Nominal Stress Based Fatigue Design

Fracture Control Design of Steel structure, #3

Fatigue Design Recommendations

Safety Assessment
in the Fatigue Limit State of Steel Structural Members

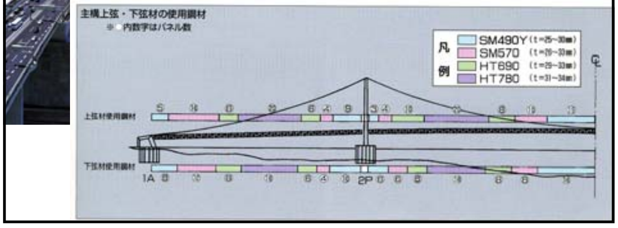
Fatigue Design Recommendations
For Steel Structures
By Japanese Society of Steel Construction (JSSC)
1993(in Japanese), 1995(in English)

⇨ The Reference of Today's Lecture

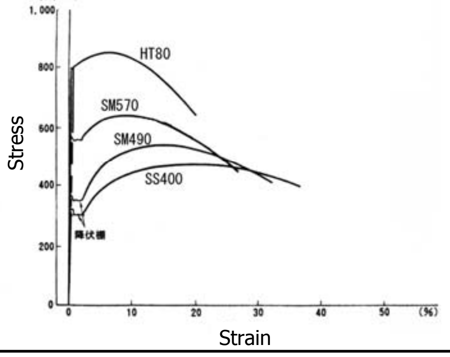
Other Organizations with Recommendations:
AASHTO (American Association of State Highway and Transportation Officials),
IIW (International Institute of Welding) , …

Introduction

Used Steels
in Akashi Bridge (1998)



Stress – Strain Relationship of Various Types of Steels



Steels

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

Ultimate Strengths:

Steels ⟶ 330MPa-1GPa

Wires ⟶ up to 1.6GPa

High Strength Bolts ⟶ up to 1.2GPa

Predominant Factors Controlling Fatigue Strength

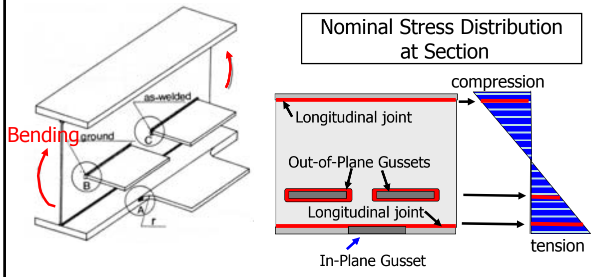
1. Joint Types
2. The Magnitude of The Nominal Stress Range
3. Number of Stress Cycles

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

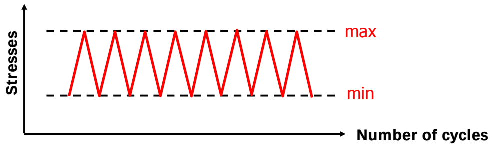
Nominal Stress Ranges

Structures subjected to loads

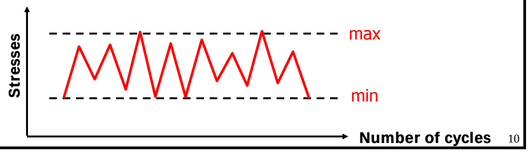


Stress Cycles

Constant Amplitude Stresses



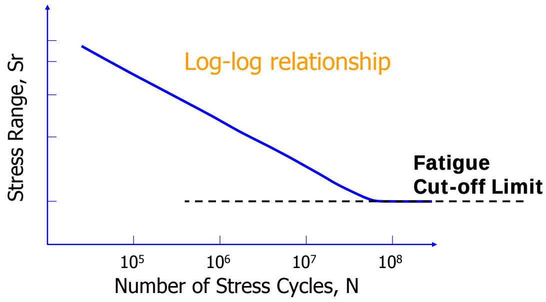
Variable Amplitude Stresses

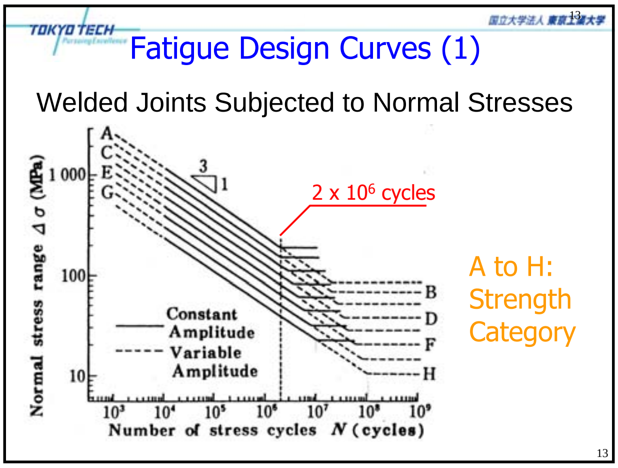


Fatigue Design Curves

Typical Fatigue Design Curves

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



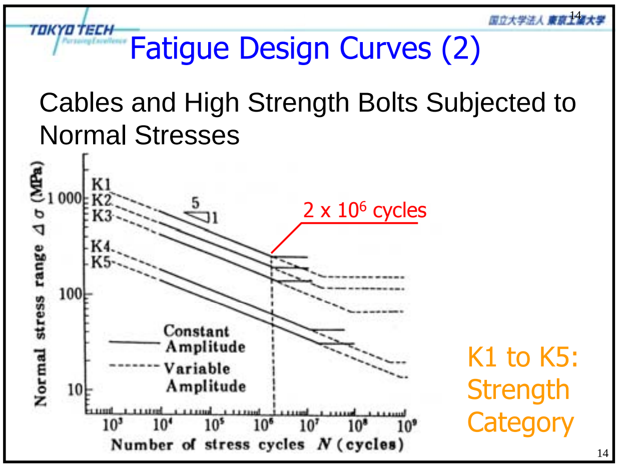


Fatigue Design Curves (1)

Welded Joints Subjected to Normal Stresses

2 x 10^6 cycles

A to H: Strength Category

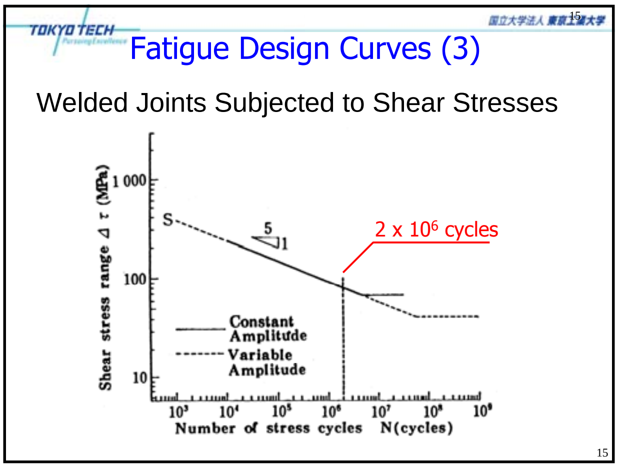


Fatigue Design Curves (2)

Cables and High Strength Bolts Subjected to Normal Stresses

2 x 10^6 cycles

K1 to K5: Strength Category

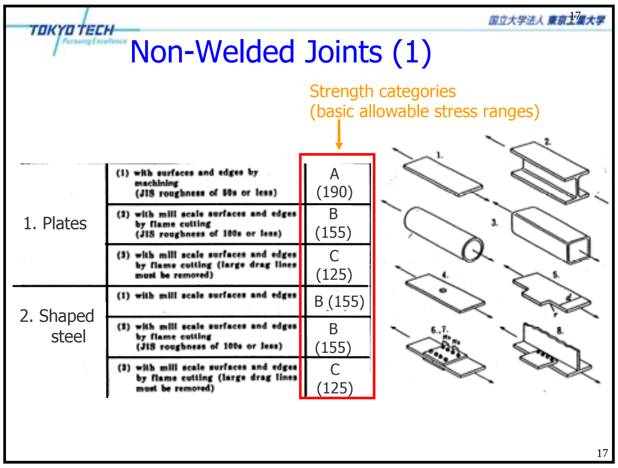


Fatigue Design Curves (3)

Welded Joints Subjected to Shear Stresses

2 x 10^6 cycles

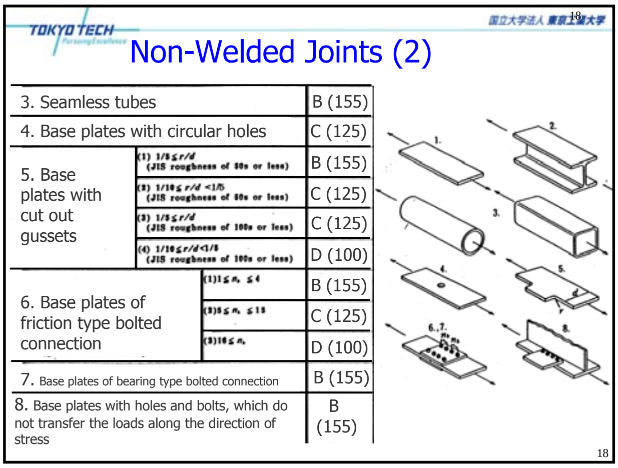
Strength Categories of Joints And Their Basic Allowable Stress Ranges



Non-Welded Joints (1)

Strength categories (basic allowable stress ranges)

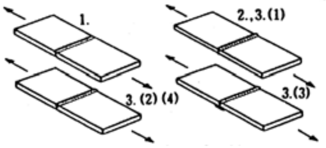
1. Plates	(1) with surfaces and edges by machining (JIS roughness of 50s or less)	A (190)
	(2) with mill scale surfaces and edges by flame cutting (JIS roughness of 100s or less)	B (155)
	(3) with mill scale surfaces and edges by flame cutting (large drag lines must be removed)	C (125)
2. Shaped steel	(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≦r/d (JIS roughness of 50s or less)	B (155)
	(2) 1/10≦r/d <1/5 (JIS roughness of 50s or less)	C (125)
	(3) 1/5≦r/d (JIS roughness of 100s or less)	C (125)
	(4) 1/10≦r/d<1/5 (JIS roughness of 100s or less)	D (100)
6. Base plates of friction type bolted connection	(1)1≦n_1 ≦4	B (155)
	(2)5≦n_1 ≦15	C (125)
	(3)16≦n_1	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)

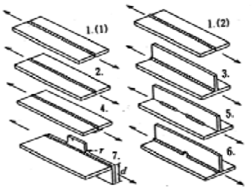
Transverse Butt Welded Joints



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 geomatry	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

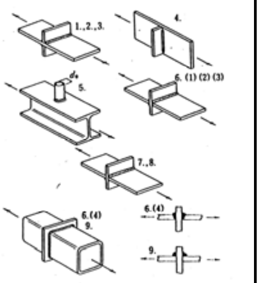
1. Complete penetration groove welded joints from both sides	(1)with ground flush surfaces	B(155)
	(2)as-welded	C(125)
2. Partial penetration groove welded joints		D(100)
3. Fillet welded joints		D(100)
4. Welded joints with backing bars		E(80)
5. Intermittent fillet welded joints		E(80)
6. Welded joints 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

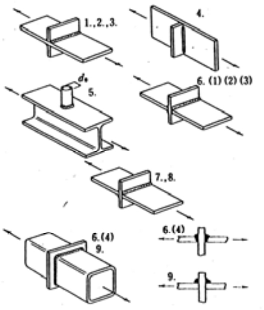
1. Fillet welded joints with smooth weld toes		D(100)
2. Fillet welded joints with finished weld toes		D(100)
3. As-welded fillet welded joints		E(80)
4. **Fillet welded joints including start and stop position**		E(80)
5. Fillet welded joints of hollow section	(1)d_s ≦100 mm	F(65)
	(2)d_s >100 mm	G(50)



Cruciform Joints (2)

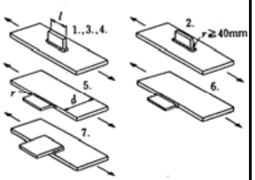
Load-carrying type

	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)



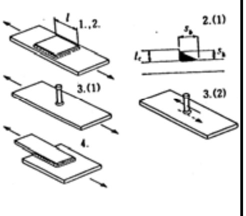
Gusset Joints

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	(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)

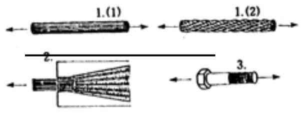


Other Welded Joints

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

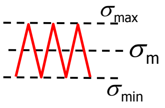
Correction for allowable stress ranges

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

Effect of mean stress

Effect of plate thickness

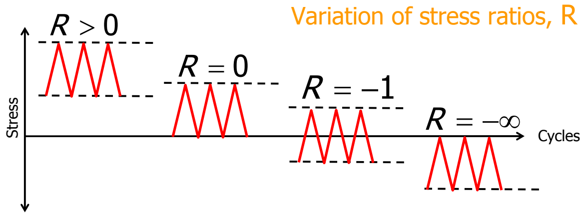
Effect of Mean Stress (1)



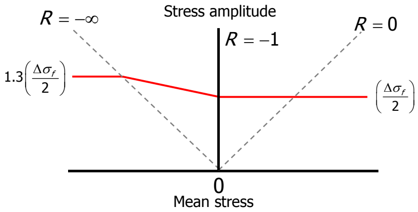
$$\sigma_m(\text{mean stress}) = \tfrac{1}{2}\left(\sigma_{\max} + \sigma_{\min}\right)$$

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

Variation of stress ratios, R



Effect of Mean Stress (2)

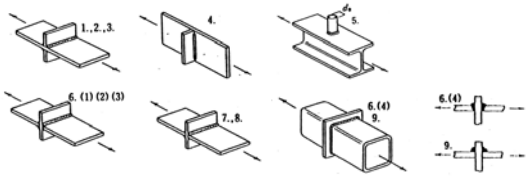


$$C_R = 1.3\left(\frac{1-R}{1.6-R}\right) \quad \text{for } R \leq -1$$

Effect of Plate Thickness

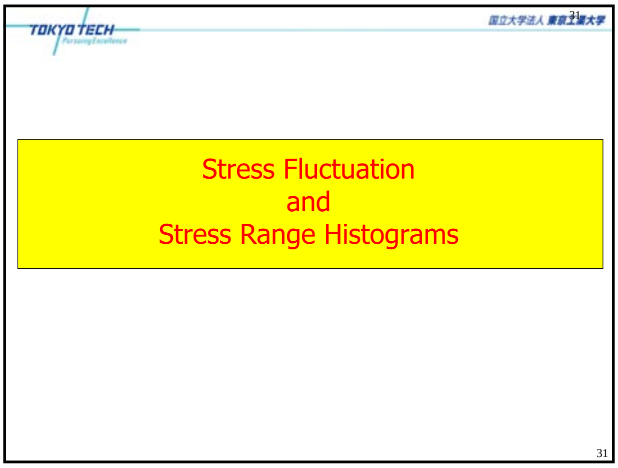
Fatigue strength decreases with increase of plate thickness in some kinds of joints

Example: Cruciform joints

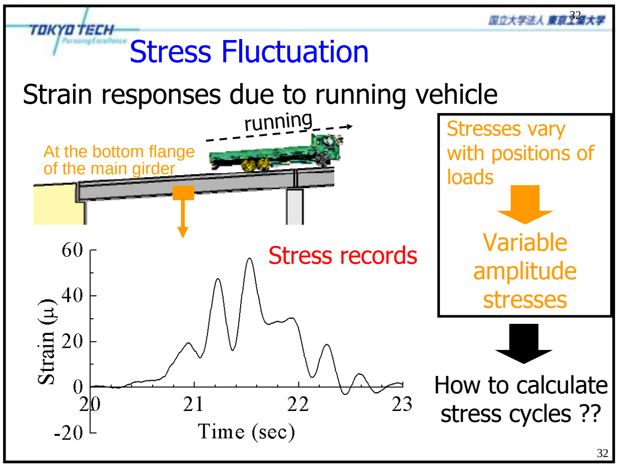


$$C_t = \sqrt[4]{25/t} \quad \text{for t > 25 mm}$$

thickness



Stress Fluctuation
and
Stress Range Histograms



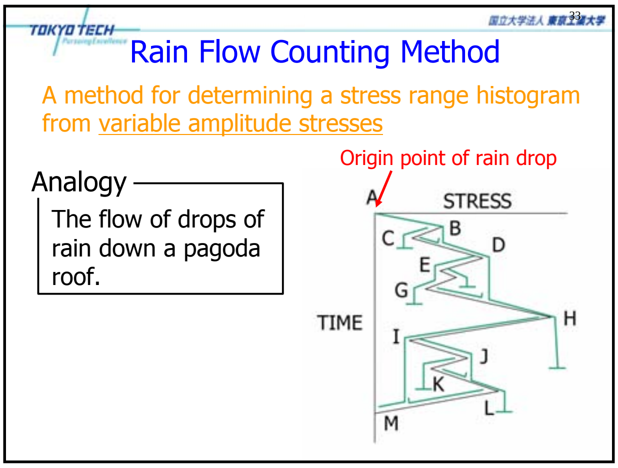
Stress Fluctuation

Strain responses due to running vehicle

Stresses vary with positions of loads

Variable amplitude stresses

How to calculate stress cycles ??

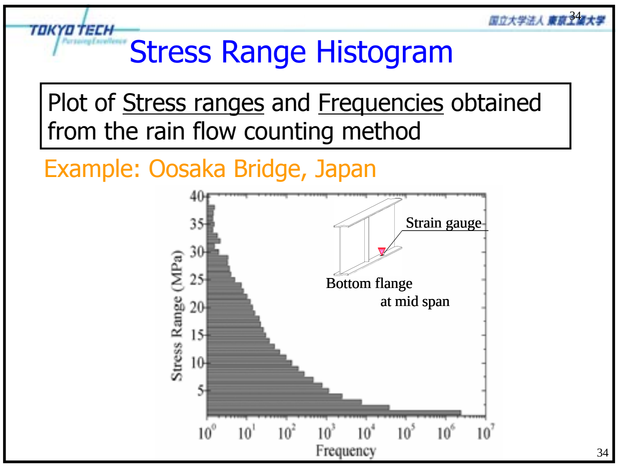


Rain Flow Counting Method

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

Analogy

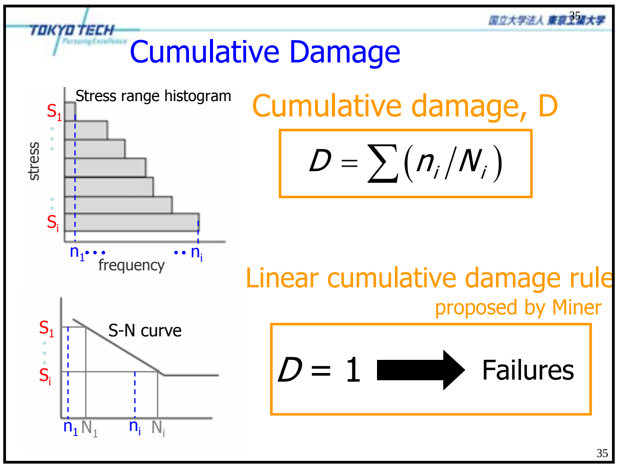
The flow of drops of rain down a pagoda roof.



Stress Range Histogram

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

Example: Oosaka Bridge, Japan



Cumulative Damage

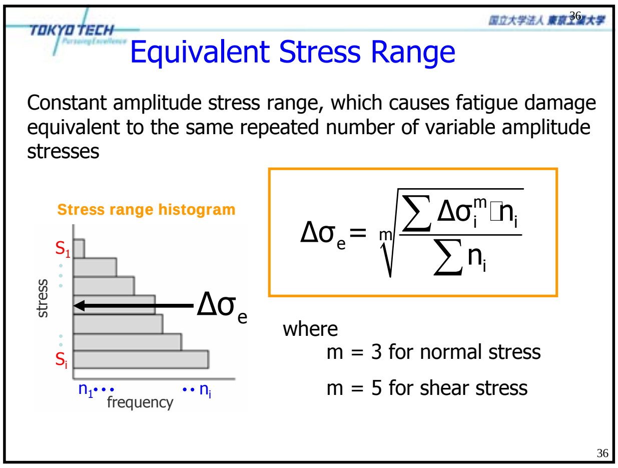
Cumulative damage, D

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

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

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

where

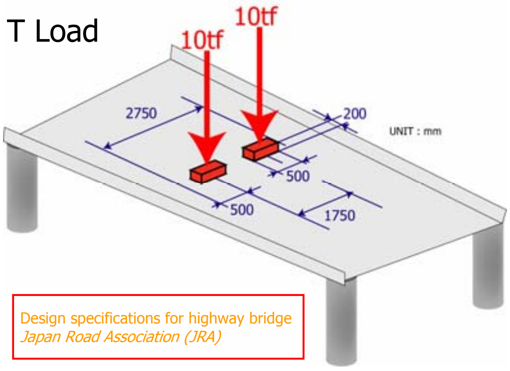
m = 3 for normal stress

m = 5 for shear stress

Fatigue Assessment

Fatigue Design Load

T Load



Design specifications for highway bridge
Japan Road Association (JRA)

Safety Factors

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

$$0.8 < \gamma_b \times \gamma_w \times \gamma_i < 1.25$$

Fatigue Assessment Based on Equivalent Stress Range

This equation should be satisfied.

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

where

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

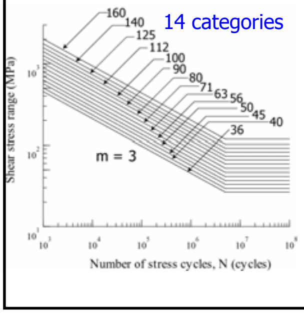
$\Delta\sigma_R$ = allowable stress range

Fatigue Design Curves from IIW and AASHTO

IIW (International Institute of Welding)

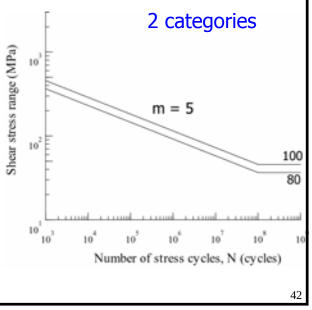
Welded joints subjected to <u>Normal Stresses</u>

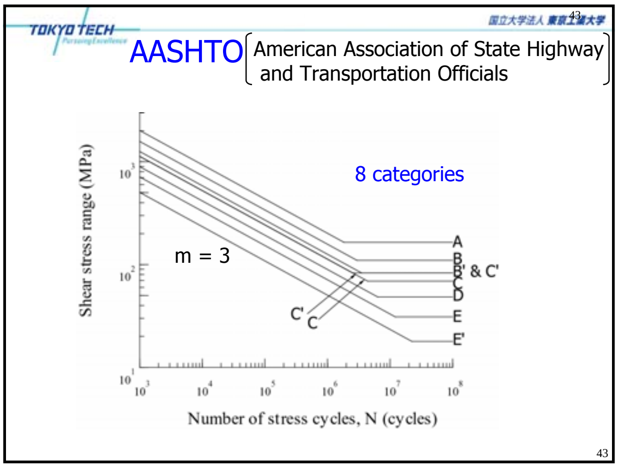
14 categories



Welded joints subjected to <u>Shear Stresses</u>

2 categories



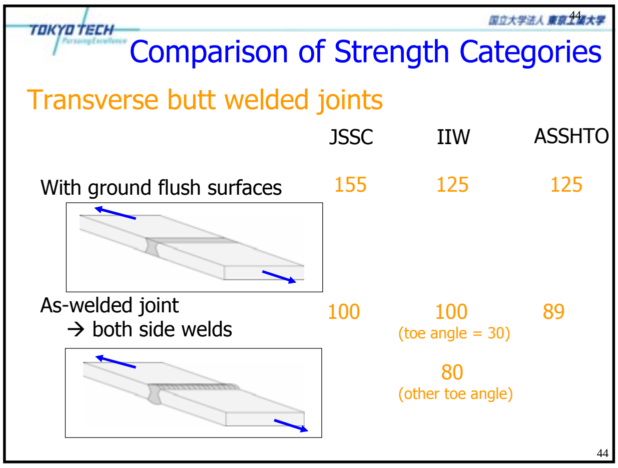


AASHTO

American Association of State Highway and Transportation Officials

8 categories

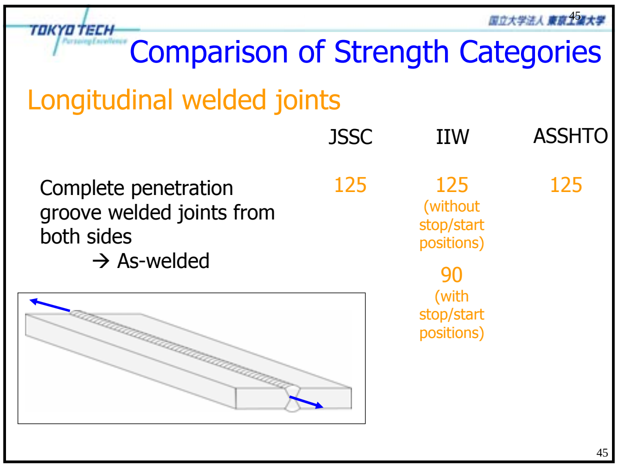
m = 3



Comparison of Strength Categories

Transverse butt welded joints

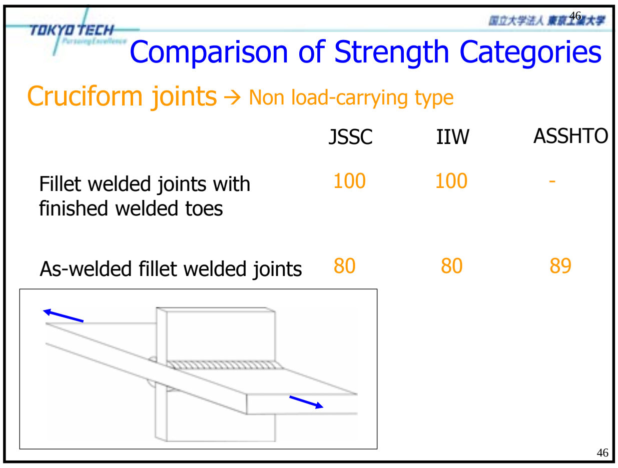
	JSSC	IIW	ASSHTO
With ground flush surfaces	155	125	125
As-welded joint → both side welds	100	100 (toe angle = 30) 80 (other toe angle)	89



Comparison of Strength Categories

Longitudinal welded joints

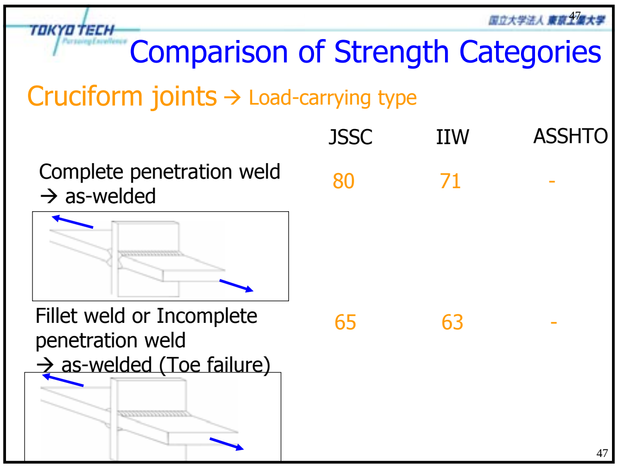
	JSSC	IIW	ASSHTO
Complete penetration groove welded joints from both sides → As-welded	125	125 (without stop/start positions) 90 (with stop/start positions)	125



Comparison of Strength Categories

Cruciform joints → Non load-carrying type

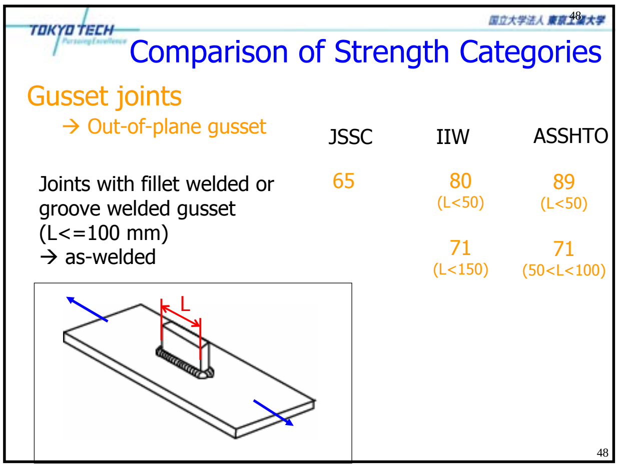
	JSSC	IIW	ASSHTO
Fillet welded joints with finished welded toes	100	100	-
As-welded fillet welded joints	80	80	89



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	-

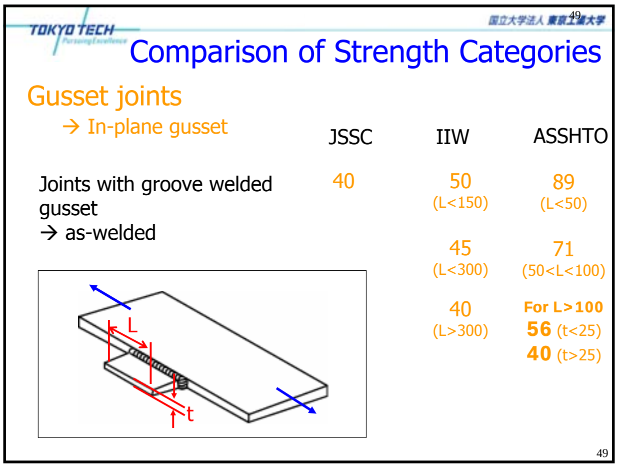


Comparison of Strength Categories

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)

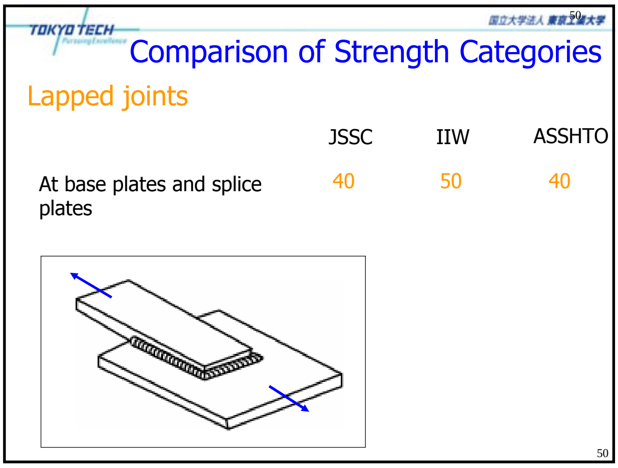


Comparison of Strength Categories

Gusset joints

→ In-plane gusset

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