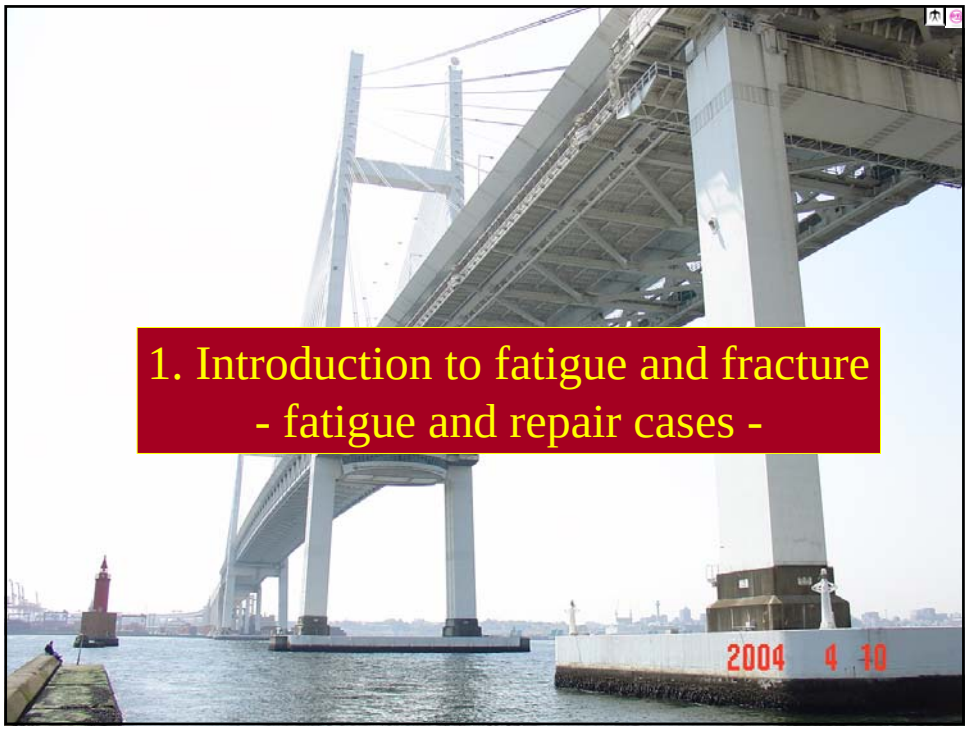


1. Introduction to fatigue and fracture
- fatigue and repair cases -

Social Infrastructure

Constructed in the Order of Demand (1960s-1970s)

The Greater the Importance
The More Severe the Service Condition
The older the Used Technology

Fix it？

or

Scrap it？

3

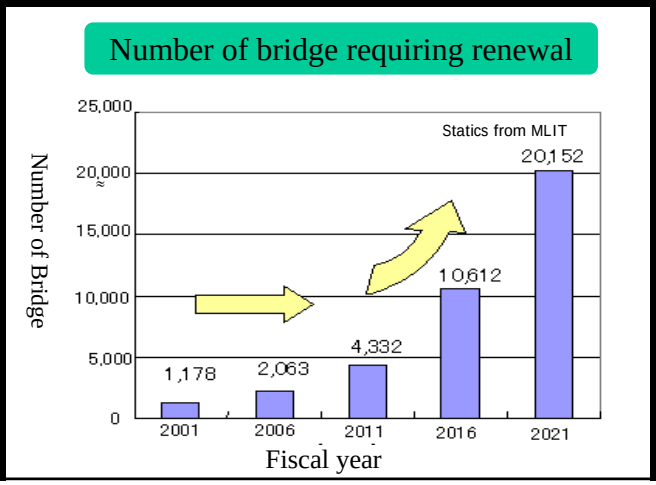
(2005)

The Metropolitan Expressway (40 Years Ago)

4

Design life of bridge ≈ 50 years(?)

Number of bridges requiring renwal increases rapidly from now

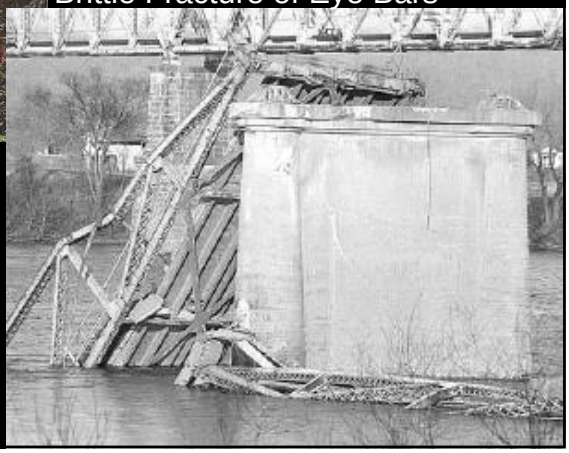


Silver Bridge (Point-Pleasant Br.)

At 5:00 PM on December 15, 1967

Overload due to Christmas Rush

Brittle Fracture of Eye Bars



- claiming 46 lives and injuring 9

Collapse of the Silver Bridge

At 5:00 PM on December 15, 1967, the Silver Bridge collapsed claiming 46 lives and injuring 9. The Christmas rush applied an extra load to the 39 year old bridge causing a cleavage fracture in one of the “eyebars”. This was followed by a ductile fracture near the pin. Unable to support the weight of the entire bridge, the south side chain also snapped. The structure only took about 1 minute to completely fall into the river below. An investigation, led by John Bennett, immediately followed the collapse of the Silver Bridge. The bridge was constructed of carbon steel, which tends to crack. Many cracks were found throughout the bridge among extensive corrosion. The failure resulted from stress corrosion and corrosion fatigue, two concepts which were not known in 1927.(1) It was also found that the flaw could not have been detected, even by today's methods, unless the bridge was taken apart and tested.(1) In addition to the investigation, “the federal government mandated the National Bridge Inspection Standards (NBIS). The new standards required periodic inspection of all the nation's bridges.”(3)

7

Williamsburg Bridge Open on December 19, 1903 (103 years)

- deterioration has been progressed in some damage prone part where difficult to maintain or reach.
- NY spent so much money on old but irreplaceable bridge to improve bridge health condition.

8

Williamsburg Bridge

9

Williamsburg Bridge

10

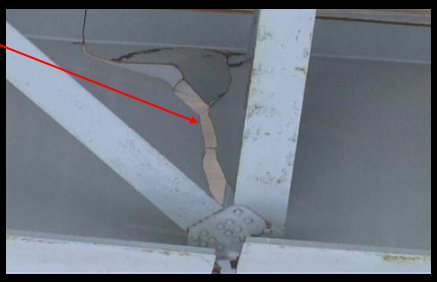
2000 Brittle Fracture
In Hoan Bridge

brittle ⟺ ductile

- two of the bridge's three support beams had failed and the deck was sagging approximately four feet.
- The Hoan was immediately closed in both directions

11

Hoan-bridge Brittle fracture



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

12

on December 28, 2000, the buckled portion of the bridge was removed without incident.
the southbound lanes were reopened on February 17, 2001 with one lane of traffic in each direction.
on October 11, 2001, re-opening the bridge to traffic, although only two lanes in each direction were initially available.

All six lanes were cleared and made available on November 1, 2001.
11 month after the fracture.

http://www.jsonline.com

Hoan Bridge

Two of the bridge's three support beams had failed and the deck was sagging approximately four feet. The Hoan was immediately closed in both directions with no injury or loss of life while engineers then rushed to the scene to examine the situation and begin mulling over potential solutions. The affected span did not collapse, though, as the third and final support beam kept it from failing, although one source notes "the final girder sustained considerable stress damage until the bridge span was felled two weeks later."
on December 28, 2000, the buckled portion of the bridge was removed without incident.
the southbound lanes were reopened on February 17, 2001 with one lane of traffic in each direction.
on October 11, 2001, Governor Scott McCallum was the first to drive over the newly-repaired northbound lanes at 10:00 am, officially re-opening the bridge to traffic, although only two lanes in each direction were initially available. All six lanes were cleared and made available on November 1, 2001, officially completing the repair work in less than eleven months.

http://www.wisconsinhighways.org/indepth/hoan_bridge.html

Fatigue and Repair Cases in Steel Bridges

Causes of Fatigue Damage

Welded bridges : positively adopted since 1960

Main highways and railways in Japan
Tomei, Metropolitan Exwy,
Shinkansen, ...

Sensitive to fatigue

Fatigue damage
1960- in USA
1970- Shinkansen in Japan
1980- Highway bridges in Japan

Repair and retrofit

Identify the cause of fatigue damage

Information from experiences

IIW Com. XIII, WG 5
Collection of damage and repair cases
Arrange these as the database on internet

17

Fatigue Cases and Retrofit Works in Steel Bridges

Causes of fatigue damage

1. Weld-defects
2. Inappropriate structural details
3. Unforeseen stresses and displacements
4. Unexpected structural behavior, such as vibration

Approach to repair and retrofit

Remove the causes of damage
Increase fatigue resistance

-----→Design of New Structures

18

Selection of repair and retrofit methods and/or replacement

Explanation of the causes of damage is indispensable

There are cases,
*immediate measure is necessary
*leave the component untouched some years

Depending on the cause of damage
Mechanism of crack initiation and propagation

Cause of Fatigue

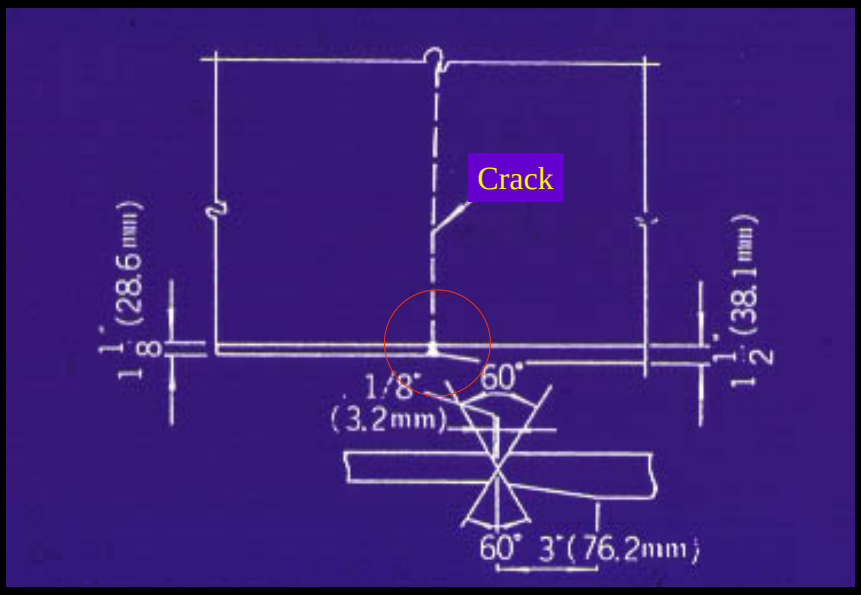
1. Existence of weld-defects
   1. Butt welds (U.S)
   2. Butt weld (Japan)
2. Adoption of low fatigue resistance detail
   - Case-1: Bridges were not designed against fatigue.
   - Case-2: Inappropriate Allowable fatigue stresses in old codes and specifications
3. Unforeseen stresses and displacements
4. Unexpected structural behavior (vibration)
   - Fatigue Crack due to Vibration Induced by Wind

Case 1 : Cracked Girder: Fatigue crack initiated from insufficient penetration

21

- two spans continuous girder(45.7 + 45.7m), constructed in 1949.
- This cracking accident was found in 1981.

22



23

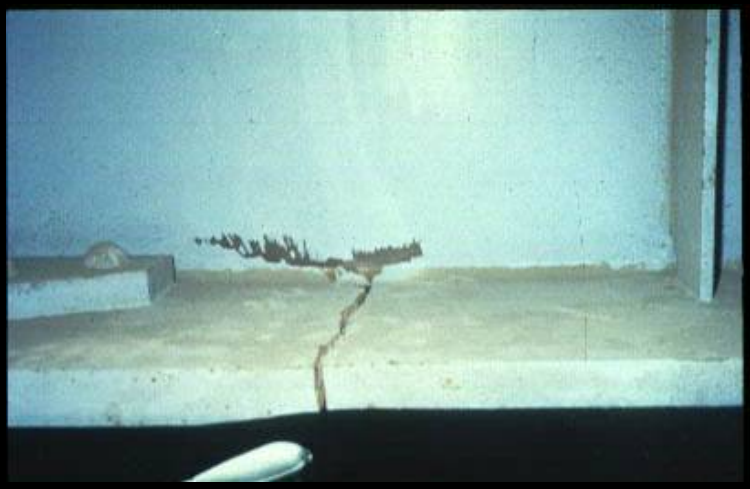
wide zone of incomplete penetration was remained in the center part of joints.

24

CASE2 : Case in a simply supported composite girder bridge of 30.3m span in Tokyo, Japan. This bridge was constructed in 1973 and fatigue cracks were found in 1988.

Imperfect butt-welding of bottom flanges

25

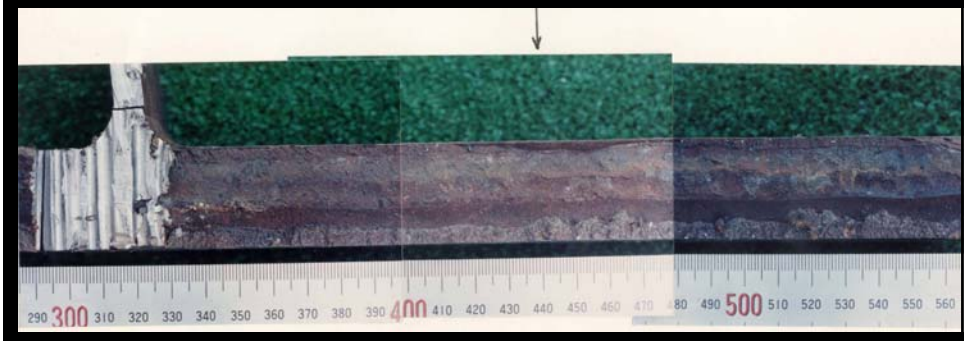


- Fatigue cracks cut the whole section of bottom flange
- Cracks are arrested in fillet welds between the flange plate and the web plate due to large plastic deformation of weld metal.

Fracture Surface

26

Unwelded Zone reaches 60-80% of thickness

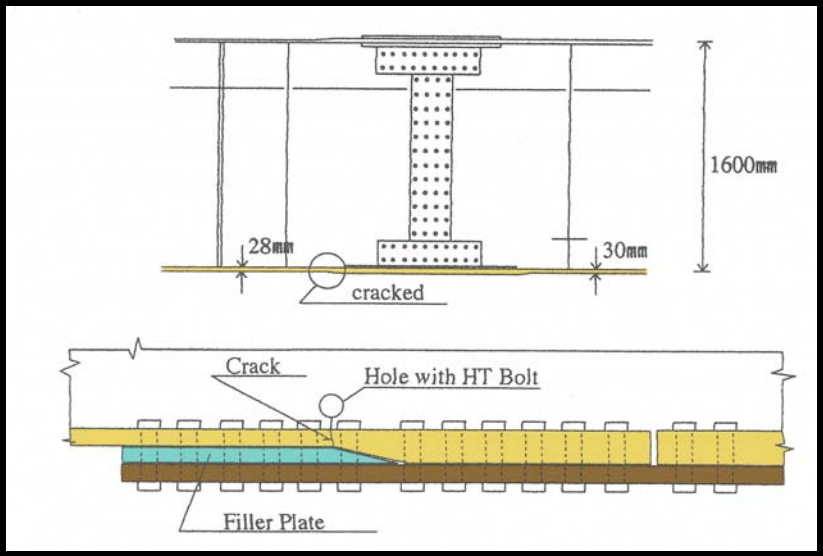


- Multiple fatigue cracks initiated along the root of incomplete penetration welds in the plate butt welds.
- The zone of incomplete penetration occupied about 60% of width and 60% of thickness of butt weld.
- The groove of butt welds should have been K shape for full penetration.

- It is close to impossible to predict the occurrences of fatigue damage caused by defects because these are failures of quality control of factory.
- However, it will be possible to inspect intensively upon joints made in the same factory around the same time using the same welding details.
- Weld defects of incomplete penetration were discovered in 45 joints out of 388 joints.

Inspection by Ultrasonic Testing and Macro Etching was conducted to all the joints

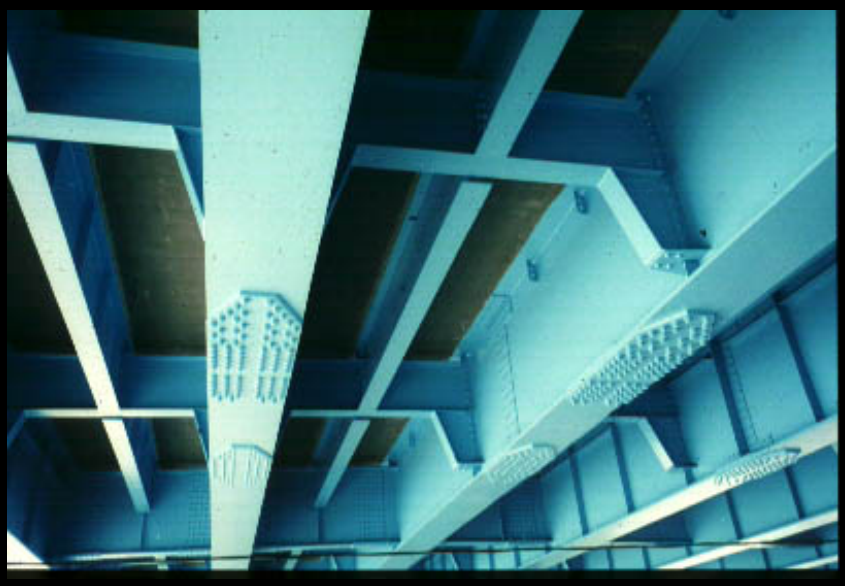
Repairing by bolted splice



29

Splice only on flange

30



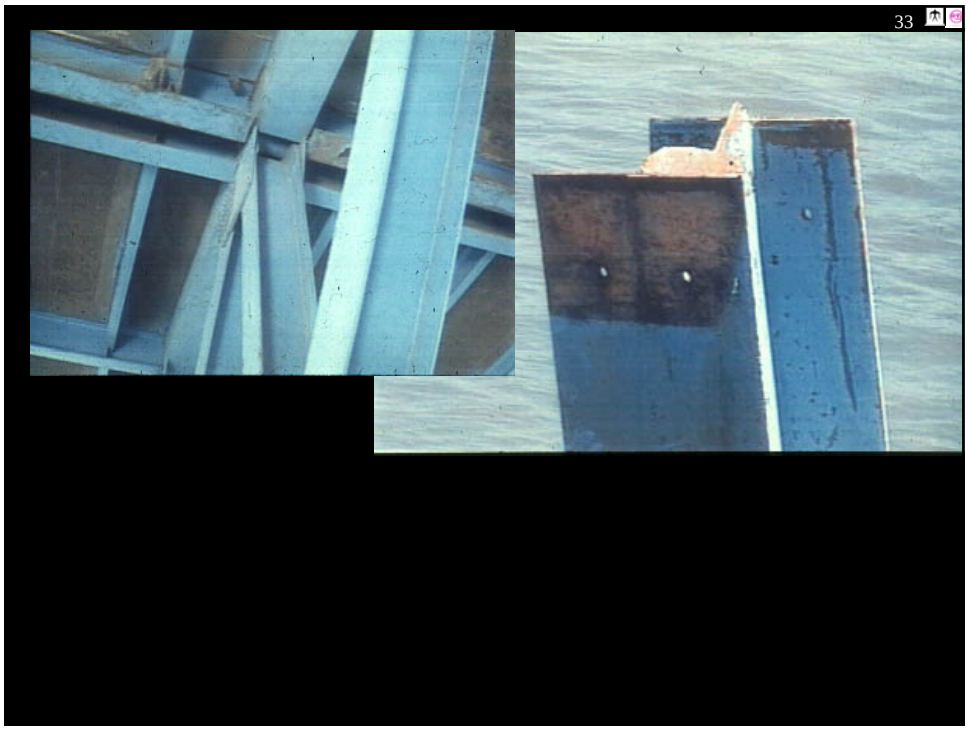
Songsu Bridge

Collapse of the Songsu Bridge

The disaster struck at 7:38 am, on October 21, 1994, when the bridge was full of vehicles. It was the beginning of the morning rush hour, and many people were riding and driving to work. Suddenly the central part of the famous 120-meter span collapsed and fell into the water. Fortunately, traffic was moving slowly, so most cars could stop within a few seconds. Nonetheless, all the vehicles passing along the part of the bridge that collapsed fell into the Han River.
This happened to five vehicles, including a city bus, No. 16. As a result of the disaster 32 people died.

The Songsu Bridge was merely 15 years old when it collapsed.

The bridge was 1,160 meters long, 19.4 meters wide, had four traffic lanes and contained a number of important technical innovations. For example, it was the first welded truss bridge in Korea, and its construction was at the limit of the then technical capabilities available in the country, especially as it included the central 120m span.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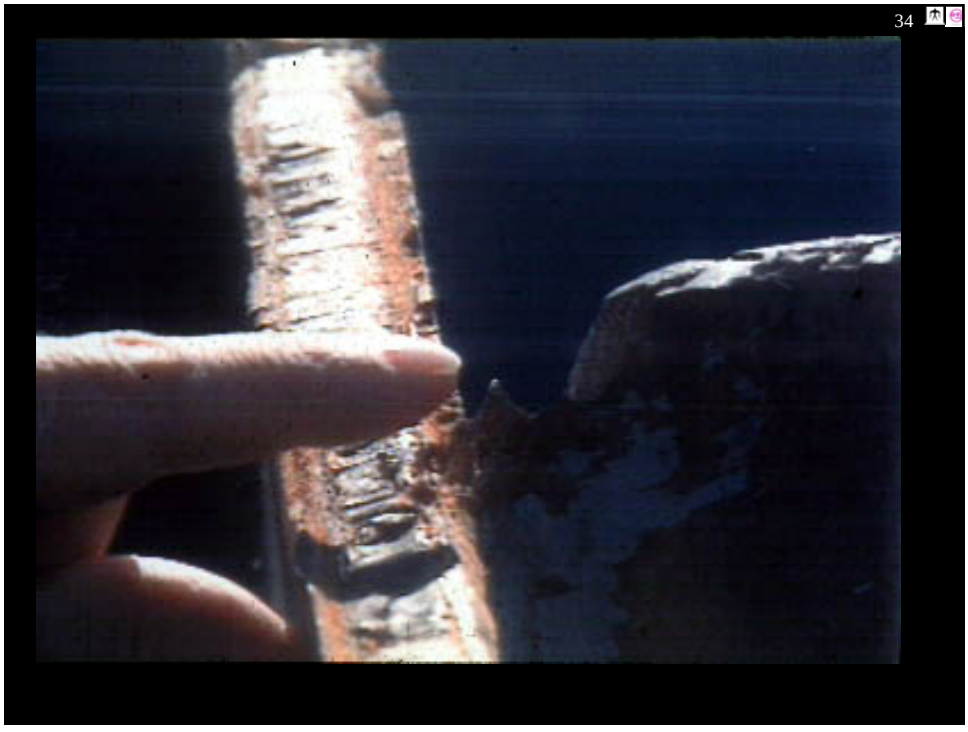
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35

Cause of Fatigue

1. Existence of weld-defects
   1. Butt welds (U.S)
   2. Butt weld (Japan)
2. Adoption of low fatigue resistance detail
   - Case-1: Bridges were not designed against fatigue.
   - Case-2: Inappropriate Allowable fatigue stresses in old codes and specifications
3. Unforeseen stresses and displacements
4. Unexpected structural behavior (vibration)
   - Fatigue Crack due to Vibration Induced by Wind

Most of the highway bridge in Japan are classified in this group

Joint details and attachments with low fatigue strength in high stress region leaded fatigue cracks in many bridges.

36

Cause of Fatigue 2: Adoption of low fatigue resistance detail

Case-2: Allowable fatigue stresses were inappropriate old codes and specifications

Most of cases, size effects of fatigue performances

Full size and large size fatigue tests
in U.S.A. 1970-
in Japan 1975-

- Size Effects
- Poor Structural Details
  Ex. Gusset Joints
  Cover Plates

Importance of Size Effects

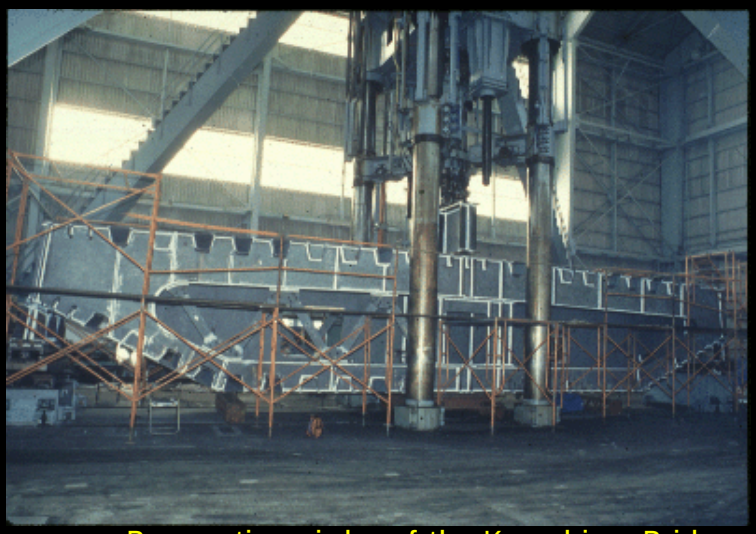
Welded joint specimen

Real scale floor beam of the Seto Bridge

Girder specimen at Lehigh University in the US

39

Full Size Fatigue Test --Honshu-Shikoku Bridge--



Box section girder of the Kurushima Bridge
Several types of diaphragms, connections of ribs

40

Results of Fatigue Tests S-N Curve

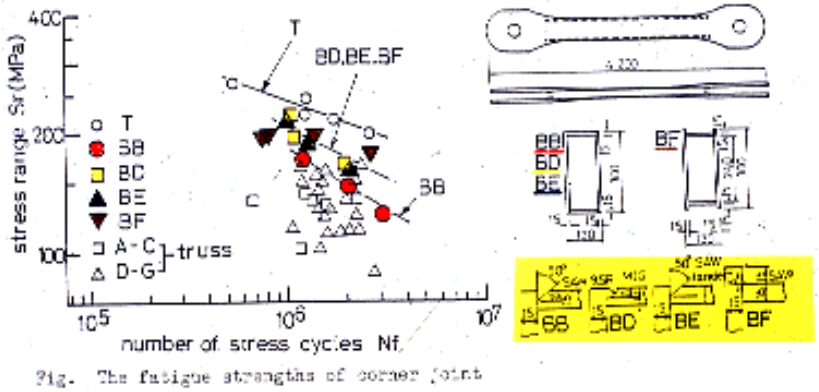


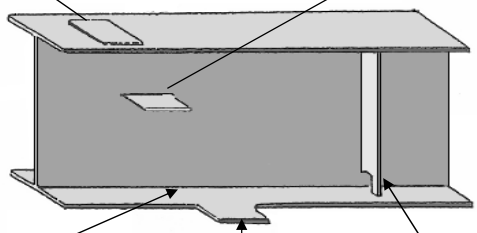
Fig. The fatigue strengths of corner joint

Wide variation of fatigue strength
Effects of size, joint details, defects,....

Change of allowable fatigue stresses from ’60 code to ’92 code

Joint Type	Sleeper pad	
Code	Class	Fatigue strength at 2 million cycles (MPa)
Old code '60	D	120
Current code '92	F	65

Joint Type	Out-plane gusset (t=20mm)	
Code	Class	Fatigue strength at 2 million cycles (MPa)
Old code '60	D	100
Current code '92	F	65



Joint Type	Longitudinal welding	
Code	Class	Fatigue strength at 2 million cycles (MPa)
Old code '60	B	150
Current code '92	C	125

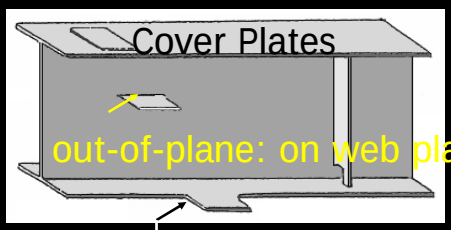
Joint Type	Cruciform weld	
Code	Class	Fatigue strength at 2 million cycles (MPa)
Old code '60	D	100
Current code '92	E	80

Joint Type	In-plane gusset (t=20mm)	
Code	Class	Fatigue strength at 2 million cycles (MPa)
Old code '60	C	126
Current code '92	F	65

- comprehensive fatigue damage prevention works in the Tokaido Shinkansen
- 1511 girders and total length is 27km,

Poor Structural Details to be retrofitted:

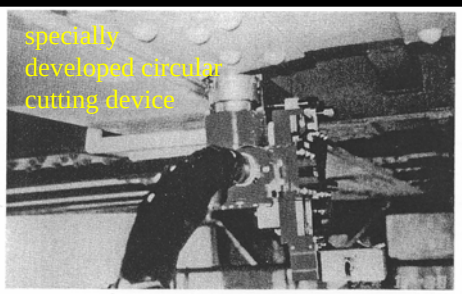
- In-plane gusset plate joints
- Out-of-plane gusset
- Cover Plates



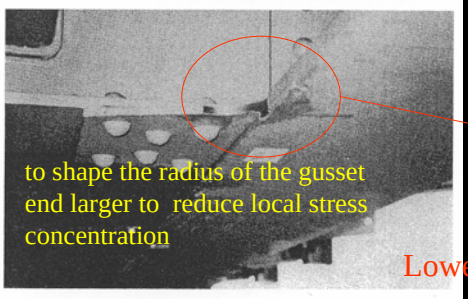
Actual stresses in girders were lower than calculated stresses, about 50-65% of calculated ones

43

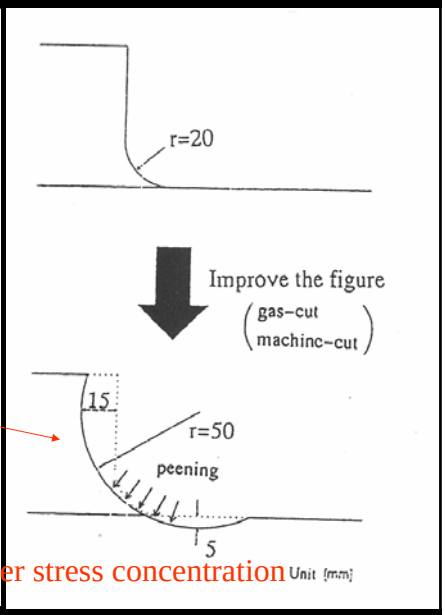
Improving works of flange gusset detail



specially developed circular cutting device



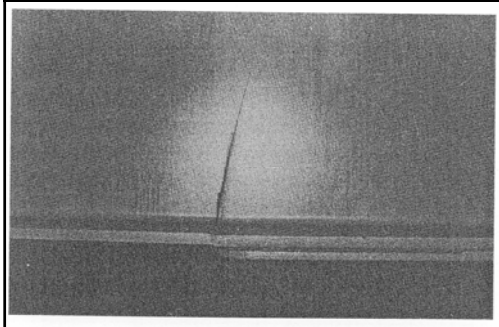
to shape the radius of the gusset end larger to reduce local stress concentration

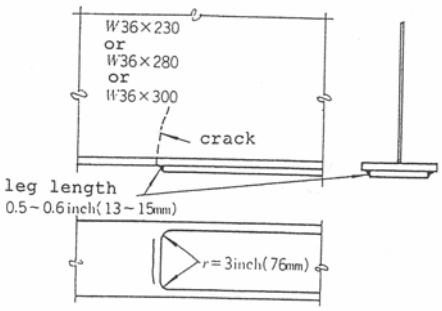


Lower stress concentration

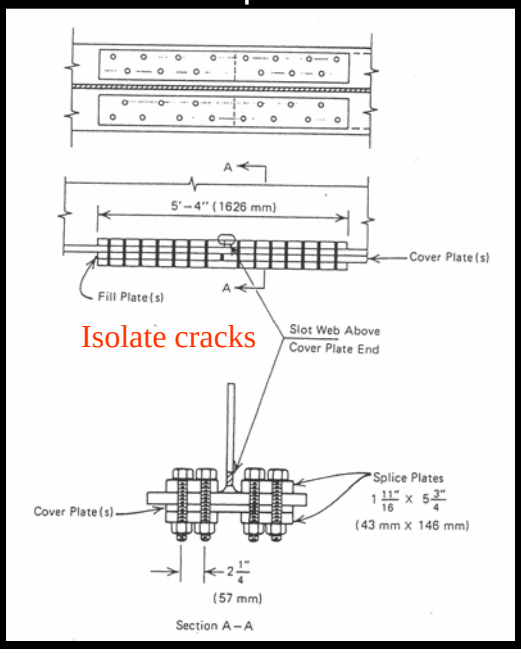
44

Fatigue crack initiated from the weld toe at the end of a cover plate





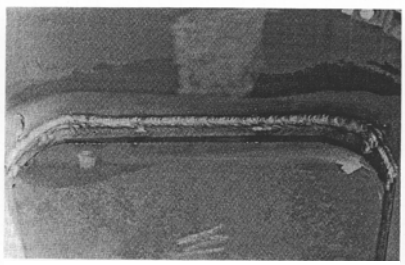
Retrofit details of bolted splice



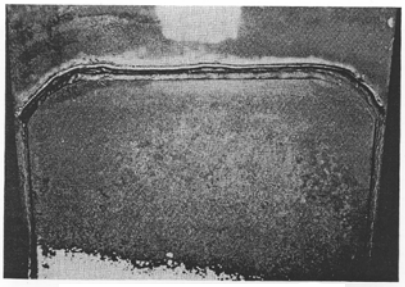
Isolate cracks

Retrofit by TIG dressing and hammer peening

Improve fatigue performance



Gas tungsten arc remelted weld toe



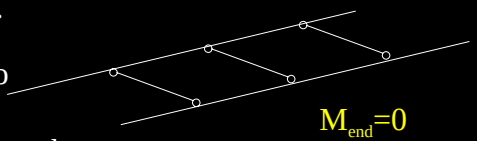
Peened weld toe

Cause of Fatigue

1. Existence of weld-defects
   1. Butt welds (U.S)
   2. Butt weld (Japan)
2. Adoption of low fatigue resistance detail
   - Case-1: Bridges were not designed against fatigue.
   - Case-2: Inappropriate Allowable fatigue stresses in old codes and specifications
3. Unforeseen stresses and displacements
   - Design simplification
   - Concentrated loading region
4. Unexpected structural behavior (vibration)
   - Fatigue Crack due to Vibration Induced by Wind

3. Unforeseen stresses and displacements
1) Design simplifilcation

- Various simplifications and assumptions have been established in order to calculate stresses in the structural members in bridge design.
- Particularly, with regard to connections between perpendicularly crossing members

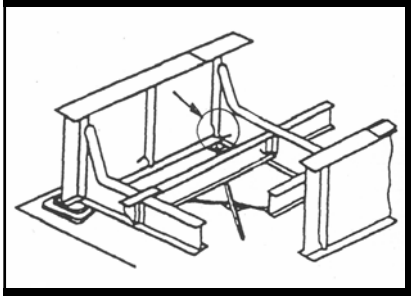


Design model

- Consequently, stresses and deformations obtained from design calculations differ considerably from those in actual structures, especially in the vicinities of connections.
- These calculations are on the conservative side when determining cross-sectional dimensions, but often causes fatigue because of secondary stresses due to restraint moments.

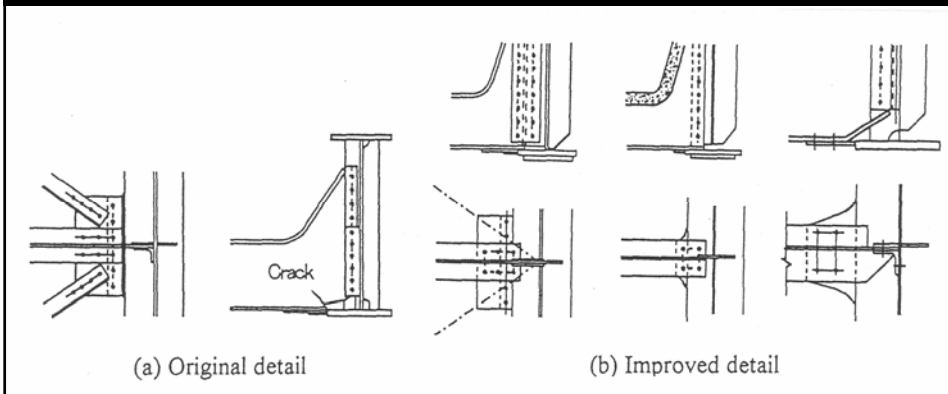
3-1 Cross Beam

Brittle Fracture Originated from Fatigue Crack



- through-type plate girder railway bridge
- the flanges of floor beams were provided with cut-outs to facilitate joining at connections attaching floor beams to main girders
- In the design, floor beams are provided simple support by main girders and thus only shear force are supposed to be transmitted at the joints.

Retrofitting works at girder to cross beam connections



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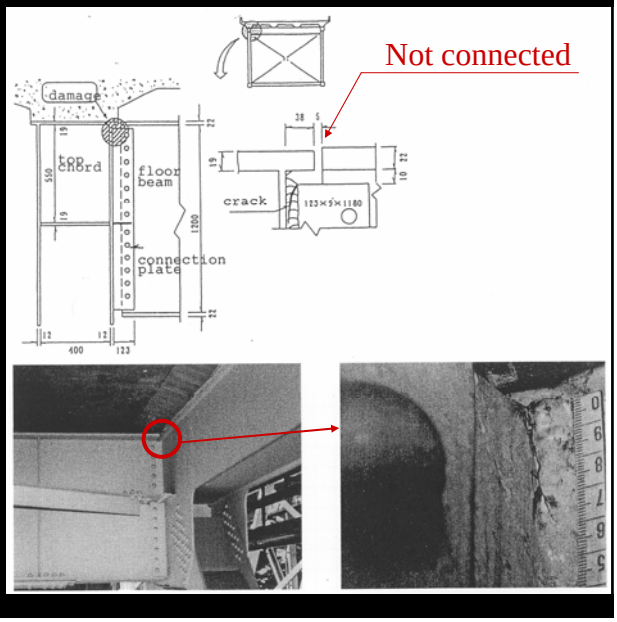
3-2 Fatigue crack at the connection between floor beam and truss panel point

Connection between floor beams and panel points of trusses in a deck-type truss girder in highway bridge

due to the occurrence of restraint moment at the end of floor beam.



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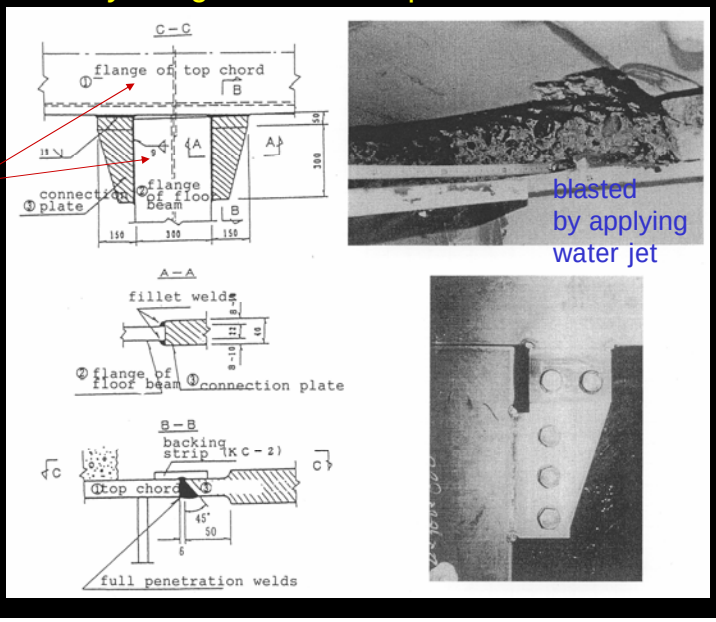
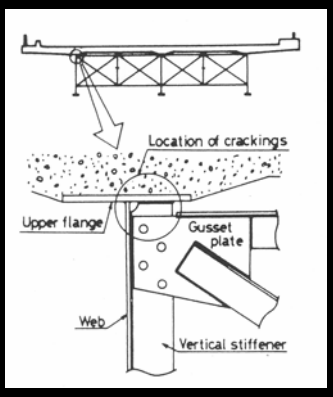
Retrofitting works: Floor beam and the flange of truss top chord was connected directly using a connection plate

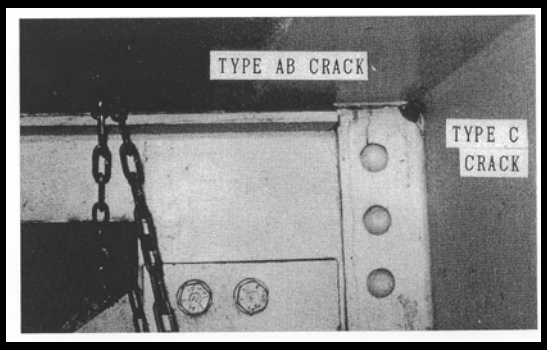
Both flange should be joined using a connection plate

40mm thick plates were adopted to Adjust the GAP



3-3 Fatigue cracks at the cross bracing connection details

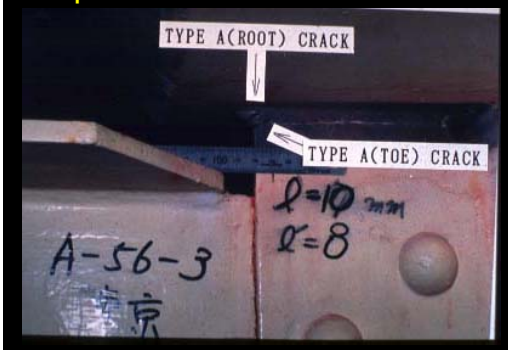




large forces are produced in cross bracing from

- Difference in deflection between main girders caused by vehicle loads
- forced deformation of the upper flanges of plate girders by deflection of the concrete deck in a direction perpendicular to the bridge axis.

Repair Work 1



1. For small cracks : re-welding the crack is done by TIG dressing
2. small size fillet weld (possibility of crack from root) : after fillet welding on top of the crack, the toe is finished by TIG or grinding
3. When a crack is large : the crack is removed by gouging, full-penetration welding is performed, with toe finishing done by TIG or grinding.

Repair Work 2

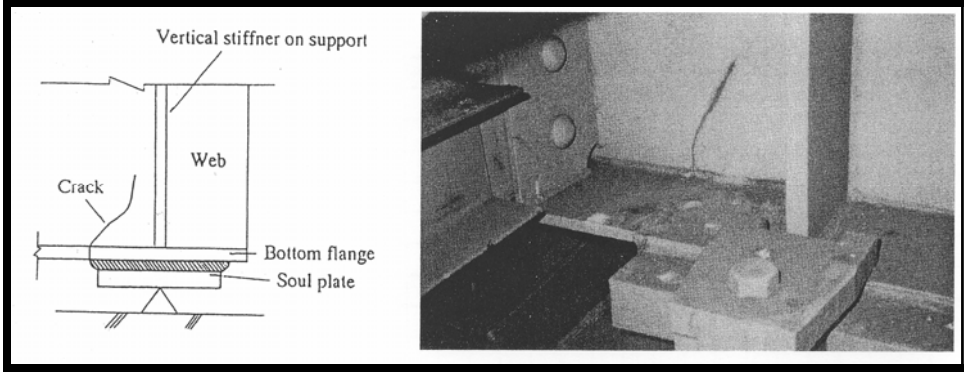
1. Fatigue cracks have occurred again where stresses produced were large and where cracks had been large.

2. To improving the deformation behavior of the structure, cross bracings and stringers are installed. In this case, 16 mm thick vertical stiffeners are used instead of 10 mm used, their widths were made as large as possible.

3. Further, to lower stresses at damaged parts, horizontal members of old cross bracings were removed.

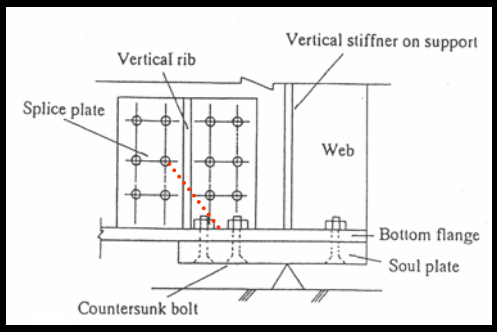
3. Unforeseen stresses and displacements
2) Concentrated Load

3-4 Fatigue damage in sole plate connection detail at support



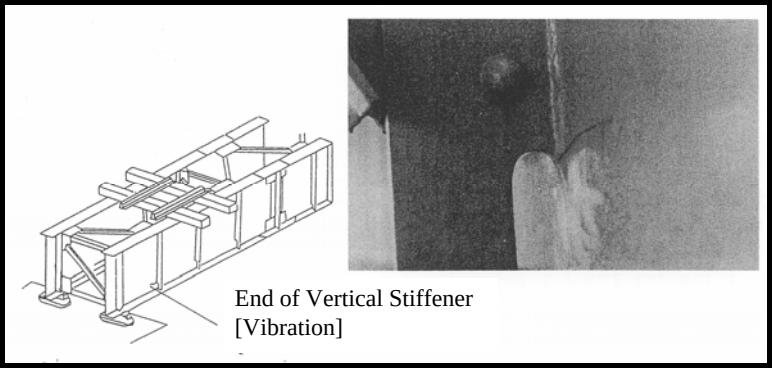
- Stresses occurring near support points differ considerably from those obtained by the beam theory.
- A sole plate was attached to the underside of a bottom flange by fillet welds.
- Very high stresses occur at the front surface of the sole Plate when rotating function is lost

Repair example



- The sole plate was changed to a longer one and joining with the bottom flange was done using high-strength bolts.
- Cracks which had penetrated into the web, holes were drilled at the tips along with which splicing was done using high strength bolts.
- The holes at the tips of cracks were also tightened with high-strength bolts.
- When cracks of webs are large, welding may also be done.

4-1 Fatigue Crack due to Sympathetic Vibration caused by High Speed Passage of Shinkansen



End of Vertical Stiffener
[Vibration]

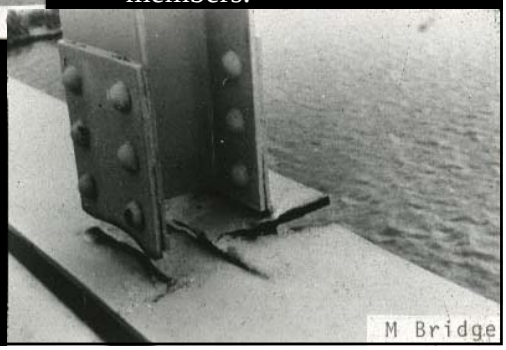
- When speed exceeded 200 km/h, vibrations of bottom flanges of stringers in directions perpendicular to bridge axes began to appear.
- Out-of-plane vibrations in diaphragms of box girder bridges
- Fatigue cracks have initiated in vertical stiffeners and ribs restraining such vibrations.

4-2 Fatigue Crack due to Vibration Induced by Wind

59

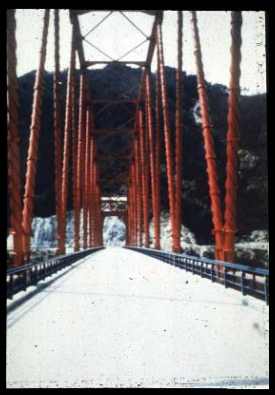
- Karman vortex shedding may cause fatigue damage in bridge members.
- fatigue cracks cut the connection plates between the main girder and the vertical suspension members.

The End of Vertical Member In Ranger Type Bridge



Countermeasurments for wind vibration

60

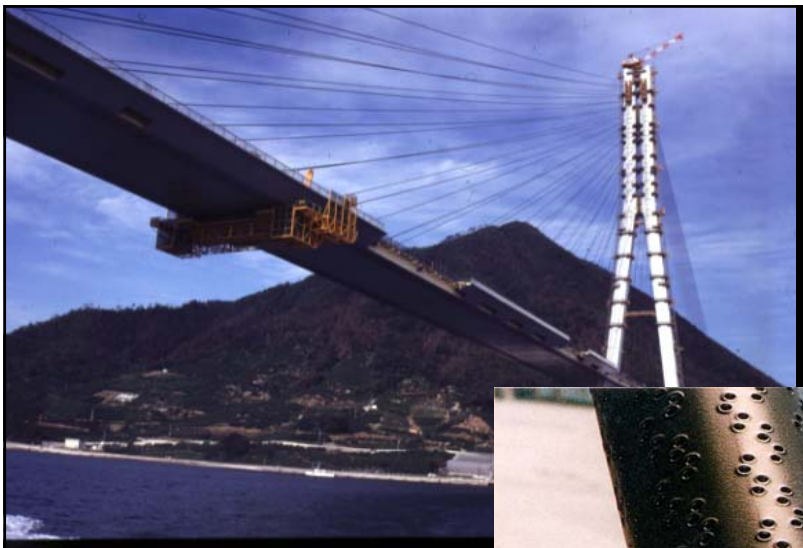


Spiral wires applied to vertical members

Wires connecting vertical members

Retrofitting Works

Reinforcement of vertical members



Tatara (1999) 270 + 890 + 320
(The Largest Cable Stayed Bridge)

Rain vibration ➡

Recent Investigations on Steel Bridge Bents

- Causes of Fatigue Damage
- Retrofitting Works
- Material Problems

63

Fatigue Problems in Steel Bridge Bents

more than 5000 bents in MEX way

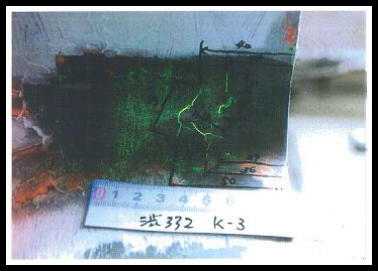
Stress calculation in design:
frame analysis
+ shear-lag effect
Okumura et-al 1968

No consideration on fatigue
Because of highway structures and bents

64

Fatigue crack in beam-column connection of steel pier

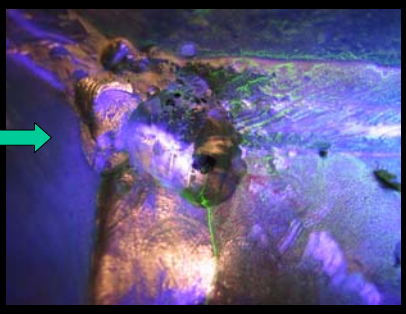
- Cracks come out from inside of weld metal.
- From unwelded zone, Lack of fusion, weld crack, or other weld defects



65

Cause of fatigue crack

1. Intersection of weld line →high restraint stress, weld flaw (blow hole,slag inclusion, weld crack)
2. Stress concentration (Geometry, shear lag, bead, notch)
3. Inherent Internal Flaw

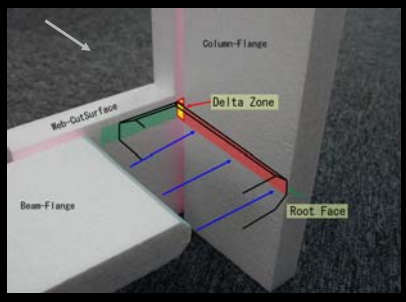


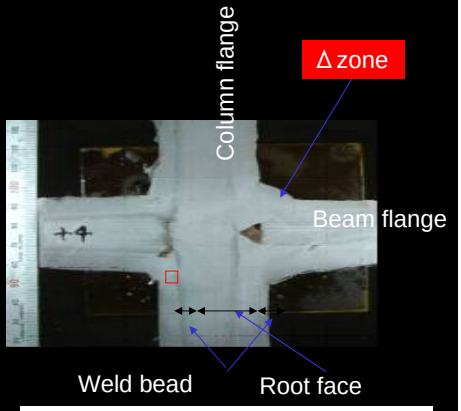
66

Inherent Internal Flaw

=unwelded zone inherent to plate arrangement = delta zone, root-face, metal touch zone

Grinding direction (right picture)

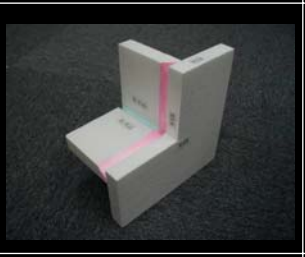




Slice specimen
(Web−4mm)

67

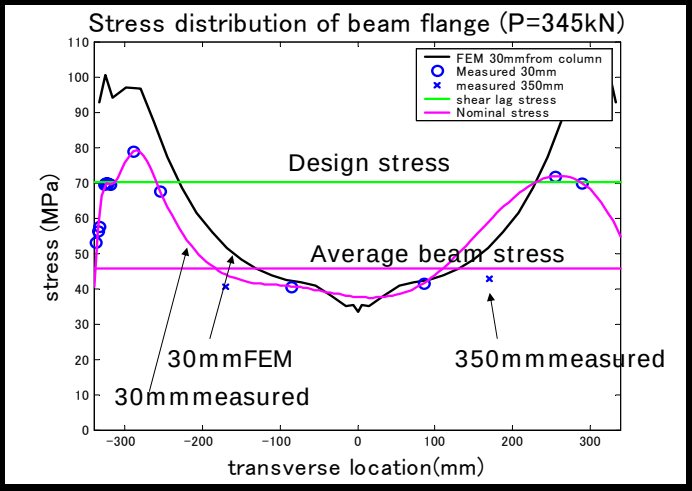
Typical Plate Assembling Methods

WW	WF	FW
		
FF	**SWW**	**SFF**
		

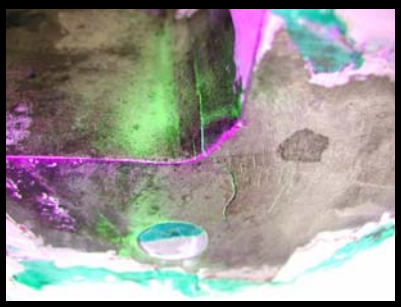
δ zone

68

stress concentration



Retrofitting of fatigue damage



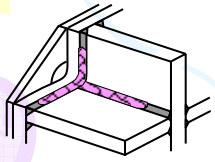
Retrofitting

Cause investigatrion

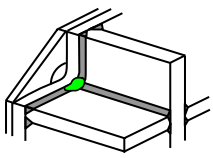
stiffenning

Crack removal, stop hole

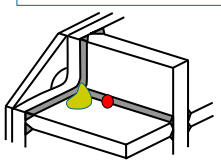
①weld repair



②crack grinding

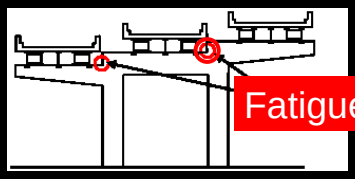


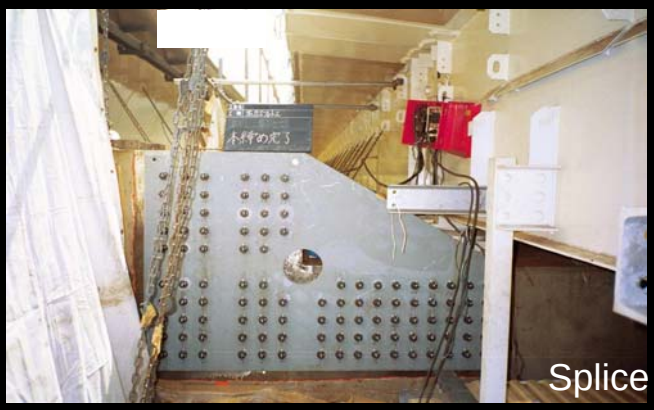
③scalop, core drilling, stop hole



71

Temporary Repair by Bolt Splicing



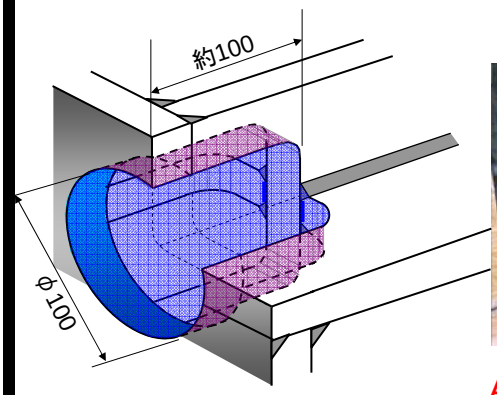


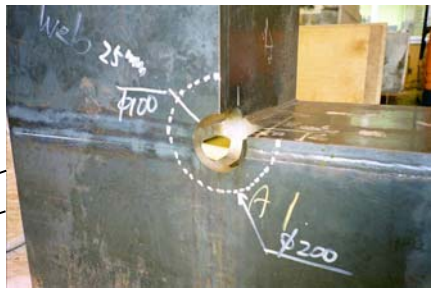
72

Drilling Stop Holes

Cut out of Intersection of Three Weld Bead Lines At Corner by Large Hole Drill

73





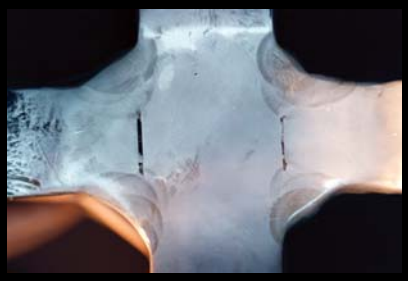
Applicability was examined by Specimen, first.

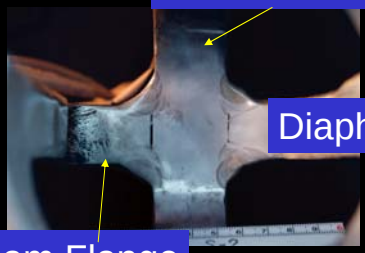
Application to Actual Structure

74

Application to Actual Structure

75



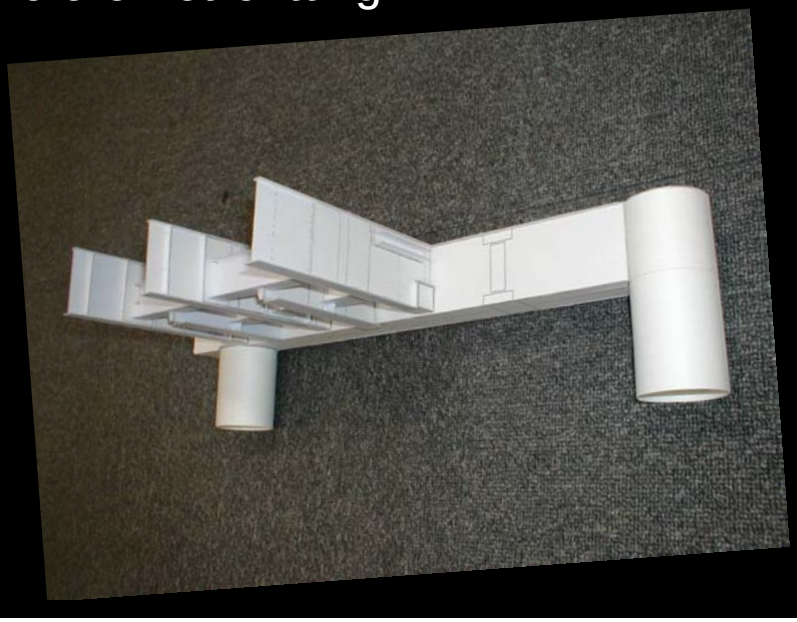


76

Kanda Bridge

77

Before Retrofitting

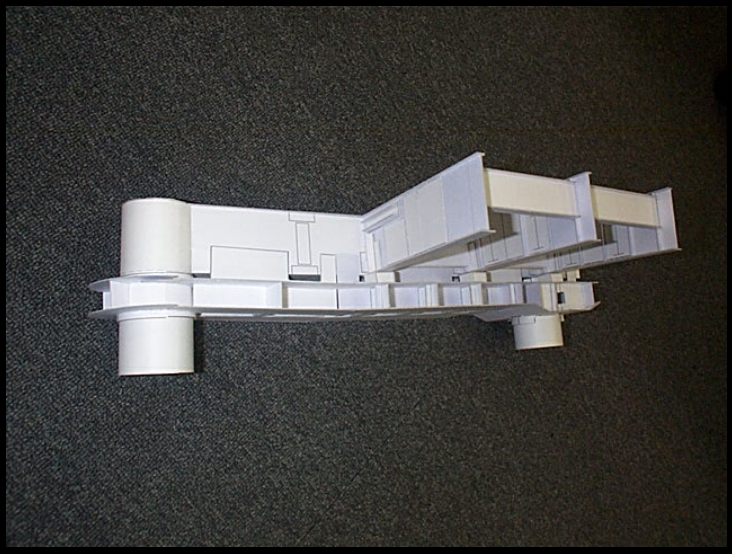


78

79

80

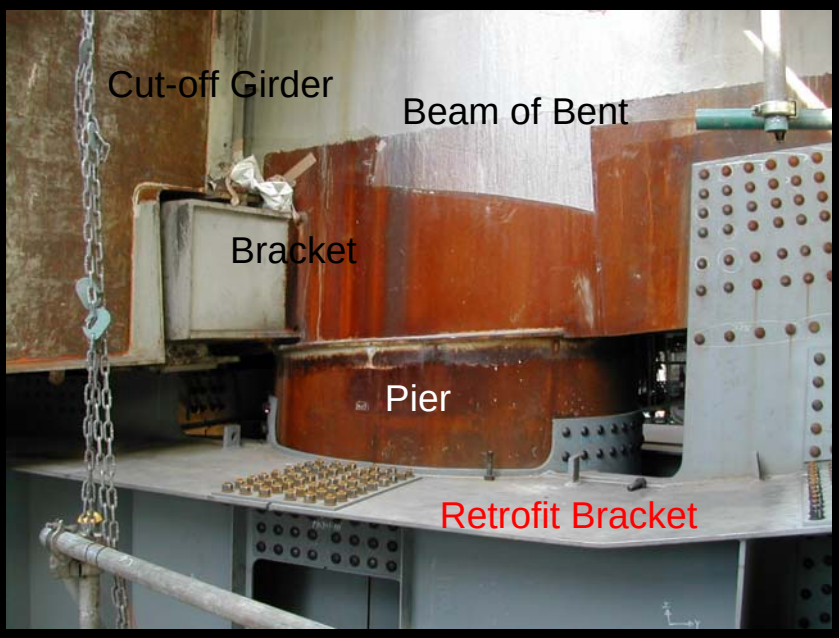
After Retrofitting



Bracket for Retrofit under fabrication

Setting Up of Bracket for Retrofit

83



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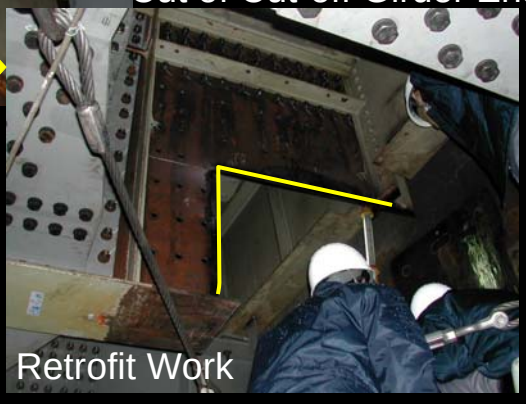
After Setting Up of Retrofit Bracket

Cut of Cut-off Girder End



After Set Up of Retrofit Bracket

Before Retrofit

Removal of Bracket

Retrofit Work

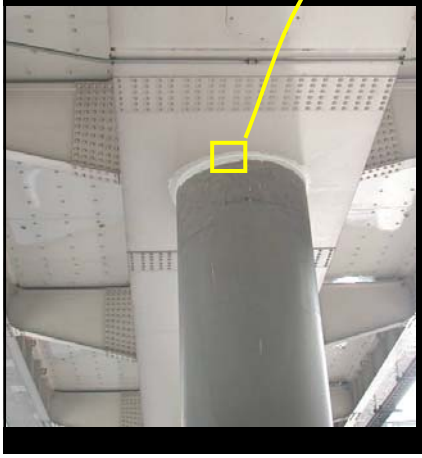
Retrofit Work

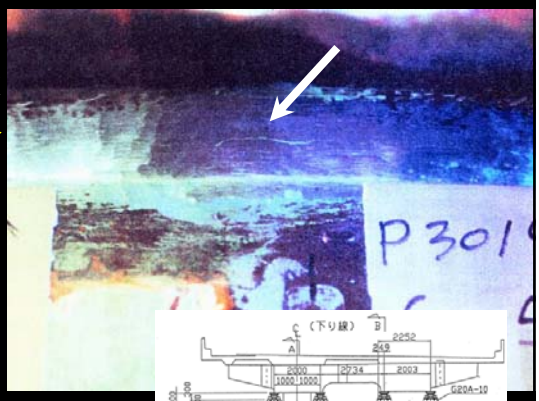
Kanda Bridge
After Retrofitting Works

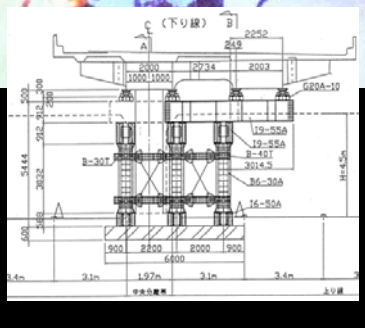
88

Hirakawa-Cho

Fatigue Crack



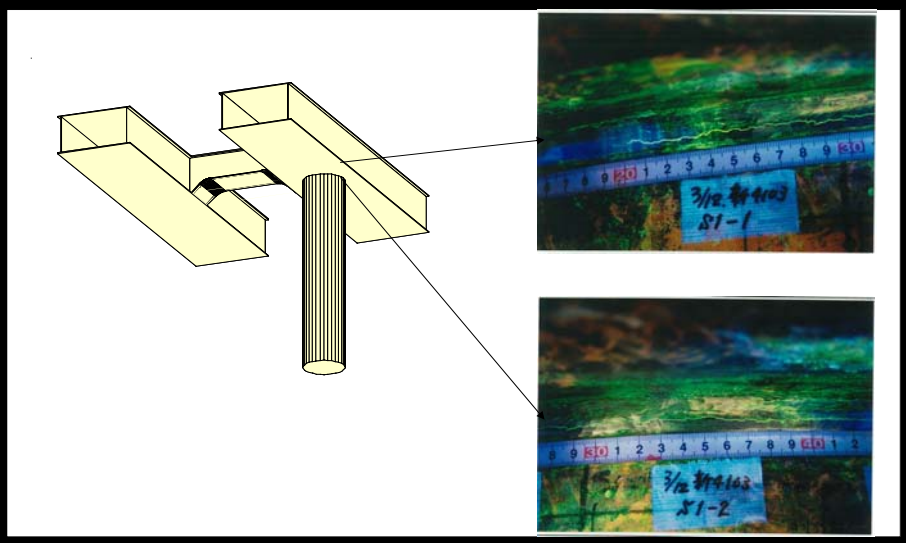




89

Fatigue Crack

crack length 340mm

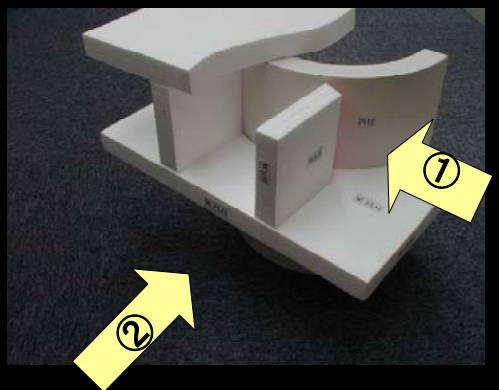


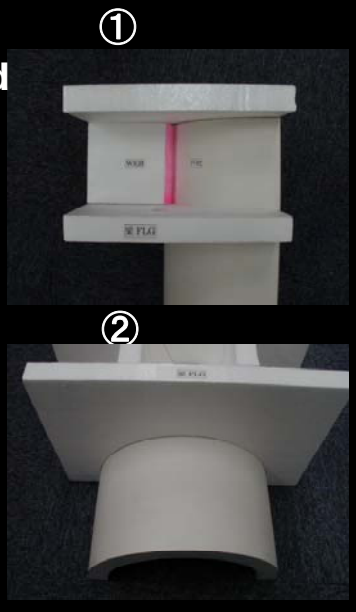
90

With Circular Column

Column cylinders penetrated

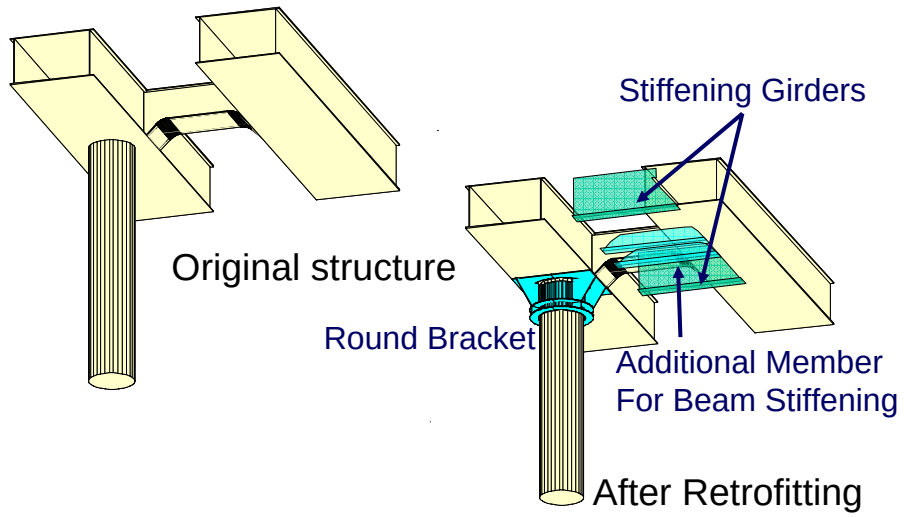
(Beam is larger than column)





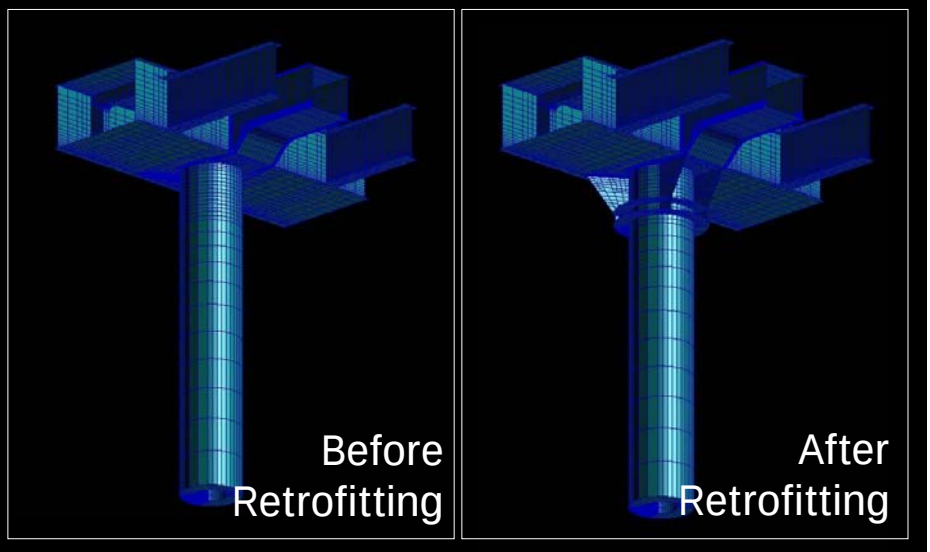
Retrofitting work

91



FEM Model

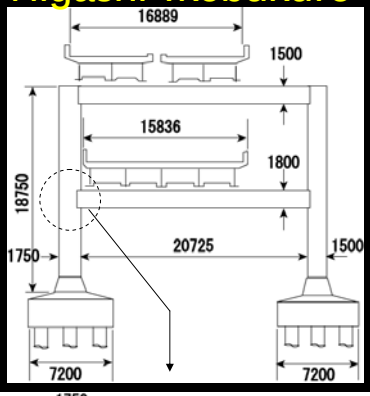
92

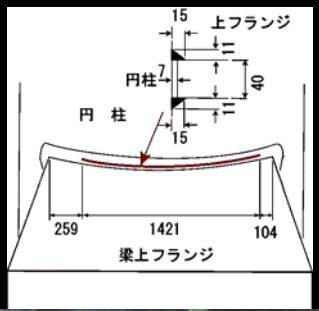


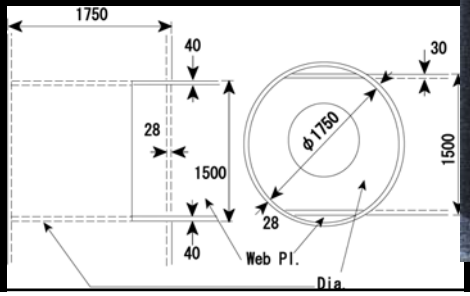
93

94

Higashi Ikebukuro





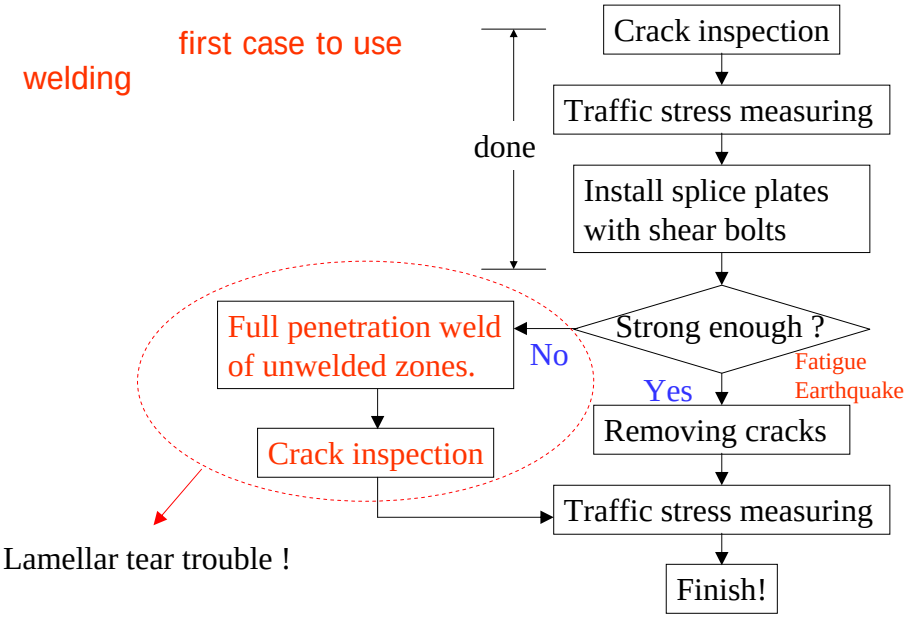


95

Fatigue Crack (Inside of the Pier)

Welding plan(at first)

first case to use welding

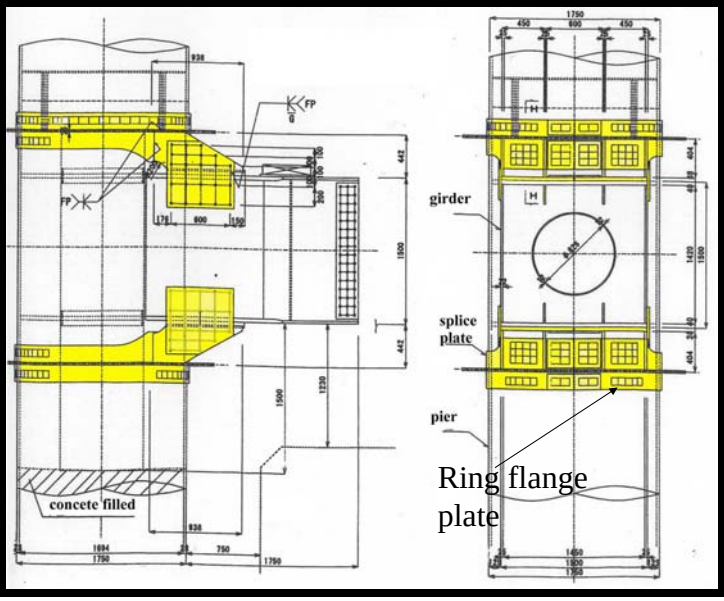


Lamellar tear trouble !

Support members for welding

97

- Decreasing the traffic stress by more than 50%.



Material property(1)

98

- Sulfur level is not so high, compared to contemporary steels
- Some samples show very low RAZ.

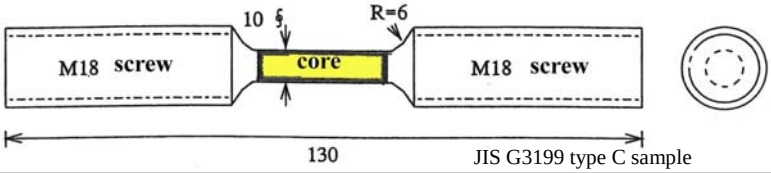
Chemical compositions

sample No.	chemical compositin(mass %)										parameters	
	C	Si	Mn	P	S	Ni	Cu	Cr	Mo	V	Ceq	Pcm
No.1	0.16	0.29	1.36	0.012	0.012	0.017	0.04	0.018	0.012	0.003	0.406	0.242
No.2	0.17	0.29	1.36	0.012	0.01	0.017	0.04	0.018	0.012	0.003	0.416	0.252
No.3	0.17	0.29	1.35	0.012	0.009	0.016	0.04	0.017	0.012	0.003	0.414	0.251

Z-direction tensile test result

sample No.	diameter (mm)	0.2% load		tensile stress		elongation (%)	RAZ (%)	break point
		Load(kN)	N/mm2	Load(kN)	N/mm2			
No.1a	9.99	26.81	342	27.89	356	3	0.2	connection
No.1b	9.99	28.34	362	39.78	508	12	8	A
No.1c	9.99	27.57	352	40.13	512	10	12	A
No.2a	10.00	26.49	337	39.41	502	18	20	A
No.2b	10.00	26.39	336	40.16	511	10	19	A
No.2c	9.99	24.92	318	36.84	470	6	10	A

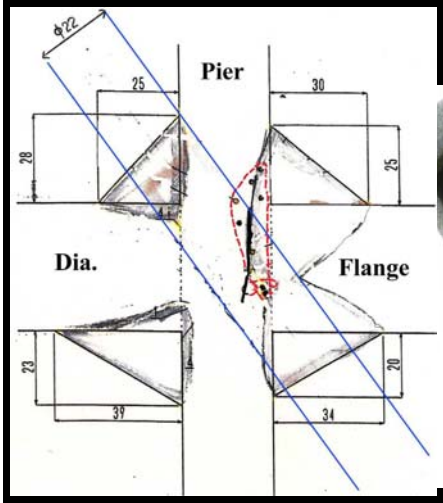
Bolt hole core sample

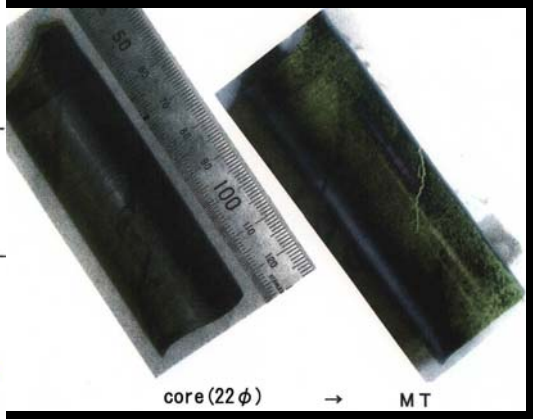


JIS G3199 type C sample

Material property(2)

- To check results of UT, a core was taken from welded section. And cracks were found.



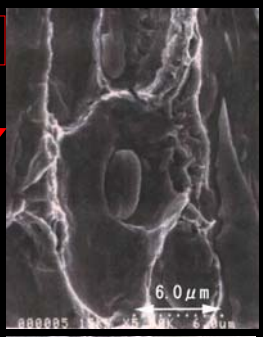


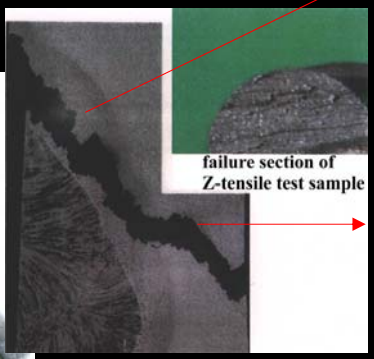
Core position&UT result

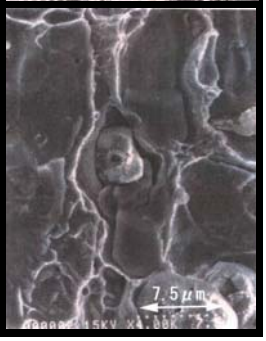
Material property(3)

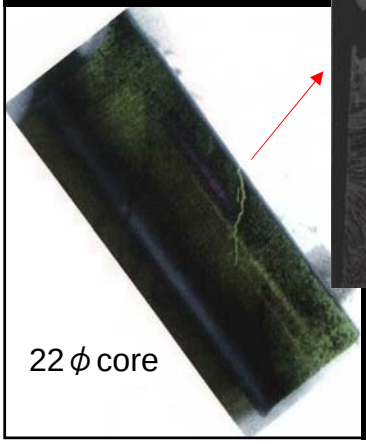
- Crack was initiated from HAZ, but MnS was found on surface of crack. → Lamellar tear

MnS









22 ϕ core

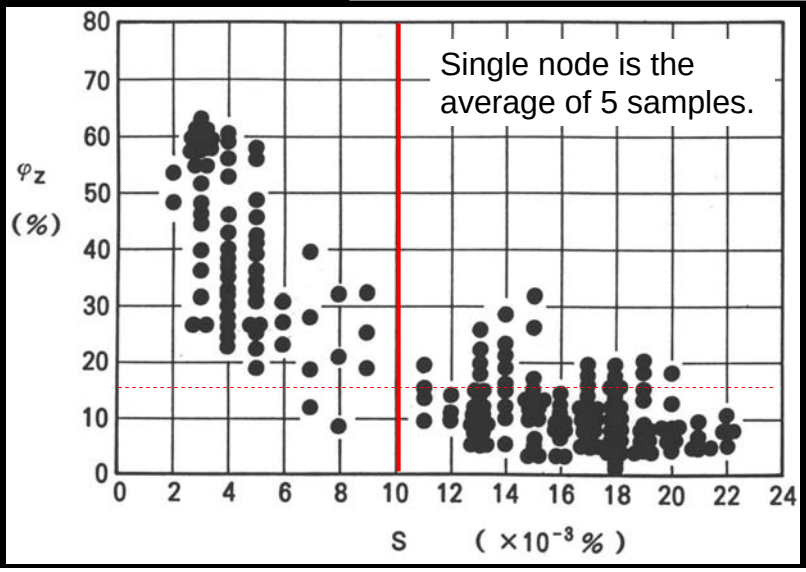
Crack section macro

AlO

Sulfur and RAZ

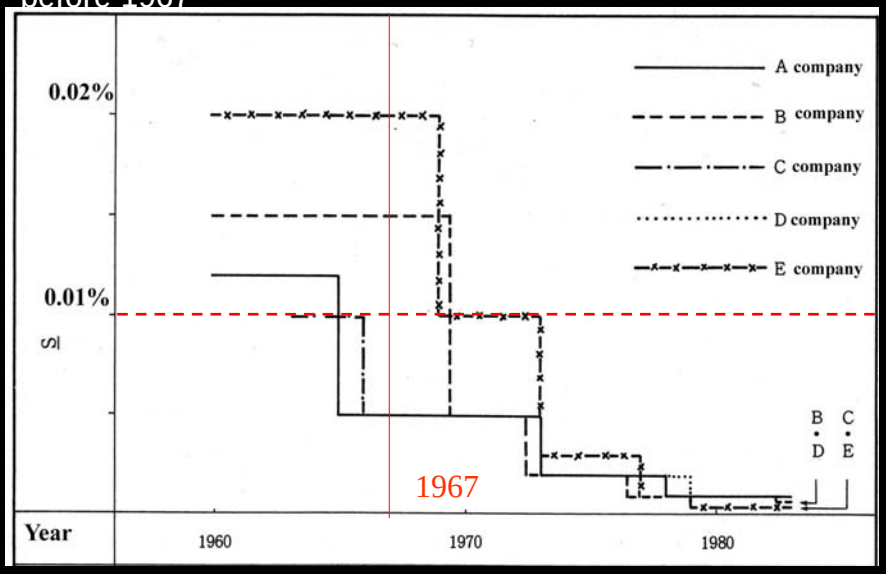
- RAZ is strongly related, but not determined only by sulfur.

Production data from Hirohata works.



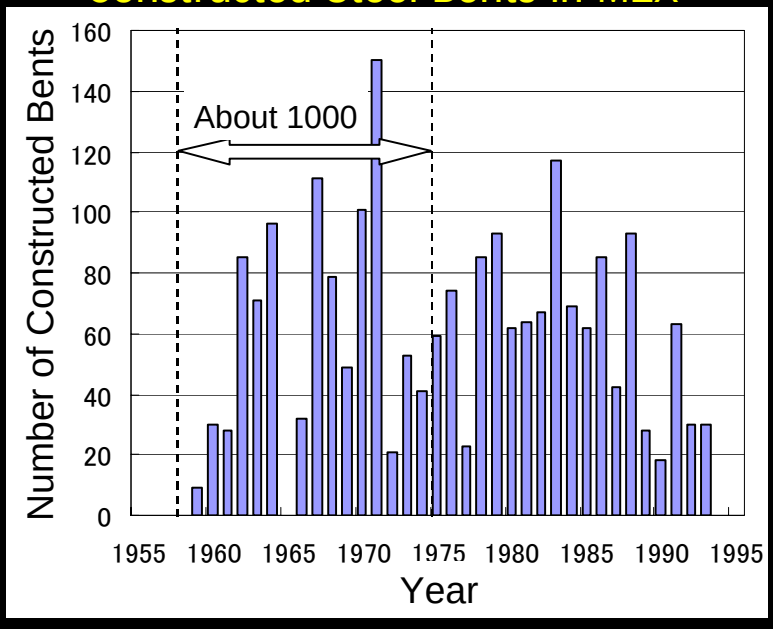
History of Sulfur Inclusion in Steel

- Difficult to Apply Weld Repairing to Piers constructed before 1967



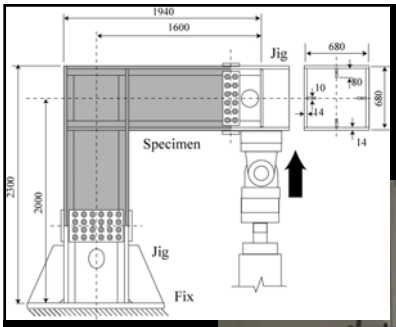
Construction Year and Number of Constructed Steel Bents in MEX

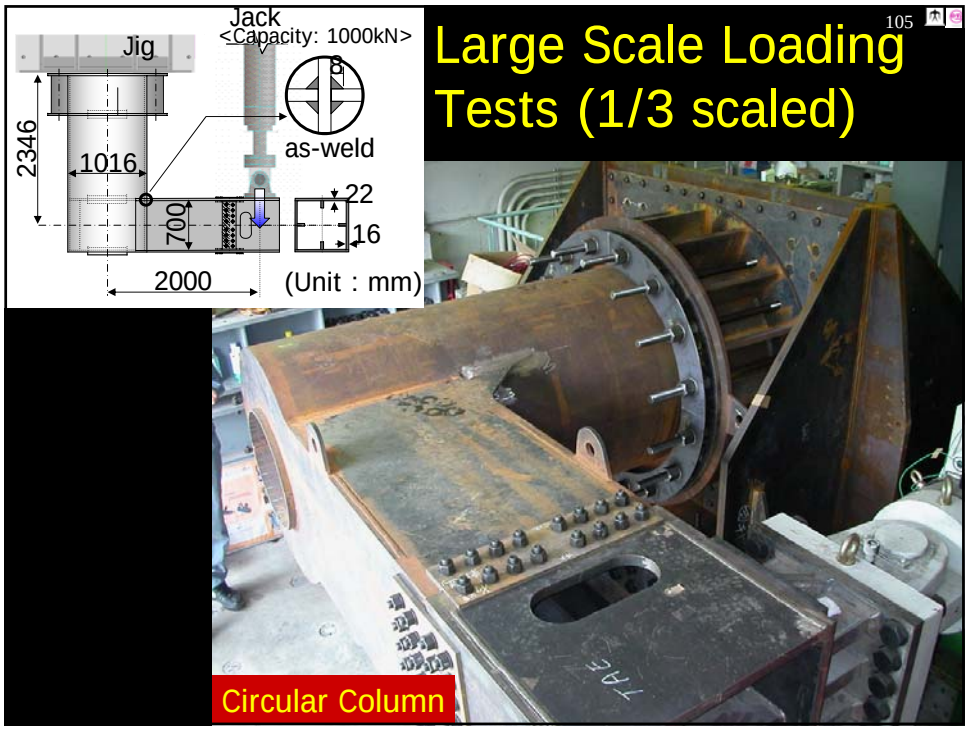
103

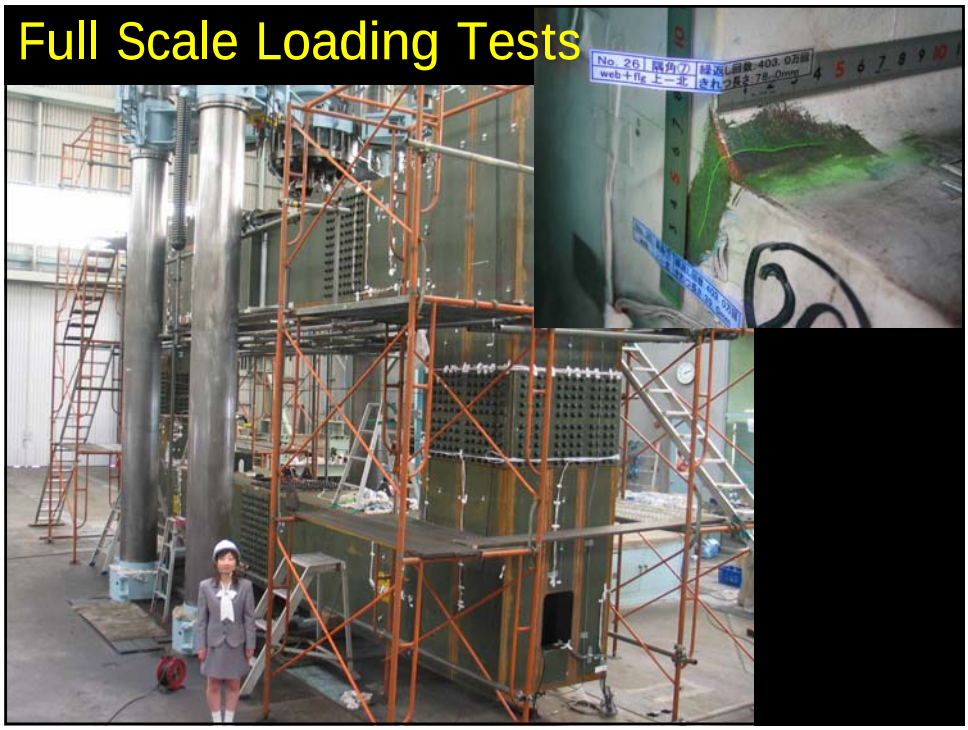


Large Scale Loading Tests (1/3 scaled)

104




Jack
<Capacity: 1000kN>
Jig
2346
1016
700
2000
as-weld
22
16
(Unit : mm)
Large Scale Loading Tests (1/3 scaled)
105
Circular Column


Full Scale Loading Tests