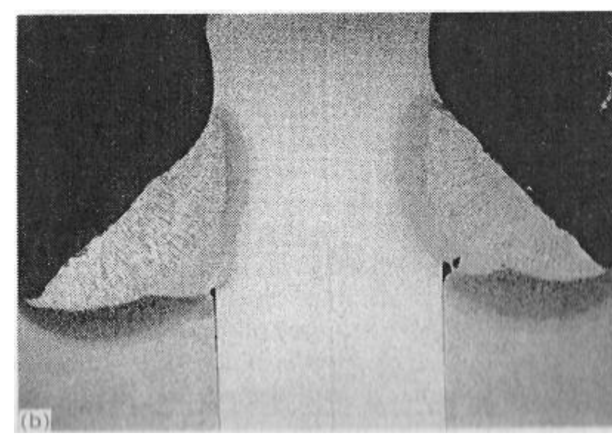
Hammer peening - compressive residual stress

❖ Hammer peening

- pneumatic or electric hammer with round-ended tool → compressive stress on the surface of stress concentration
- Noise problem : sometimes not allowed for health reasons → Needle peening

Hammer peeing fillet weld toe

Needle peeing fillet weld toe



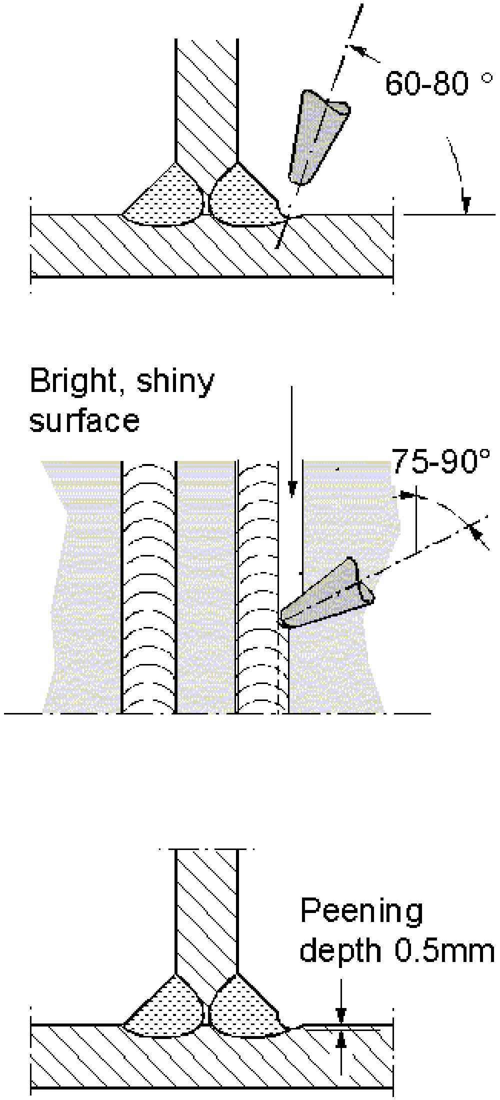
Weld cross-section

Hammer peening - Equipment

- Suitable pneumatic hammer gun has a 15 to 30 mm diameter piston, operates at an air pressure of 5 to 7 bars and delivers 25 to 100 blows per second. Impact energy is typically in the range 5 to 15 Joules.
- The weight of the gun is from about 1 to 3.5 kg.
- Hammer peening have made use of hammer gun, both of which are primarily intended for use as chipping (쪼다) hammers.

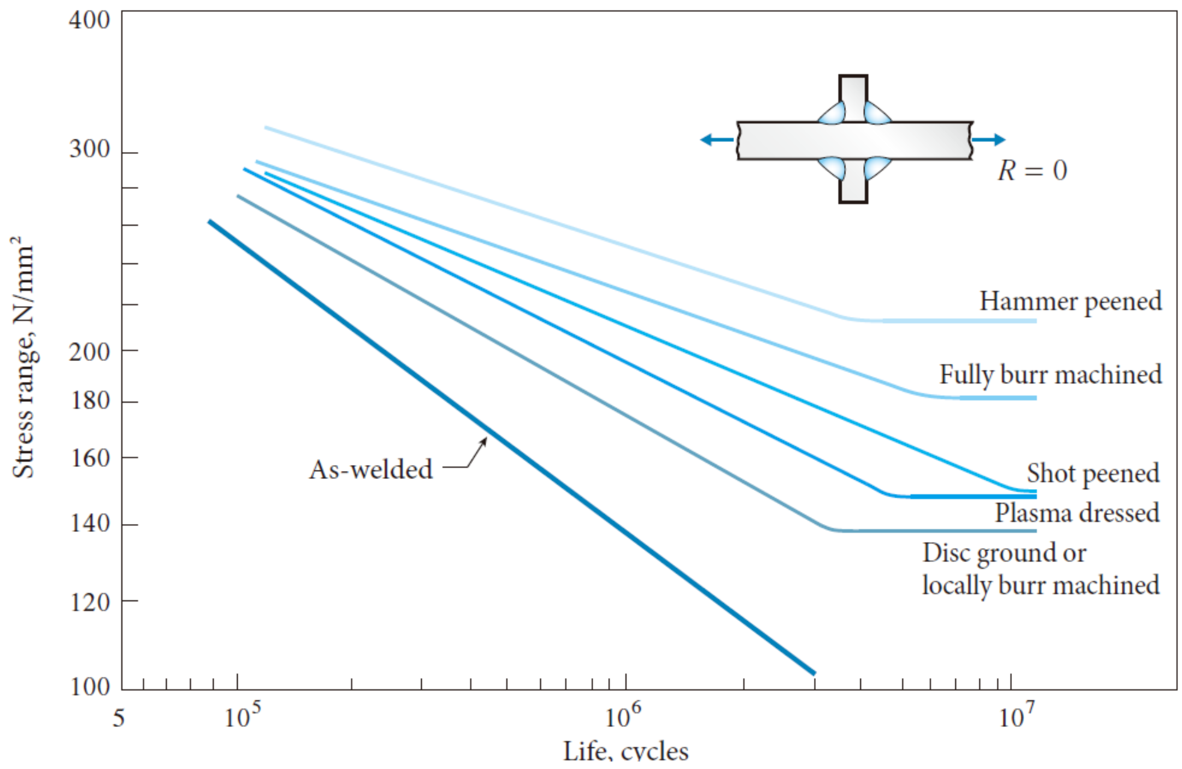
Pneumatic riveting guns used for hammer peening.

Hammer Peening - Procedure



Effects of Post Weld Improvement

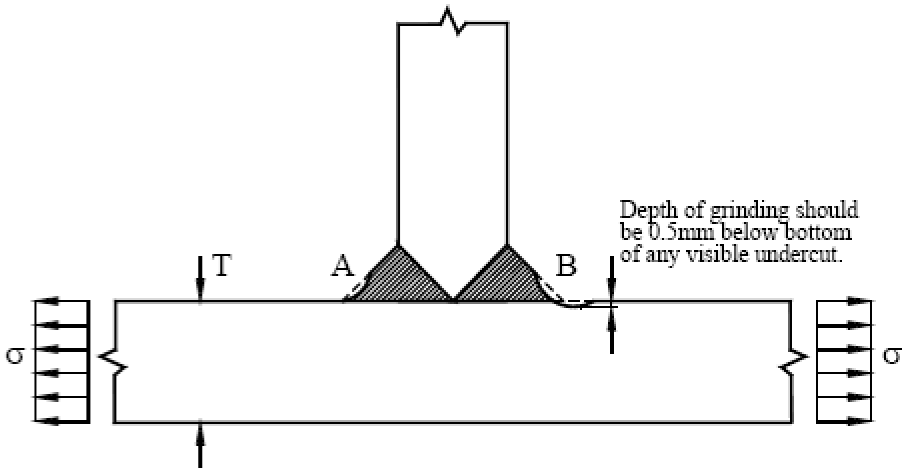
- Comparison of post weld improvement methods



Improvement of S-N curve

Improvement of Fatigue Life by Fabrication DNV RP-C203

- Grinding should extend below the plate surface by a rotary burr.
- The grinding depth should not exceed min (2 mm, 7% of the plate thickness).
- A good design practice to exclude this factor at the design stage and to keep the possibility of fatigue life improvement as a reserve.
- Crack grows faster after initiation → shorter inspection intervals during service life in order to detect the cracks before they become dangerous.



Grinding of welds

Improvement of Fatigue Life by Fabrication DNV RP-C203

- **Improvement on fatigue life by different methods**

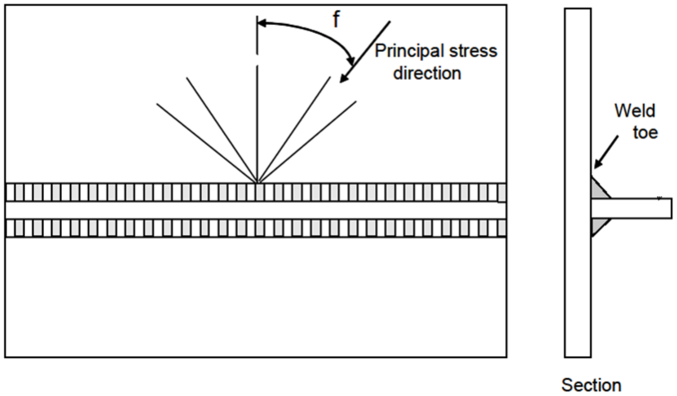
Improvement method	Minimum specified yield strength	Increase in fatigue life
Grinding	Less than 350 MPa	$0.01\ f_y$ [1)]
	Higher than 350 MPa	3.5
TIG dressing	Less than 350 MPa	$0.01\ f_y$
	Higher than 350 MPa	3.5
Hammer peening [2)]	Less than 350 MPa	$0.011\ f_y$
	Higher than 350 MPa	4.0

[1)] f_y = characteristic yield strength for the actual material

[2)] The improvement effect is dependent on tool used and workmanship.

Example 2

- **The following welded joint is subjected to cyclic load which gives the following nominal stress range during 10 years in seawater with cathodic protection in accordance with DNV RP-C203**



Applied nominal stress range (MPa)	Number of applied cycles
70	$5.0X10^5$
80	$4.0X10^5$
90	$3.0X10^5$
100	$2.0X10^5$
110	$1.5X10^5$

- Principal stress direction (f) = 40 degrees
- Plate thickness = 30 mm
- Static nominal mean stress : 20 MPa (Tensile stress)
- Steel : High Tensile steel (Yield stress = 355 MPa)
- Weld toe grinding is applied.

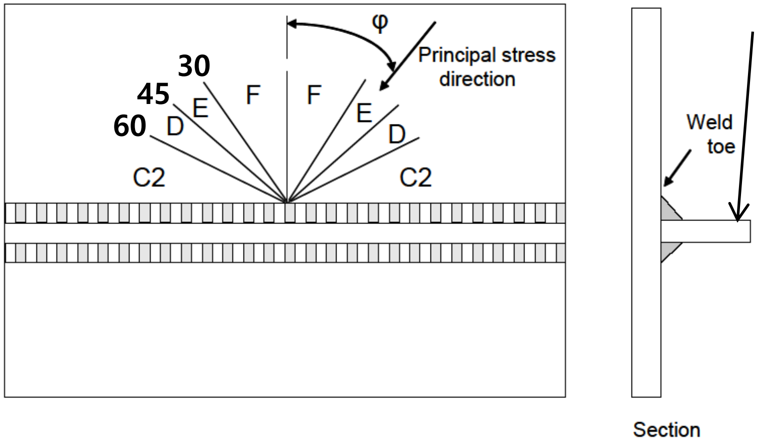
Calculation of Fatigue life -Post weld improvement

Example 2 : Solution

✓ Principal stress direction (f) = 40 degrees

✓ Plate thickness = 30 mm

t>25



$$\log N = \log \bar{a} - m \log\left(\Delta\sigma\left(\frac{t}{25}\right)^{0.20}\right)$$

$$\log N = 11.610 - 3.0 \log\left(\Delta\sigma\left(\frac{t}{25}\right)^{0.20}\right) \quad N < 10^6$$

$$\log N = 15.350 - 5.0 \log\left(\Delta\sigma\left(\frac{t}{25}\right)^{0.20}\right) \quad N > 10^6$$

2.4.5 S-N curves in seawater with cathodic protection

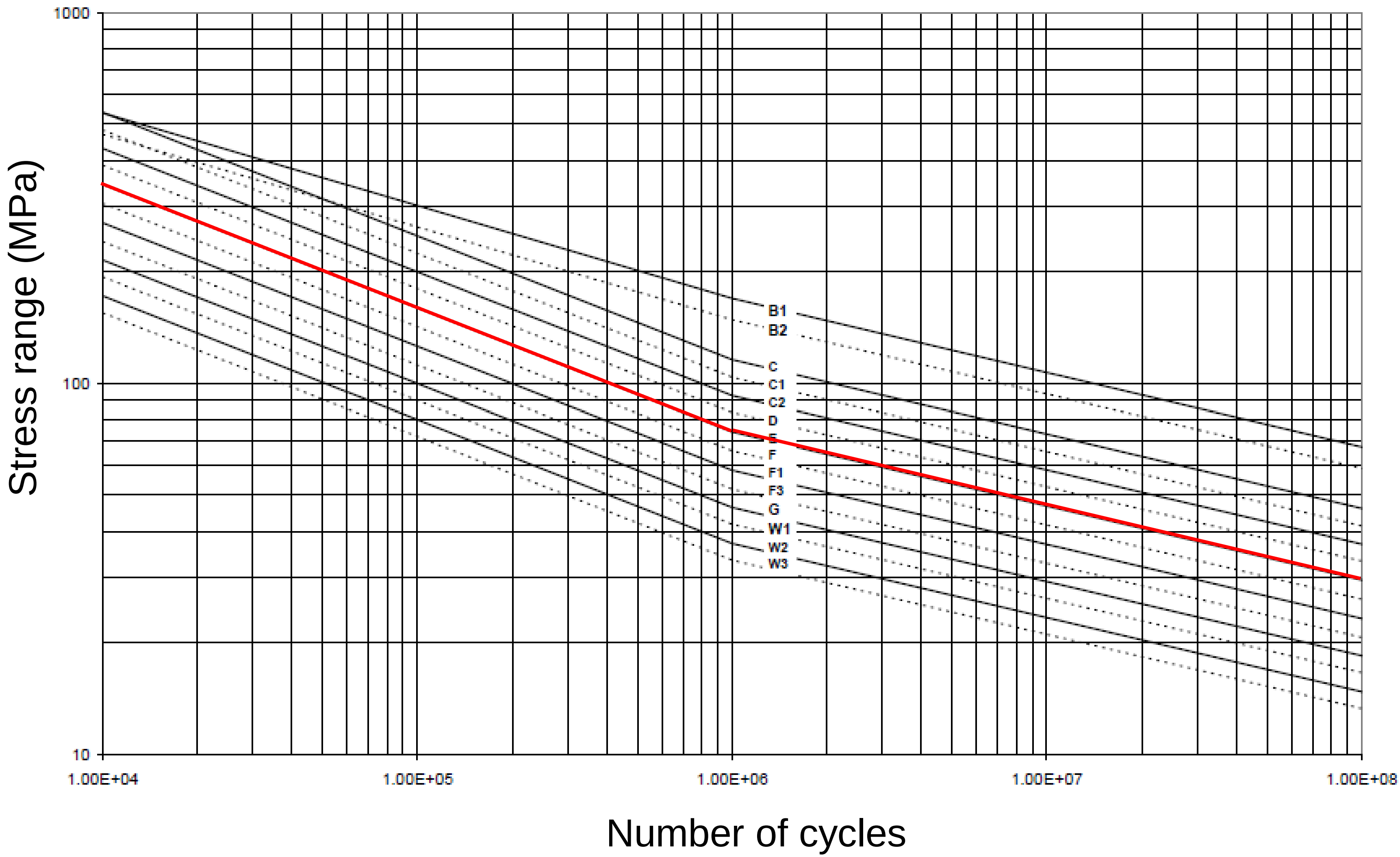
S-N curves for seawater environment with cathodic protection are given in Table 2-2 and Figure 2-7. The T curve is shown in Figure 2-8. For shape of S-N curves see also comment in 2.4.4.

Table 2-2 S-N curves in seawater with cathodic protection

S-N curve	*$N \le 10^6$ cycles*		*$N > 10^6$ cycles* $\log \bar{a}_2$ *$m_2 = 5.0$*	*Fatigue limit at 10^7 cycles*)*	*Thickness exponent k*	*Stress concentration in the S-N detail as derived by the hot spot method*
	m_1	$\log \bar{a}_1$				
B1	4.0	14.917	17.146	106.97	0	
B2	4.0	14.685	16.856	93.59	0	
C	3.0	12.192	16.320	73.10	0.15	
C1	3.0	12.049	16.081	65.50	0.15	
C2	3.0	11.901	15.835	58.48	0.15	
D	3.0	11.764	15.606	52.63	0.20	1.00
E	3.0	11.610	15.350	46.78	0.20	1.13

Example 2 : Solution

- E Curve



Example 2 : Solution

✓ Static nominal mean stress : 20 MPa (Tensile stress)

→ Mean stress effect is not allowed in DNV RP-C203.

✓ Fatigue Damage Calculation

$\Delta\sigma_{nominal}$	n_i	N_i	D_i	Remarks
70	500,000	1,110,014	0.45044	Use $N>10^6$ curve
80	400,000	713,216	0.56084	Use $N<10^6$ curve
90	300,000	500,915	0.59890	Use $N<10^6$ curve
100	200,000	365,167	0.54769	Use $N<10^6$ curve
110	150,000	274,355	0.54674	Use $N<10^6$ curve
		D=	2.705	

For $N < 10^6$

$$\log N = 11.610 - 3.0\log\left(\Delta\sigma\left(\frac{t}{25}\right)^{0.20}\right)$$

For $N > 10^6$

$$\log N = 15.350 - 5.0\log\left(\Delta\sigma\left(\frac{t}{25}\right)^{0.20}\right)$$

Fatigue Life = 10 year / 2.705 = 3.7 year

✓ Steel : High Tensile steel (Yield stress = 355 MPa)
✓ Weld toe grinding is applied.

Post Improvement : yield stress > 350 MPa , **Improvement on fatigue life** = 3.5
Fatigue Life = 3.7 year X 3.5 = **13.0 years**

Example 3

- **The following welded joint is subjected to cyclic load which gives the following hotspot stress range during 20 years in seawater with cathodic protection in accordance with DNV CN-30.7**

Applied hotspot stress range (MPa)	Number of applied cycles
40	20,000,000
90	1,000,000
120	500,000
150	200,000
200	100,000
Total number of cycles = 21,800,000	

- Plate thickness = 30 mm
- Static nominal mean stress : 20 MPa (Tensile stress)
- Steel : High Tensile steel (Yield stress = 355 MPa)
- Weld toe grinding is applied.

Example 3 : Solution

✓ Static nominal mean stress : 20 MPa (Tensile stress)

$$f_m = \frac{\sigma_t + 0.7|\sigma_c|}{\sigma_t + |\sigma_c|}$$

$$\sigma_t = tensile\ stress = \max(\sigma_{static} + \Delta\sigma/2, 0)$$

$$\sigma_c = compressive\ stress = \min(0, \sigma_{static} - \Delta\sigma/2)$$

✓ Fatigue Damage Calculation

$\Delta\sigma_i$(MPa)	N_i	σ_t(MPa)	σ_c(MPa)	f_m	N_i	D_i
40	20,000,000	40	0	1.0000	31,385,098	0.64
90	1,000,000	65	-25	0.9167	1,978,118	0.51
120	500,000	80	-40	0.9000	881,745	0.57
150	200,000	95	-55	0.8900	466,842	0.43
200	100,000	120	-80	0.8800	203,740	0.49
						$D = 2.63$

For $N < 10^6$

$$\log N = 12.164 - 3.0 \log\left(f_m \Delta\sigma \left(\frac{t}{25}\right)^{0.25} \right)$$

For $N > 10^6$

$$\log N = 15.606 - 5.0 \log\left(f_m \Delta\sigma \left(\frac{t}{25}\right)^{0.25} \right)$$

Fatigue Life = 20 year / 2.63 = 7.61 year

✓ Steel : High Tensile steel (Yield stress = 355 MPa)
✓ Weld toe grinding is applied.

Post Improvement : yield stress > 350 MPa , **Improvement on fatigue life** = 3.5
Fatigue Life = 7.61 year X 3.5 = **26.63 years**