Fatigue assessment of existing steel bridges

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Type 1 fatigue damage

- SN approach is considered to be a basic of fatigue assessment. Assessment differs with type of structure and fatigue.
- Most common fatigue approach is SN curve approach can be applied to web gusset or flange gusset detail. Those gusset is used for connection between transverse girder and main girder.

  - This fatigue damage is often due to poor details with neglecting fatigue problem.
  - This type of fatigue will spread rapidly in the near future judging from severe live load condition of highway in Japan and experience of the other country
  - should be treated as first priority fatigue problem.

2

Type 2 fatigue damage

- 2nd common fatigue problem which hold the majority of highway bridge's fatigue crack is located at joint between perpendicularly connected members. Displacement induced fatigue or web gap fatigue is relating to this problem.
- The cause of this fatigue is directory connected to live load and assessment is relatively easy.

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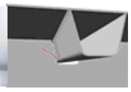
Type 3 fatigue damage

- 3rd important fatigue problem is complicated and detailed analysis is required to clear the phenomena. Fatigue on steel bent beam column connection, Orthotropic deck plate fatigue problems are also assessed by SN approach.

  - Design stress often differ much from actual stress
  - Weld quality or unwelded zone caused by plate arrangement has strongly related.
  - Additional consideration is necessary when the SN approach is applied.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Fatigue failure

- Fatigue can be classified in 3 stages
- 1st stage : initiation of fatigue crack $S_r \cdot N^{-5} = const$
- 2nd stage : propagation of fatigue crack $S_r \cdot N^{-3} = const$
- 3rd stage : unstable fatigue crack propagation $K \geq K_{IC}$
- It is said that initiation of fatigue crack is depth of 0.1 mm order.

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Overview

- There are different expressions to express fatigue strength.
- Stress range corresponding to 200 million cycle on SN curve is called "allowable fatigue stress range".
- 1) Stress range with variable amplitude is converted to equivalent stress range and compared to allowable fatigue stress range of a specific fatigue class. $\Delta\sigma_1 \leq \Delta\sigma_{a200}$
- 2) Cumulative damage [D] is calculated from stress histogram by adapting a specific SN curve

$$D = \sum \frac{n_i}{N_i} \leq 1.0$$

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JSHBFR Fatigue assessment stage 1 : rough assessment

- Following Bridge is regarded to have safety against fatigue crack.

Type	Steel girder bridge with concrete slab
Joint type	Fatigue class A to F
Steel material	SS400, SM400–520, SMA400–520
Span length	≧50m
$ADTT_{SL,i}$	≦ 1000/(day,lane)

- JSHBFR :Japan Steel Highway Bridge Fatigue Design Recommendation

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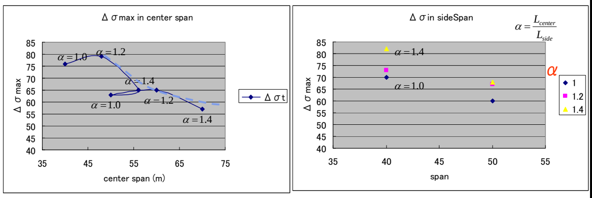
Δ σ max vs Span length



Class F : Δ σ ce = 46 MPa

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JSBFR Fatigue assessment stage 2

- Safe when following relation is satisfied

$$\Delta\sigma_{max} \le \Delta\sigma_{ce} \cdot C_R \cdot C_t$$

- Δ σ $_{max}$: maximum stress range due to design fatigue live load
- Δ σ $_{ce}$: Fatigue cut off limit under constant amp.
- Δ σ $_t$: stress range due to design fatigue load (200kN).
- C_R : average stress correction factor
- C_t : thickness effect correction factor

$$\Delta\sigma_{max} = \gamma_{t1} \cdot \gamma_{t2} \cdot (1 + i_f/2) \cdot \gamma_a \cdot \Delta\sigma_t$$

$\gamma_{t1} = \log L_{B1} + 1.50, (2.0 \le \gamma_{t1} \le 3.0)$ Live load correction factor

$\gamma_{t2} = 1.10 (for\ 50m < L_{B2}\ \&\ 2000 < ADTT_{SLi})\ or\ 1.0$ simultaneous loading correction

$i_f = 10/(50 + L)$ Impact factor

$\gamma_a = 0.8\ or\ 1.0$ Concrete slab girder with Grid or beam model

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JSBFR Fatigue assessment stage 3

- Safe when following relation is satisfied

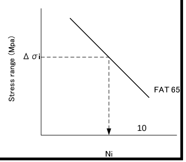
$$D = \sum \frac{n_i}{N_i} \le 1.0$$

- D : cumulative damage, sum up of damages due to stress ranges larger than cut off limit of variable amplitude stress
- Ni : fatigue life corresponding to i-th stress range
- ni : number of repetition of stress range i.

$$N_i = (C_R \cdot C_t)^m \cdot C_0 / \Delta\sigma_i^{\ m}$$

$$C_0 = 2 \times 10^6 \cdot \Delta\sigma_f^{\ m}$$

$$\Delta\sigma_i = \gamma_{t2} \cdot (1 + i_f/2) \cdot \gamma_a \cdot \Delta\sigma_t$$



Fatigue assessment stage 3

- Stage 3 Process
  - Select fatigue critical joint. Fatigue class of F(65), G(50), H(40) are targets.
  - Fatigue design load W=20 ton is modified by impact, analysis correction, simultaneous loading correction
  - Δ σ $_i$: Maximum live load stress range due to W
  - Repetition of live load in each line : n_i=ADTT*0.03*365*Year/n_L ; n_L : number of lane
  - Safe if $n_i/N_i \le 1.0$
  - If more than one stress range exist, use $\sum n_i/N_i \le 1.0$

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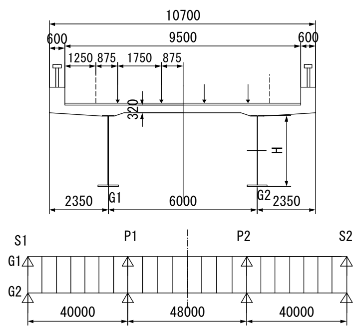
Example of Fatigue assessment with Steel Girder Bridge



Fatigue assessment conditions	
Design life	100 years
Design fatigue load	200 kN
Frequency correction Factor	0.03
Structural analysis correction factor	1
Impact Factor	1/2 of JSHBS
ADTT	1000 2000 3000

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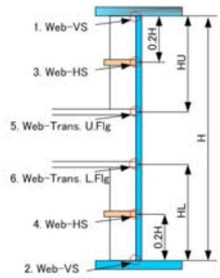
Fatigue Check Points on Girder



Check Point	Joint Detail	
1	Non-load carrying cruciform joint Fillet weld including weld start end	E
2		E
3	Out of Plane Gusset with Fillet Weld (L>100mm)	G
4		G
5		G
6		G

H=2900,HU-HL=1150

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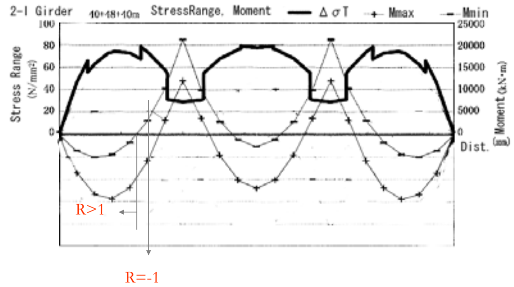
Stress Range $\Delta\sigma_T$ calculation



Actual moment distribution

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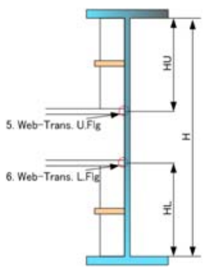
Fatigue Check for Cross Beam



In case of 2 I girder bridge, Fatigue stress in load carrying cruciform joints between main girder web and cross beam flange is small enough that fatigue check can be neglected.

In case of multi girder bridge, it is necessary to check root failure (H class) by using throat length. tw=10mm, s=6mm (weld size)

$$a = s/\sqrt{2} \times 2 = 8.5mm$$

stress correction =t/a=1.18

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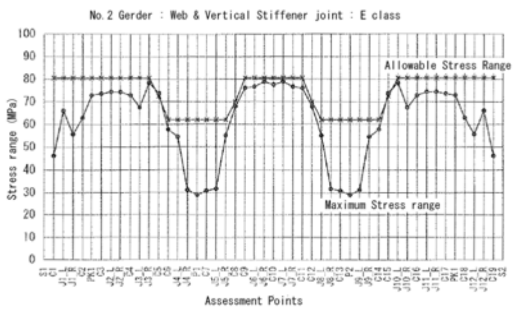
Stress Range calculation



Calculation of stress range

- Calculate stress fluctuation by grid model with moving fatigue load.
- Distribution of stress range is obtained from the difference of max. and min. live load moments divided by section modulus.
- Dead load stress is necessary to obtain R (stress ratio) to accomr $\Delta\sigma_{max} \leq \Delta\sigma_{ce} \cdot C_R \cdot C_t$
- JSHBS stage2
  - σ_{ce}=62(E), 32(G)

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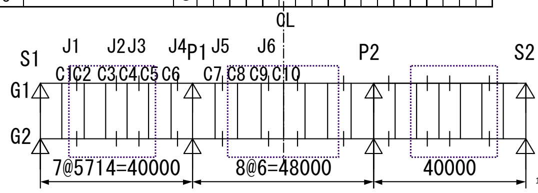
Results of Stage 2

Joints not satisfying constant amplitude fatigue cut off conditior

Check	Joint Detail		S1	C1	J1	C2	C3	J2	C4	J3	C5	C6	J4	P1	C7	J5	C8	C9	J6	C10
1	Non-load carring cruci. joint Fillet weld including weld end	E									×									
2		E			×	×	×	×	×	×	×							×	×	×
3	Out of Plane Gusset with Fillet Weld (L>100mm)	G					×	×	×	×	×						×	×	×	×
4		G									×						×			
5		G																		
6		G																		



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Fatigue assessment stage 4

- Assessment based on inspection and stress measurement
  Improve the accuracy by measurement data. Select target members by stage 1,2 or fatigue prone portions as reported to have fatigue crack, vibration, and other damages before.
  - Assessment is based on hot spot stress.
- Required data
  - hot spot stress measured in field
  - 24 hours stress histogram obtained by rain-flow method.
  - Assumed fatigue stress history during its service period.

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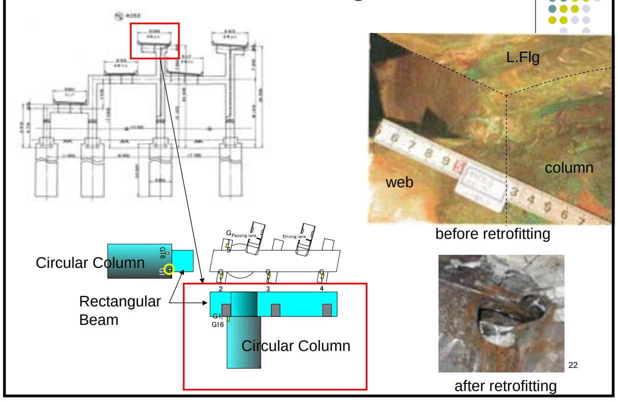
Circular column fatigue crack



before retrofitting

after retrofitting

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Fatigue assessment stage 5

- Assessment after the detection of fatigue crack, remaining fatigue life is calculated.
  - Fracture mechanics is applied to calculate the remaining life based on the crack information and stress data. Retrofitting detail is discussed.
- Required data
  - Crack size and shape : Semi elliptical shape can be used for estimation when depth information is unavailable.
  - Stress to calculate stress intensity factor. Coefficients C, m, ΔKth from JSSC. Average or most safe line is selected.
  - Fatigue life of plate is ended when 80 % of thickness is cracked in case of Surface crack.
  - Risks are classified into 3 categories, 30, 100, 500mm of surface crack length. Correction is necessary with consideration of joint type, stress state, and structural redundancy.

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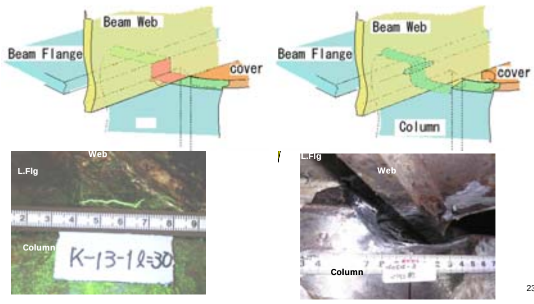
Kan4054 Retrofitting

Before the removal

After the removal



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Fatigue Assessment stage 4

- Rain flow stress range calculation applied to dynamic stress records
- Fatigue assessment of weld root of joint

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Measurement & analysis

1. 24h stress measurement
2. Relation between stress and location of loading vehicle.
3. Stress histogram & dynamic stress record analysis
4. Maximum stress range distribution（24h ＆ 1min）
   ⇒determine measurement point for local fatigue
   stress on weld bead
5. Detailed stress measurement（1 weld bead 1.5h）

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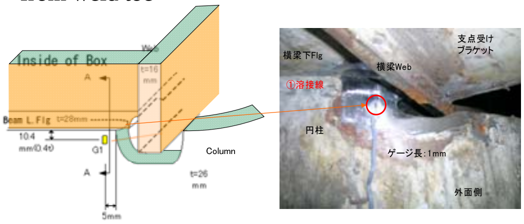
1. 24 h stress measurement

- Location of gauges･･･stress concentrated area near retrofitted scurrup, 5mm apart from cutting edge, 0.4t from weld toe



Trans-beam L.Flg & Column weld (external side)

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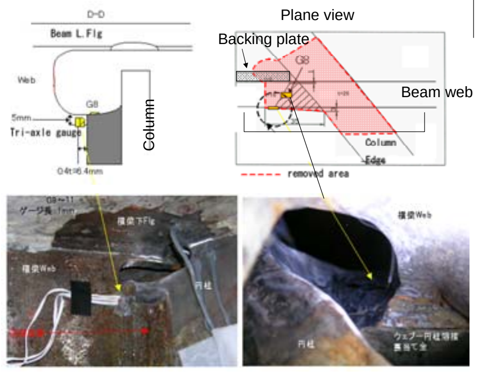
Inserted Web local stress at beam-column junction after the remedy (G8-11)



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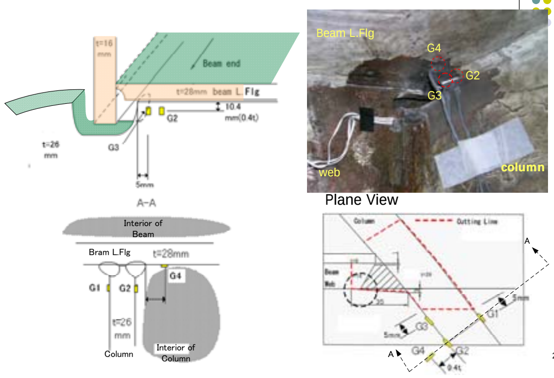
Beam L.flg & column local stress at beam-column junction (internal side G1-G4)



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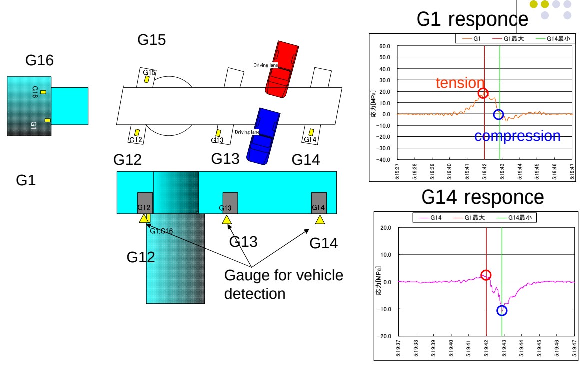
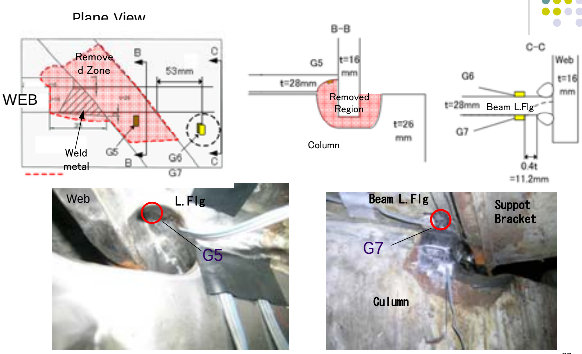
2.Response of G1 gauge during the passage of loading 1



Beam corner Local Stress at beam-column junction after the remedy (G5-7)



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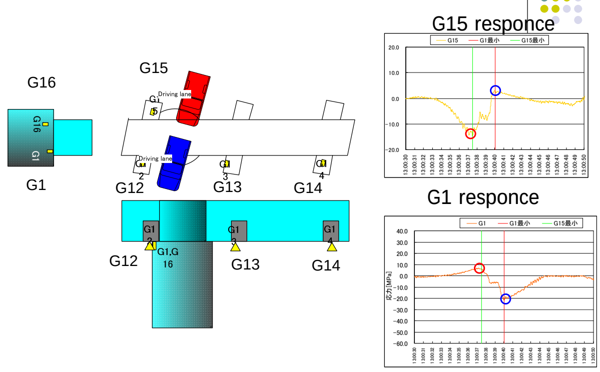
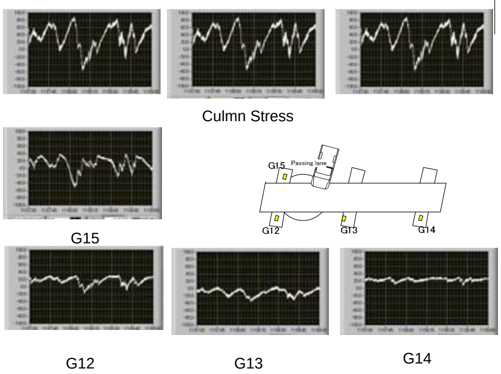
2.Response of G1 gauge during the passage of loading 2



Response due to passig lane load



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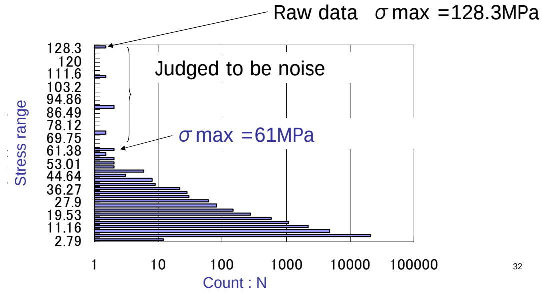
3. Calculation of stress histogram and maximum stress range

G1ゲージ

Histogram obtained by rain flow method



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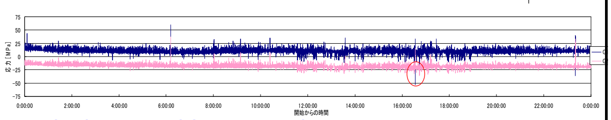
Noise filtering & Rain flow

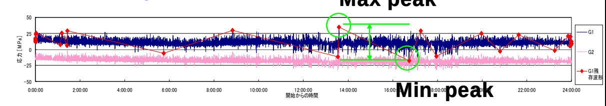
24h stress record (without filtering)



Noise is removed from Dynamic stress data by visual check.

Noise components

Max peak



Min. peak

Peak value extracted from 24h dynamic data

Max stress range = max peak – min peak = 52MPa
Rain flow applied to 1 minute segment of dynamic data : 36.3MPa in tension, 34.2MPa in compression

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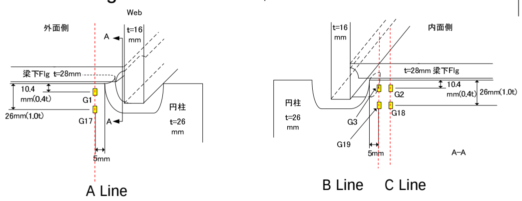
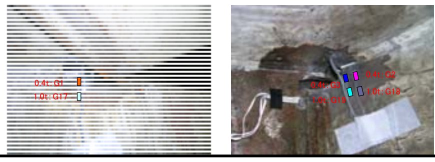
5. Maximum hot spot stress range measurement

Gauge location : 0.4t, 1.0t from weld toe





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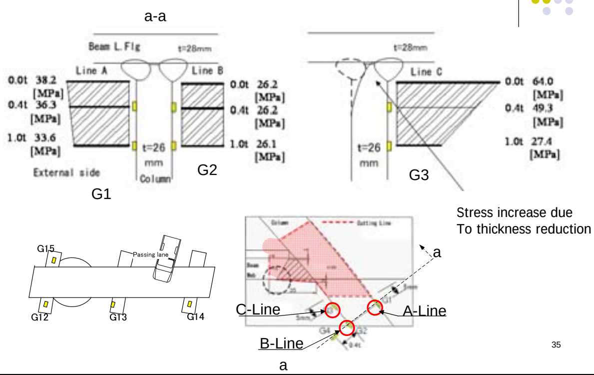
Hot spot stress with vehicle on cruising lane



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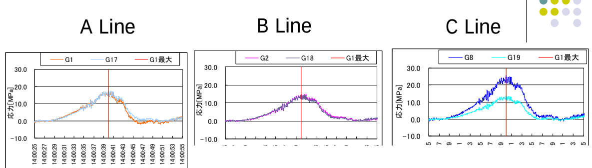
Hot Spot Stress Response due to Loading Vehicle



vehicle location	gauge line	1.0t	0.4t	H.S.S.
cruising lane	A	0.92	1.00	1.05
	B	1.00	1.00	1.00
	C	0.55	1.00	1.00
passing lane	A	0.84	1.00	1.11
	B	1.07	1.00	0.96
	C	0.59	1.00	1.28

Hot spot stress : stress extrapolated to weld toe normalized by stresses at 0.4t

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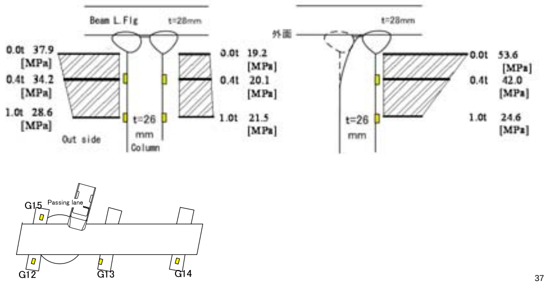
Hot spot stress with vehicle on passing lane



2. fatigue assessment using Local stress

1. Assessment using Structural Hot Spot Stress
   1. Applicable to the point where Nominal Stress can not be determined
   2. Dynamic stress records are necessary because distribution of stresses at the same moment of time are required.
   3. Understanding of relation between stress histogram and actual stress fluctuation is necessary.
   4. Not applicable to root crack in general

Remarks on measured stresses

1. Stresses response in the beam column joint are affected by the location of vehicle.
2. Stress range is the largest in the weld at G1 gauge (50 MPa at outside 0.4t)
3. Stress increase due to geometric concentration is small but due to thickness change for retrofit is remarkable.
4. Histogram meter sometimes gives extreme value which is caused by noise and hard to check later.

Fatigue strength w.r.t H.S.S

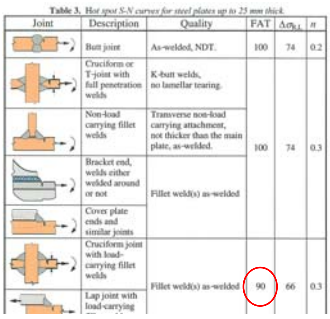
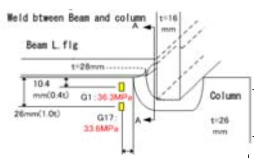


Table 3. Hot spot S-N curves for steel plates up to 25 mm thick.

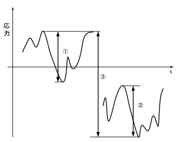
Joint	Description	Quality	FAT	$\Delta\sigma_{k,L}$	n
	Butt joint	As-welded, NDT.	100	74	0.2
	Cruciform or T-joint with full penetration welds	K-butt welds, no lamellar tearing.	100	74	0.3
	Non-load carrying fillet welds	Transverse non-load carrying attachment, not thicker than the main plate, as-welded.			
	Bracket end, welds either welded around or not	Fillet weld(s) as-welded			
	Cover plate ends and similar joints				
	Cruciform joint with load-carrying fillet welds	Fillet weld(s) as-welded	90	66	0.3
	Lap joint with load-carrying …				

IIW-1819-00 Structural Hot-spot Stress Approach to Fatigue Analysis of Welded Component

6.Results of stress measurement



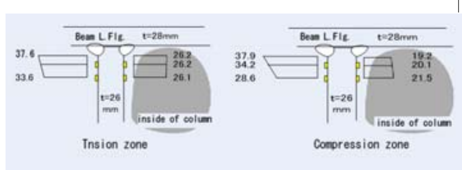
Max Stress point



Stress Range calcuration of 24h measurement (1.0t)

processor	data	Stress Range	
Spectrum meter	raw data	128	
	noise filtered	61	
dynamic wave analysis	noise filtered	52	
	tension zone	36	①
	compression zone	33.6	②
	max range	50.1	③

H.S.S. at the pier connection



	1.0t	0.4t	H.S.S	24 h measurement: HSS increment to 0.4t stress	Stress Peak Value at 0.4t	H.S.S.
tension	33.6	36	37.6	4%	19.8	20.6
compression	28.6	34.2	37.9	11%	−32.7	−36.3
				maximum H.S.S. range		56.9