OVERVIEW AND APPLICATION

OF LOCAL EXCITATION METHOD (LEM)

FOR MONITORING OF SMALL DAMAGE OF REAL BRIDGES

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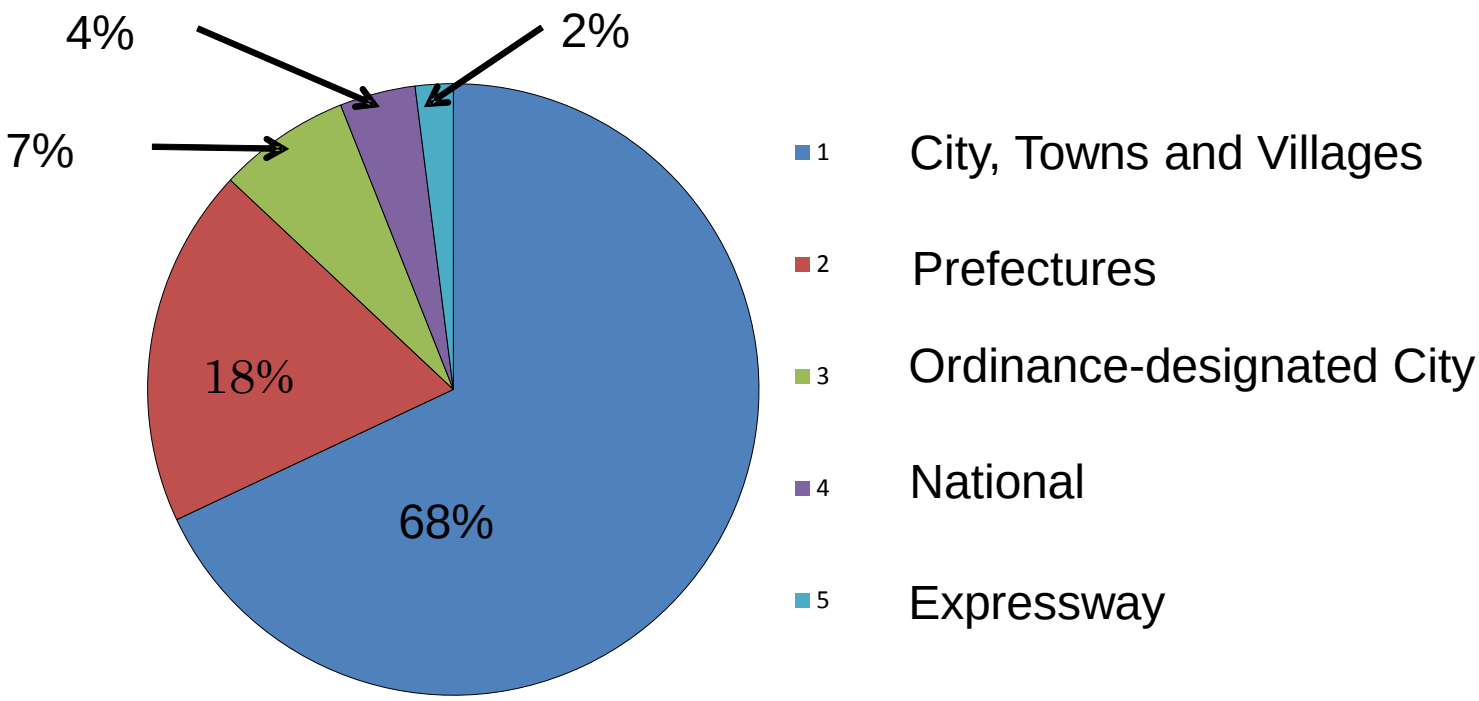
Background in Japan

During 1960-1990 much bridges have constructed for rapid economic growth of Japan

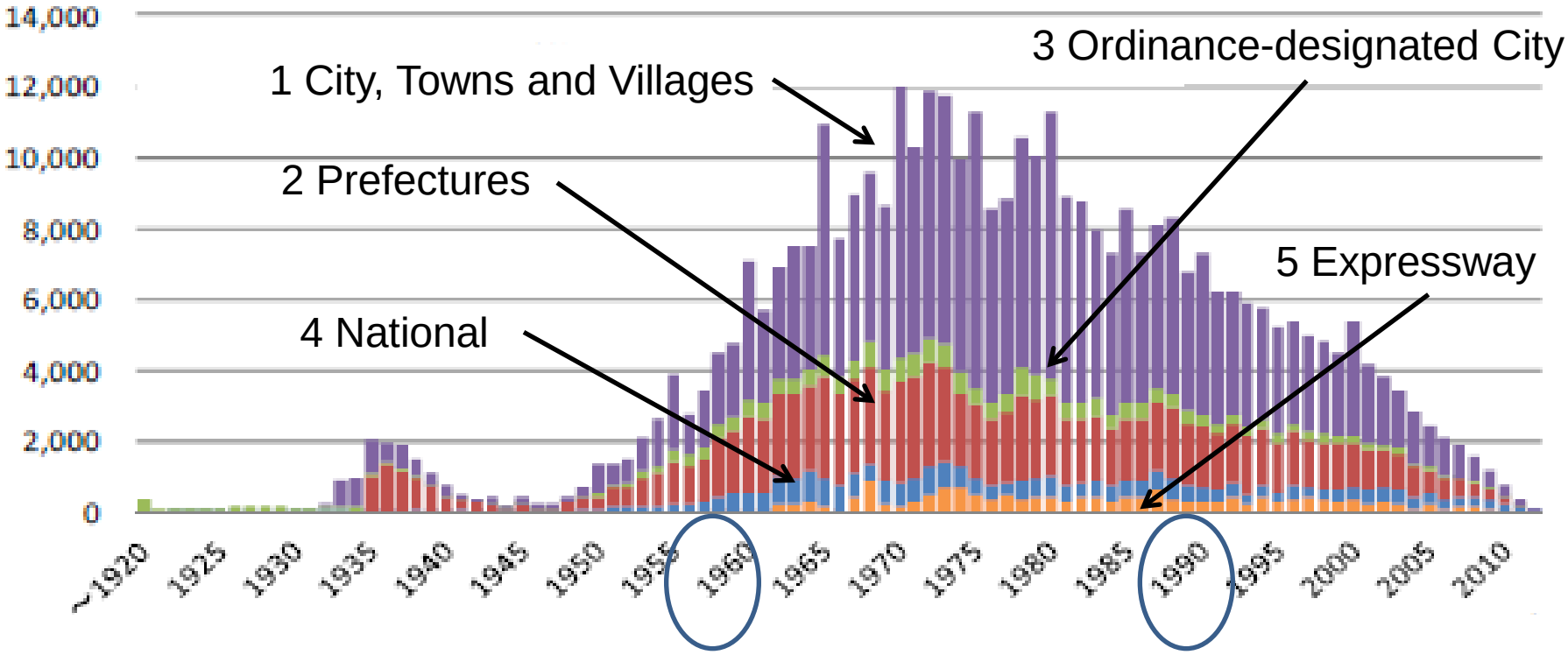
Nowadays total about 700,000 bridges were stocked

Distribution of Management Agency

over 700,000 bridges



150,000 bridges are constructed by national government support (23%)


14,000
12,000
10,000
8,000
6,000
4,000
2,000
0
1 City, Towns and Villages
2 Prefectures
3 Ordinance-designated City
4 National
5 Expressway
~1920
1925
1930
1935
1940
1945
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010

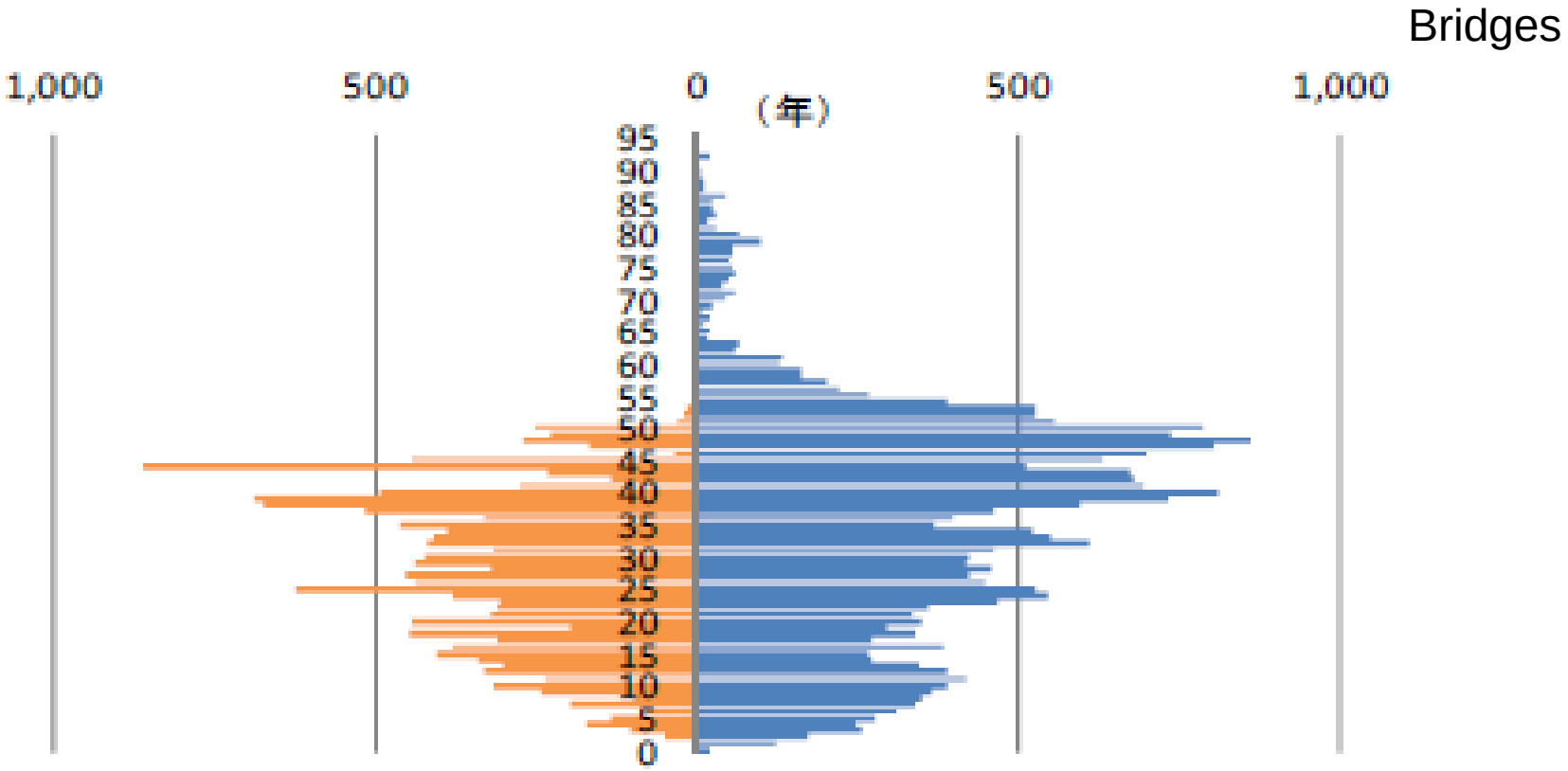
Stock Pyramid of Bridges

Express Way

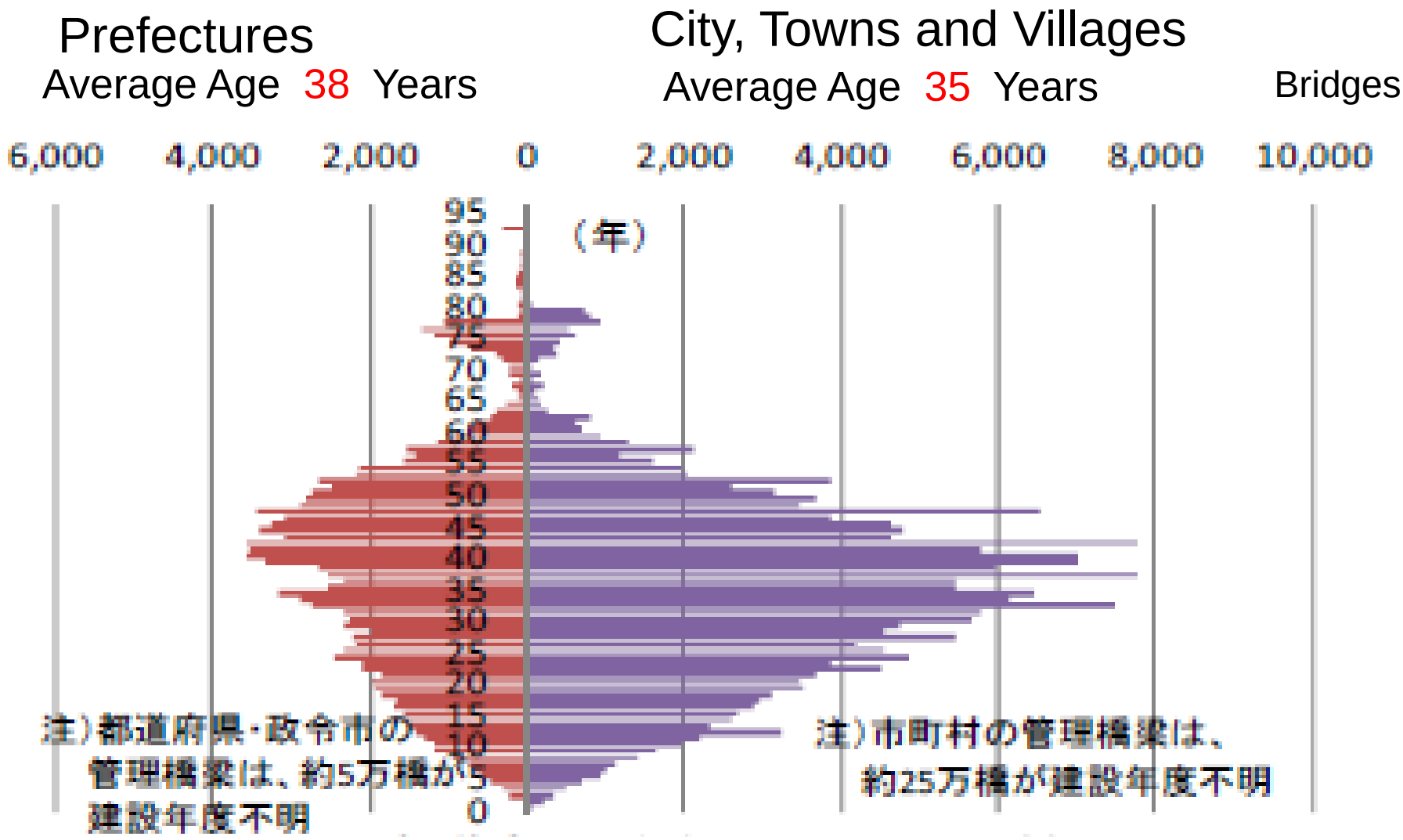
Average Age 29 Years

National Road

Average Age 35 Years



Stock Pyramid of Bridges



Background in Japan

During 1960-1990 much bridges have constructed for rapid economic growth of Japan

Nowadays total about 700,000 bridges were stocked

As a result of this history Short and Medium Span Bridges (SMSB) are dominated in those total 700,000 bridges

and it is clear that maintenance of structural health and its monitoring of those bridges are very important task here.

Algorithm of Monitoring Method

Algorithm of Monitoring Method

Vibration-based damage detection

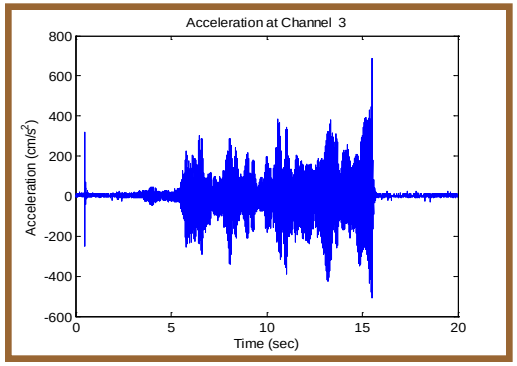
using Local Excitation Method (LEM)

Measured Acceleration → PSD

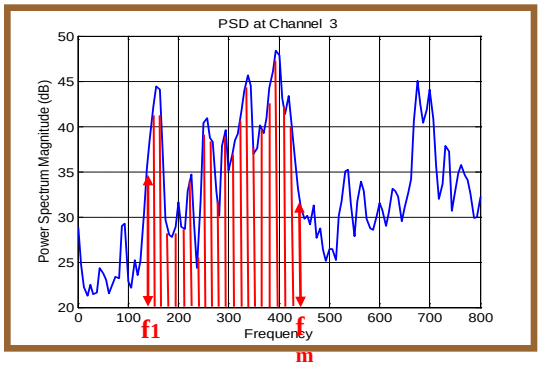
Damage Detection Algorithm

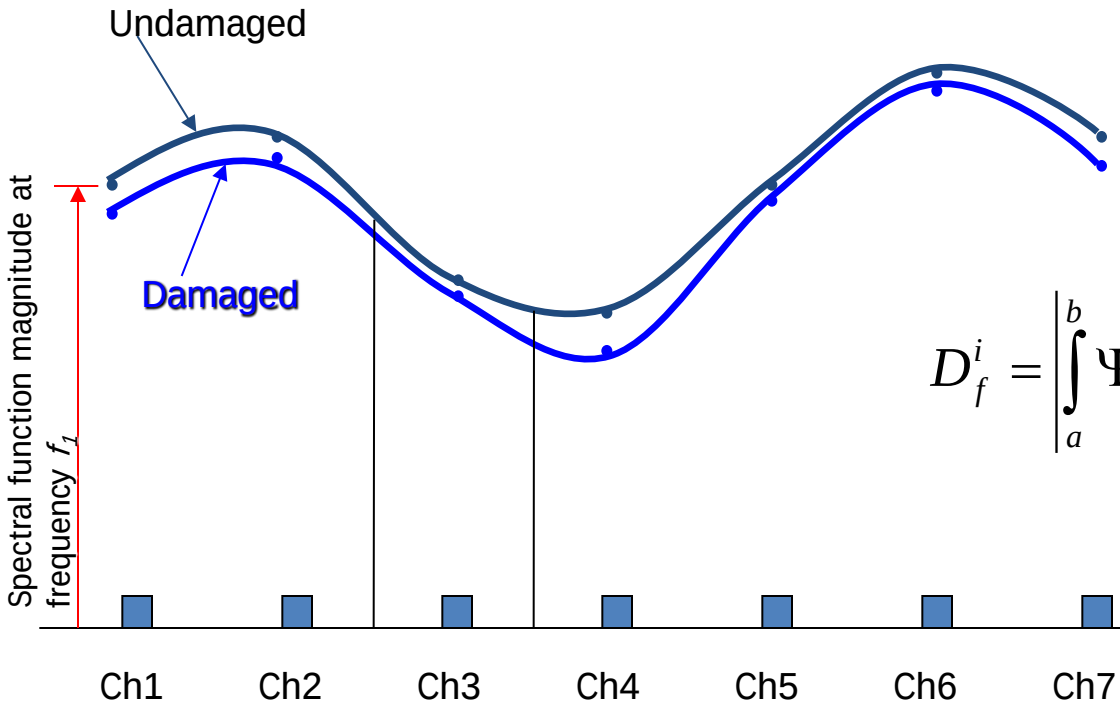
Damage Indicator

Basic Idea of Proposed Method



Spectral Analysis



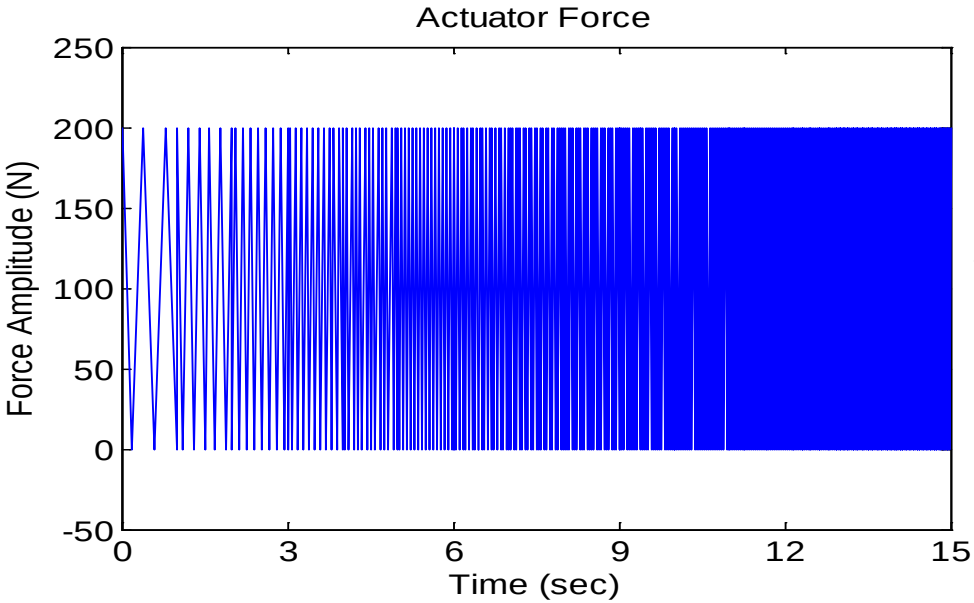


$$D_f^i = \left| \int_a^b \Psi_f(x)dx - \int_a^b \Psi_f^*(x)dx \right|$$

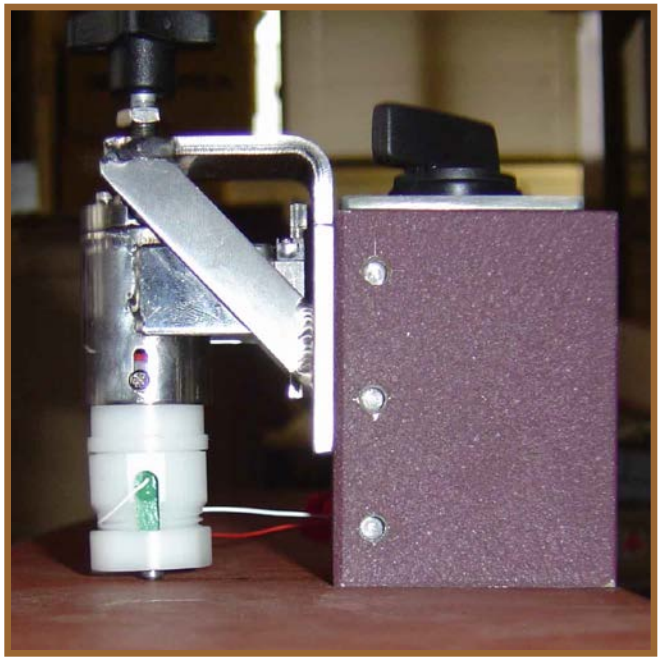
Experiment Setup

Wave function generator

Power supplier



Simulation of the actuator force



Piezoelectric actuator

$$D_i = \frac{\left| G_i(f) - G^*{}_i(f) \right|}{1 + \left| G_i(f) \right|}$$

$$\mathbf{D} = \begin{bmatrix} D_1(f_1) & D_2(f_1) & \ldots\ldots & D_n(f_1) \\ D_1(f_2) & D_2(f_2) & \ldots\ldots & D_n(f_2) \\ . & . & \ldots\ldots & . \\ . & . & \ldots\ldots & . \\ . & . & \ldots\ldots & . \\ D_1(f_m) & D_2(f_m) & \ldots\ldots & D_n(f_m) \end{bmatrix}$$

$$\mathrm{C} = \begin{bmatrix} C_1(f_1) = \dfrac{D_1(f_1)}{D_3(f_1)} & C_2(f_1) = \dfrac{D_2(f_1)}{D_3(f_1)} & \cdots & C_n(f_1) = \dfrac{D_n(f_1)}{D_3(f_1)} \\ C_1(f_2) = \dfrac{D_1(f_2)}{D_2(f_2)} & C_2(f_2) = \dfrac{D_2(f_2)}{D_2(f_2)} & \cdots & C_n(f_2) = \dfrac{D_n(f_2)}{D_2(f_2)} \\ \vdots & \vdots & & \vdots \\ \vdots & \vdots & & \vdots \\ C_1(f_m) = \dfrac{D_1(f_m)}{D_5(f_m)} & C_2(f_m) = \dfrac{D_2(f_m)}{D_5(f_m)} & \cdots & C_n(f_m) = \dfrac{D_n(f_m)}{D_5(f_m)} \end{bmatrix}$$

Total Change (TC)

$$\mathrm{SMD} = \left\{ \sum_f D_1(f) \quad \sum_f D_2(f) \quad . \quad . \quad . \quad \sum_f D_n(f) \right\}$$

$\longrightarrow$ **Channel Number**

Damage Detection (DD)

$$\mathrm{SCD} = \left\{ \sum_f C_1(f) \quad \sum_f C_2(f) \quad . \quad . \quad . \quad \sum_f C_n(f) \right\}$$

$$\textbf{SMD1} = \left\{ \sum_f D_1(f) - \sigma \quad \sum_f D_2(f) - \sigma \quad . \quad . \quad . \quad \sum_f D_n(f) - \sigma \right\}$$

$$\textbf{SMD2} = \left\{ \sum_f D_1(f) - 2\sigma \quad \sum_f D_2(f) - 2\sigma \quad . \quad . \quad . \quad \sum_f D_n(f) - 2\sigma \right\}$$

$$\sigma = \sqrt{\sum_{i=1}^{n} (SM(i) - \overline{SM})^2} \Big/ (n-1)$$

$$\overline{SM} = \sum_{i=1}^{n} SM(i) \Big/ n$$

$$\mathbf{SCD1} = \left\{ \sum_f C_1(f) - \lambda \quad \sum_f C_2(f) - \lambda \quad . \quad . \quad . \quad \sum_f C_n(f) - \lambda \right\}$$

$$\mathbf{SCD2} = \left\{ \sum_f C_1(f) - 2\lambda \quad \sum_f C_2(f) - 2\lambda \quad . \quad . \quad . \quad \sum_f C_n(f) - 2\lambda \right\}$$

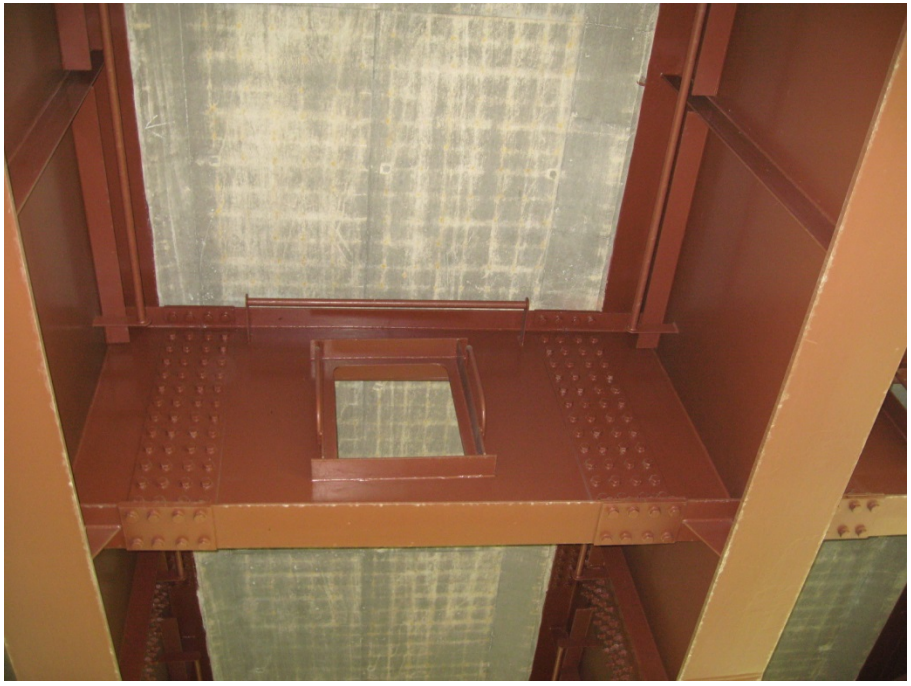
$$\lambda = \sqrt{\sum_{i=1}^{n} (SC(i) - \overline{SC})^2} \Big/ (n-1)$$

$$\overline{SC} = \sum_{i=1}^{n} SC(i) \Big/ n$$

Damage Indicators DI1 DI2

$$DI1 = \{SMD1(1) \times SCD1(1) \quad SMD1(2) \times SCD1(2) \quad \ldots \quad SMD1(n) \times SCD1(n) \}$$

$$DI2 = \{SMD2(1) \times SCD2(1) \quad SMD2(2) \times SCD2(2) \quad \ldots \quad SMD2(n) \times SCD2(n) \}$$

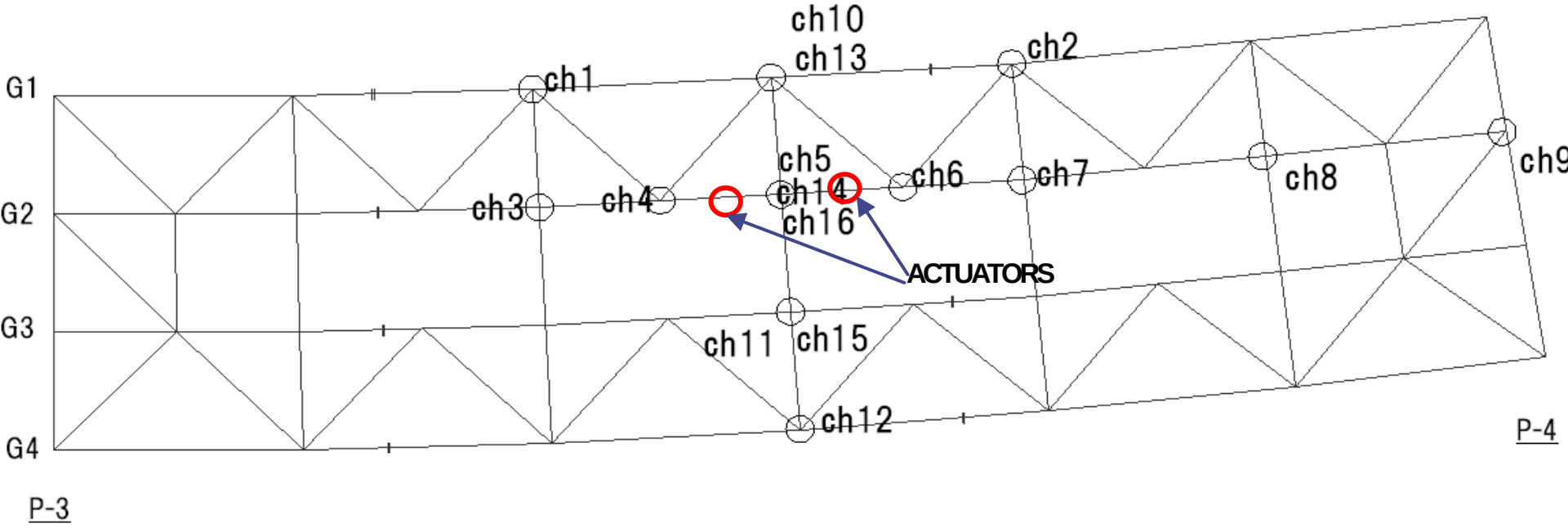


Medium Span Bridge

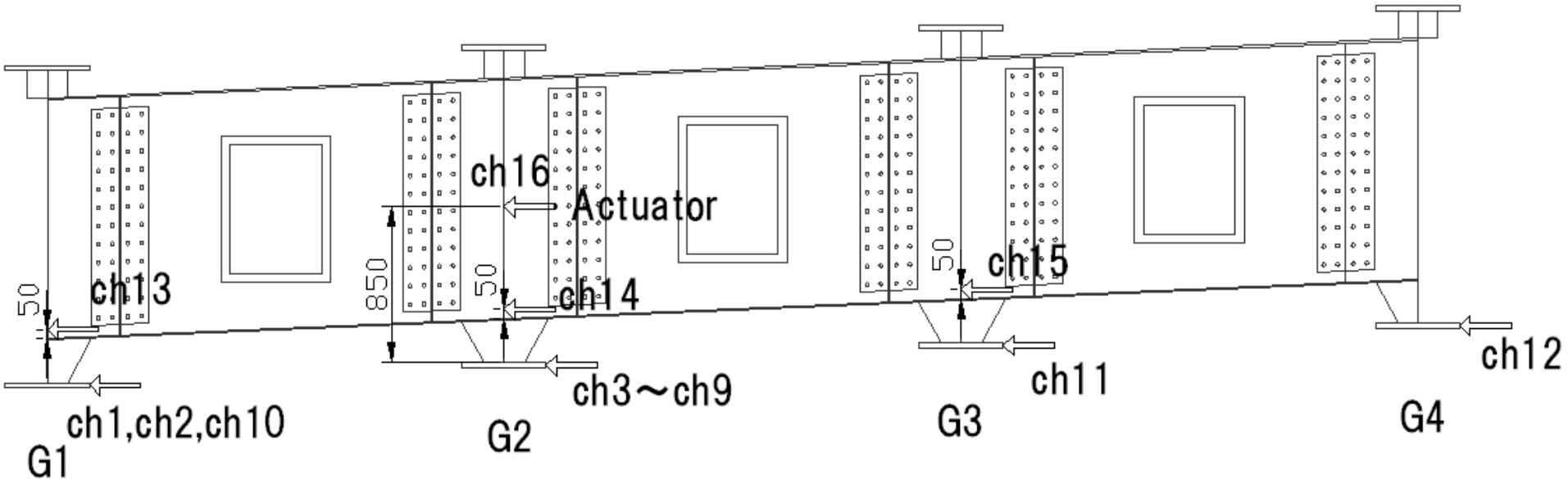
30 m span continuous bridge

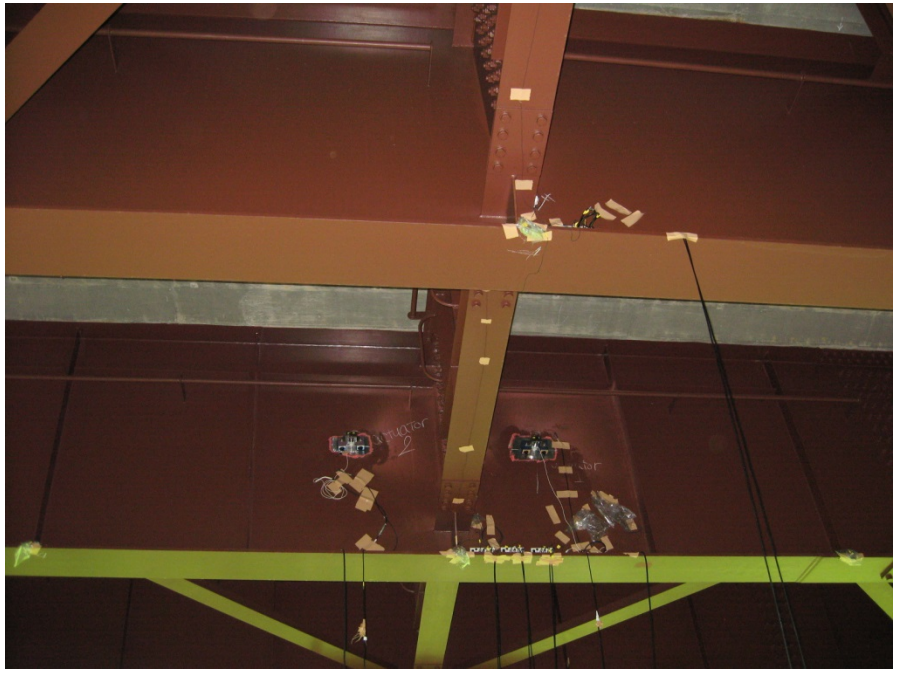
Location of Accelerometers and Actuators

(At end span)



Accelerometers detect horizontal acceleration at each location



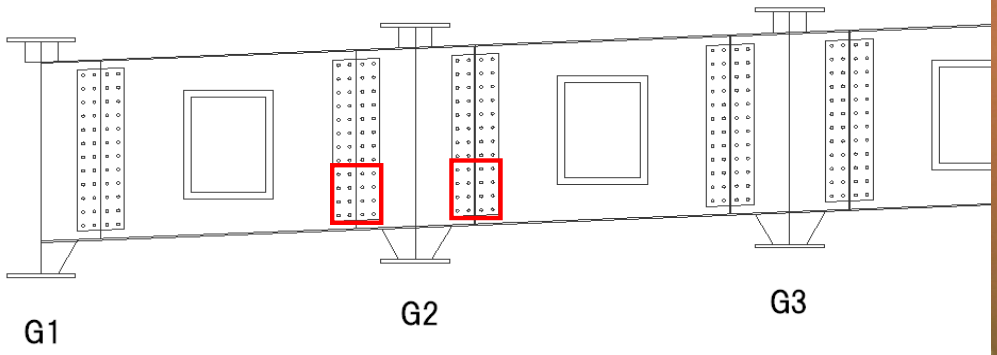


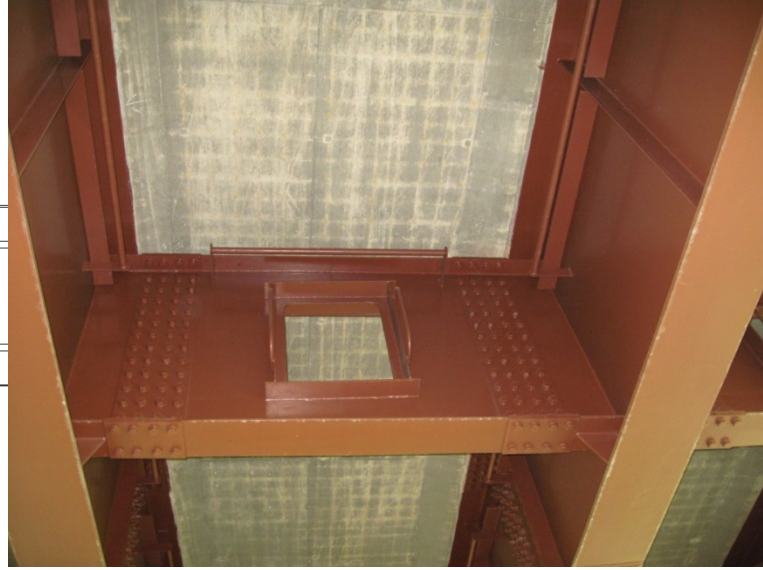
Two Actuators
are synchronized

Measuring Station

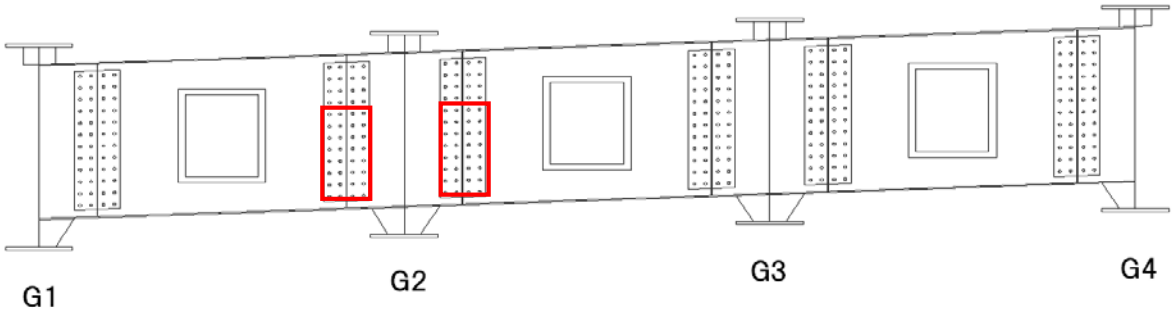
Bolt Tension Release

D3

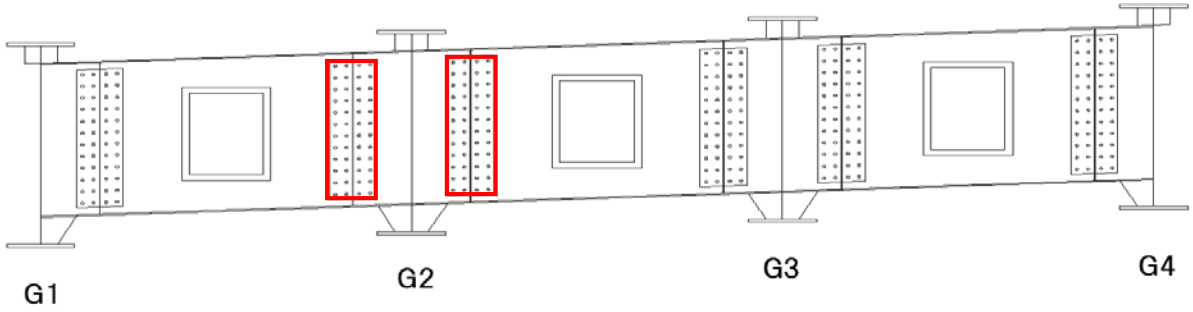


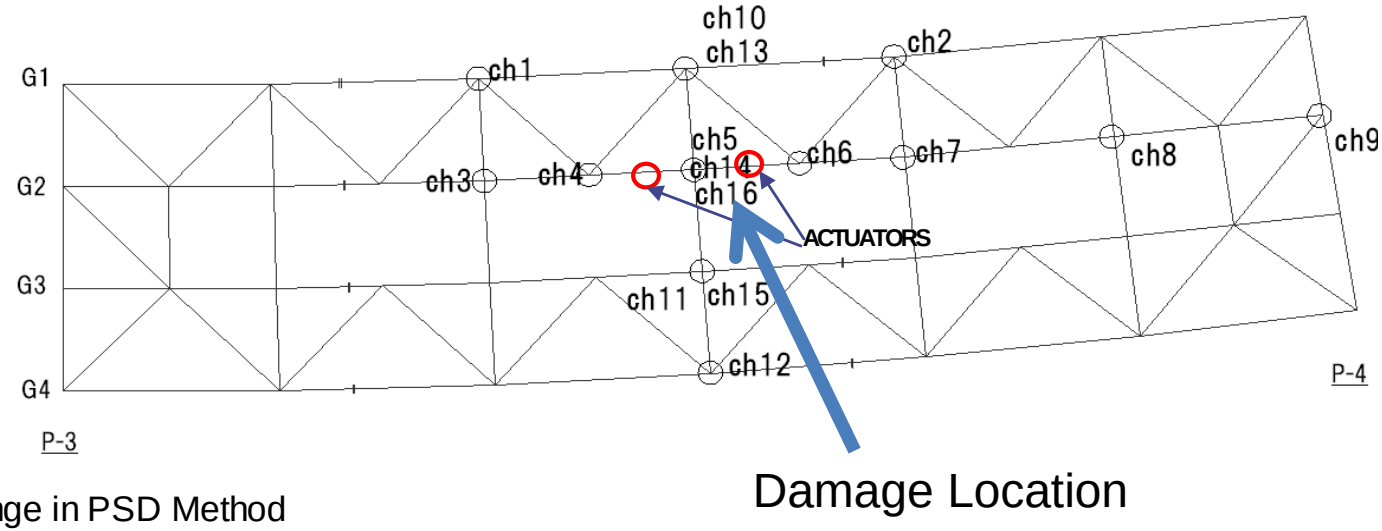


D4

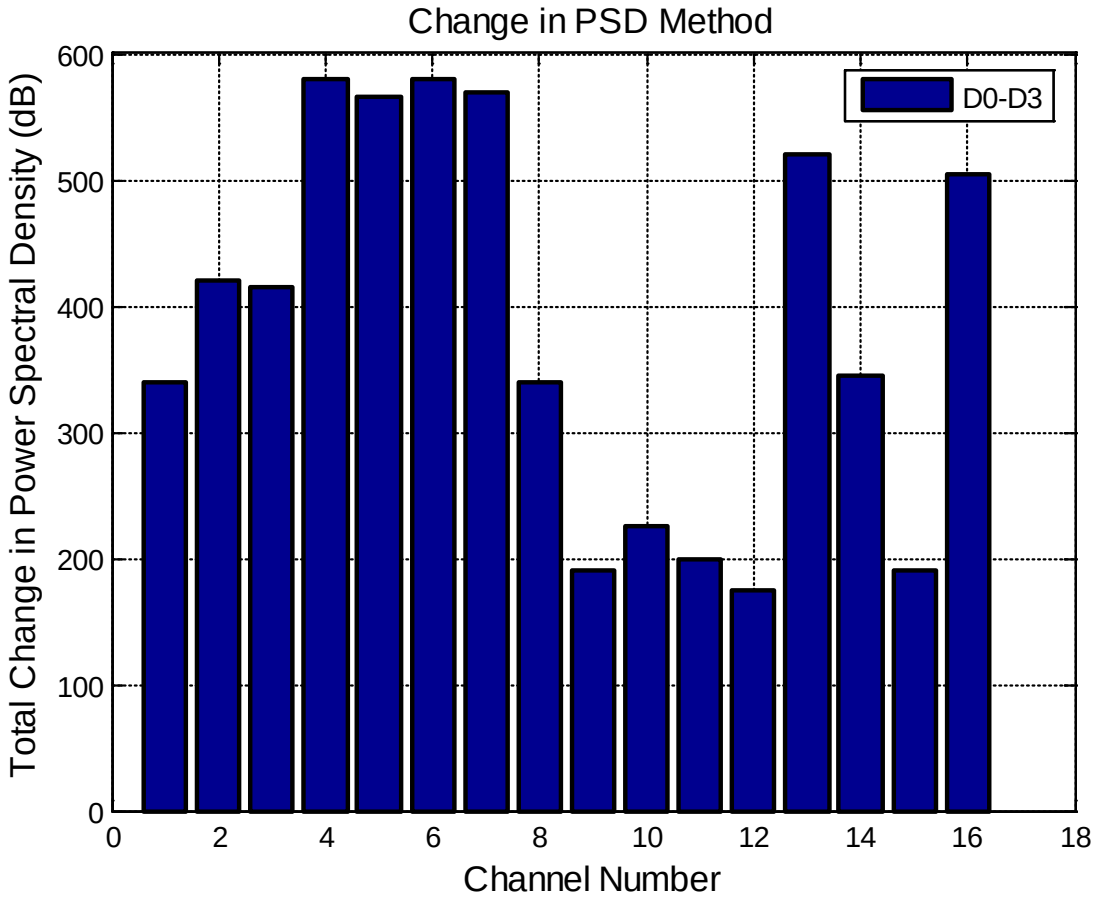


D5

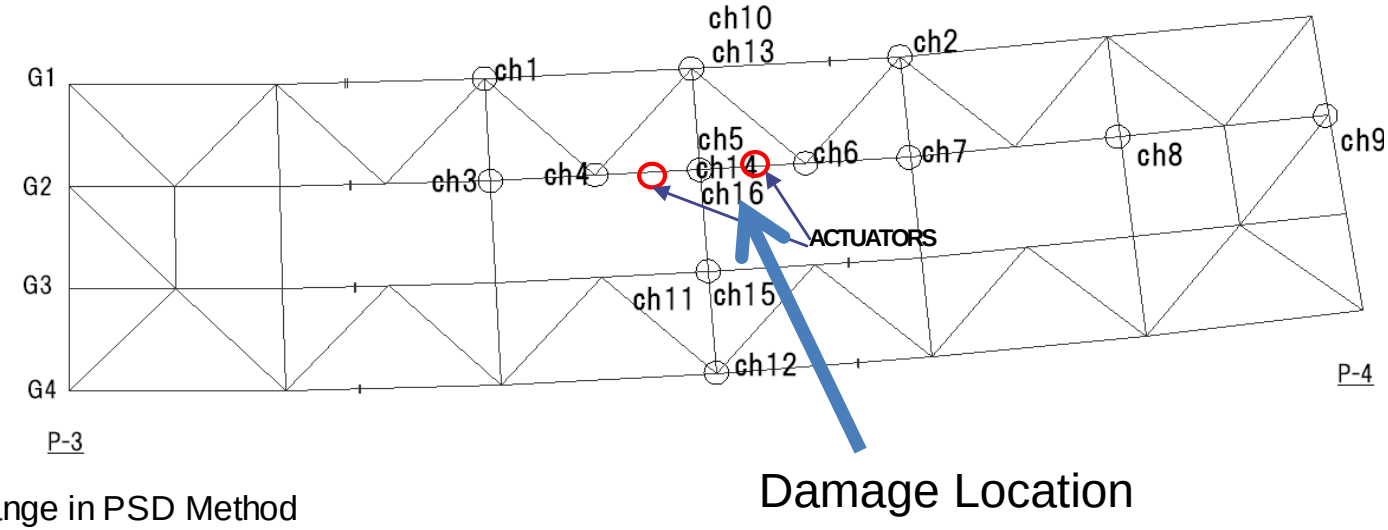




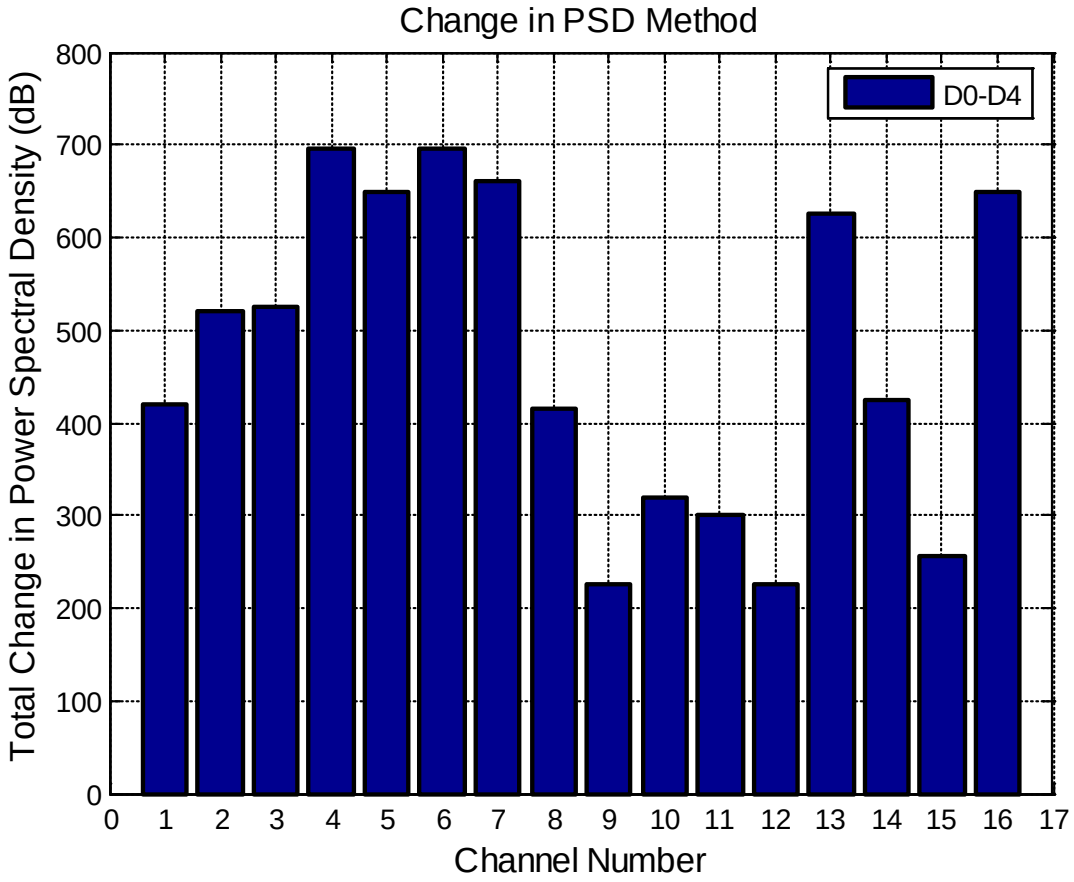
Damage Location



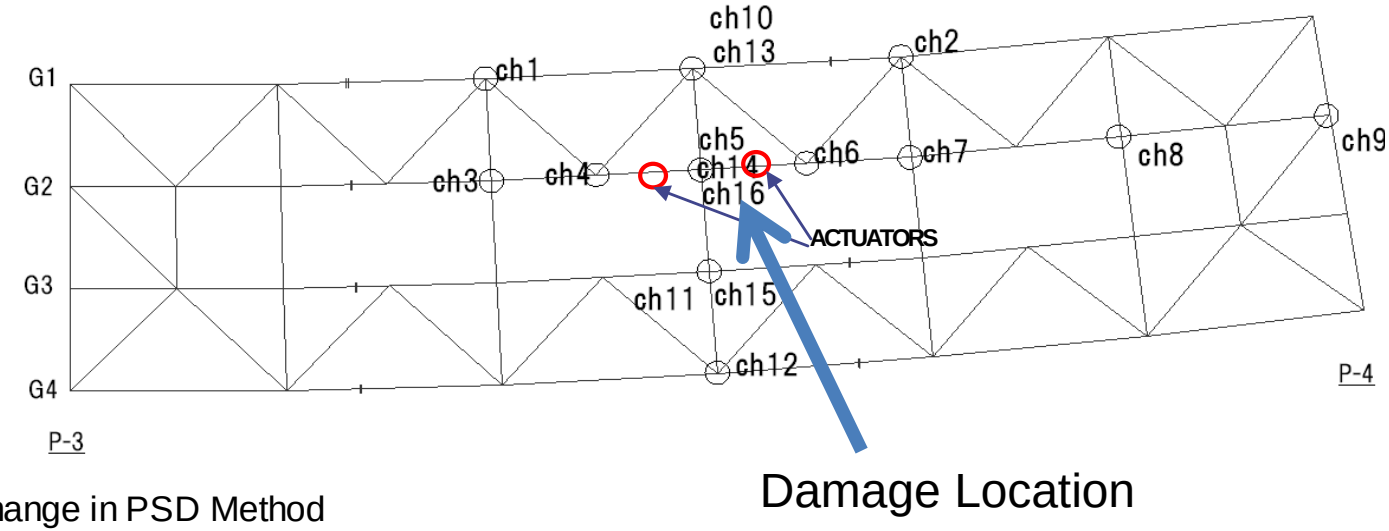
Total Change for D3



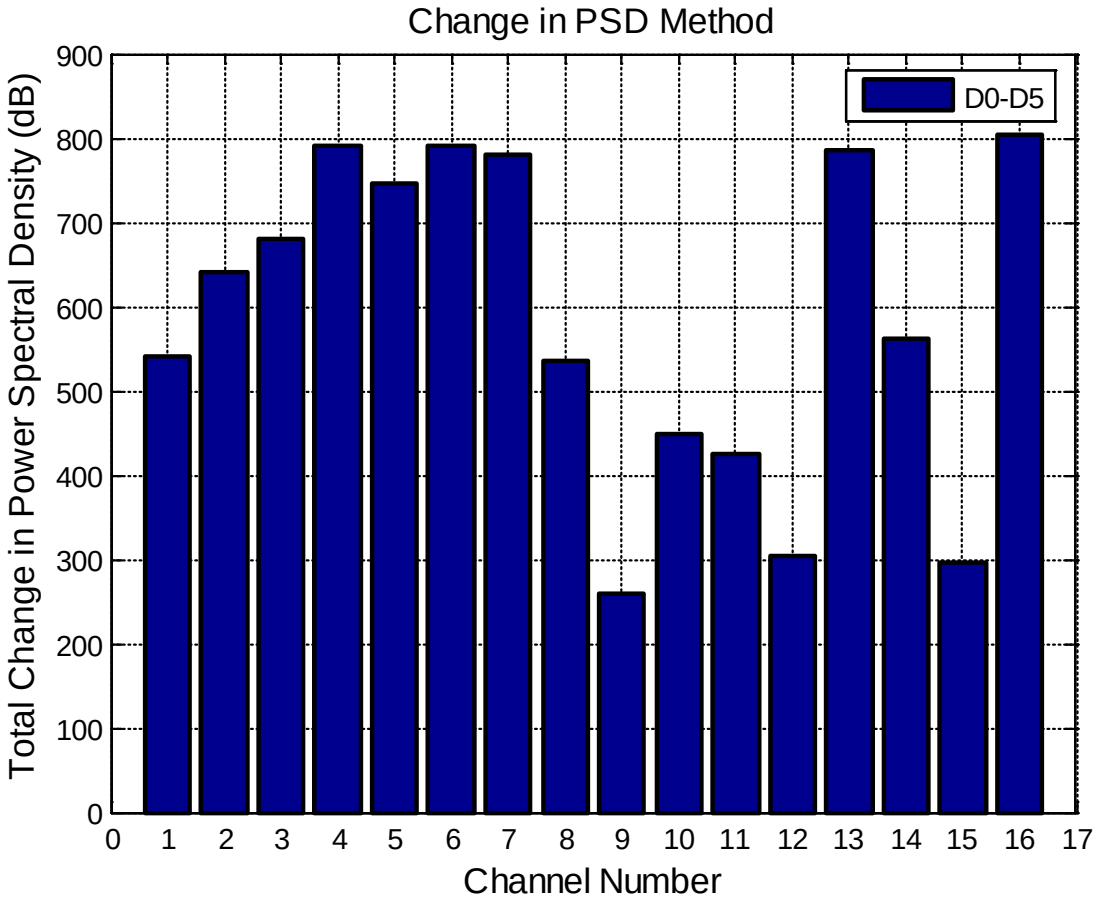
Damage Location



Total Change for D4



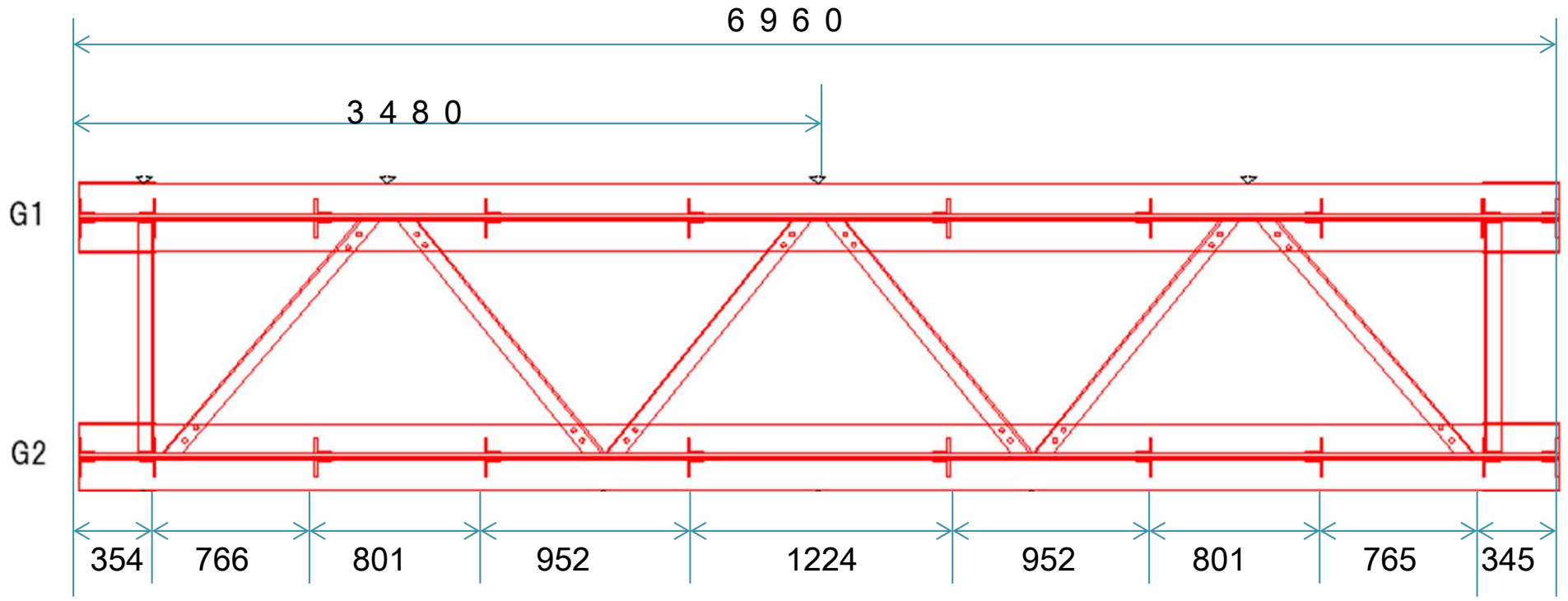
Damage Location

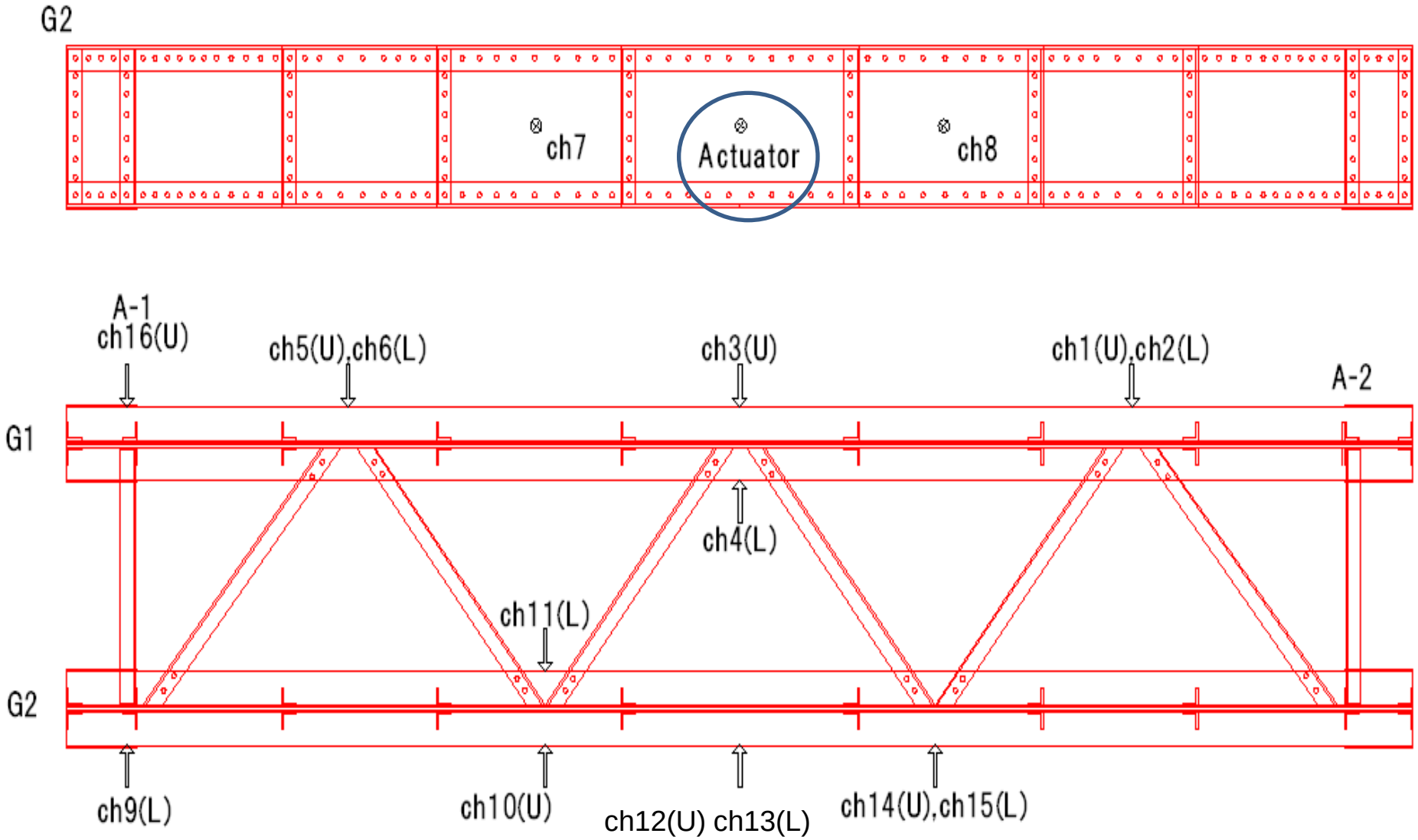


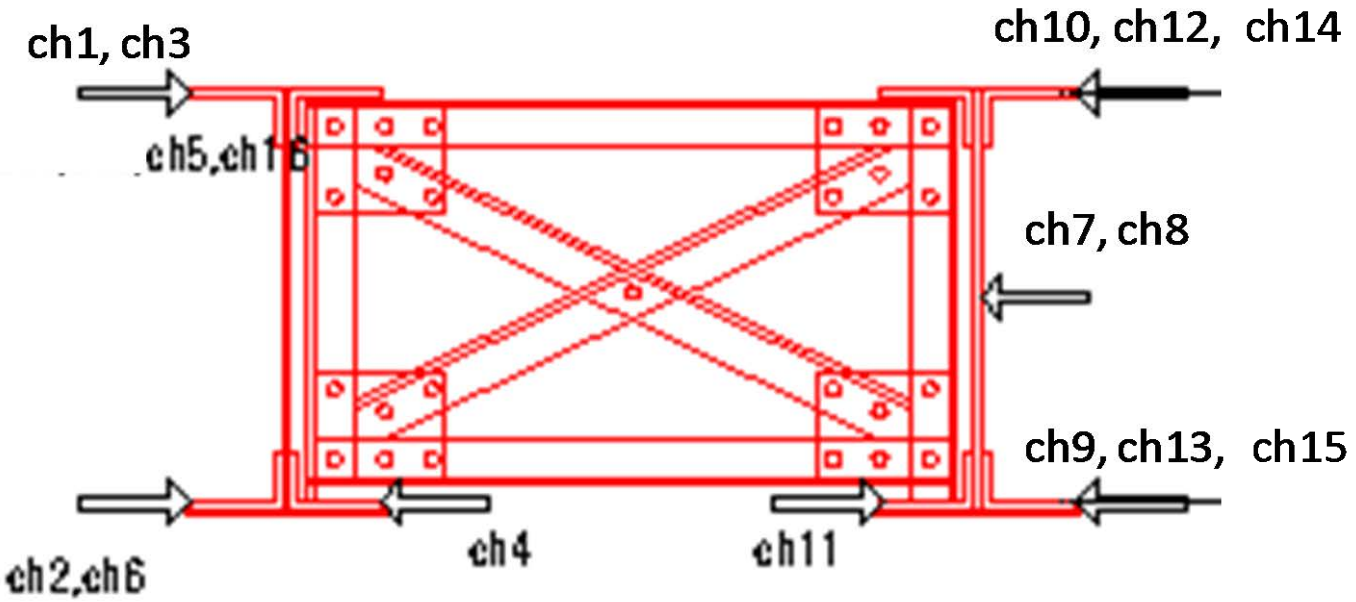
Total Change for D5

Short Span Bridge 7 m Simple Beam

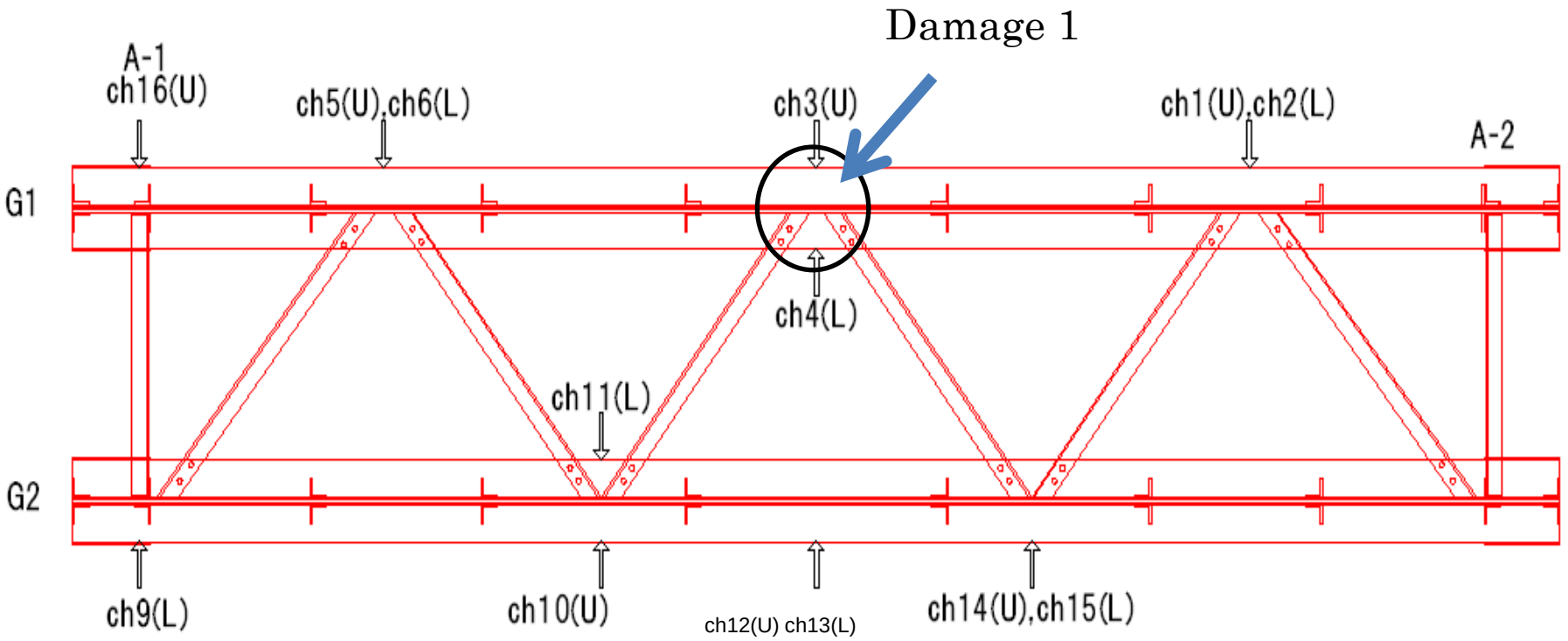
Rail Way Bridge


6 9 6 0
3 4 8 0
G1
G2
354
766
801
952
1224
952
801
765
345


G2
ch7
Actuator
ch8
A-1
ch16(U)
ch5(U),ch6(L)
ch3(U)
ch1(U),ch2(L)
A-2
G1
ch4(L)
ch11(L)
G2
ch9(L)
ch10(U)
ch12(U) ch13(L)
ch14(U),ch15(L)


ch1, ch3
ch10, ch12, ch14
ch5,ch16
ch7, ch8
ch9, ch13, ch15
ch2,ch6
ch4
ch11

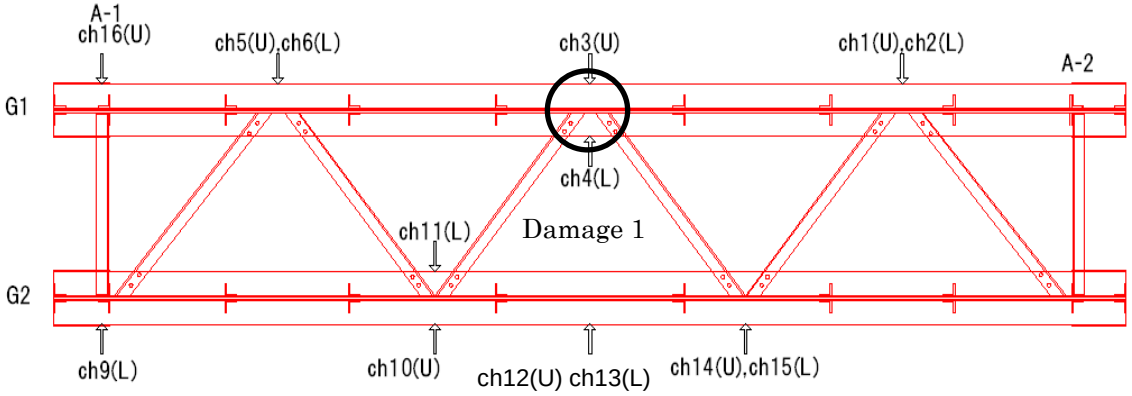
Damage is set under Ch. 3

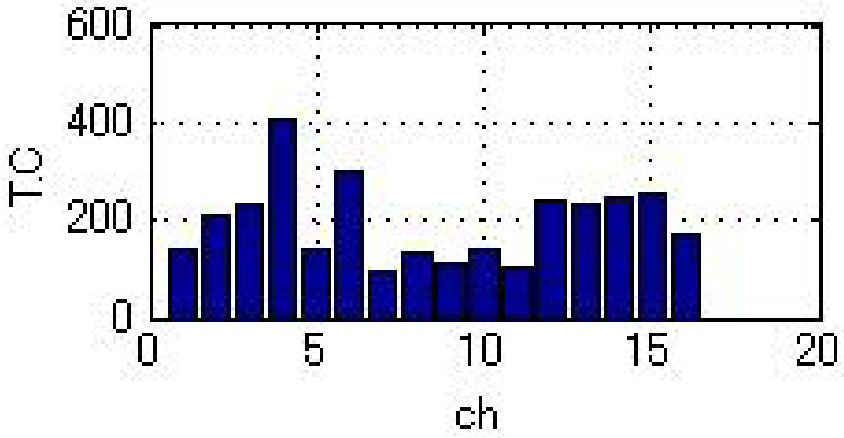


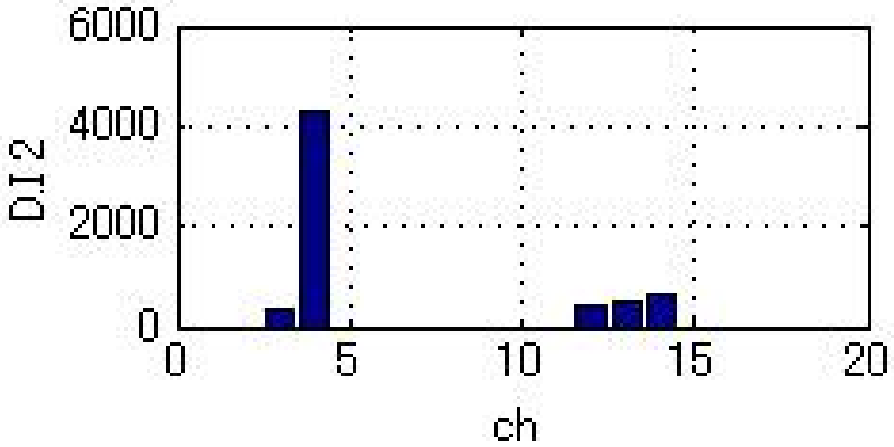
D1

D2

$$D = \frac{|G_i(f) - G^*{}_i(f)|}{1 + (G_i(f), G^*{}_i(f))_{\min}}$$

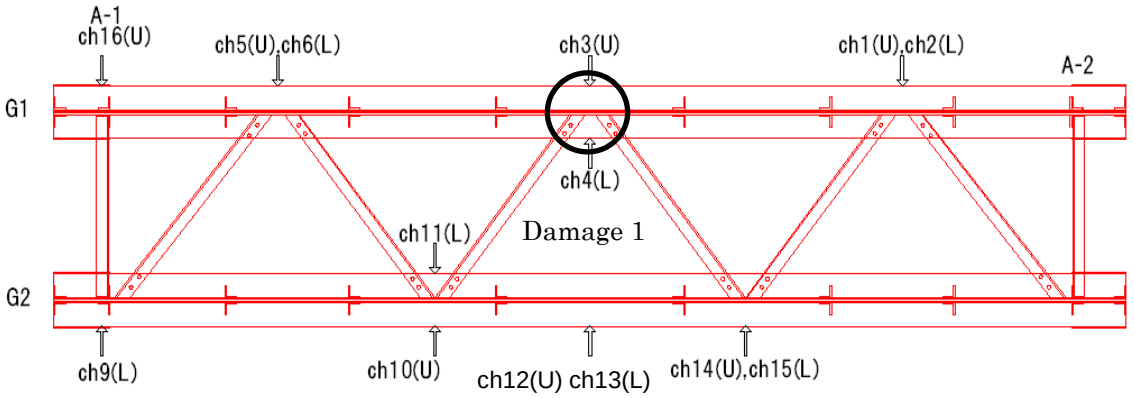


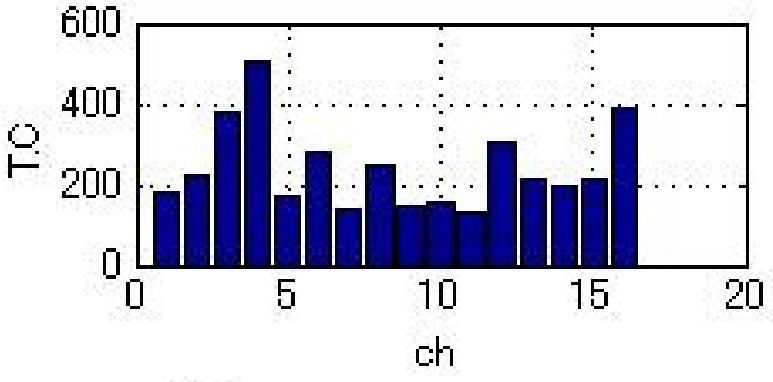




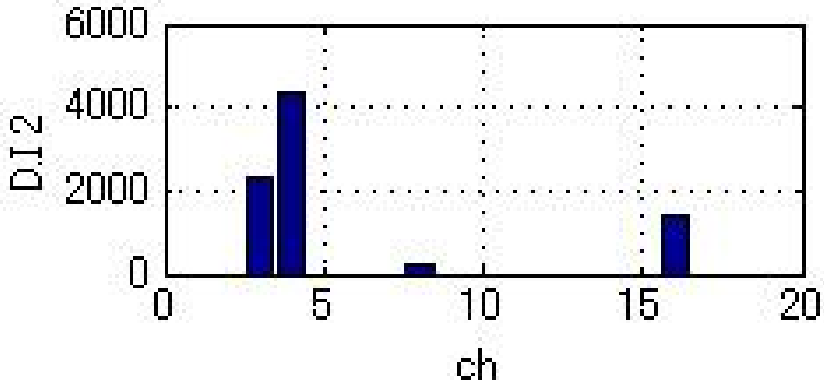
Total Change for D1

Damage Indicator DI2 for D1



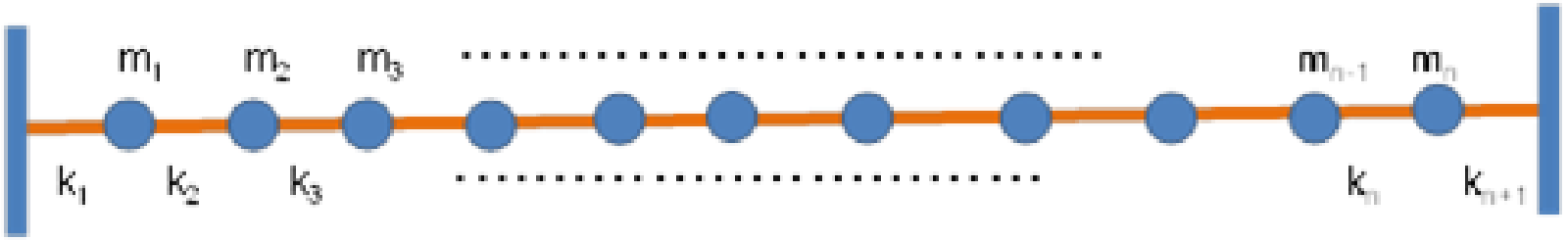


Total Change for D2



Damage Indicator DI2 for D2

Numerical Simulation

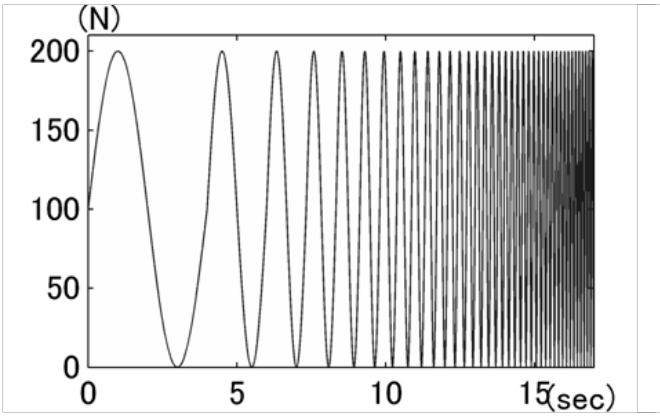


- Total Mass : n = 21, m_i = 10.8 kg , End Support : Fixed
- Stiffness : k_i = 100,000 (N/m) , Damping: c_i = 100.0 (N·sec/m)

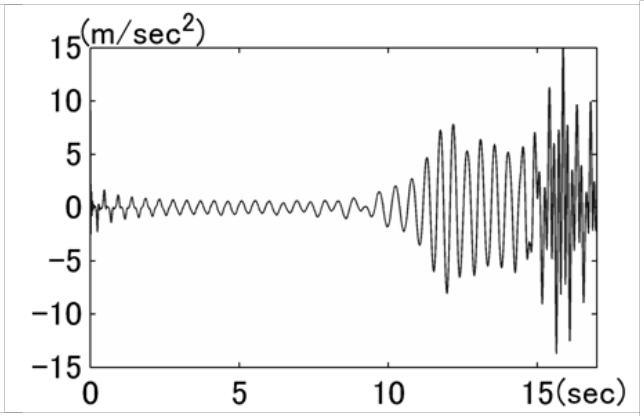
- Transfer Function
- Damage Case (Case1, Case 2 and Case 3)
  - Stiffness 10% Decrease
  - Sweep Excitation up to 50Hz
  - Newmark β Method（β=1/4, Δt=1/5000）

Numerical Simulation

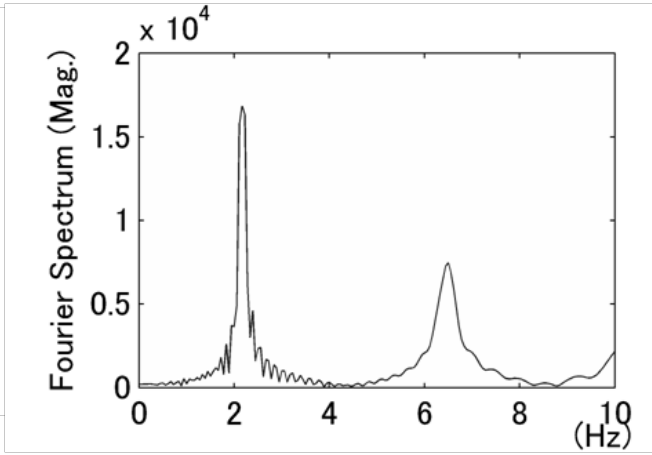
- Input：Sweep Excitation （$0 < f_m \leqq 50\mathrm{Hz}$）
- Input Location：Span Center



Input Wave



Acceleration（Span Center）



Fourier Spectrum

Multi modes are excited and not any others

- Transfer Function

$$\{\mathrm{R}(p)\} = \frac{\{\mathrm{Y}(p)\}}{\{\mathrm{U}(p)\}} = [\mathrm{E}](p[\mathrm{I}] - [\mathrm{A}])^{-1}[\mathrm{B}] + [\mathrm{D}]$$

- Change from *R*(*p*) to *R**(*p*) by Damage

$$[\mathrm{A}] = \begin{bmatrix} 0_{nn} & \mathrm{I}_{nn} \\ -\mathrm{M}^{-1}\mathrm{K} & -\mathrm{M}^{-1}\mathrm{C} \end{bmatrix}, [\mathrm{B}] = \begin{bmatrix} 0 \\ \mathrm{M}^{-1}\mathrm{G} \end{bmatrix}$$

$$[\mathrm{E}] = [-[\mathrm{M}]^{-1}[\mathrm{K}] \quad -[\mathrm{M}]^{-1}[\mathrm{C}]], \quad [\mathrm{D}] = [\mathrm{M}]^{-1}[\mathrm{C}]$$

- Detect Change of *R*(*p*) as PSD

$$D_i(f) = \frac{\left||\mathrm{R}_i(f)| - |\mathrm{R}_i^*(f)|\right|}{1 + |\mathrm{R}_i(f)|} \Rightarrow [\mathbf{D}] = \begin{bmatrix} D_1(f_1) & D_2(f_1) & \cdots & D_n(f_1) \\ D_1(f_2) & D_2(f_2) & & D_n(f_2) \\ \vdots & & \ddots & \vdots \\ D_1(f_m) & D_2(f_m) & \cdots & D_n(f_m) \end{bmatrix}$$

Matrix Expression

Maximize Damage Effect

Normalize by Max Element

$$D=\begin{bmatrix} D_1(f_1) & D_2(f_1) & \cdots & D_n(f_1) \\ D_1(f_2) & D_2(f_2) & & D_n(f_2) \\ \vdots & & \ddots & \vdots \\ D_1(f_m) & D_2(f_m) & \cdots & D_n(f_m) \end{bmatrix} \Rightarrow H=\begin{bmatrix} H_1(f_1)=\frac{D_1(f_1)}{D_3(f_1)} & H_1(f_1)=\frac{D_2(f_1)}{D_3(f_1)} & \cdots & H_1(f_1)=\frac{D_n(f_1)}{D_3(f_1)} \\ H_1(f_2)=\frac{D_1(f_2)}{D_2(f_2)} & H_2(f_2)=\frac{D_2(f_2)}{D_2(f_2)} & & H_2(f_2)=\frac{D_n(f_2)}{D_2(f_2)} \\ \vdots & & \ddots & \vdots \\ H_1(f_m)=\frac{D_1(f_m)}{D_5(f_m)} & H_2(f_m)=\frac{D_2(f_m)}{D_5(f_m)} & \cdots & H_n(f_m)=\frac{D_n(f_m)}{D_5(f_m)} \end{bmatrix}$$

Summing along column elements

$$SM=\left\{\sum_f D_1(f) \quad \sum_f D_2(f) \quad \cdots \quad \sum_f D_n(f)\right\} \qquad SH=\left\{\sum_f H_1(f) \quad \sum_f H_2(f) \quad \cdots \quad \sum_f H_n(f)\right\}$$

Total Change （Extent of Change） Damage Detection （Larger Change）

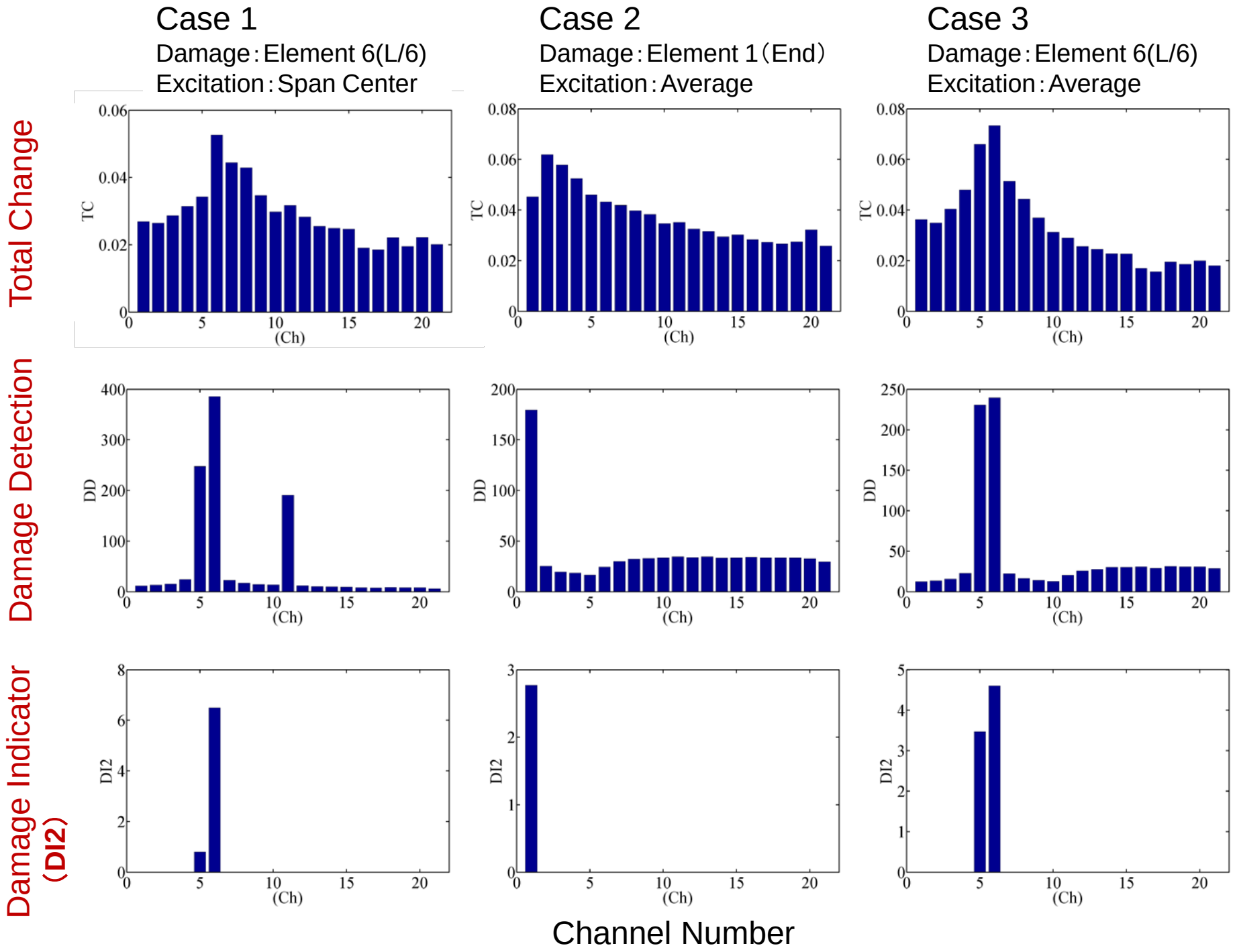
Shift by Standard Deviation

$$SMDb=\left\{\sum_f D_1(f)-b\sigma \quad \sum_f D_2(f)-b\sigma \quad \cdots \quad \sum_f D_n(f)-b\sigma\right\}$$

$$SHDb=\left\{\sum_f H_1(f)-b\lambda \quad \sum_f H_2(f)-b\lambda \quad \cdots \quad \sum_f H_n(f)-b\lambda\right\}$$

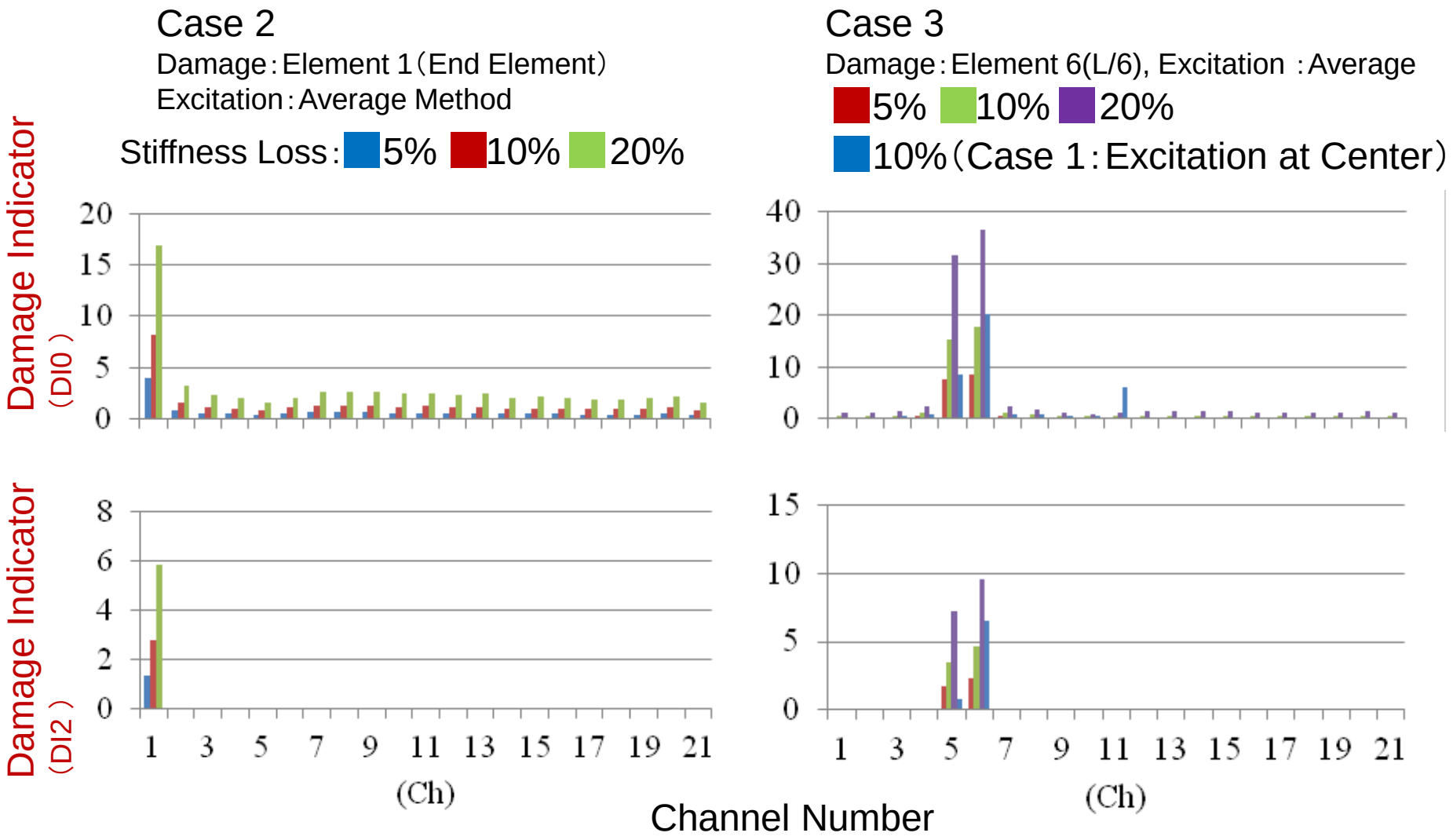
$$DI0=\{SM(1)\times SH(1), SM(2)\times SH(2), \ldots, SM(n)\times SH(n)\}$$ Damage Indicator (DI0)

$$DI2=\{SMDb(1)\times SHDb(1), SMDb(2)\times SHDb(2), \ldots, SMDb(n)\times SHDb(n)\}$$ Damage Indicator (DI2)


Case 1
Damage : Element 6(L/6)
Excitation : Span Center
Case 2
Damage : Element 1（End）
Excitation : Average
Case 3
Damage : Element 6(L/6)
Excitation : Average
Total Change
Damage Detection
Damage Indicator
（DI2）
TC
DD
DI2
(Ch)
Channel Number

Effect of Damage Size

- Case 2 and Case 3



Summary

- Proper Damage Information by LEM for SMSB
- Smaller Damage for SMSB can be detected by LEM
- Array Sensing improves Accuracy
  (Excitation and Receiving over
  Moving Excitation and take Average)

Goal

- Experimental Environment for SHM using Smart Sensors
- International Collaboration for SHM

Acknowledgement
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SMSB Test bed

Thank you

for your kind Attension !