Structural Response of Bridge Structures

Department of Civil Engineering
Tokyo Institute of Technology

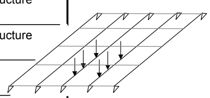
Class 2 : Structural Response of Bridge Structure

1. Design stress and actual stress : Stress reduction factors of 7 existing bridges
2. Proof loading test in Tomei
   1. Proof loading test on Sakabe bridge
   2. Comparison between Design and Actual stress
   3. Modeling of Bridge
   4. Contributions of Members on FEM Result
3. Proof loading test in Houkigawa bridge
4. Capacity evaluation : Monoi, Sakabe, Hirono br.

1. Design Stress and Actual Stress

Target Bridges : Various Types of Bridges

Route	Bridge	Bridge Type	Length (m)	Width (m)	Design Calculation Method
Tomei	Takamatsu No.1	PC-Post Tens. T-Section Simple Girder	27.76	13.154	Simple Supported Girder
	Katayama	Steel Composite Girder	47.30	12.60	Grid Structure Effective Width
	Katayama	3 Span Continuous Girder, RC Hollow	35.571	12.60	Grid Structure
	Sagamigawa	2 Span Continuous Girder, PC Box	73.90	16.35	Grid Structure
Chuo	Uenohara	Truss	84.115	12.101	Truss
	Uenohara	Steel Composite Girder	28.039	12.101	Grid Structure Effective Width
	Komiya	Steel Box	50.149	12.50	Grid Structure

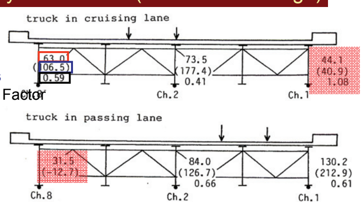


Stress Reduction Factors of Steel girder bridges

$$\text{Stress Reduction Factor} = \frac{\sigma\ \text{measured}}{\sigma\ \text{calculated}}$$

Katayama Viaduct (Steel Girder Bridge)

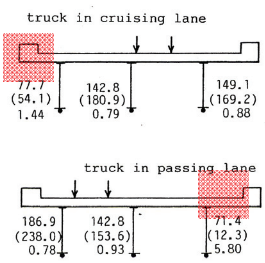
Measured Stress
Calculated Stress
Stress Reduction Factor



( ) with Impact

Takayama	Steel Composite Girder	47.30	12.60	Grid Structure Effective Width

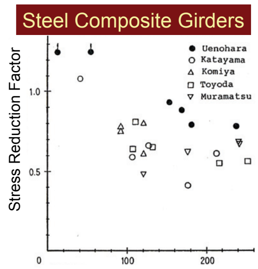
Uenohara Bridge (Composite Girder)



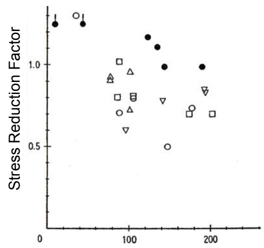
( ) with Impact

Stress Reduction Factor

Steel Composite Girders

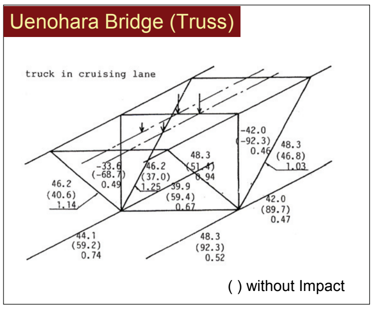


Calculated Stress (with Impact)

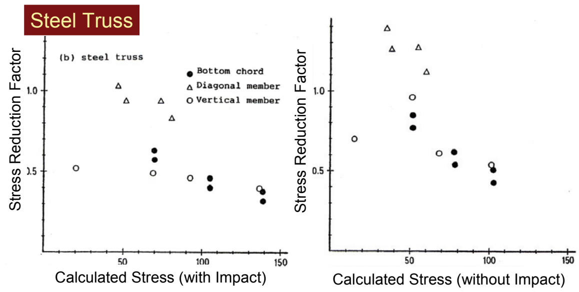


Calculated Stress (without Impact)

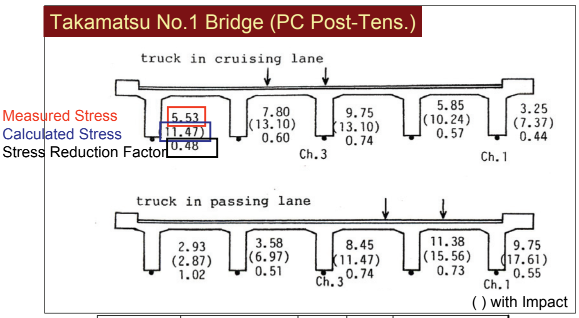
Steel Truss Bridge



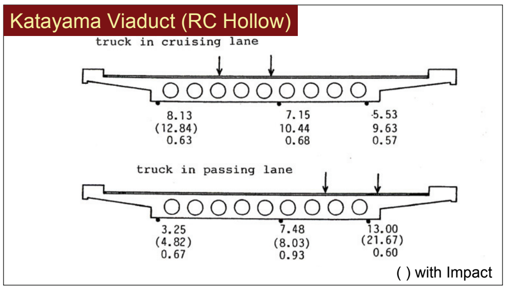
Stress Reduction Factor



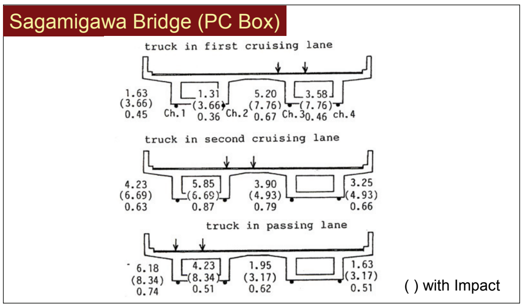
Stress Reduction Factors of RC bridges



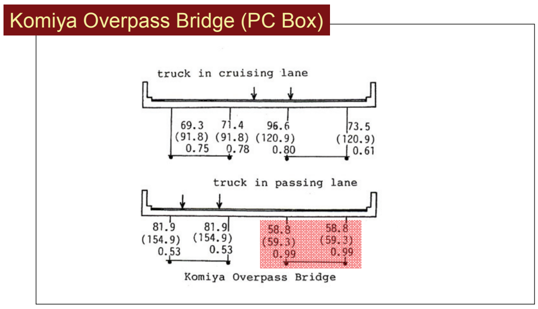
Takamatsu No.1	PC-Post Tens. T-Section Simple Girder	27.76	13.15 4	Simple Supported Girder



Katayama	3 Span Continuous Girder, RC Hollow	35.571	12.60	Grid Structure

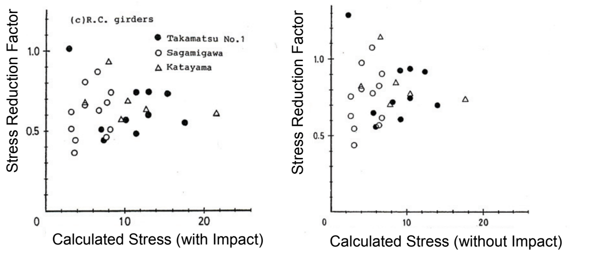


Sagamigawa	2 Span Continuous Girder, PC Box	73.90	16.35	Grid Structure



Stress Reduction Factor

RC Girders



BRIDGE	IMPACT FRACTION	STRESS REDUCTION FACTOR WITH IMPACT	STRESS REDUCTION FACTOR WITHOUT IMPACT
Takamatsu No.1	0.260	0.64	0.81
katayama(steel)	0.207	0.67	0.81
Katayama(R.C.)	0.235	0.68	0.84
Sagamigawa(R.C.)	0.231	0.60	0.75
Uenohara(steel)	0.259	0.85	1.07
Komiya	0.200	0.75	0.90
Toyoda(steel)*	0.253	0.64	0.81
Muramatsu(steel)**	0.250	0.65	0.82

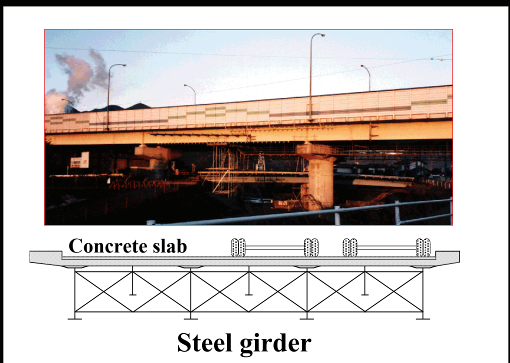
*Tomei expressway, 3 span continuous girders with three girders 28.62 + 29.00 + 28.63m

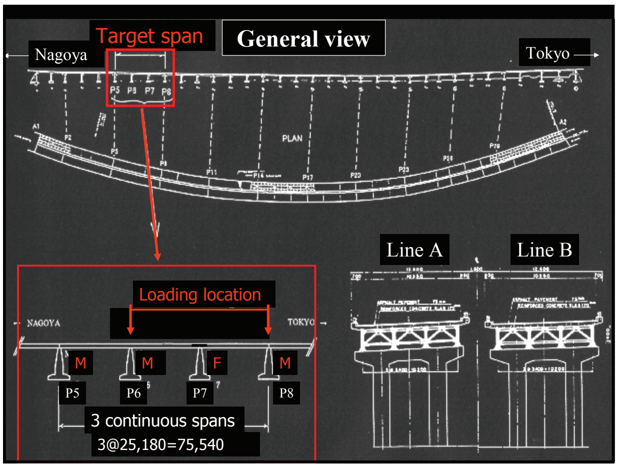
**Tomei expressway 3 span continuous girders with four girders 3 x 30m

Average 0.69 w. impact
0.85 w/o impact

2.1 Proof Loading Test in Sakabe Bridge

Target Bridge

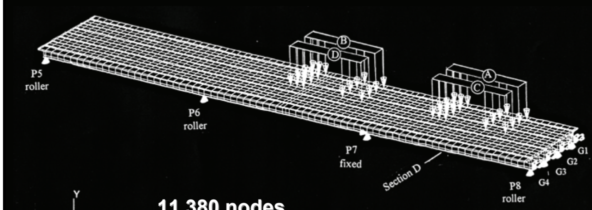




Proof Loading Test on Sakabe Bridge

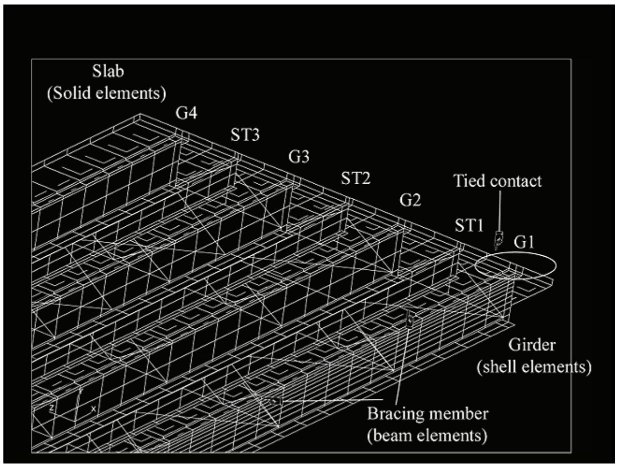
2.2 Comparison between Design and Actual stress

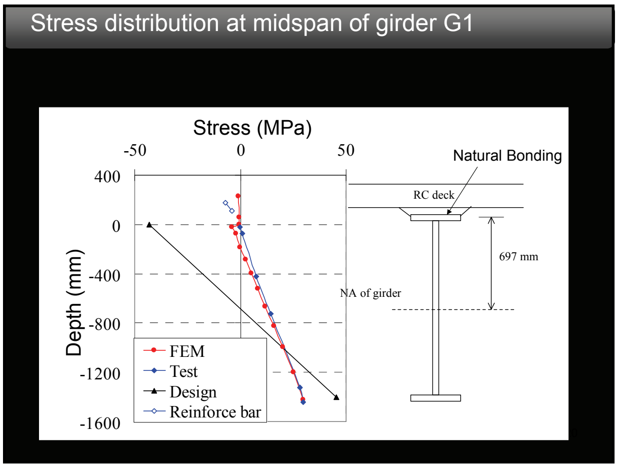
FEM Model

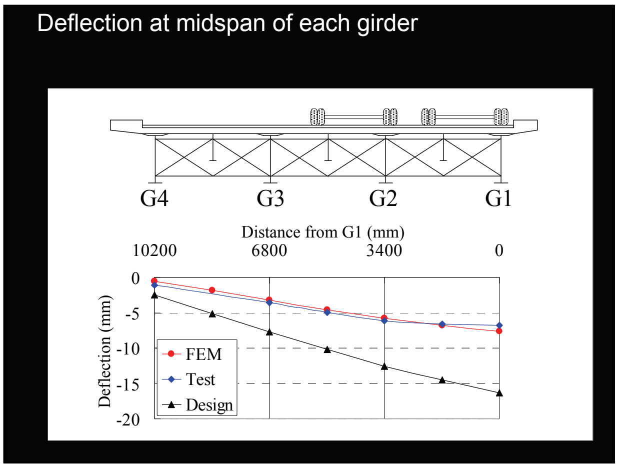


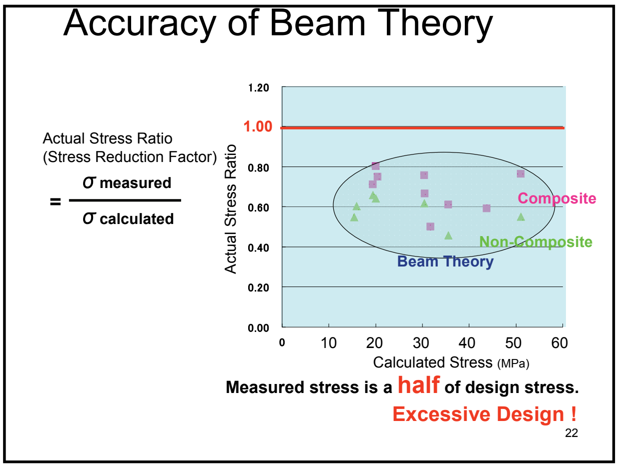
11,380 nodes
8,538 elements
56,667 DOF

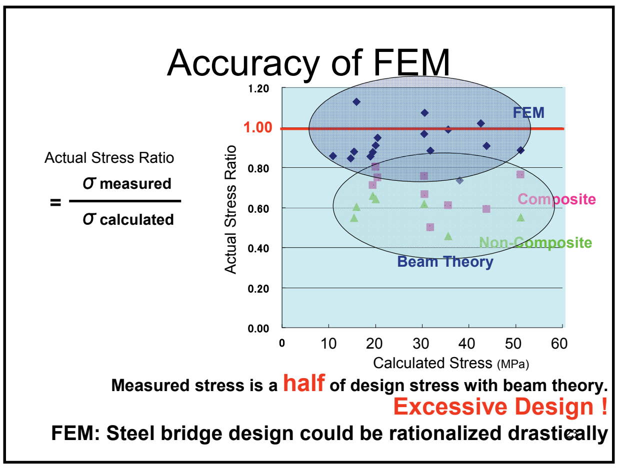
ABAQUS v.5.8


Slide (Solid elements)
Slab
(Solid elements)
G4
ST3
G3
ST2
G2
Tied contact
ST1
G1
Girder
(shell elements)
Bracing member
(beam elements)


Stress distribution at midspan of girder G1
Stress (MPa)
-50
0
50
Natural Bonding
RC deck
697 mm
NA of girder
Depth (mm)
400
0
-400
-800
-1200
-1600
FEM
Test
Design
Reinforce bar


Deflection at midspan of each girder
G4
G3
G2
G1
Distance from G1 (mm)
10200
6800
3400
0
Deflection (mm)
0
-5
-10
-15
-20
FEM
Test
Design


Accuracy of Beam Theory
Actual Stress Ratio
(Stress Reduction Factor)
σ measured
=
σ calculated
Actual Stress Ratio
1.20
1.00
0.80
0.60
0.40
0.20
0.00
Composite
Non-Composite
Beam Theory
0
10
20
30
40
50
60
Calculated Stress (MPa)
Measured stress is a half of design stress.
Excessive Design !
22


Accuracy of FEM
Actual Stress Ratio
σ measured
=
σ calculated
Actual Stress Ratio
1.20
1.00
0.80
0.60
0.40
0.20
0.00
FEM
Composite
Non-Composite
Beam Theory
0
10
20
30
40
50
60
Calculated Stress (MPa)
Measured stress is a half of design stress with beam theory.
Excessive Design !
FEM: Steel bridge design could be rationalized drastically
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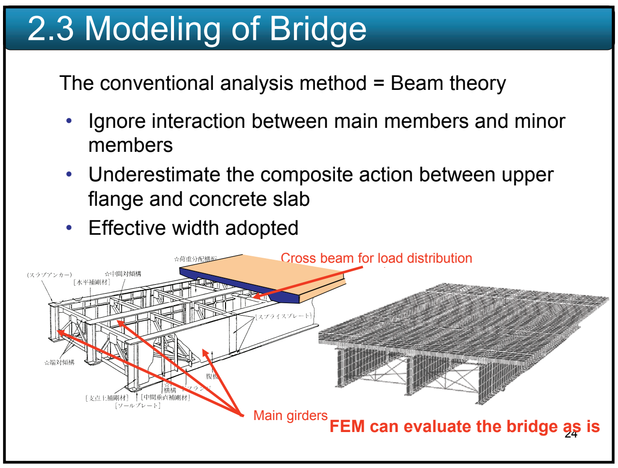
2.3 Modeling of Bridge
The conventional analysis method = Beam theory
• Ignore interaction between main members and minor members
• Underestimate the composite action between upper flange and concrete slab
• Effective width adopted
Cross beam for load distribution
Main girders
FEM can evaluate the bridge as is
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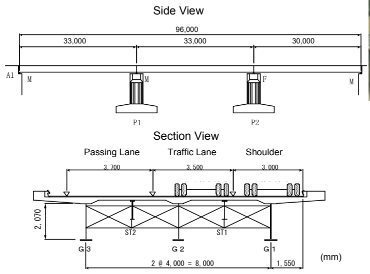
Target Bridge



3-continuous span
3 main girders.

Typical type of Toumei-Highway bridge

- **Additional bracings for slab refinement**

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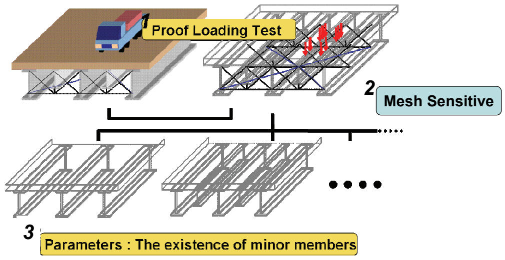
Analysis Procedure

Requirement of time and effort for modeling



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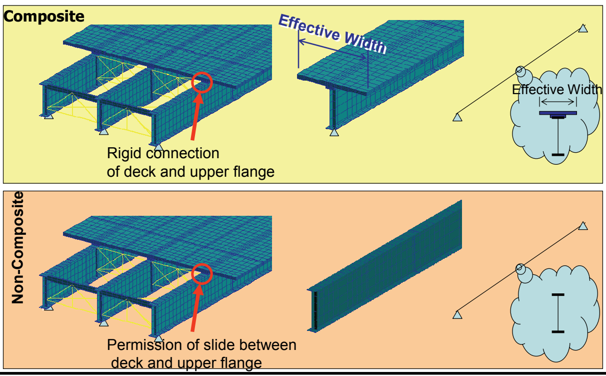
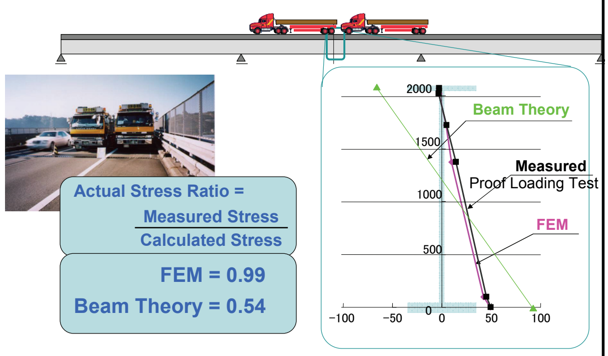
Analysis Models

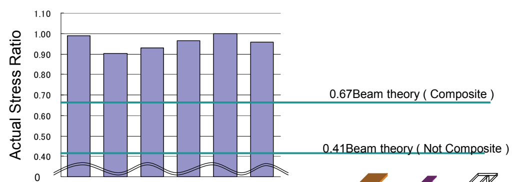


Accuracy of FEM

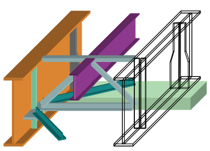


FEM Model : Good Performance

2.4 Contribution of Members



Omitted Members						
Lateral Brace	◎	✖	◎	◎	◎	◎
Brace	◎	◎	✖	◎	◎	◎
Stringer	◎	◎	◎	✖	◎	◎
V-Stiffener	◎	◎	◎	◎	✖	◎
V-Stiffener on Supports	◎	◎	◎	◎	◎	✖



Members that connect girders are high efficiency for Stress distribution

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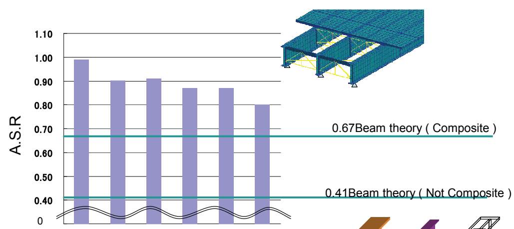
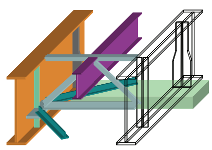
Contribution of Members 2



Omitted Members						
Lateral Brace	◎	✖	✖	✖	✖	✖
Brace	◎	◎	✖	✖	✖	✖
Stringer	◎	◎	◎	✖	✖	✖
V-Stiffener	◎	◎	◎	◎	✖	✖
V-Stiffener on Supports	◎	◎	◎	◎	◎	✖



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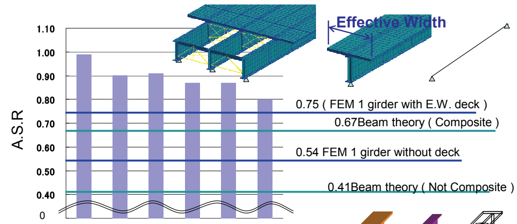
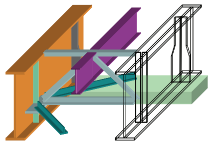
Effects of Members



Omitted Members

Lateral Brace	◎	✖	✖	✖	✖	✖
Brace	◎	◎	✖	✖	✖	✖
Stringer	◎	◎	◎	✖	✖	✖
V-Stiffener	◎	◎	◎	◎	✖	✖
V-Stiffener on Supports	◎	◎	◎	◎	◎	✖



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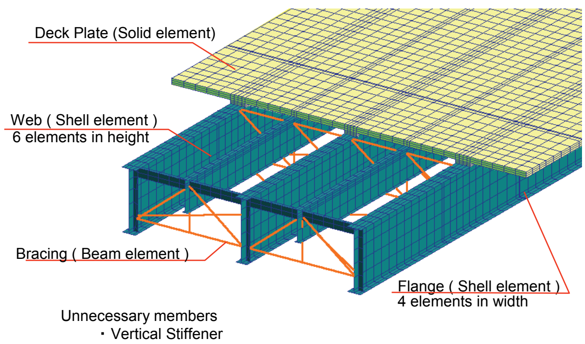
Proposed FEM Model for Actual Stress Evaluation



Unnecessary members
・Vertical Stiffener

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3. Proof Loading Test in Houkigawa Bridge

Objective

Verification of Load-Carrying Capacities of Existing Bridges, especially after the Change of Design Loads

Method

Loading Tests on Actual Bridges
using Heavy Trucks with Already-Known Weights

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Target Bridge for Proof Loading Tests

Houkikawa Bridge

4 Span Continuous Non-Composite Steel Girder with RC Deck (1973)
2 Lanes, Deck Thickness: 220mm,
Span:47.6m
Design Live Load: TL-20
(Old Specification)

➡ B-Live Load
(Present Design)

Sakabe Bridge

3 Span Continuous Non-Composite Steel Girder with RC Deck (1968)
2 Lanes, Deck Thickness: 170mm
Span: 25.2m
Design Live Load: TL-20
(Old Specification)

➡ B-Live Load
(Present Design)

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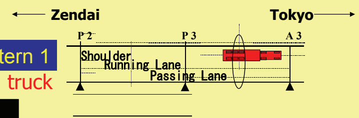
Loading Patterns on Houkigawa Br.

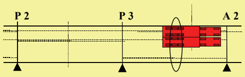
Bending moment at Target span

Pattern 1
1 truck



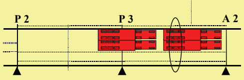
59% of B-live load
78% of L-20 live load

Pattern 2
2 trucks



63% of B-live load
83% of L-20 live load

Pattern 3
4 trucks



136% of B-live load
179% of L-20 live load

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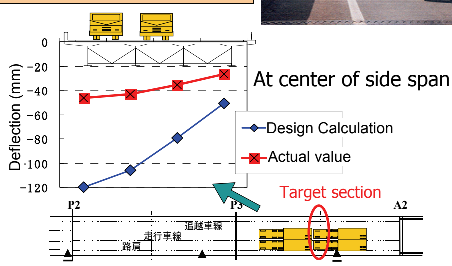
Test Results –Deflection-

Houkikawa bridge

4 trucks(69 tons)
on the center of a side span
136% of B-live load
179% of L-20 live load



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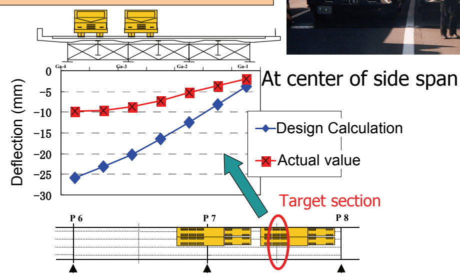
Test Results –Deflection-

Sakabe bridge

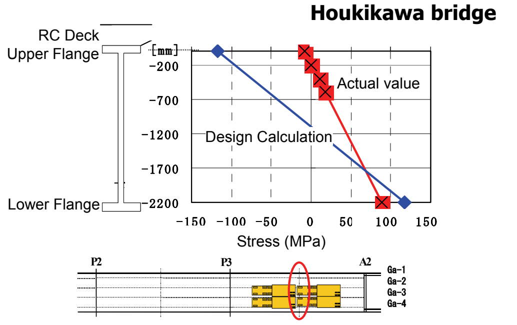
4 trucks(39 tons)
on the center of a side span
172% of B-live load
181% of L-20 live load



Test Results –Stress-

Stress Distribution of A Main Girder at center of side span

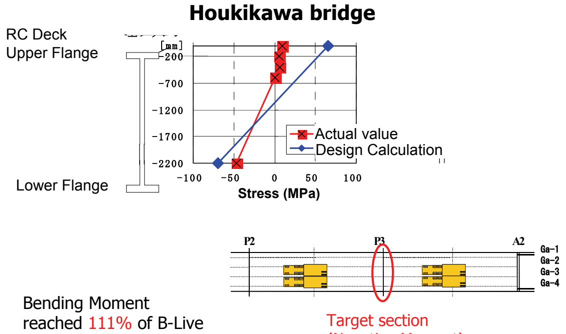
Houkikawa bridge



Test Results –Stress-

Stress Distribution of A Main Girder at an intermediate support

Houkikawa bridge

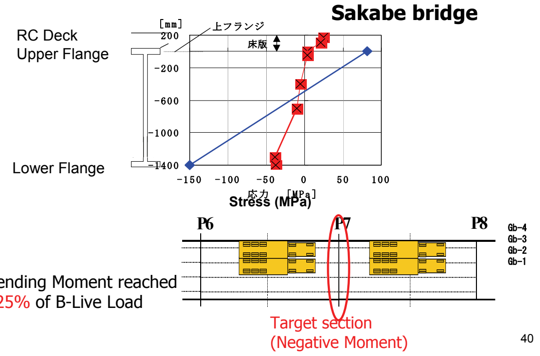


Bending Moment reached 111% of B-Live Load

Test Results –Stress-

Stress Distribution of A Main Girder at an intermediate support

Sakabe bridge



Bending Moment reached 125% of B-Live Load

Evaluation of Load-Carrying Capacity

Safety condition

$$\varphi \cdot \sigma_r \geq \gamma_D \cdot \sigma_D + \gamma_L \cdot \sigma_L$$

σ_r = Stress of limit state (σ_Y or σ_{cr})

$\sigma_{D,L}$ = Stress due to dead load and live load

$\gamma_{D,L}$ = Factor for dead load and live load

(γ_D=1.2 γ_L=1.7)

φ = resistance factor = 1.0

4. Capacity evaluation with proof load test

Concept of proof load test

- loading the bridge up to the required load level
- If the target load level is reached without distress, the bridge is proved to have capacity up to the target load level

Procedure

- FEM analysis
  - Calculate the capacity required by B-live load
  - Design loading patterns (weight, number, arrangement of test trucks)
- Field load testing
  - Gradually load the bridge with designed proof load patterns
  - Monitor and collect the bridge responses (stresses and deflections)

Target Bridges

- Monoi Bridge
  - Since 1971 (32 yrs)
  - Composite plate girder
  - 5 main girders
  - Simple span, 29.5 m

- Sakabe Bridge
  - Since 1968 (35 yrs)
  - Non-composite plate girder
  - 4 main girders
  - 3-continuous span, 3@25.1 m

- Hirono Bridge
  - Since 1968 (35 yrs)
  - Non-composite plate girder
  - 3 main girders
  - 3-continuous span, 30.4~33.0 m

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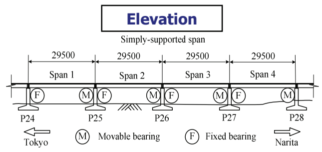
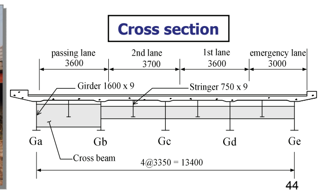
The Monoi Bridge

- Since 1971 (32 yrs.)
- Composite RC slab-on-girder
- Multi simple span
- Designed for **L20** (1964 code)
- Current **B-live load** (heavier)





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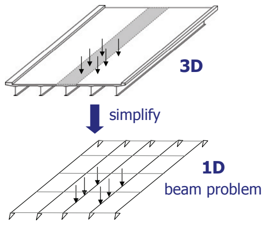
Capacity evaluation based on grid analysis

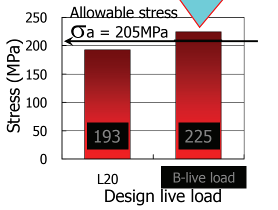


Assumptions in grid analysis:

- Effective slab width
- Equivalent section
- Load distribution

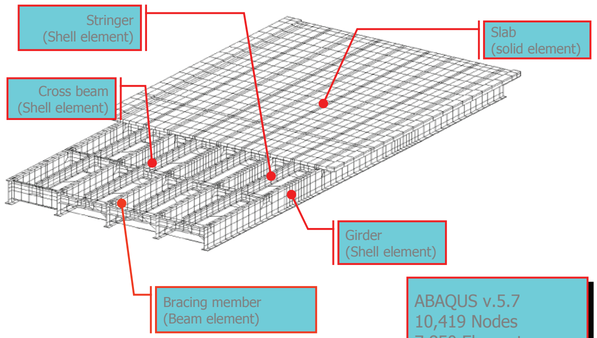
Stress produced by design live loads
By grid analysis

Exceed allowable stress (σa)



This bridge should be replaced or strengthened

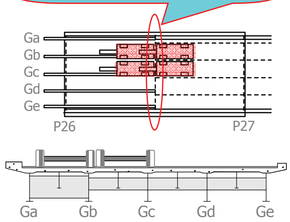
FEM model for Monoi bridge

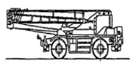


ABAQUS v.5.7
10,419 Nodes
7,850 Elements

Design of proof load

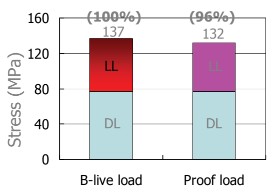
Maximum force effect at midspan





Test truck = 34.7 ton
(4 trucks)

Stress produced by B-live load
& Proof Load
(Based on FEM)

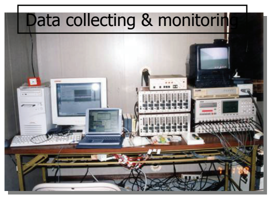


Stress produced by proof load is almost equal to required stress

Proof load test results

Loading

Data collecting & monitoring



Monitoring results

- The proof load was successfully reached without any distress
- The stress and deflection rebound to the initial conditions after load removal

The bridge was proved to have enough capacity to safely carry load up to proof load level

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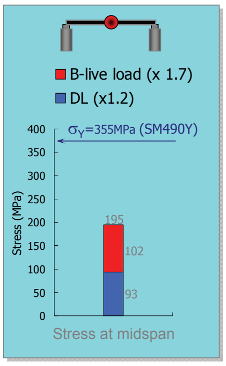
Safety verification (1)



Safety condition

$$\varphi \bullet \sigma_r \geq \gamma_D \bullet \sigma_D + \gamma_L \bullet \sigma_L$$

σ_r = Stress of limit state (σ_Y or σ_{cr})

$\sigma_{D,L}$ = Stress due to dead load and live load

$\gamma_{D,L}$ = Factor for dead load and live load (γ_D=1.2 γ_L=1.7)

φ = resistance factor = 1.0

➢ Strength of structure ≥ force effects from load

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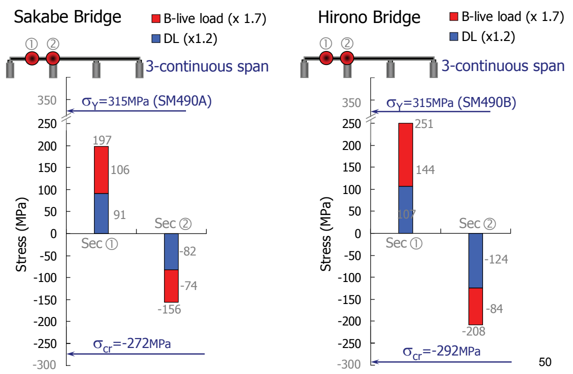
Safety verification (2)



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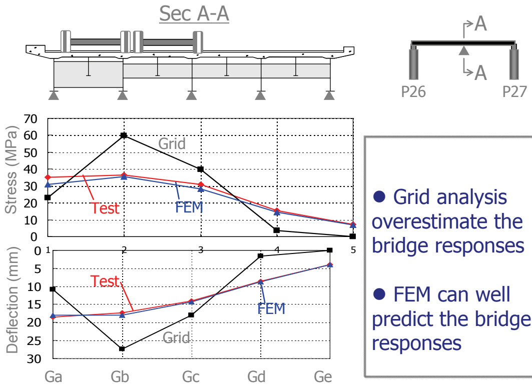
Test & analytical results



- Grid analysis overestimate the bridge responses
- FEM can well predict the bridge responses

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