2. Fatigue Strength of Welded Structural Components

Contents

Fatigue Design Recommendations

Safety Assessment
in the Fatigue Limit State of Steel Structural Members

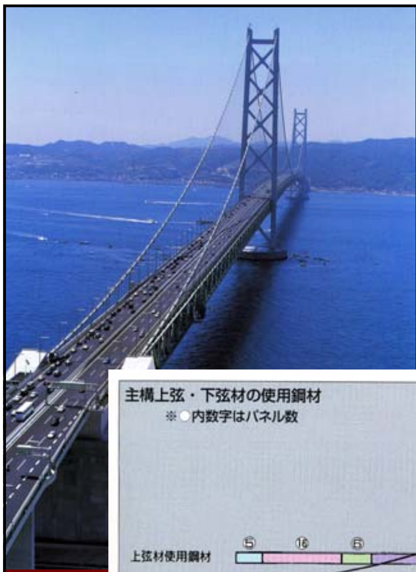
Fatigue Design Recommendations
For Steel Structures
By Japanese Society of Steel Construction (JSSC)
1993(in Japanese), 1995(in English)

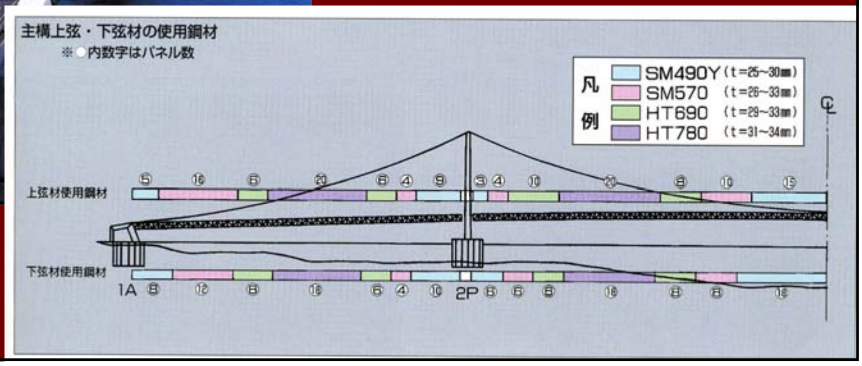
→ The Reference of Today's Lecture

Other Organizations with Recommendations:
AASHTO (American Association of State Highway and Transportation Officials),
IIW (International Institute of Welding) , …

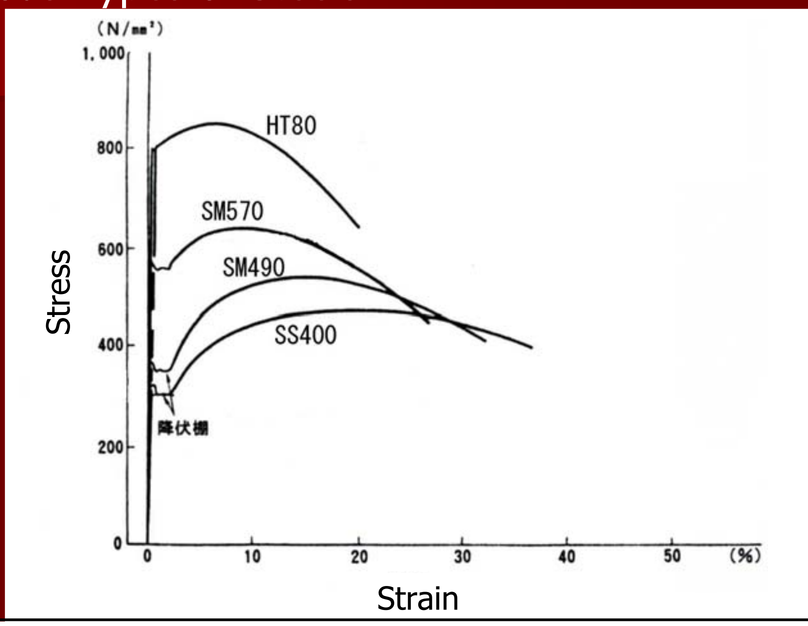
Introduction

Used Steels in Akashi Bridge (1998)





Stress – Strain Relationship of Various Types of Steels



Strength of Various Types of Steels

t=20mm　　MPa

	σa	σy	σt	Price(¥)	σt/2.2	σy/1.7
SM400	140	235	400	96,000	182	138
SM490Y	210	355	490	104,500	223	209
SM570	255	450	570	138,500	259	265
HT690	310	590	690		314	347
HT780	350	690	780		355	406

Steels

Steels intended for the Recommendations are carbon steel and low alloy steel

Ultimate Strengths:

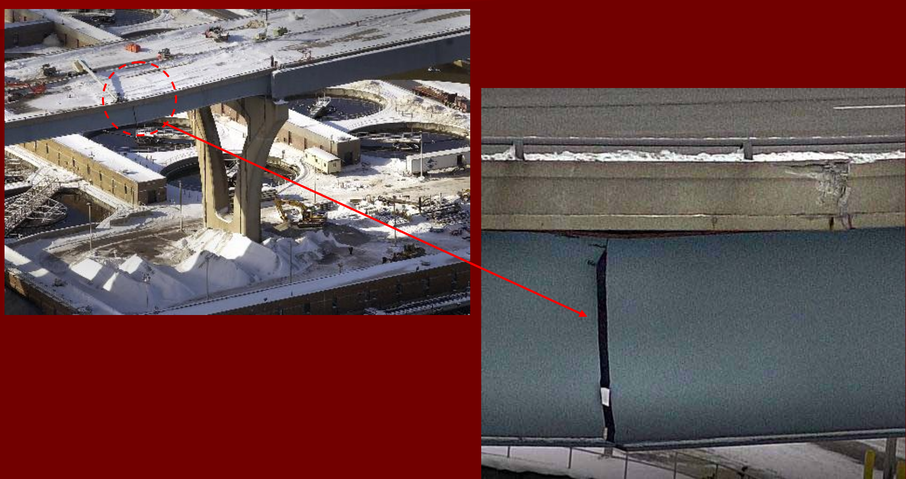
Steels $\longrightarrow$ 330MPa-1GPa

Wires $\longrightarrow$ up to 1.6GPa

High Strength Bolts $\longrightarrow$ up to 1.2GPa

What’s fatigue

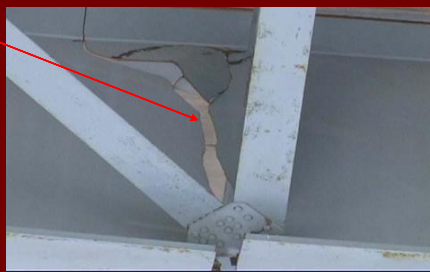
Brittle fracture from fatigue crack
Hoan-bridge in U.S.A



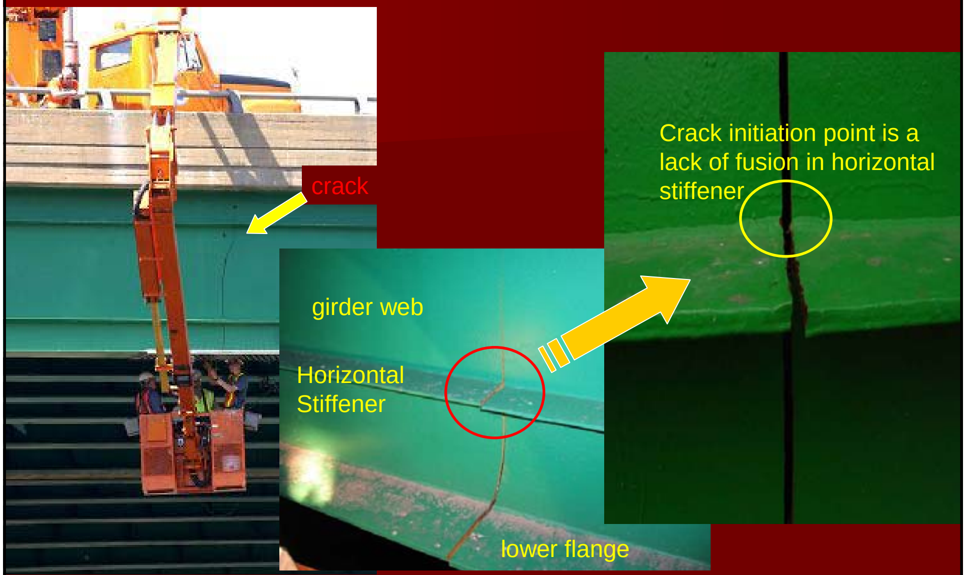
http://www.jsonline.com

Hoan-bridge

I-Girder Web Gusset



http://www.lichtensteinengineers.com/Hoan/Hoan-Failure-Investigation.PDFより引用



From "FORENSIC ANALYSIS OF THE STEEL GIRDER FRACTURE IN THE I-95 BRANDYWINE RIVER BRIDGE, Spencer Quiel, University of Notre Dame, August 8, 2003 "

What's Fatigue

- **Fatigue: Deterioration of a component caused by crack initiation and/or by the growth of cracks.**
- **Crack is initiated and propagate and causes fatigue failure of the component under the repetition of load.**
- **Fatigue limit : Fatigue strength under constant amplitude loading corresponding to a high number of cycles large enough to be considered infinite by a design code.**

IIW Fatigue Recommendation 2005 Feb.

Propagation of Fatigue Crack

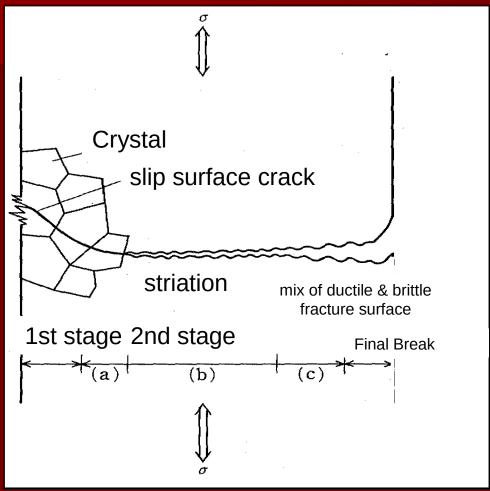
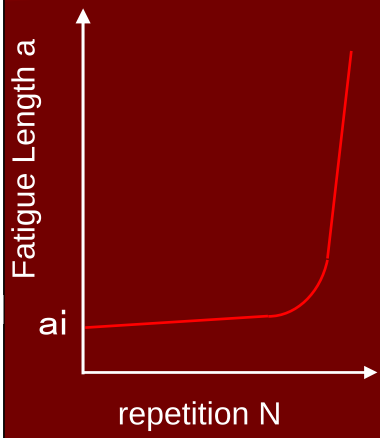
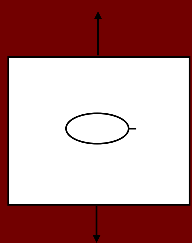


Image View of
Fatigue Propagation



propagation speed

Propagation Speed



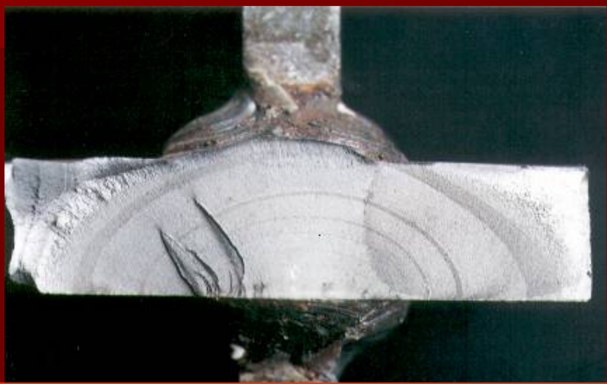
ΔKth	2	$MPa\sqrt{m}$	
C	2.70E-11		
m	2.75		
Δσ	50	MPa	

$$\frac{da}{dN} = C\left(\Delta K^m - \Delta K_{th}{}^m\right)$$

: JSSC Fatigue Design

a(mm)	ΔK	da/dN(m)	mm/0.1mil.cycle
1	2.802496	2.77683E-10	0.02776832
5	6.266571	4.01785E-09	0.401785208
10	8.862269	1.07105E-08	1.071048471
20	12.53314	2.8069E-08	2.806902616

Beach Mark



beach marks are inserted with the same interval

example : A-B-A-B-... cyclic loading

A:P=50kN - 800 kN & N=100,000 ,
B:P=400kN-800kN & N=20,000,

Striation

Characteristic fracture surface pattern of Fatigue crack (magnify ratio:8000)

Why fatigue becomes problems

- After the propagation, crack may lead to brittle fracture to cause structural failure.
- Common sense for statistic design is not applicable. Local stress concentration dominate the phenomena. Fatigue strength of each connection type differs.
- Evaluation of fatigue damaged part based on stress analysis is sometimes hard to apply.

Knowledge and experience of fatigue is required for judgment of retrofitting

Characteristics of fatigue damage 1

- Stress range and repetition
  Most influential factors on fatigue are stress range and number of repetition of it. Fatigue strength of steel itself is increased with their strength, but fatigue strength of weld joints has little dependency on the material strength.

- Fatigue strength : Fatigue crack is initiated from weld defects, notch, or stress concentrated part in weld joints and propagate. Residual stress influences on the fatigue strength.

Characteristics of fatigue damage 2

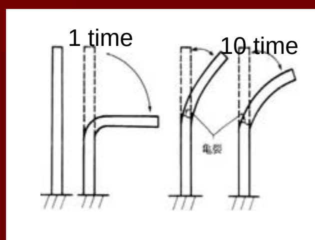
- Crack propagation
  After propagation, Crack will break the material with brittle fracture, or will stop propagation after the release of stress due to the cracking.

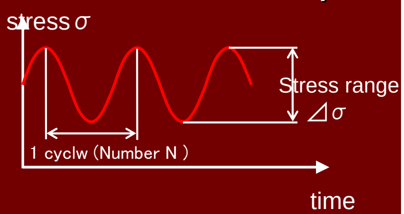
- Relation between stress range and fatigue life
  Linear relation on Log-Log plot

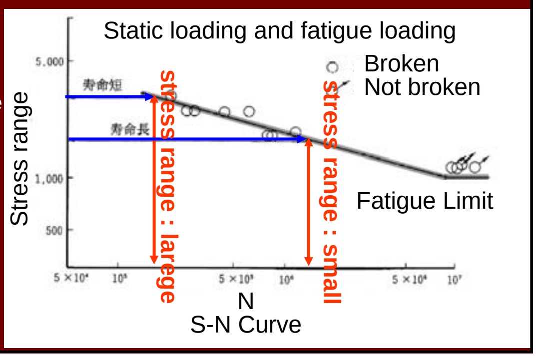
- Fatigue in highway bridge : People considered that Fatigue of primary member never happen except Steel deck under vehicle's load in Japan before.

Fatigue strength

- Static strength : Yielding and breaking with ductile manner
- Fatigue strength : Under the load repetition, break without ductility





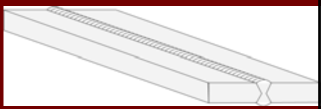


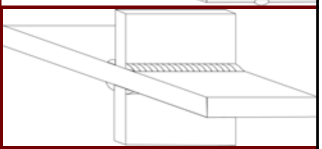
Predominant Factors Controlling Fatigue Strength

1. Joint Types
2. The Magnitude of The Nominal Stress Range
3. Number of Stress Cycles

Joint Types

1. Welded Connections
   - o Transverse butt welded joints
   - o Longitudinal welded joints
   - o Cruciform joints
   - o Gusset joints
   - o Other welded joints

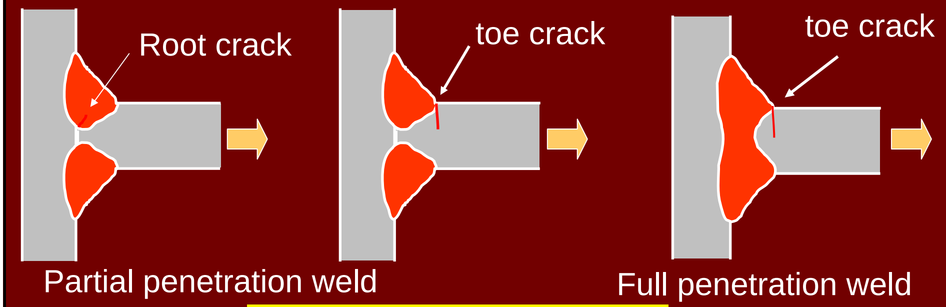




2. Cable Connections
3. High Strength Bolted Connections

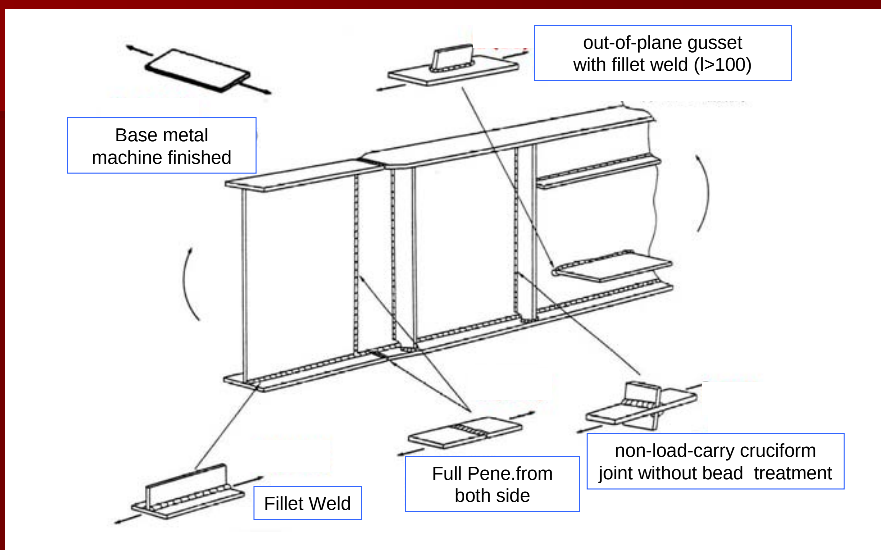
Fatigue : initiate from welding

- In bridge structures, fatigues are initiated from stress concentrated part of welding joints.
- Strongly dependent on geometry of welding



Fatigue of welded structures discussed in Lec #6

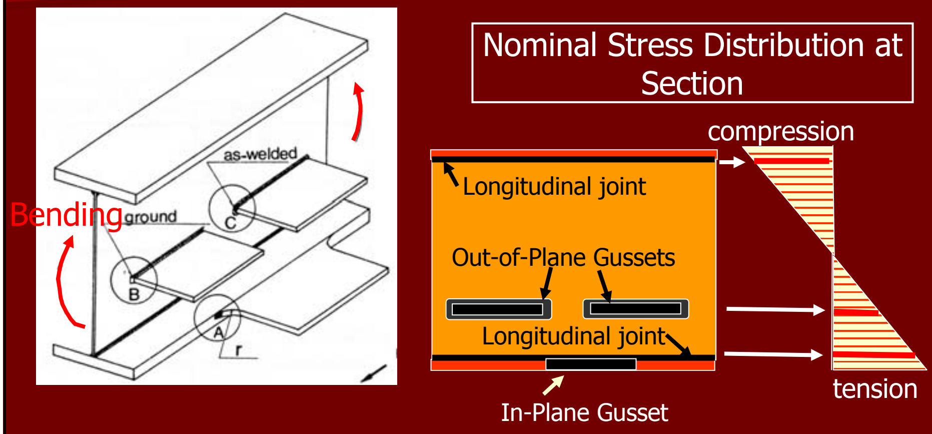
fatigue strength of weld joint in plate girder



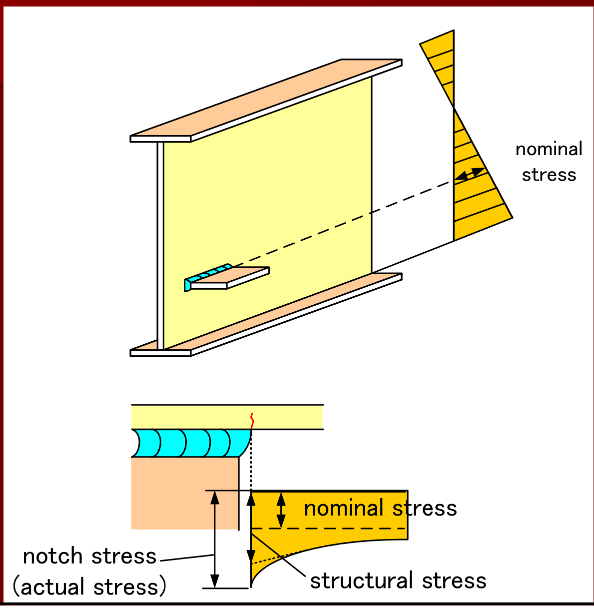
Fatigue strengths are specified for each joint type

Nominal Stress Ranges

Structures subjected to loads



Fatigue stress on a gusset



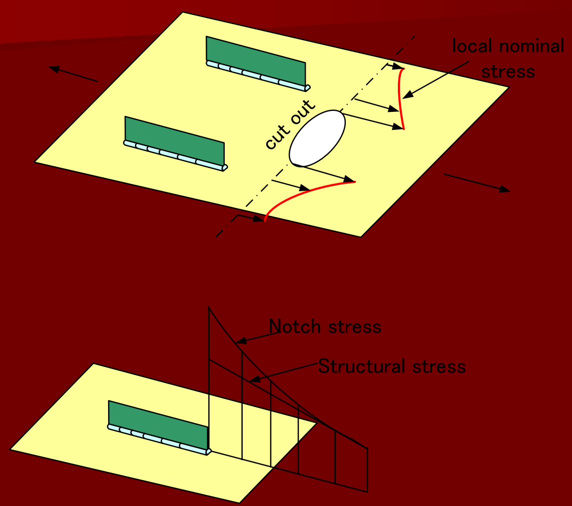
- stress

1. nominal stress
2. structural hot spot stress
3. notch stress concentration due to weld bead

Type of Stress for Fatigue Assessment

Type	Stress raisers	Stress determined	Assessment procedure	
A	General analysis of sectional forces using beam theory, no stress raiser considered	Gross average stress from sectional forces	not applicable for fatigue analysis, only component testing	Beam model
B	A + macrogeometrical effects due to the design of the component, but excluding stress risers due to the welded joint itself.	Range of nominal stress (also modified or local nominal stress)	Nominal stress approach	Shell model
C	A + B + structural discontinuities due to the structural detail of the welded joint, but excluding the notch effect of the weld toe transition	Range of hot-spot structural stress	hot-spot structural stress approach	Shell or Solid model
D	A + B + C + notch stress concentration due to the weld bead notches a) actual notch stress b) effective notch stress	Range of elastic notch stress (total stress)	a) Fracture mechanics approach b) effective notch stress approach	Solid detailed FEM model with bead

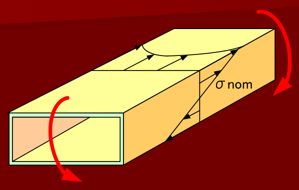
Type of stress



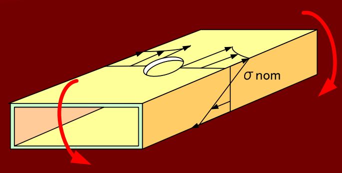
Local nominal stress includes

- The effects of macro-geometric features of the component
- stress fields in the vicinity of concentrated loads
- significant shell bending stress

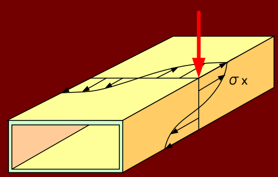
modified nominal stress



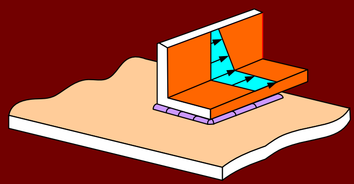
shear lag



Large opening



near concentrated load



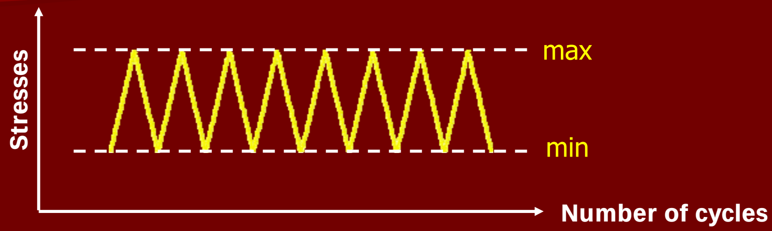
eccentric joint

Calculation of Nominal Stress

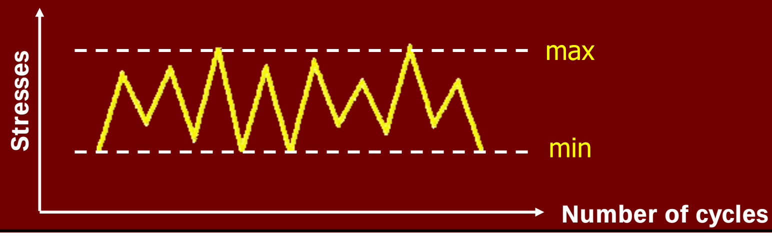
1. use elementary theories of structural mechanics (linear elastic)
2. FEM may be used in case,
   1. over-determined structures
   2. macro-geometric discontinuities
   - meshing can be simple and coarse (3*t),
   - CARE must be taken to ensure that all stress raising effects of the structural detail of the weld joints are excluded (stress concentration due to weld joint)

Stress Cycles

Constant Amplitude Stresses



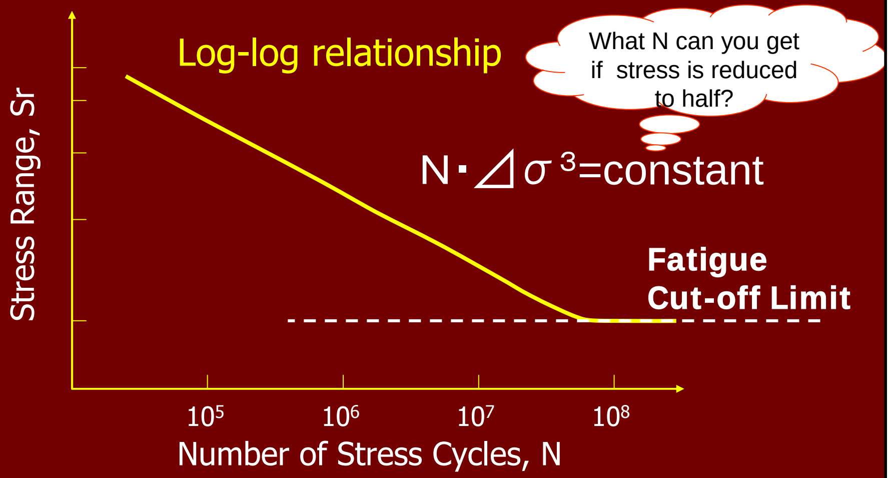
Variable Amplitude Stresses



Fatigue Design Curves

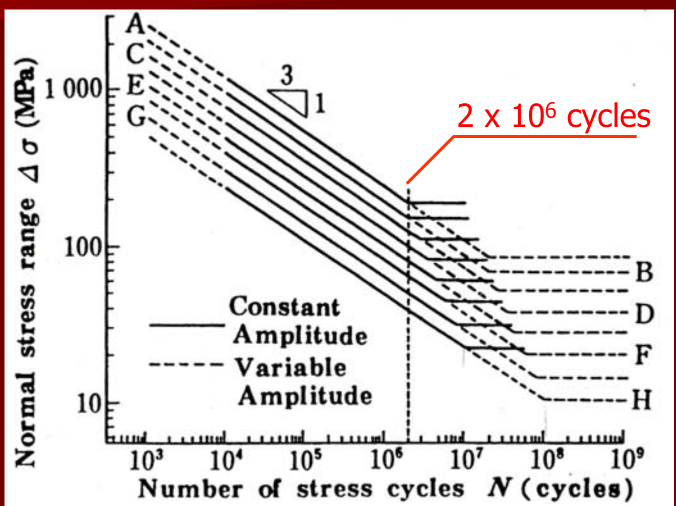
Typical Fatigue Design Curves

The curve that represents the relationship between the stress range and the fatigue life



Fatigue Design Curves (1)

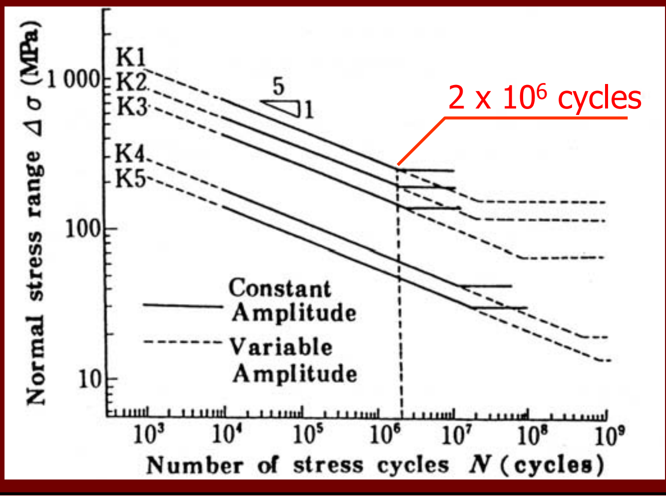
Welded Joints Subjected to Normal Stresses



joint class	2 million allowable fatigue stress range
A	190
B	155
C	125
D	100
E	80
F	65
G	50
H	40
H'	30

Fatigue Design Curves (2)

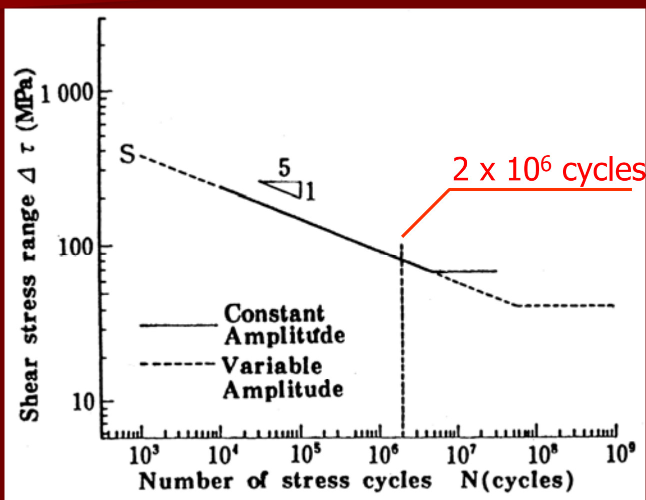
Cables and High Strength Bolts Subjected to Normal Stresses



K1 to K5: Strength Category

Fatigue Design Curves (3)

Welded Joints Subjected to Shear Stresses

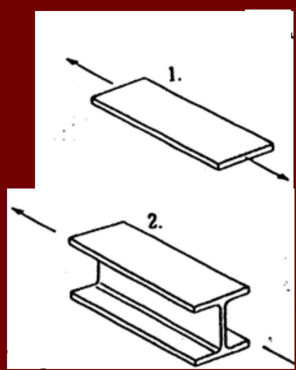


Strength Categories of Joints
And Their Basic Allowable Stress Ranges

Non-Welded Joints (1)

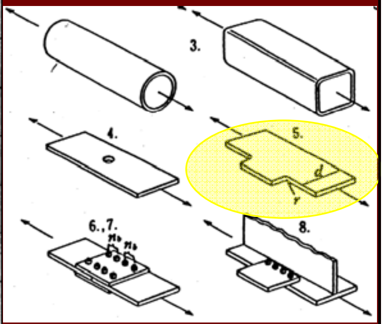
Strength categories
(basic allowable stress ranges)

1. Plates	(1) with surfaces and edges by machining (JIS roughness of 50s or less)	A (190)
	(2) with mill scale surfaces and edges by flame cutting (JIS roughness of 100s or less)	B (155)
	(3) with mill scale surfaces and edges by flame cutting (large drag lines must be removed)	C (125)
2. Shaped steel	(1) with mill scale surfaces and edges	B (155)
	(2) with mill scale surfaces and edges by flame cutting (JIS roughness of 100s or less)	B (155)
	(3) with mill scale surfaces and edges by flame cutting (large drag lines must be removed)	C (125)

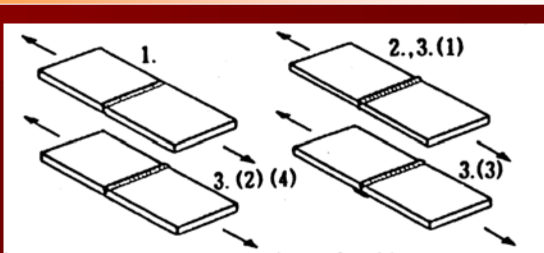


Non-Welded Joints (2)

3. Seamless tubes		B (155)
4. Base plates with circular holes		C (125)
5. Base plates with cut out gussets	(1) $1/5 \leq r/d$ (JIS roughness of 50s or less)	B (155)
	(2) $1/10 \leq r/d < 1/5$ (JIS roughness of 50s or less)	C (125)
	(3) $1/5 \leq r/d$ (JIS roughness of 100s or less)	C (125)
	(4) $1/10 \leq r/d < 1/5$ (JIS roughness of 100s or less)	D (100)
6. Base plates of friction type bolted connection	(1) $1 \leq n_s \leq 4$	B (155)
	(2) $5 \leq n_s \leq 15$	C (125)
	(3) $16 \leq n_s$	D (100)
7. Base plates of bearing type bolted connection		B (155)
8. Base plates with holes and bolts, which do not transfer the loads along the direction of stress		B (155)



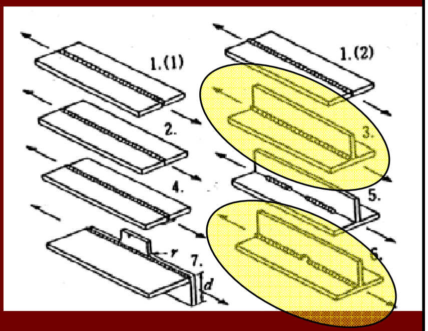
Transverse Butt Welded Joints



1. With ground flush surfaces		B(155)
2. With finished weld toe		C(125)
3. As-welded joint	(1) both side welds	D(100)
	(2) one side welds with smooth back-side weld geometry	D(100)
	(3) one side welds with backing bars	F (65)
	(4) one side welds unable to inspect those back surfaces	F (65)

Longitudinal Welded Joints

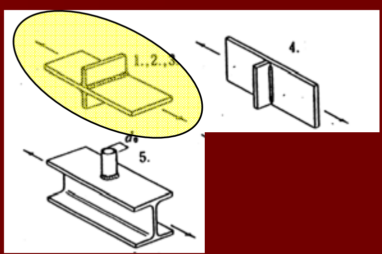
1. Complete penetration groove welded joints from both sides	(1)with ground flush surfaces	B(155)
	(2)as-welded	C(125)
2. Partial penetration groove welded joints		D(100)
3. Fillet welded joints		D(100)
4. Welded joints with backing bars		E(80)
5. Intermittent fillet welded joints		E(80)
6. Welded joints with copes		G(50)
7. Welded joints adjacent to fillets of cut out gussets	(1)1/5≦r/d	D (100)
	(2)1/10≦r/d<1/5	E (80)



Cruciform Joints (1)

Non load-carrying type

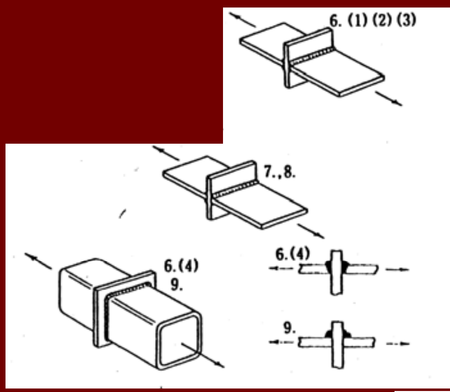
1. Fillet welded joints with smooth weld toes		D(100)
2. Fillet welded joints with finished weld toes		D(100)
3. As-welded fillet welded joints		E(80)
4. Fillet welded joints including start and stop position		E(80)
5. Fillet welded joints of hollow section	(1)d_s ≦100 mm	F(65)
	(2)d_s >100 mm	G(50)



Cruciform Joints (2)

Load-carrying type

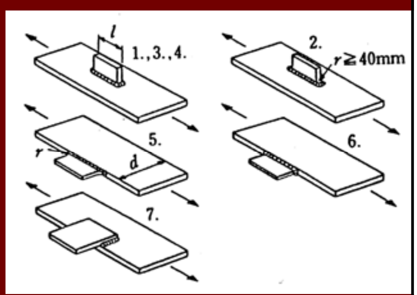
	6. Complete penetration weld	(1)with smooth weld toes welded by confirmed method	D(100)
		(2)with finished weld toes	D(100)
		(3) as-welded	E(80)
		(4)hollow section (one side welds)	F(65)
Fillet or partial penetration	7. Toe failure	(1)with smooth weld toes welded by confirmed method	E(80)
		(2)with finished weld toes	E(80)
		(3) as-welded	F(65)
		(4)including start and stop positions	F(65)
	8. Root failure		H(40)
	9. Hollow section	(1)toe failure	H(40)
		(2)root failure (throat section)	H(40)



Gusset Joints

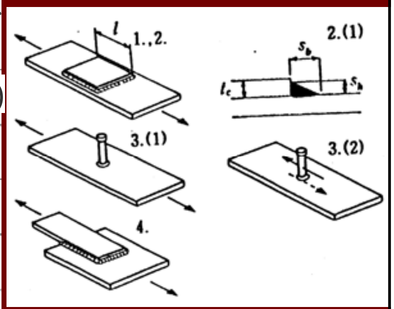
Out of plane gussets	1. Joints with fillet welded or groove welded gusset	(1)with finished weld toes	E(80)
		(2)as-welded	F(65)
	2. Joints with groove welded gusset with fillet		E(80)
	3. Joints with fillet welded gusset		G(50)
	4. Joints with groove welded gusset (L>100mm)	(1)with finished weld toes	F(65)
		(2)as-welded	G(50)
In plane gussets	5. Joints with groove welded gusset with fillet	(1)1/3≦r/d	D(100)
		(2)1/5≦r/d<1/3	E(80)
		(3)1/10≦r/d<1/5	F(65)
	6. Joints with groove welded gusset	(1)with finished weld toes	G(50)
		(2)as-welded	H(40)
7. Base plate with lap-welded gusset			H(40)

1:(L≦100mm)
3,4(L>100mm)

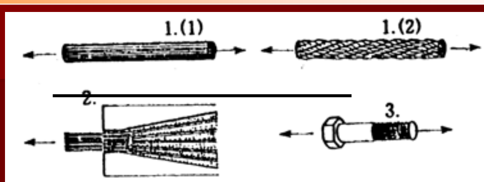


Other Welded Joints

1. Joints with fillet welded cover plates (l<300mm)	(1)with finished weld toes	E(80)
	(2)as-welded	F(65)
2. Joints with fillet welded cover plates (l>300mm)	(1)with profiled end welds	D(100)
	(2)as-welded	G(50)
3. Welded studs	(1)at base plates	E(80)
	(2)at stud sections	S(80)
4. Lapped joints	(1)at base plates	H(40)
	(2)at splice plates	H(40)
	(3)at throat sections of end fillet welds	H(40)
	(4)at throat sections of side fillet welds	S(80)



Cables and High Strength Bolts



1. Cables	(1)parallel wire stands	K1(270)
	(2)wire ropes	K2(200)
2. Cable anchorages	(1)fatigue-proof anchorages for parallel wire strands	K1(270)
	(2)Zinc-poured anchorages for parallel wire strands	K2(200)
	(3)Zinc-poured anchorages for ropes	K3(150)
3. High strength bolts	(1)rolled	K4(65)
	(2)cut	K5(50)

Correction Factor for Basic Allowable Stress Ranges

Allowable Stress Range, $\Delta\sigma_R$

Difference between real joints and the experimental specimens in scale and residual stress

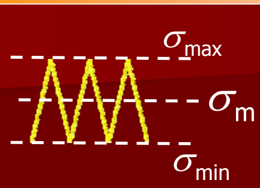
Correction for allowable stress ranges

Allowable stress range ($\Delta\sigma_R$) = Basic allowable stress range X C_R X C_T

C_R: Effect of mean stress

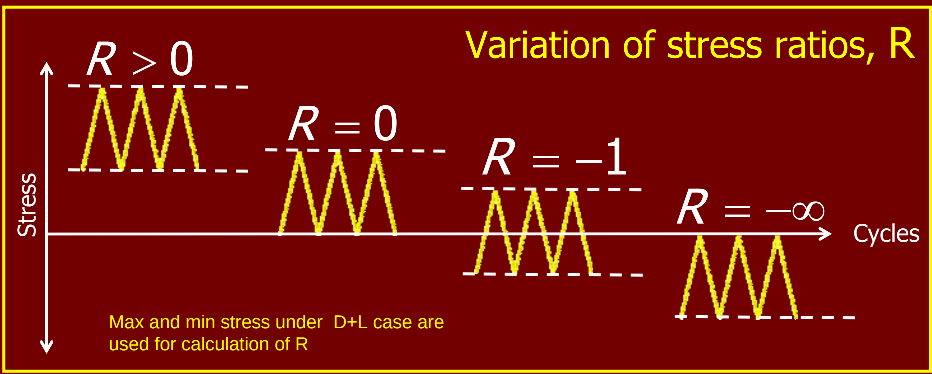
C_T: Effect of plate thickness

Effect of Mean Stress (1)

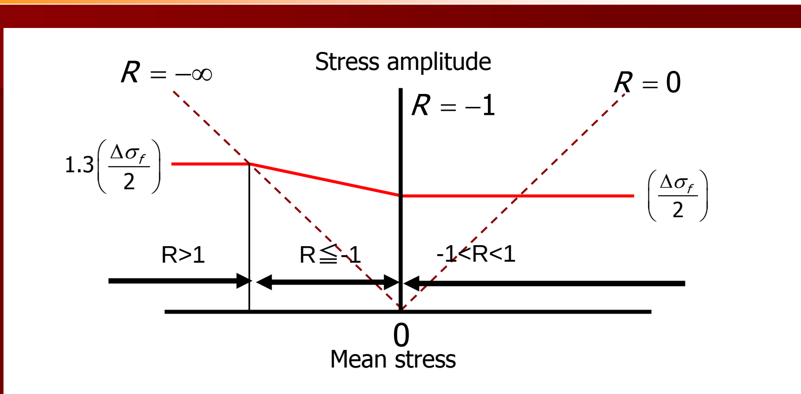


$$\sigma_m(\text{mean stress}) = \tfrac{1}{2}(\sigma_{max} + \sigma_{min})$$

$$R(\text{stress ratio}) = \frac{\sigma_{min}}{\sigma_{max}}$$



Effect of Mean Stress (2)

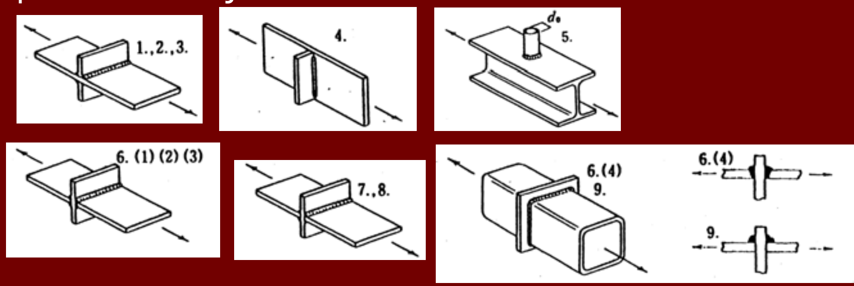


$$C_R = 1.3\left(\frac{1-R}{1.6-R}\right) \quad \text{for } R \leq -1$$

Effect of Plate Thickness

Fatigue strength decreases with increase of plate thickness in some kinds of joints

Example: Cruciform joints



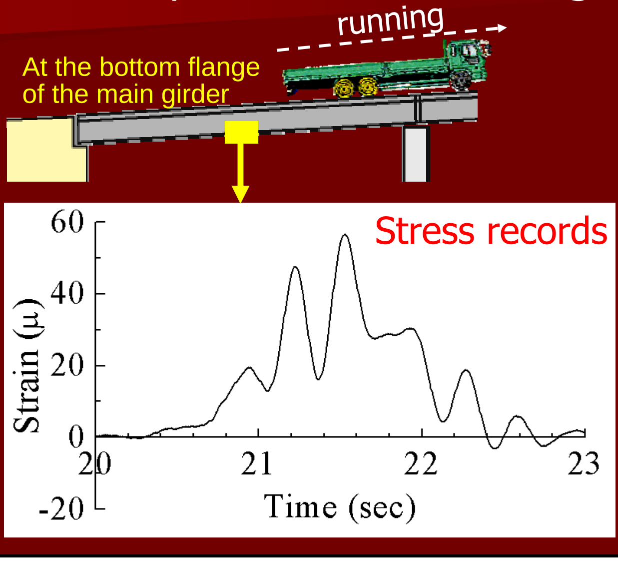
$$\boxed{C_t = \sqrt[4]{25/t} \qquad \text{for } t > 25 \text{ mm}}$$

thickness

Stress Fluctuation
and
Stress Range Histograms

Stress Fluctuation

Strain responses due to running vehicle



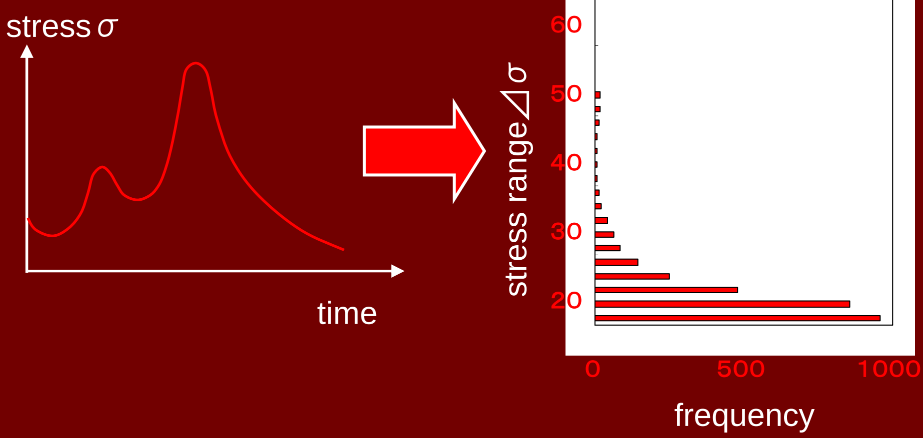
Stresses vary with positions of loads

Variable amplitude stresses

How to calculate stress cycles ??

(4) Estimation of fatigue life, Fatigue damage

rainflow method



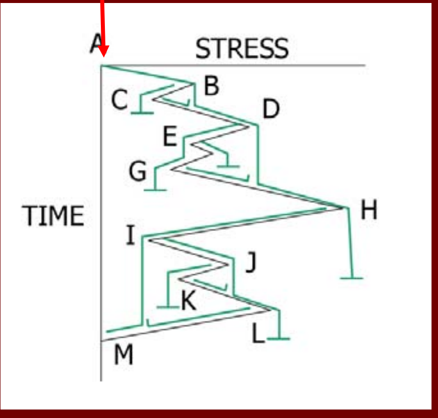
Rain Flow Counting Method

A method for determining a stress range histogram from variable amplitude stresses

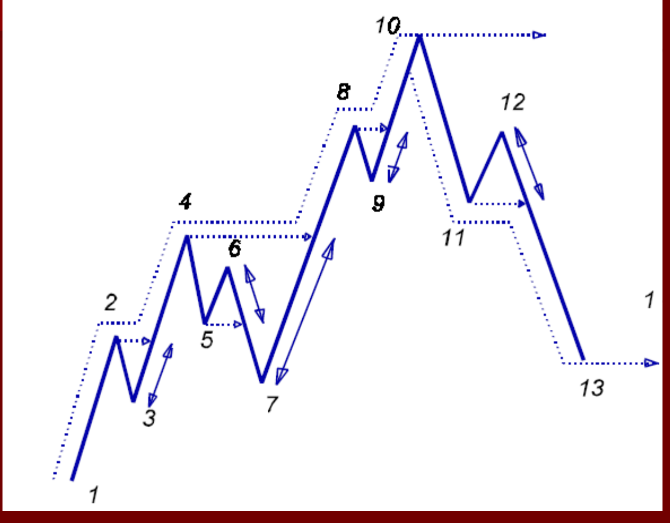
Analogy

The flow of drops of rain down a pagoda roof.

Origin point of rain drop



Rainflow Method



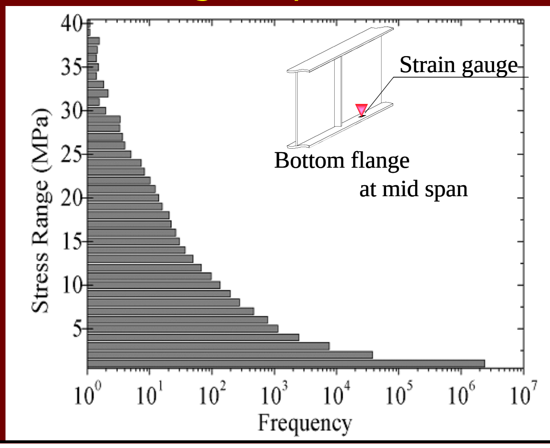
cycles
2-3
5-6
4-7
8-9
11-12

open
1-10-13

Stress Range Histogram

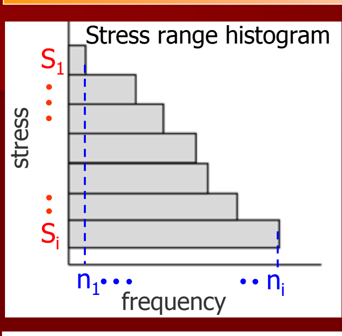
Plot of Stress ranges and Frequencies obtained from the rain flow counting method

Example: Oosaka Bridge, Japan



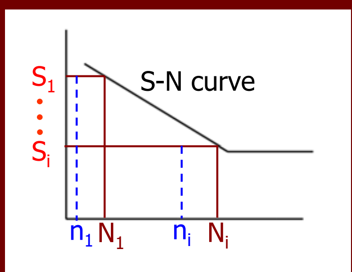
Cumulative Damage

Linear Damage Calculation by 'Palmgren-Miner" Summation



Cumulative damage, D

$$D = \sum (n_i / N_i)$$



Linear cumulative damage rule

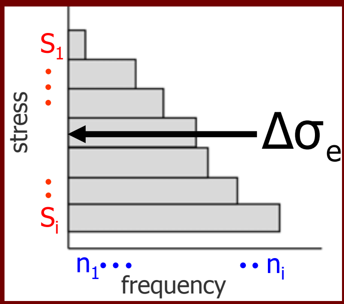
proposed by Miner

$D = 1$ → Failures

Equivalent Stress Range

Constant amplitude stress range, which causes fatigue damage equivalent to the same repeated number of variable amplitude stresses

Stress range histogram



$$\Delta\sigma_e = \sqrt[m]{\frac{\sum \Delta\sigma_i^m \bullet n_i}{\sum n_i}}$$

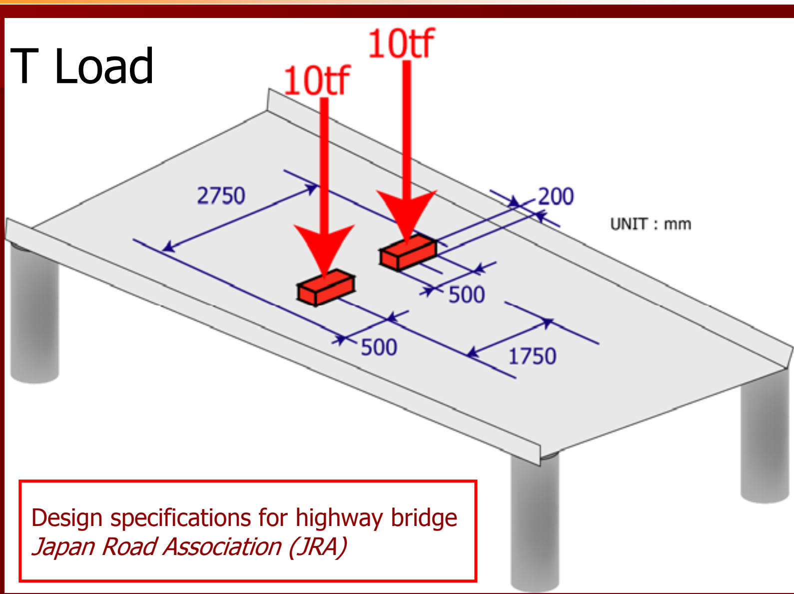
where

m = 3 for normal stress

m = 5 for shear stress

Fatigue Assessment

Fatigue Design Load



Safety Factors $(\gamma_b \cdot \gamma_w \cdot \gamma_i)\Delta\sigma_d \leq \Delta\sigma_R$

1. Redundancy factor, $\gamma_b \longrightarrow$ (0.8 - 1.1)
   When damage occurs in the objective joint, it will affect the whole structure strength
2. Importance factor, $\gamma_w \longrightarrow$ (0.8 - 1.1)
   Degree of importance of a structure (social effect)
3. Inspection factor, $\gamma_i \longrightarrow$ (0.9 - 1.1)
   Damage-detection probability by periodic inspections

Limitation

$$\boxed{0.8 < \gamma_b \times \gamma_w \times \gamma_i < 1.25}$$

Fatigue Assessment Based on Equivalent Stress Range

This equation should be satisfied.

$$\boxed{\left(\gamma_b \cdot \gamma_w \cdot \gamma_i\right)\Delta\sigma_d \le \Delta\sigma_R}$$

where

$\Delta\sigma_d$ = design stress range = equivalent stress range, $\Delta\sigma_e$

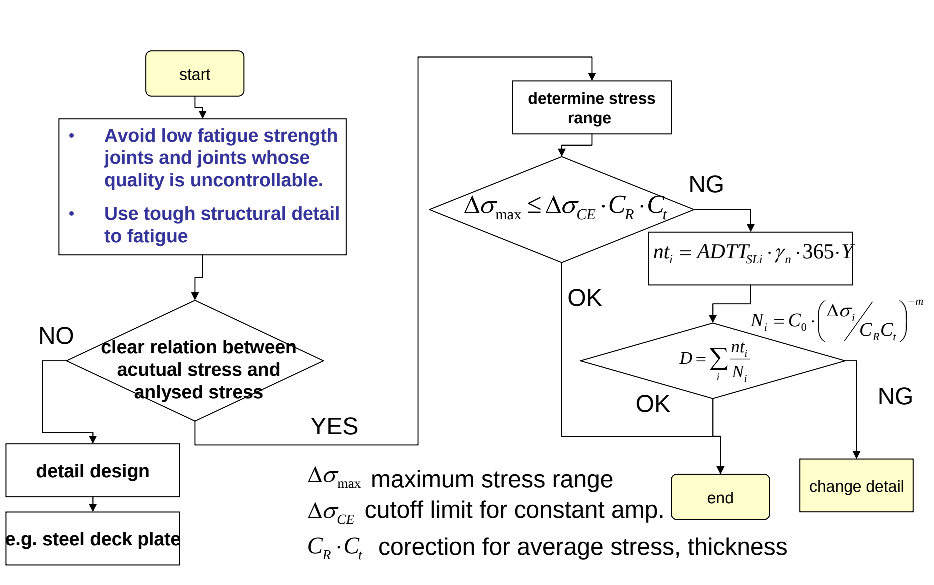
$\Delta\sigma_R$ = allowable stress range

Basic of fatigue design in Steel highway bridge in Japan

Fatigue design guideline for steel highway bridge

- Avoid low fatigue strength joints and joints whose quality is uncontrolable.
- Use tough structural detail to fatigue : refer to "Fatigue of steel bridge"
- Require quality control of welding to assure fatigue strength. (Allowable defect size, inspection area)
- Guideline is adopted to temporary members for election, stiffening, etc..

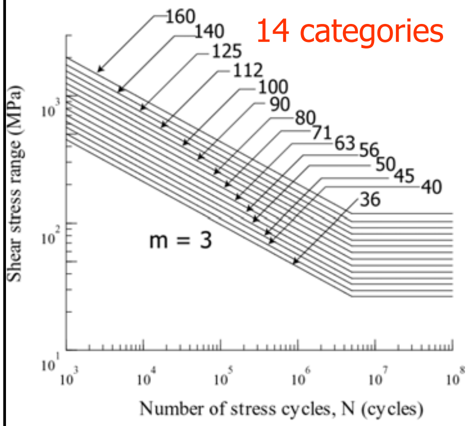
Flow of fatigue design



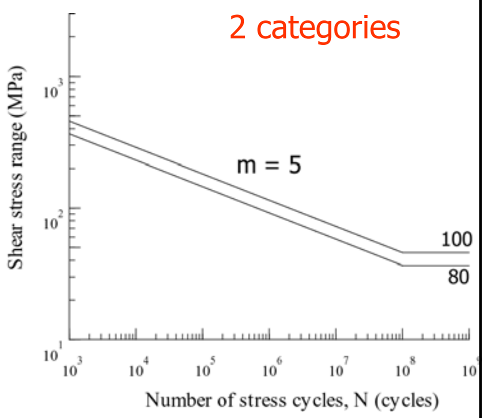
Fatigue Design Curves from IIW and AASHTO

IIW (International Institute of Welding : old)

Welded joints subjected to Normal Stresses

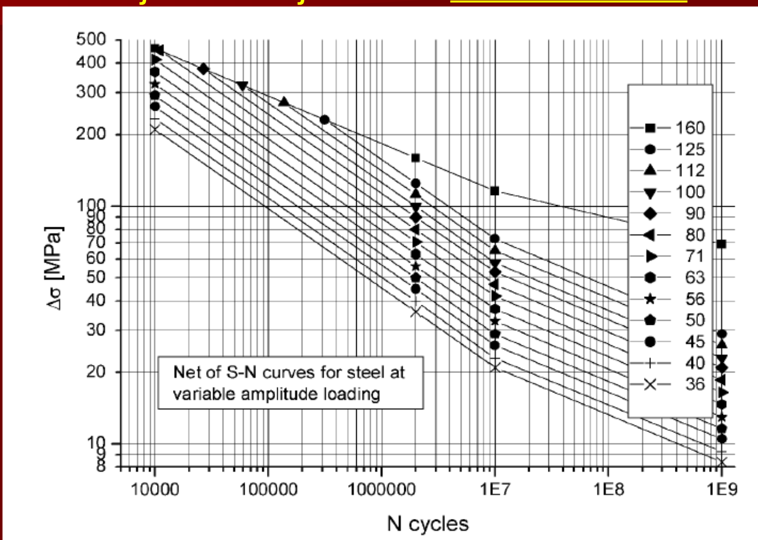


Welded joints subjected to Shear Stresses



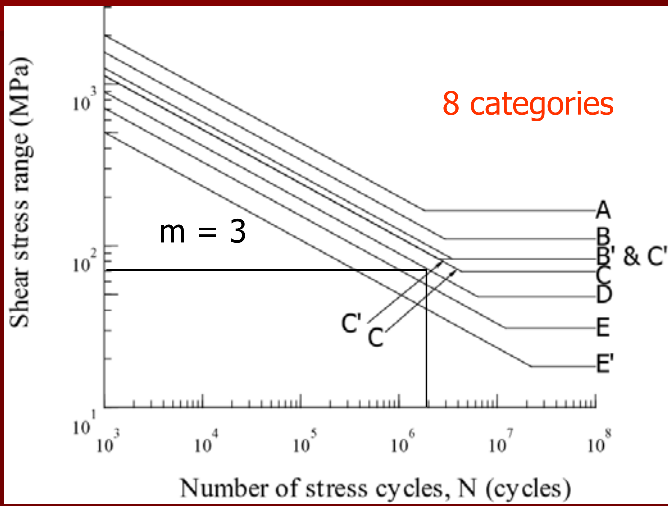
IIW (International Institute of Welding : new)

Welded joints subjected to Normal Stress



AASHTO

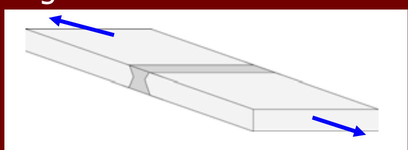
American Association of State Highway and Transportation Officials

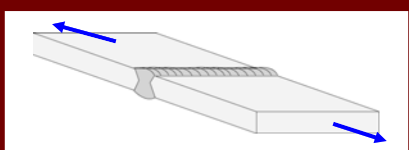


Comparison of Strength Categories

Transverse butt welded joints

	JSSC	IIW	ASSHTO
With ground flush surfaces	155	125	125
As-welded joint → both side welds	100	100 (toe angle = 30)	89
		80 (other toe angle)	

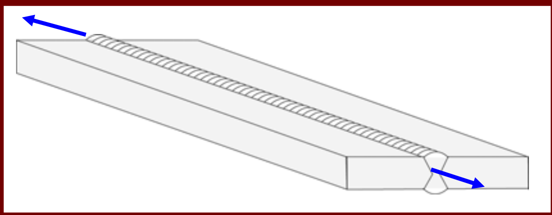




Comparison of Strength Categories

Longitudinal welded joints

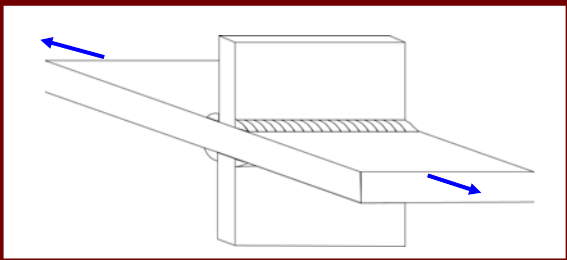
	JSSC	IIW	ASSHTO
Complete penetration groove welded joints from both sides → As-welded	125	125 (without stop/start positions) 90 (with stop/start positions)	125



Comparison of Strength Categories

Cruciform joints → Non load-carrying type

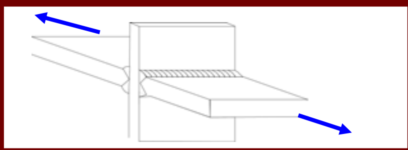
	JSSC	IIW	ASSHTO
Fillet welded joints with finished welded toes	100	100	-
As-welded fillet welded joints	80	80	89

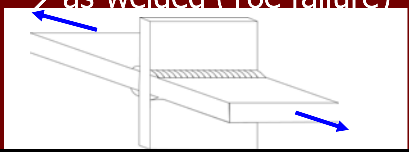


Comparison of Strength Categories

Cruciform joints → Load-carrying type

	JSSC	IIW	ASSHTO
Complete penetration weld → as-welded	80	71	-
Fillet weld or Incomplete penetration weld → as-welded (Toe failure)	65	63	-



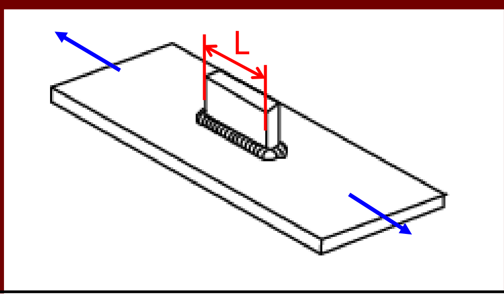


Comparison of Strength Categories

Gusset joints

→ Out-of-plane gusset

	JSSC	IIW	ASSHTO
Joints with fillet welded or groove welded gusset (L<=100 mm) → as-welded	65	80 (L<50) 71 (L<150)	89 (L<50) 71 (50<L<100)

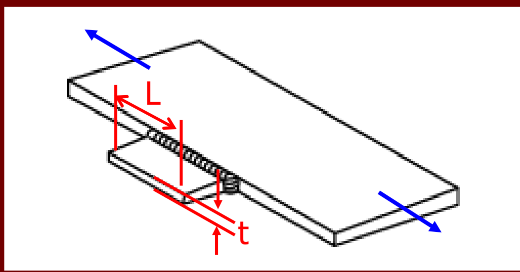


Comparison of Strength Categories

Gusset joints

→ In-plane gusset

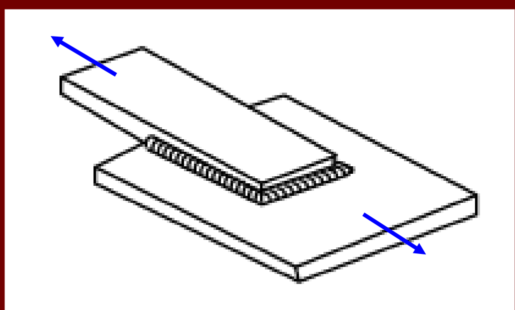
	JSSC	IIW	ASSHTO
Joints with groove welded gusset → as-welded	40	50 (L<150) 45 (L<300) 40 (L>300)	89 (L<50) 71 (50<L<100) **For L>100** **56** (t<25) **40** (t>25)



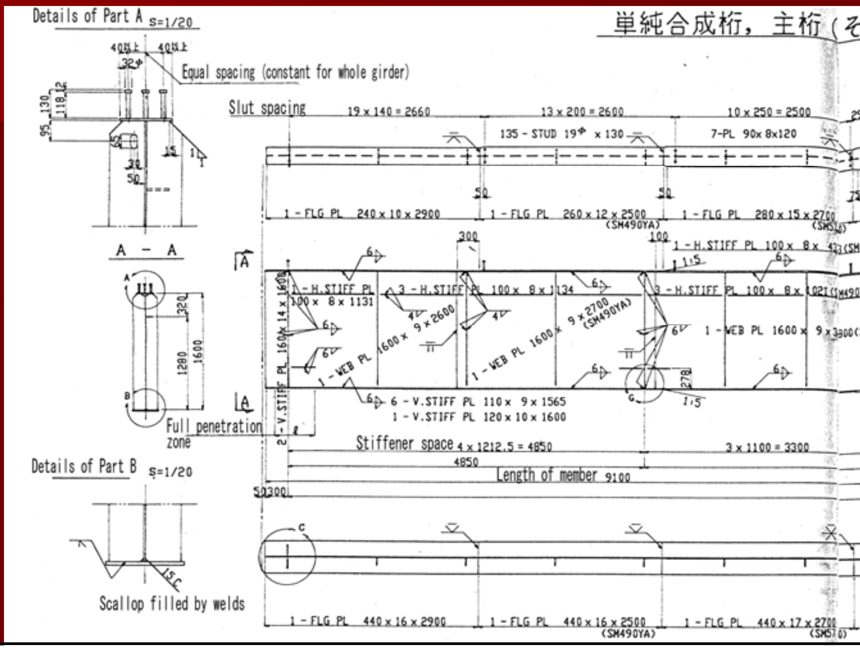
Comparison of Strength Categories

Lapped joints

	JSSC	IIW	ASSHTO
At base plates and splice plates	40	50	40



assignment


Details of Part A S=1/20
単純合成桁，主桁（そ
Equal spacing (constant for whole girder)
Slut spacing
19 x 140 = 2660
13 x 200 = 2600
10 x 250 = 2500
135 - STUD 19φ x 130
7-PL 90x 8x120
1 - FLG PL 240 x 10 x 2900
1 - FLG PL 260 x 12 x 2500
(SM490YA)
A - A
Full penetration zone
6 - V.STIFF PL 110 x 9 x 1565
1 - V.STIFF PL 120 x 10 x 1600
Stiffener space 4 x 1212.5 = 4850
3 x 1100 = 3300
4850
Length of member 9100
Details of Part B S=1/20
Scallop filled by welds
1 - FLG PL 440 x 16 x 2900
1 - FLG PL 440 x 16 x 2500
(SM490YA)