JSCE-ASCE Symposium on Infrastructure Resilience
(May 22-23, 2019, Tokyo)

Infrastructure Resilience Strategy in Structural/Earthquake Engineering

Yoshikazu Takahashi
Kyoto University

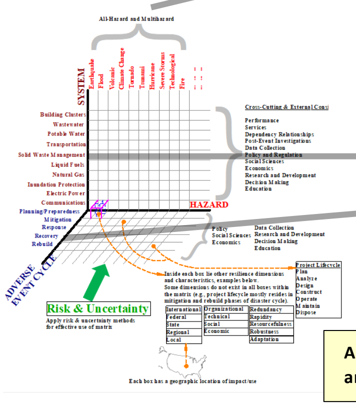
Infrastructure Resilience Framework for Assessment, Governance and Management

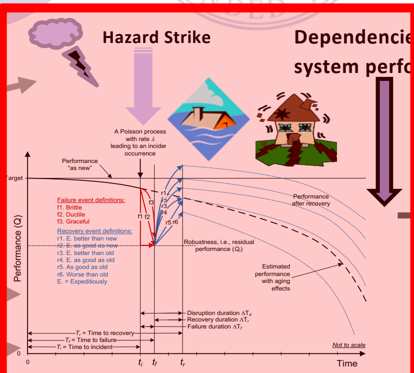
Legend
- Processes
- Tools
- Outcomes

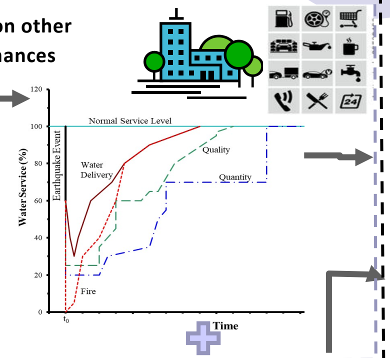
System Assessment:

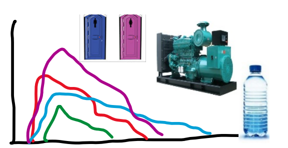
Core Infrastructure Resilience Elements

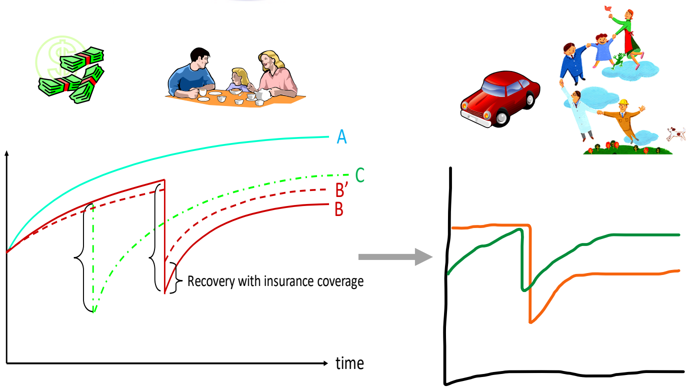
Core Community Resilience Elements











Aggregate of entire set of component and subsystem performances.

①Infrastructure Resilience Domain: Define the dimensions most relevant to engineered systems

②Building and Lifeline System Performance or Functionality (representing a single system and change in performance over time) Ayyub (2014)

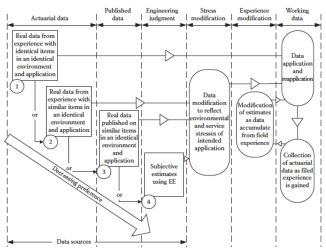
③System Service Provision & Operability (Davis, 2014)
+
④Continuity of [inoperable] Services Temporarily Lost (alternatives, substitution, stockpiles, etc.)

⑤Social & Economic activity supported directly and indirectly by infrastructure systems

⑥Community: wellbeing, equity, livability, etc.

Governance and Management:

Data needs, sources and expert opinion elicitation (Ayyub, 2001): collect in support of all resilience elements. Include sensing and monitoring of hazards and infrastructure.



Tools
Programs to operationalize resilience using characteristics (Davis et al, 2018)
Resilience standards and codes (Burton et al, 2018; Honda, 2017)
Insurance
Loss estimation methodologies
Business Continuity Plans, Continuity of Operations Plans
Emergency and incident management
Asset management
Risk management
Hazard scenarios
Life cycle cost analysis/ assessment
Land use planning
Advanced technologies
Decision support systems

Compare ②③④ with ⑧

⑧Define Infrastructure System Performance Targets to support the social and economic needs of a community.

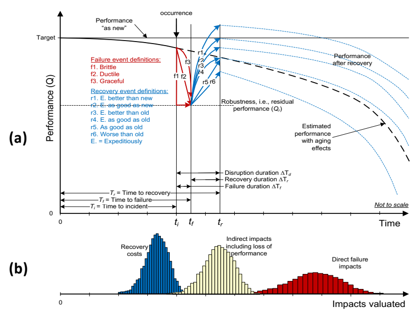
2

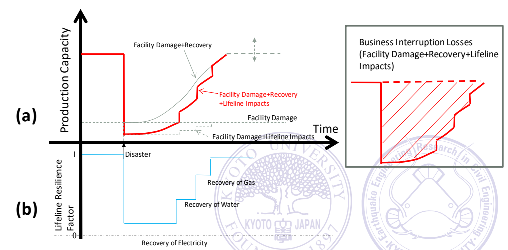
⑦Establish Community Performance Targets (e.g., NIST 2015)

Policy

Regional Social and Economic Losses from facility and lifeline losses (Kajitani and Tatano, 2009), including casualties
(a) Losses from facility and lifeline systems
(b) System restorations

Economics of resilience (Gilbert & Ayyub, 2016)
(a) Performance profile
(b) Economic valuations of direct losses, recovery costs, and indirect impacts
-Develop cost effective mitigation alternatives
-Including casualties





TOPICS

- Infrastructure in Japan
  - As a Developed Country
  - As a Country living with Severe Natural Disasters
- Challenges in Structural/Earthquake Engineering for Resilient Society
  - for changing Required Performance of Infrastructures in the Future
  - to cope with BDBE (Beyond Design Basis Event) in Infrastructure Design

About Japanese Infrastructure
http://www.japan.go.jp/infrastructure/

DESIGN
TOMORROW
INFRASTRUCTURE with JAPAN

Infrastructure with Japan

- Infrastructure, which provides the foundation of our growth, consists of unique creativity rooted in Japanese sensitivity, such as the resilience to accept harsh environmental changes and ideas to make effective use of limited (natural) resources, paired with the technological strength to convert the ideas into tangible forms.

Infrastructure Design

- Infrastructure could be designed to act as a long-term, deep-rooted foundation for sustainable economic development. Large uncertainty cannot be inevitable in the prediction of natural disasters during their service-life.
- The essence of infrastructure design is to determine the material and the structural layout and form, with public consent, under large uncertain information.

Challenges in Structural/Earthquake Engineering

- Strategy for changing Required Performance of Infrastructures in the Future
  - Non-conforming infrastructures
  - Metabolism (新陳代謝) of Infrastructures

- Strategy to cope with BDBE (Beyond Design Basis Event) in Infrastructure Design
  - From Limit State Design to “Anti-catastrophe”-oriented Design
  - From “Large Ductility” to “Collapse Control”
  - Functionalities in BDBE is different from those in DBE.
  - Validation with Qualitative Evaluation supported by Accountability (Legitimacy, Governance)

Challenges in Structural/Earthquake Engineering

Development of Robust Structures

Material science has always brought innovative progress of structural performance.

Metabolic system

Design seismic load:
0.2g < gravity in 1970s
2.0g > gravity now

Damage-free
(Material technology)

Self-healing materials

Maintenance technology

Robust Structure

Structural form considering earthquakes as the primary action
(Structural art)

Semi-sensitive response
(Material/Recovery Technology)

Accept the loss of functionality, but quick recovery

Construction technology

Planning

Insensitive response
(Base-isolation technology)

Structural analysis

Energy absorber

Sensitive response
(Structural control technology)

Monitoring technology

Design technology

From long-term infrastructure with maintenance to middle-term infrastructure without maintenance

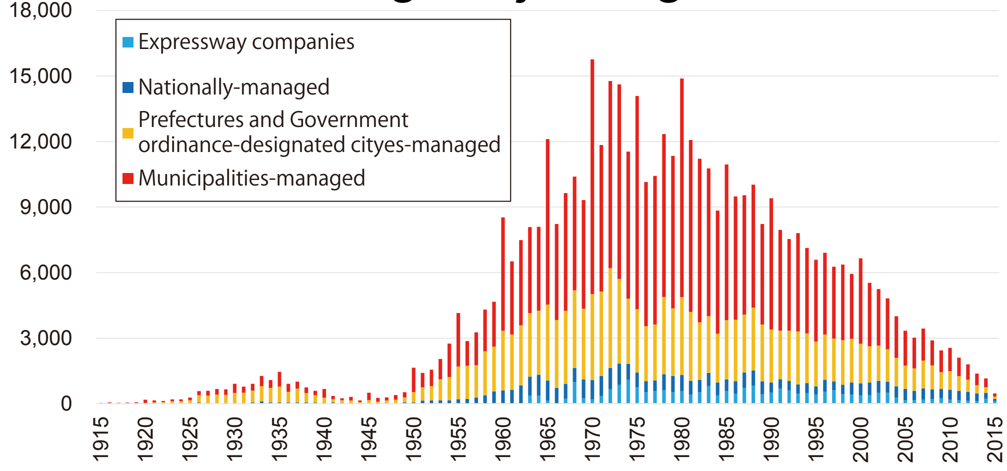
Challenges in Structural/Earthquake Engineering

- Strategy for changing Required Performance of Infrastructures in the Future
  - Non-conforming infrastructures
  - Metabolism (新陳代謝) of Infrastructures

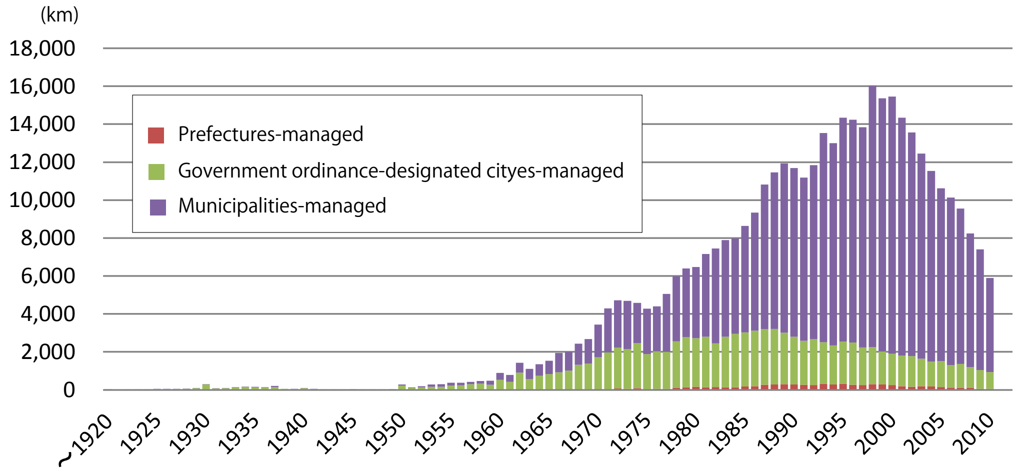
- Strategy to cope with BDBE (Beyond Design Basis Event) in Infrastructure Design
  - From Limit State Design to “Anti-catastrophe”-oriented Design
  - From “Large Ductility” to “Collapse Control”
  - Functionalities in BDBE is different from those in DBE.
  - Validation with Qualitative Evaluation supported by Accountability (Legitimacy, Governance)

Infrastructure in Japan as a Developed Country

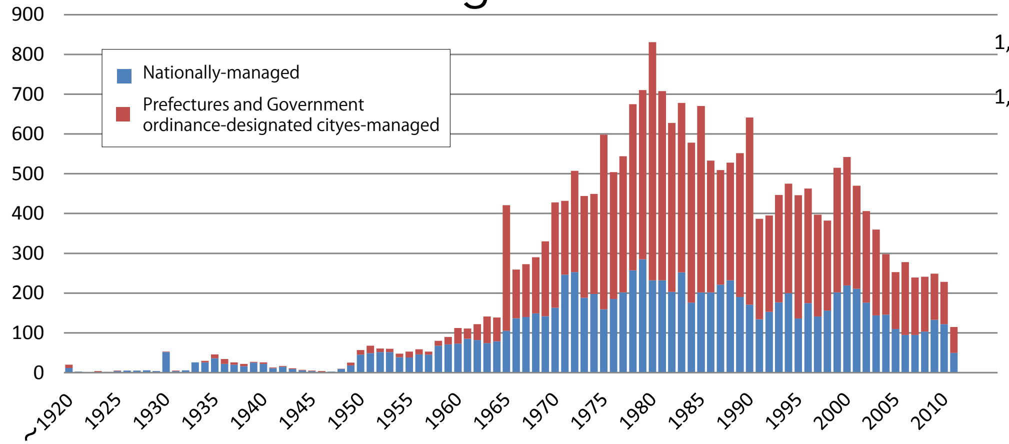
Highway Bridges



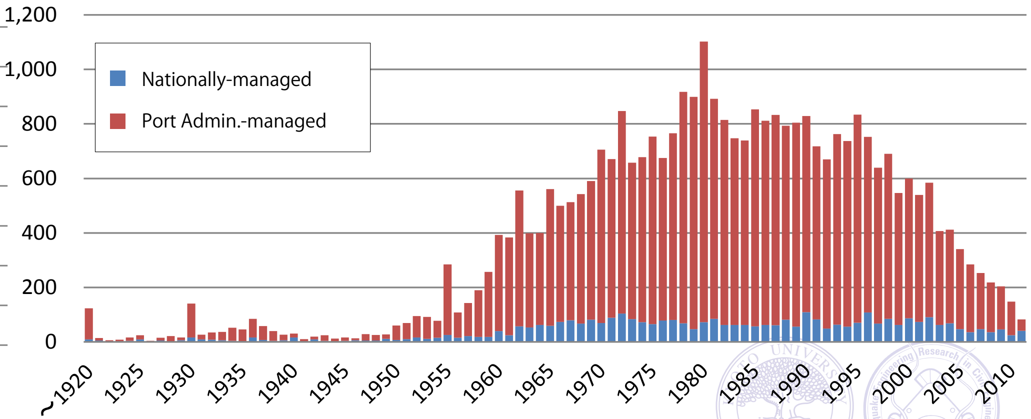
Sewage Pipe



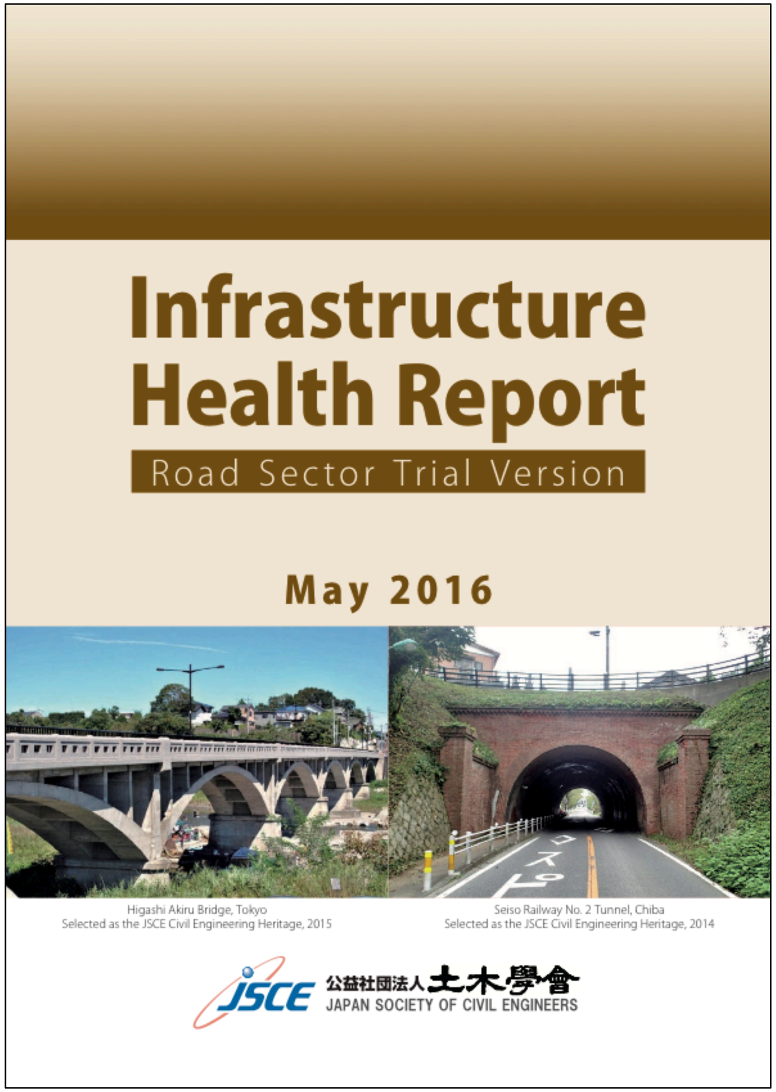
River Management Facilities



Port Management Facilities



Health Assessment of Infrastructure by JSCE



Results of the Health Assessment in the Road Sector

- Bridges: D ↗
- Tunnels: D →
- Road Surface (Pavement): C ↘

- Currently, deterioration in many bridges is obvious. There is a need for urgent maintenance and repair and to stop the progression of the deterioration process.
- Deterioration is obvious in many tunnels and maintenance and repairs on the deteriorating sites are urgently needed.
- There are always certain sections on road surfaces (pavement) which deteriorate quickly, and early repairs in accordance with the maintenance evaluation level are required.
- Regarding the management system, since the revision of the Road Act in 2014, the system for the maintenance of bridges and tunnels has improved. However, there are differences in efforts regarding the formulation of tunnel maintenance plans according to the administrator. Regarding the road surface, there are some administrators who have not yet formulated a maintenance plan. Thus, the formulation of a plan and the enhancement of a system for implementing the plan are desired.

Health Assessment Index

Health assessment is carried out by means of a method developed independently by JSCE, that of collecting released published data and surveys of inspection results and maintenance system information of the facilities. By assessing data provided by each administrator, the national average is expressed as an index.

Health Assessment Index of the Facilities

A Sound	B Satisfactory	C Caution	D Warning	E Critical
No deterioration is seen in most facilities	Deterioration is seen in some facilities	Deterioration is progressing in quite a few facilities, requiring early repairs	Deterioration is obvious in many facilities, requiring repairs and reinforcements	Deterioration is serious overall, requiring urgent measures

Management System of the Facilities

↗	→	↘
The state in which, if the present management system continues, the health condition will likely progress toward improvement.	The state in which, if the present management system continues, the current health condition will continue.	The state in which, unless there is an improvement in the present management system, there is a possibility that the health condition will deteriorate.

Situations of Developed Countries in High Seismicity

- Structural engineers always try to design their structures considering Structural Art.
- The disciplines of structural art are efficiency and economy after the Industrial Revolution, and its freedom lies in the potential it offers the individual designer for the expression of a personal style motivated by the conscious aesthetic search for engineering elegance.
- Are seismically retrofitted structures elegance?

Infrastructure in Japan
as a Developed Country in High Seismicity

Constructed in 1969

Re-Built in 1996

Metabolism (新陳代謝)

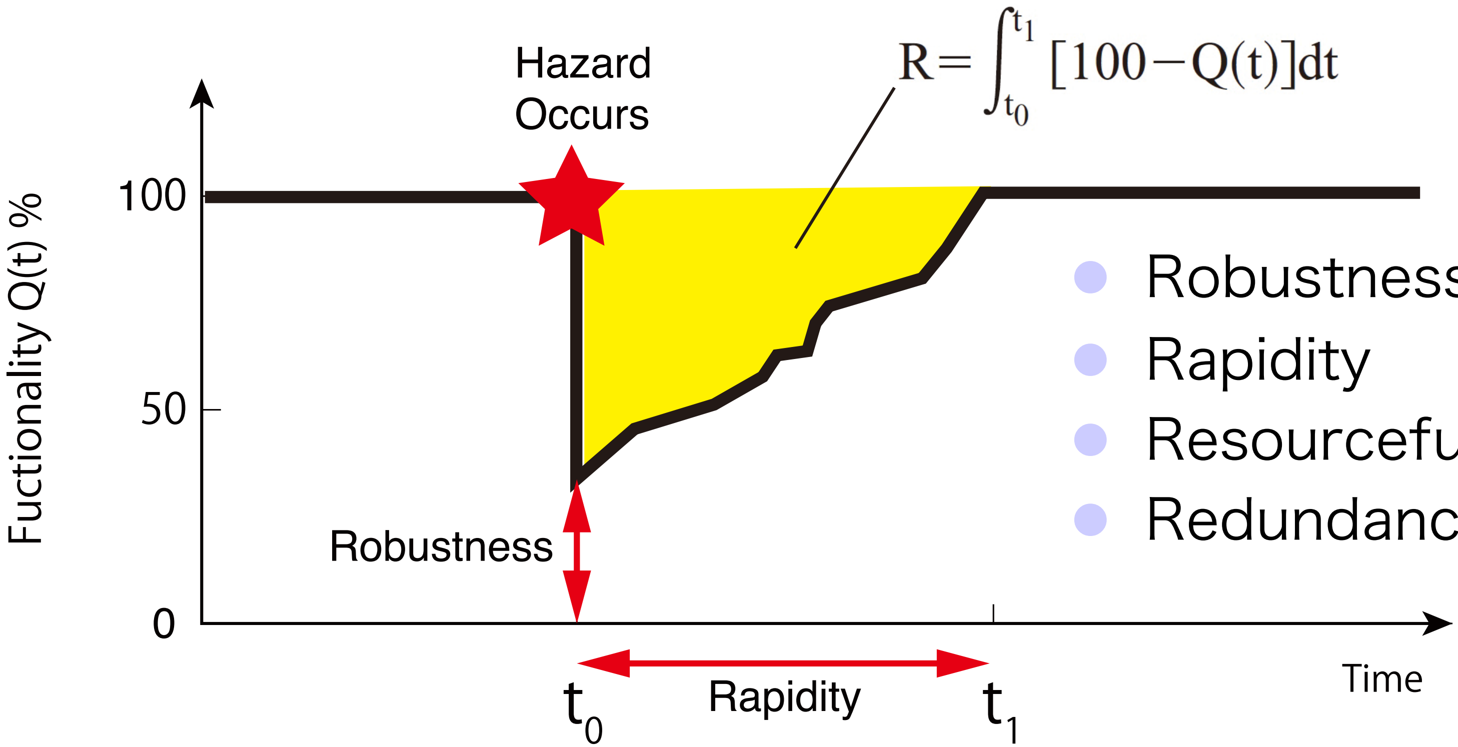
- Metabolism was a post-war Japanese architectural movement that fused ideas about architectural megastructures with those of organic biological growth. It had its first international exposure during CIAM's 1959 meeting and its ideas were tentatively tested by students from Kenzo Tange's MIT studio.
- The greatest concentration of their work was to be found at the 1970 World Exposition in Osaka where Tange was responsible for master planning the whole site whilst Kikutake and Kurokawa designed pavilions.

Metabolism (新陳代謝)

- Individual buildings that employed the principles of Metabolism were built and these included Tange's Yamanashi Press and Broadcaster Centre and Kurokawa's Nakagin Capsule Tower.

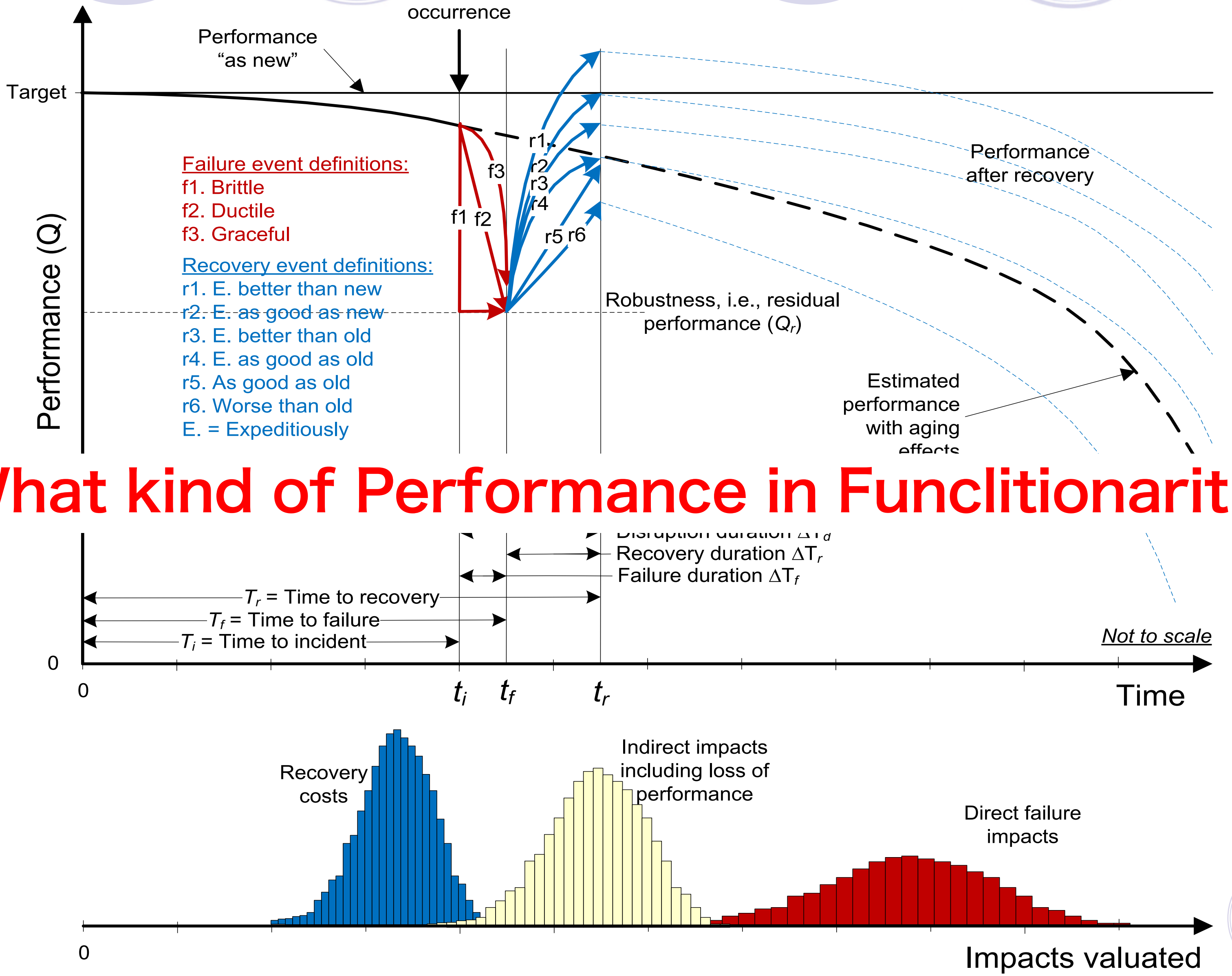
Resilience (Bruneau, et al. 2003)

"the ability of social units (e.g., organizations, communities) to mitigate hazards, contain the effects of disasters when they occur, and carry our recovery activities in ways that minimize social disruption and mitigate the effects of future earthquakes"



- Robustness
- Rapidity
- Resourcefulness
- Redundancy

Infrastructure (building or lifeline) system performance over time (Ayyub, 2015)

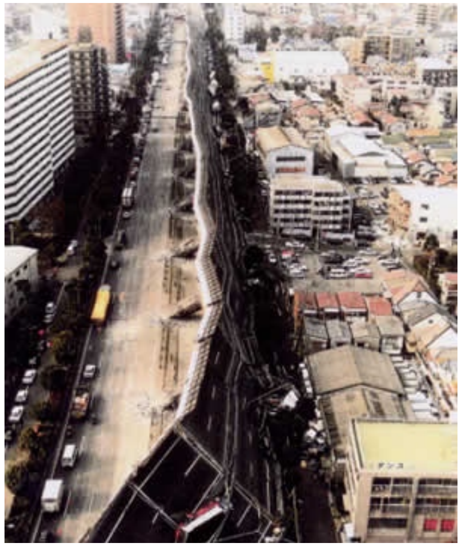


What kind of Performance in Funclitionarities?

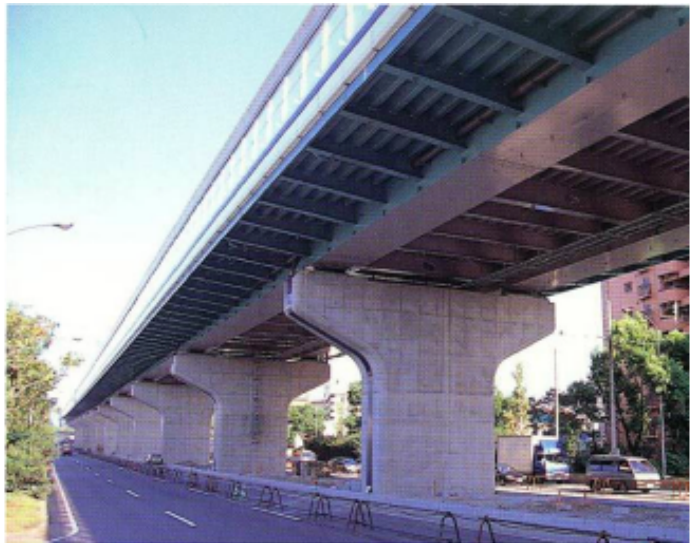
Situations of Developed Countries in High Seismicity

Case Study: Kobe route of Hanshin Expressway

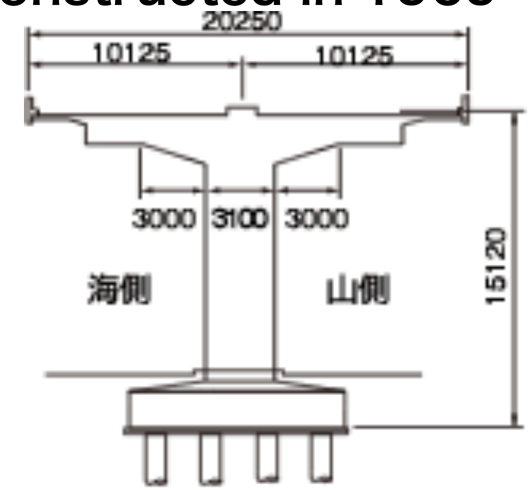
Constructed in 1969

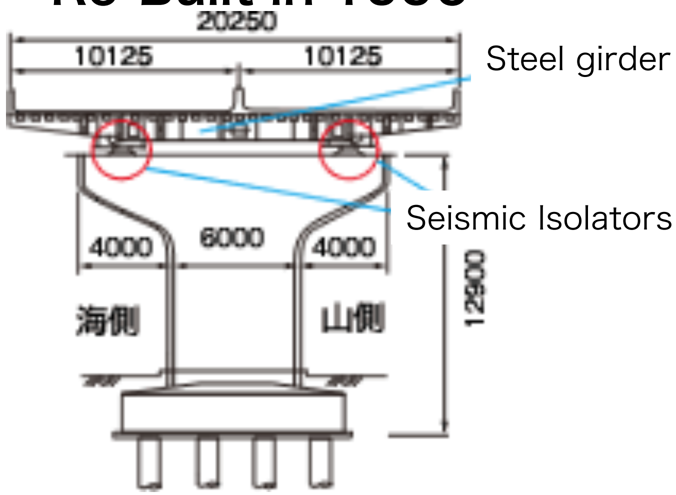


1995 Kobe EQ



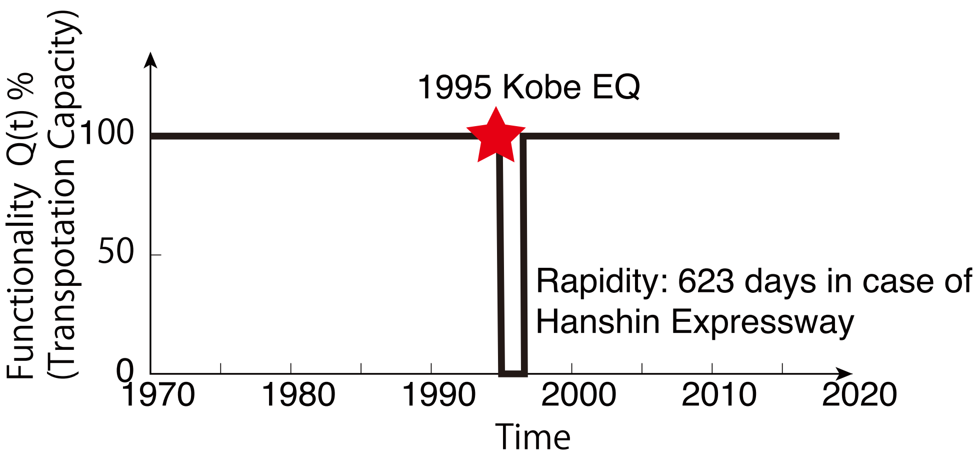
Re-Built in 1996

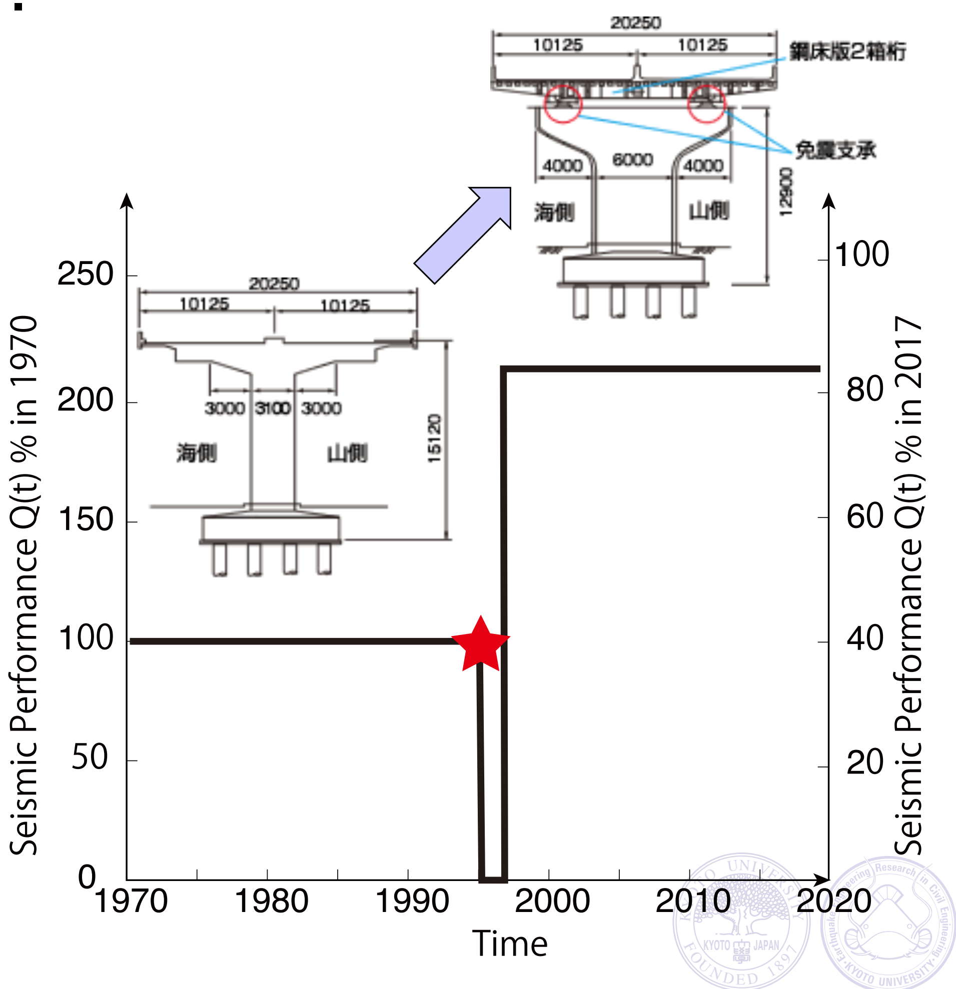




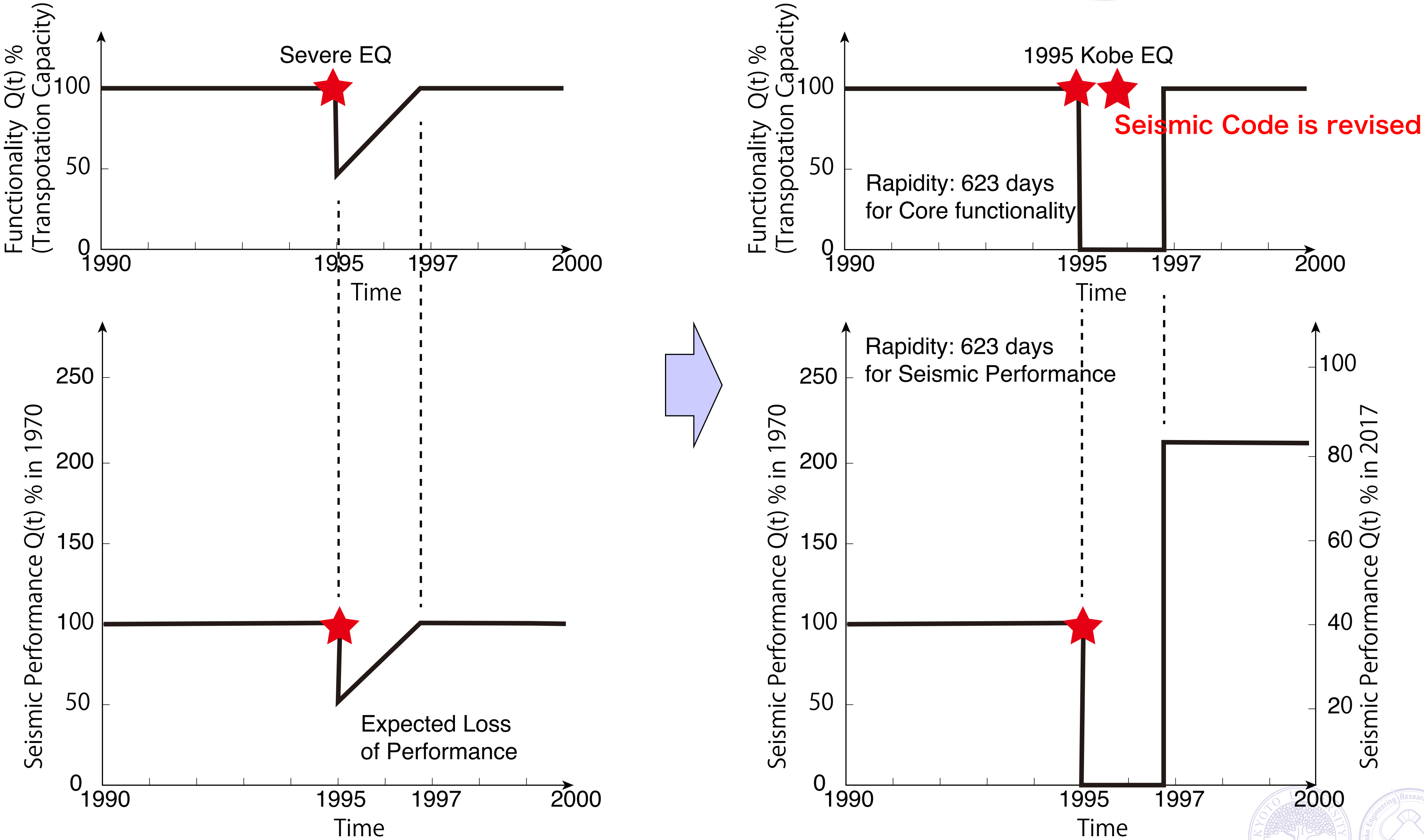
Situations of Developed Countries in High Seismicity

- **Core functionality** of highway viaduct is **transportation capacity**.
- Seismic performance improved almost double, but core functionality is unchanged before and after Kobe EQ.





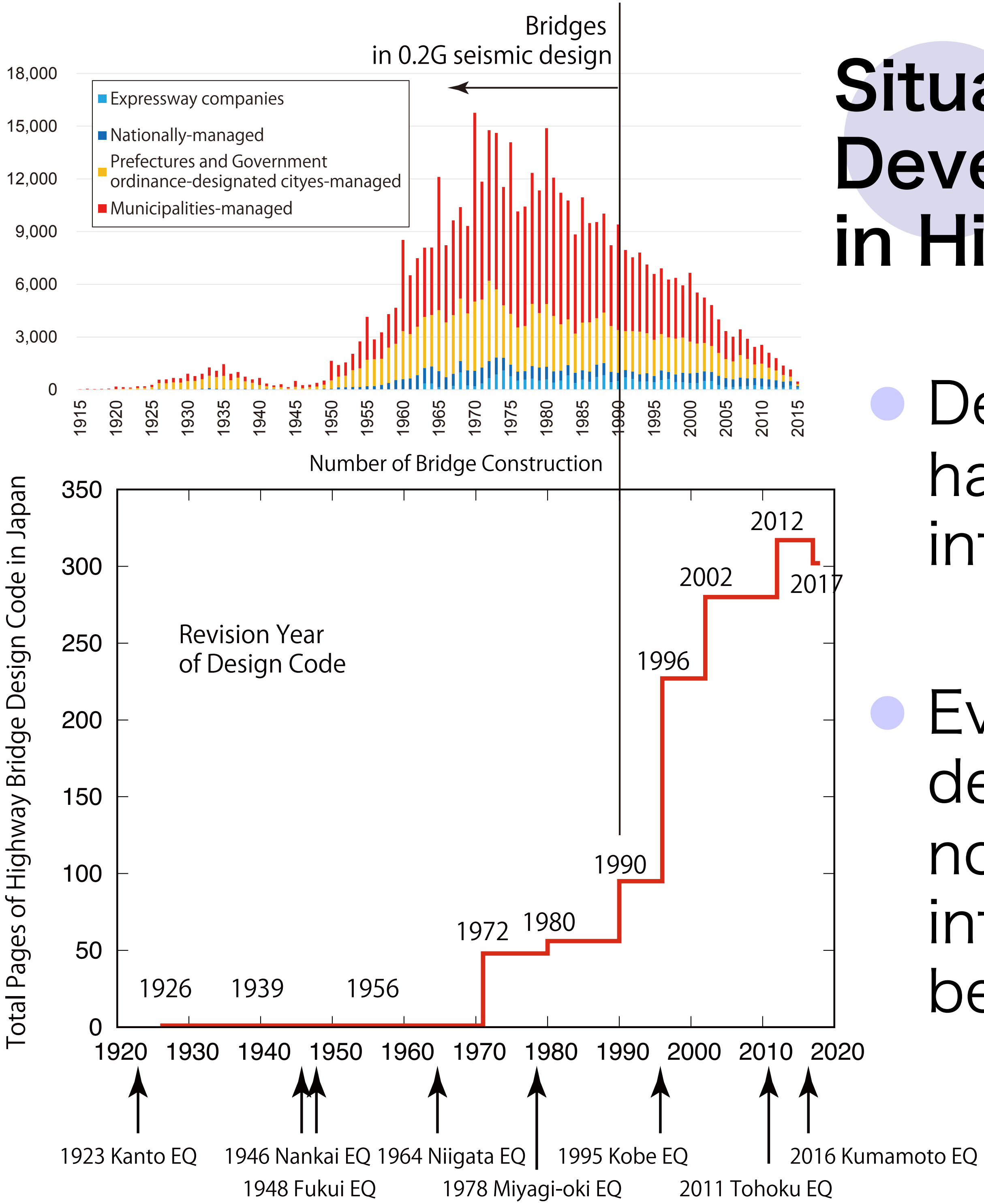
Situations of Developed Countries in High Seismicity



Expected Situation for Design Basis Events

Real Situation for Beyond Design Basis Event

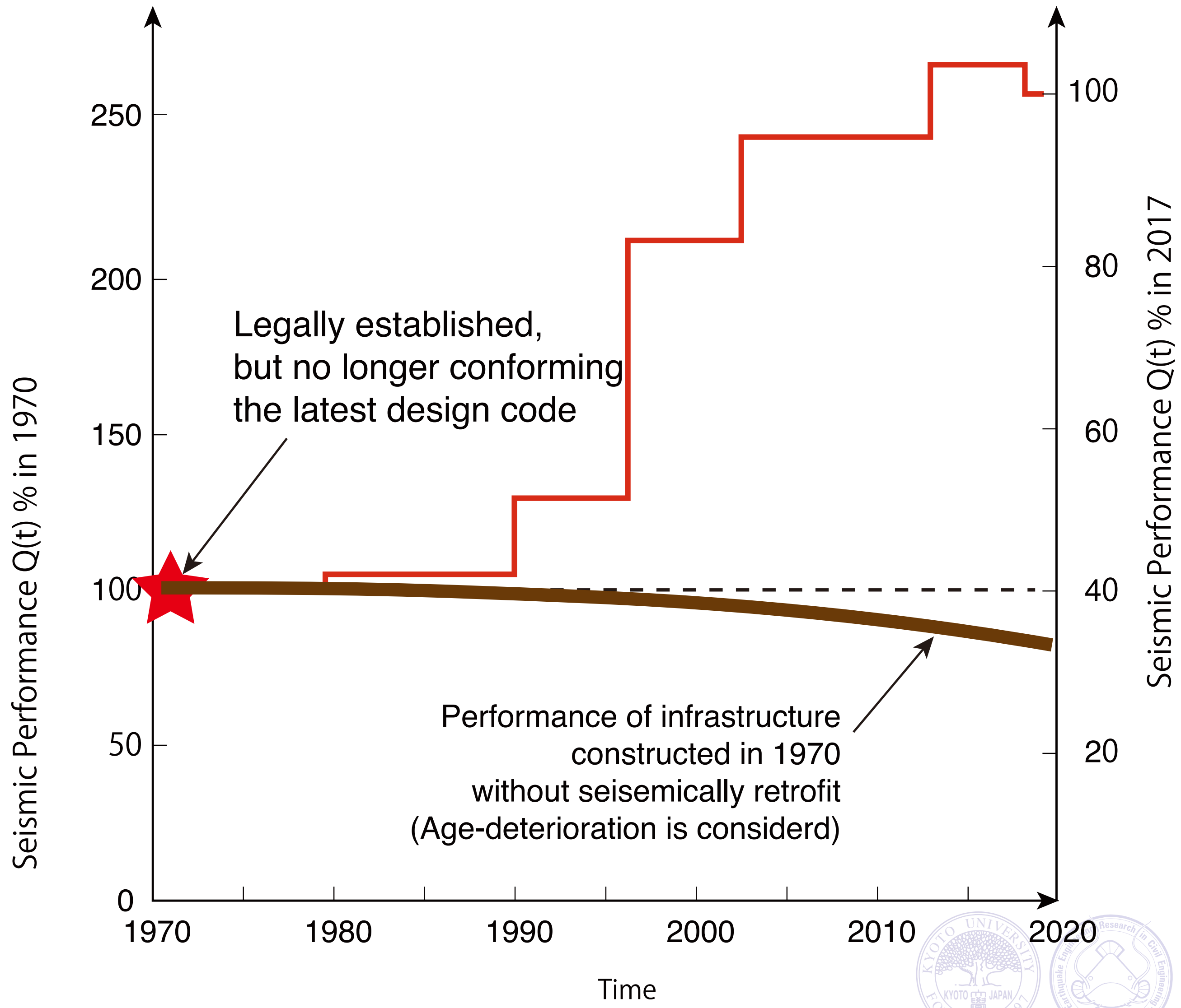
Situations of Developed Countries in High Seismicity



- Developed countries have a large stock of infrastructure.
- Even if no aging deterioration, existing non-conforming infrastructures have been increasing.

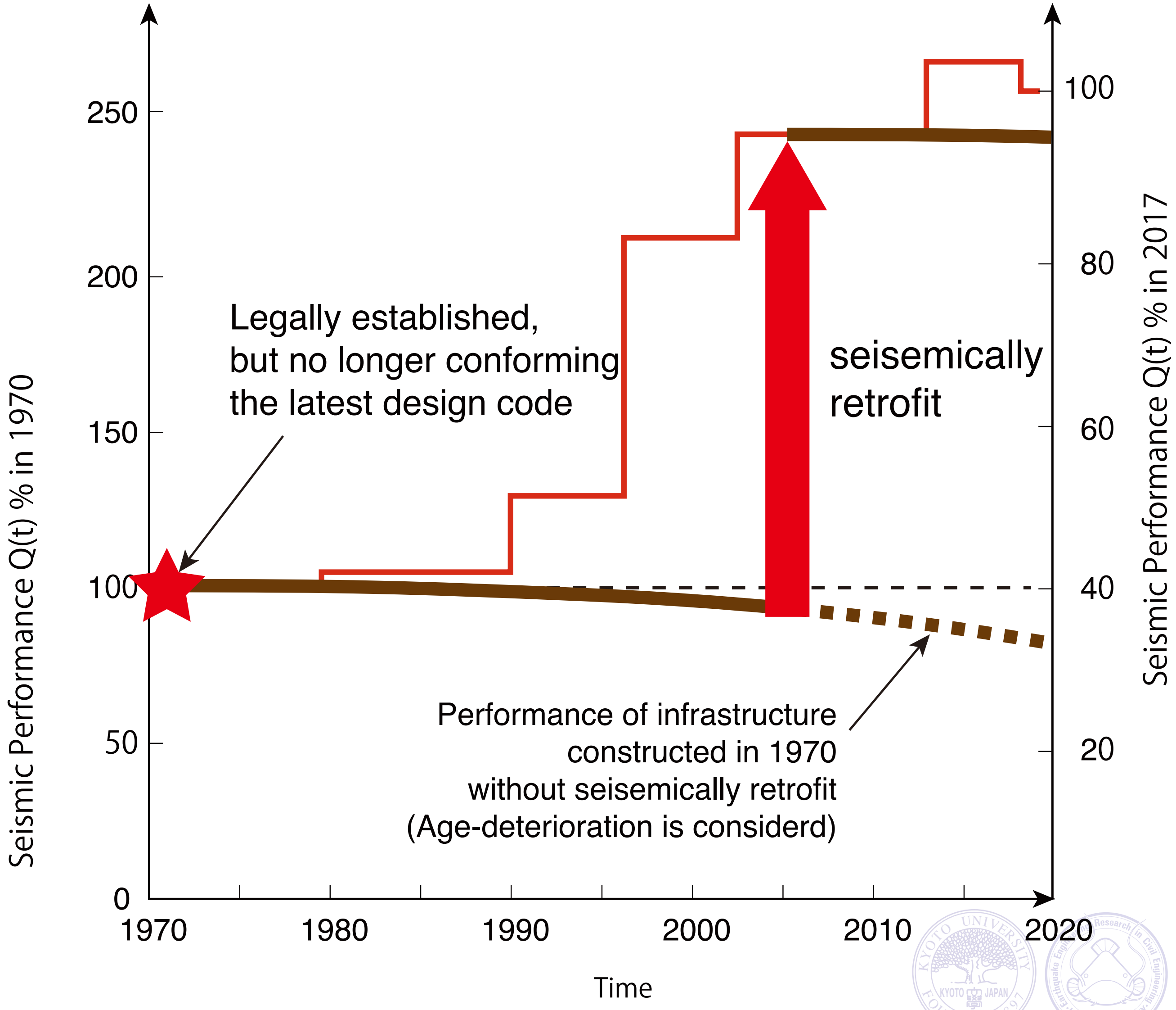
Situations of Developed Countries in High Seismicity

- Influence of non-conformity on the seismic performance had been much greater than that of age-deterioration.

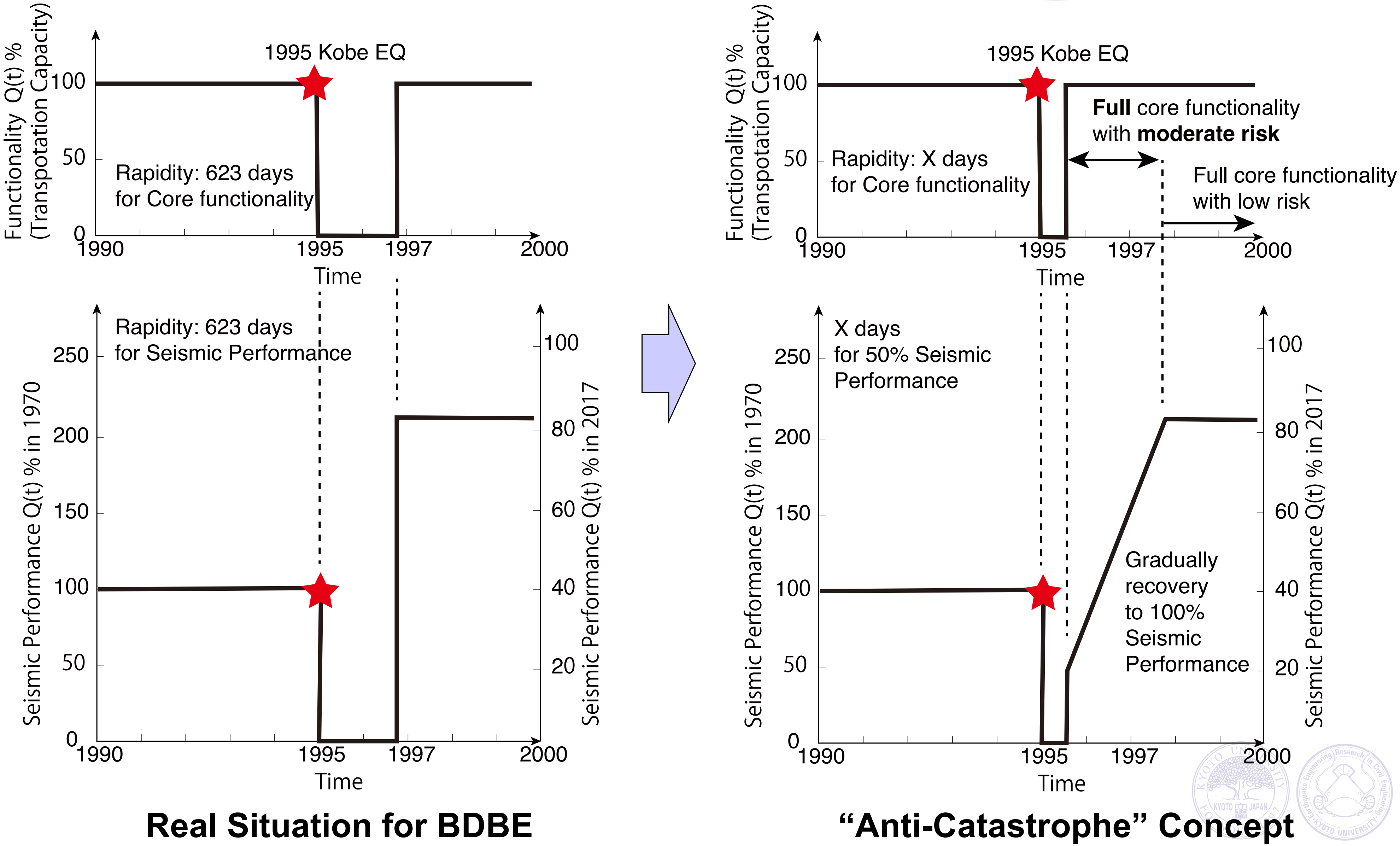


Situations of Developed Countries in High Seismicity

- Seismic retrofit could help to retrofit of age-deterioration indirectly. But the retrofitted structure will be non-conforming again in the future.
- Need robust / sustainable structure to cope with changing required performance in the future

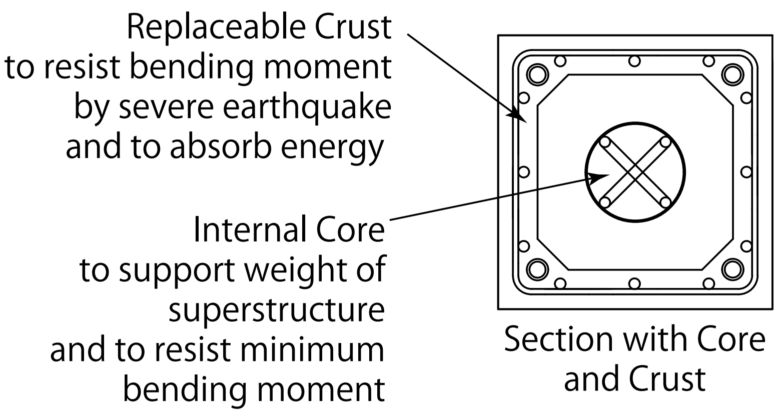


Change the functionalities of infrastructure to contribution to Rapidity

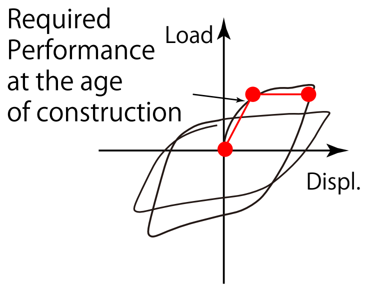


Metabolic Structure

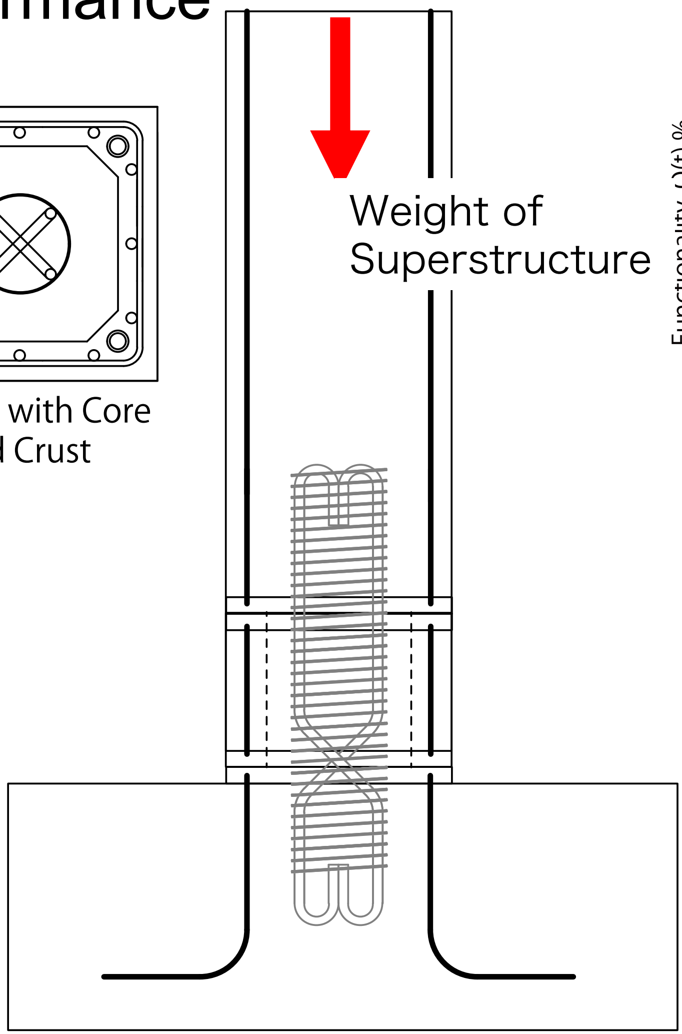
- Structural Core and Replaceable Crust
- Constructed based the latest design code at the construction.
- Not excessive performance



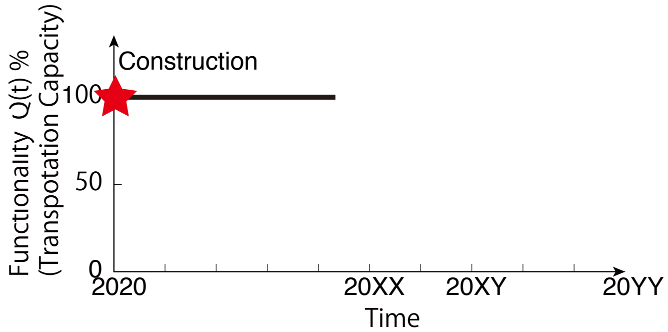
Section with Core and Crust

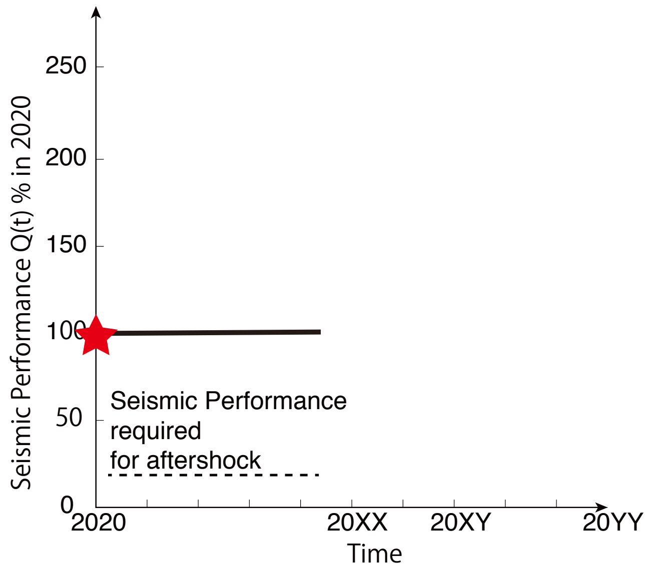


Required Performance and Structural Performance



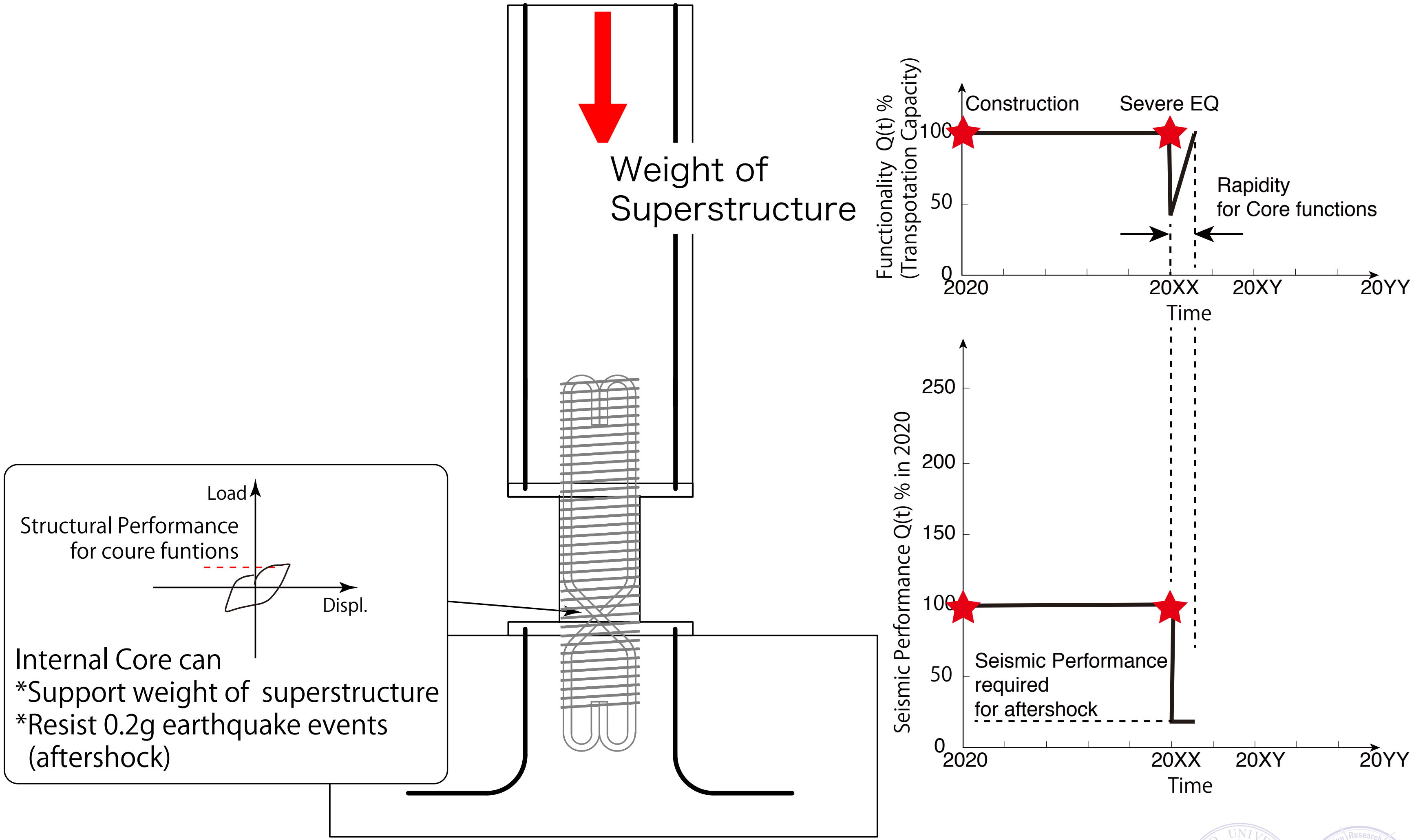
Column at Construction Age





Metabolic Structure

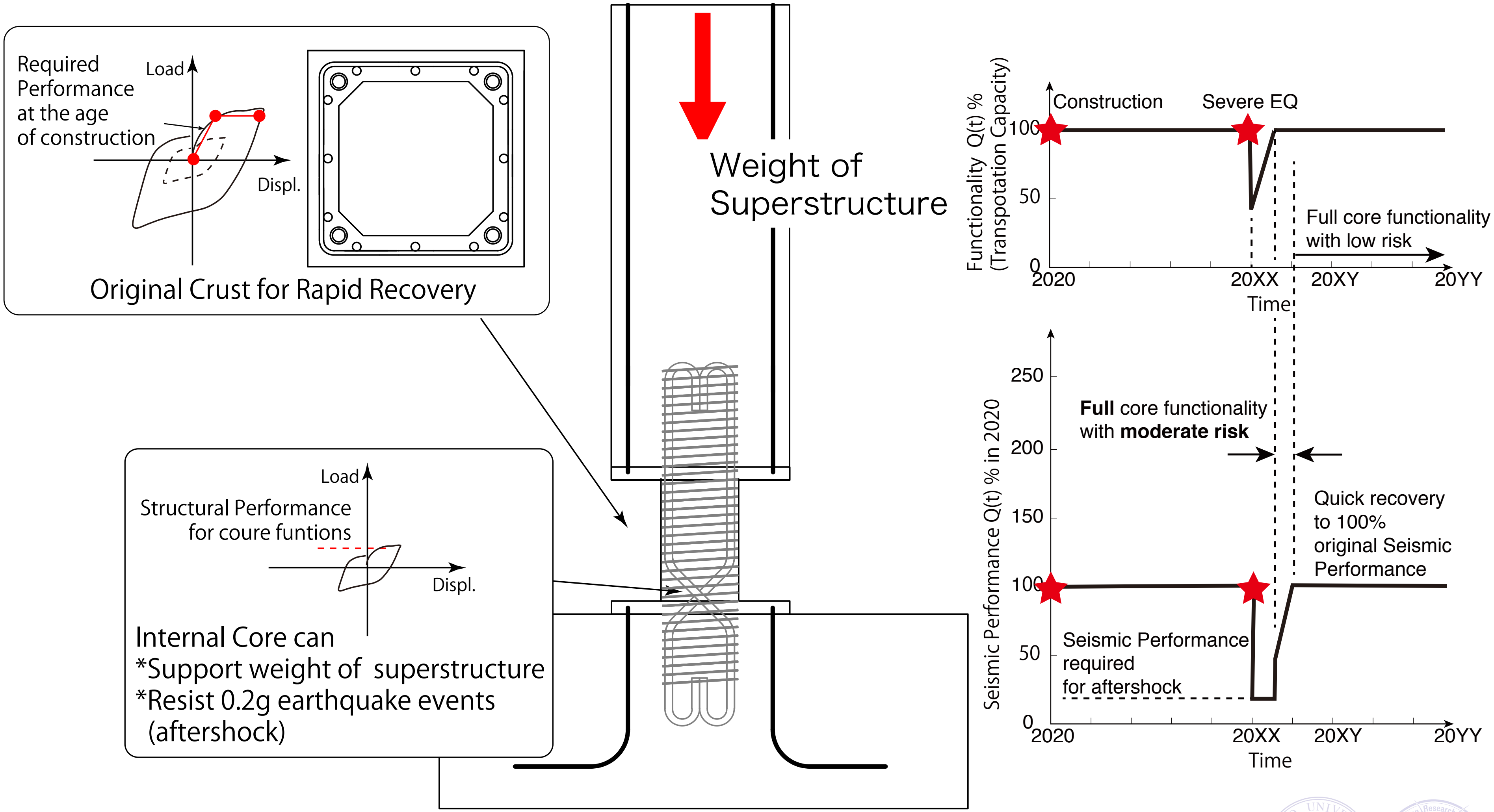
- Only Internal Core can serve core functions.
- Ttransportation with moderate risk



Column during Quick Recovery Process
after Severe Earthquake

Metabolic Structure

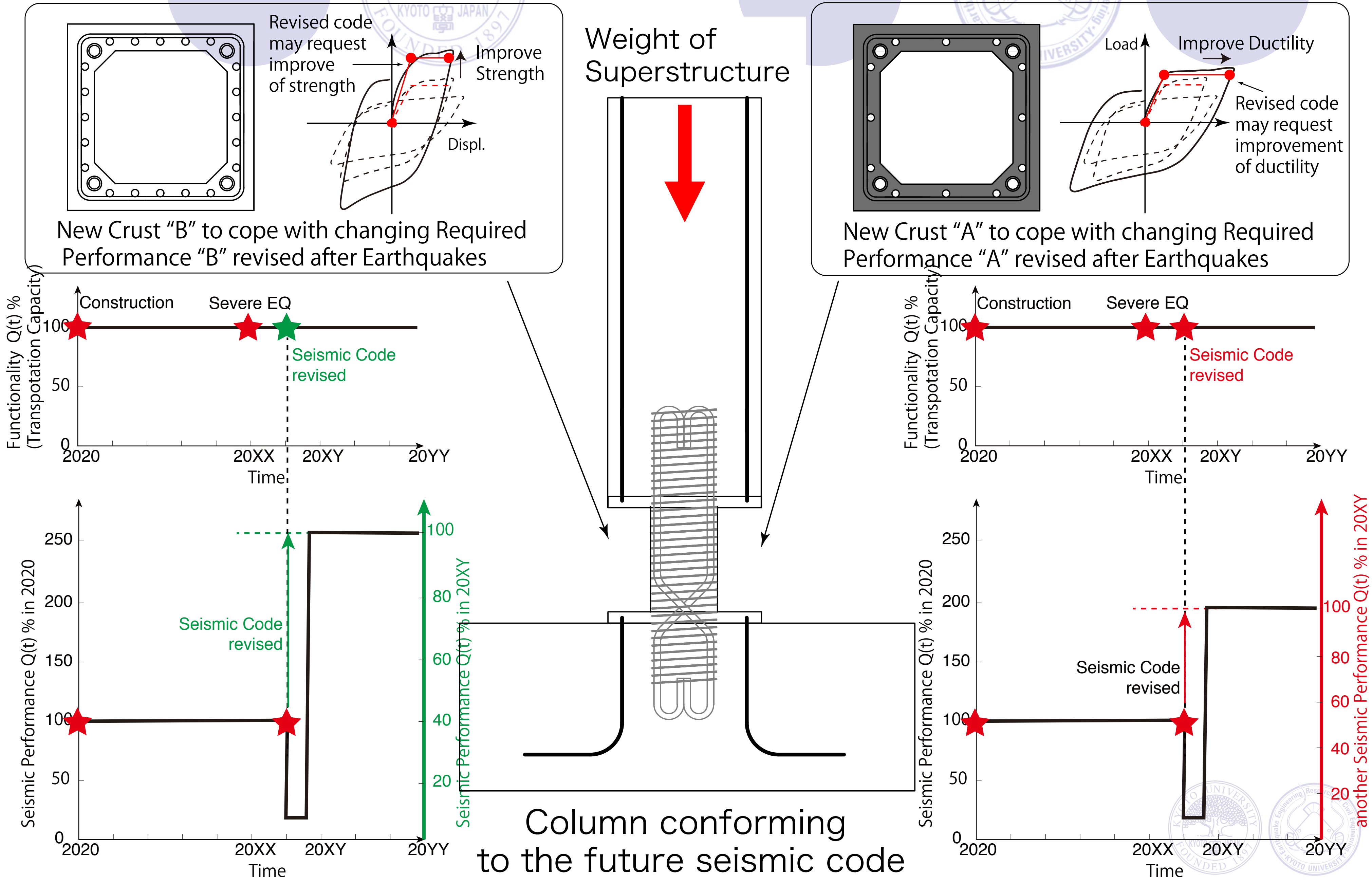
- Damaged crust will replaced to the original crust (Recovery to the original seismic performance)



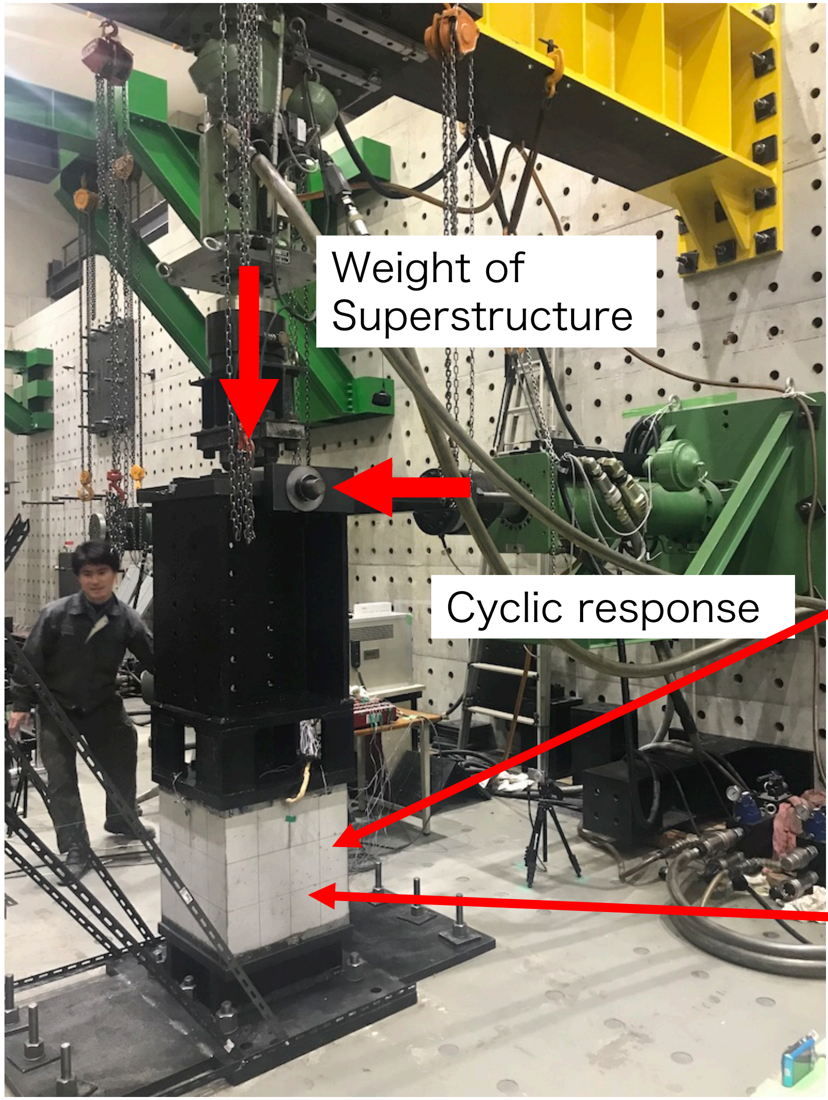
Column during Restoring Process after Severe Earthquake

Metabolic Structure

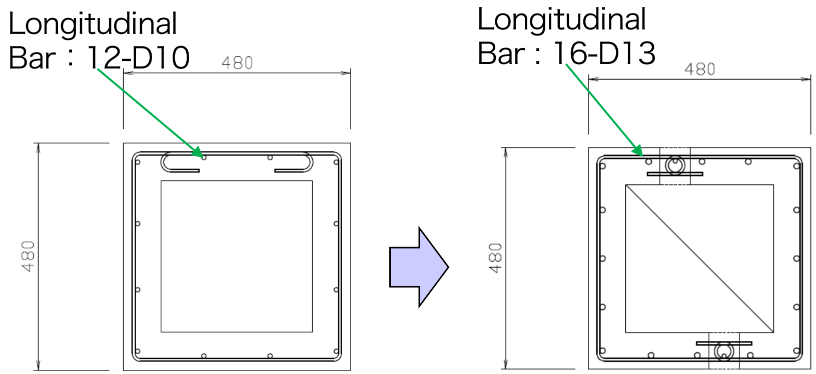
- New Crust can conform required performance (unknown at construction)



Experimental Tests for Concept Model of Metabolic Columns



Outer Replaceable Crust for Seismic Performance by Precast RC

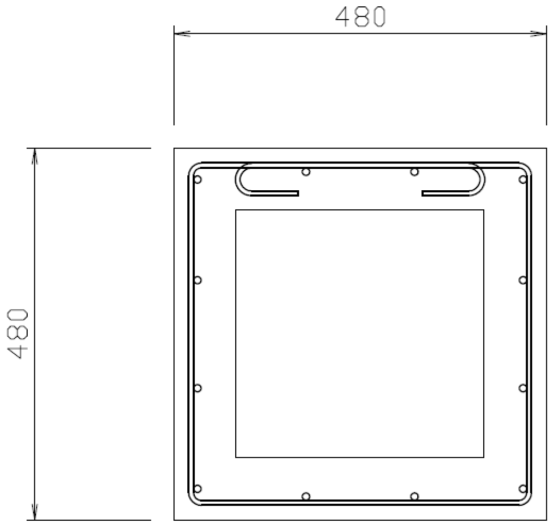


Section of
1996 Design Code

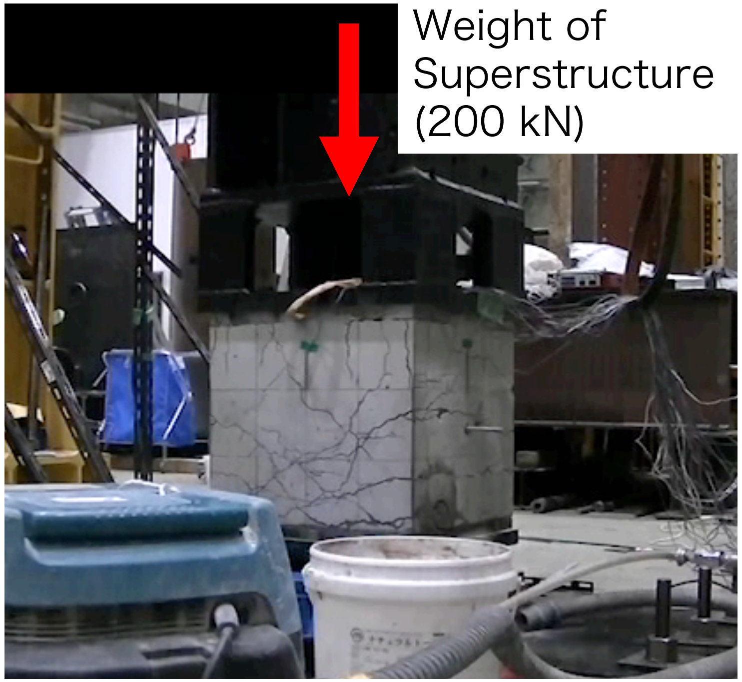
Section of
2012 Design Code

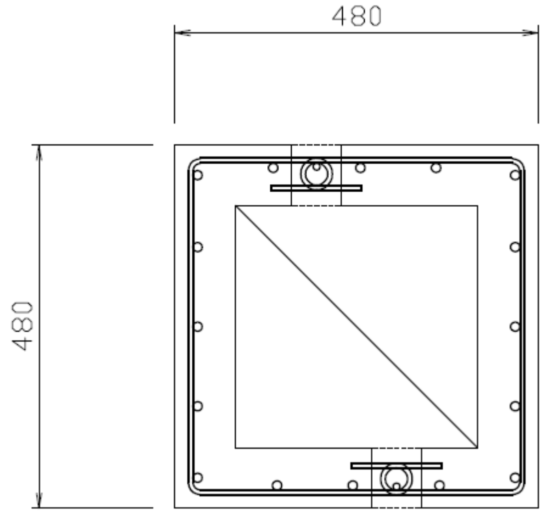
Core Component
for supporting weight of
Superstructure
by Fixed Elastomeric Bearing

Experimental Tests for Concept Model of Metabolic Columns

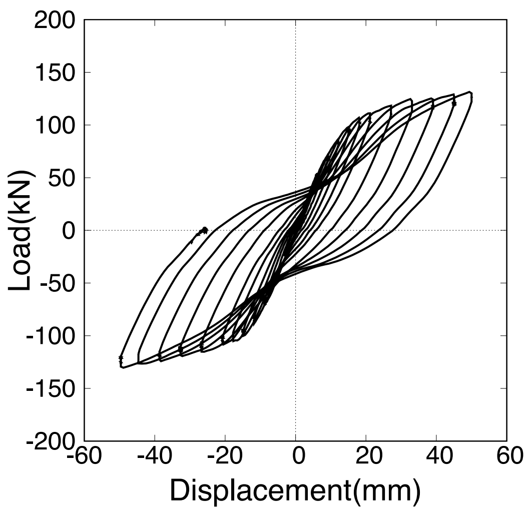


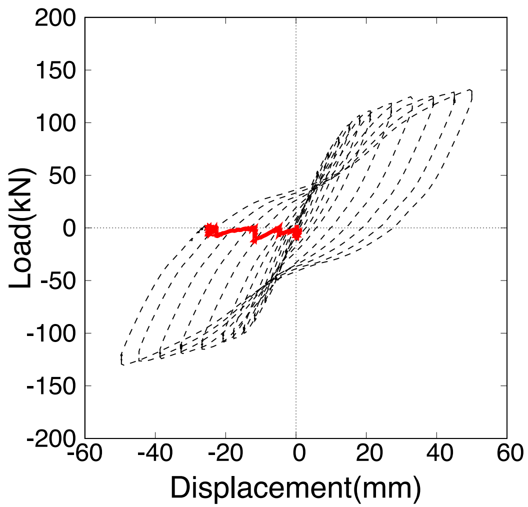
Section of
1996 Design Code

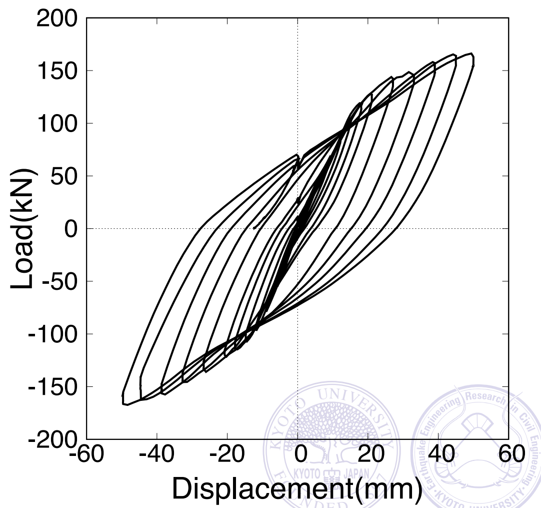




Section of
2012 Design Code







Future Discussions in Structural/Earthquake Engineering

- Discussion on how to develop next-generation infrastructure in developed countries who have a lot of existing non-conforming infrastructure
- Discussion on infrastructure performance during recovery process
  - Qualitatively, but predictable collapse behavior
  - Quick recovery of core functionality
  - Prepare for monotonically increase of seismic performance in the future

Challenges in Structural/Earthquake Engineering

- Strategy for changing Required Performance of Infrastructures in the Future
  - Non-conforming infrastructures
  - Metabolism (新陳代謝) of Infrastructures

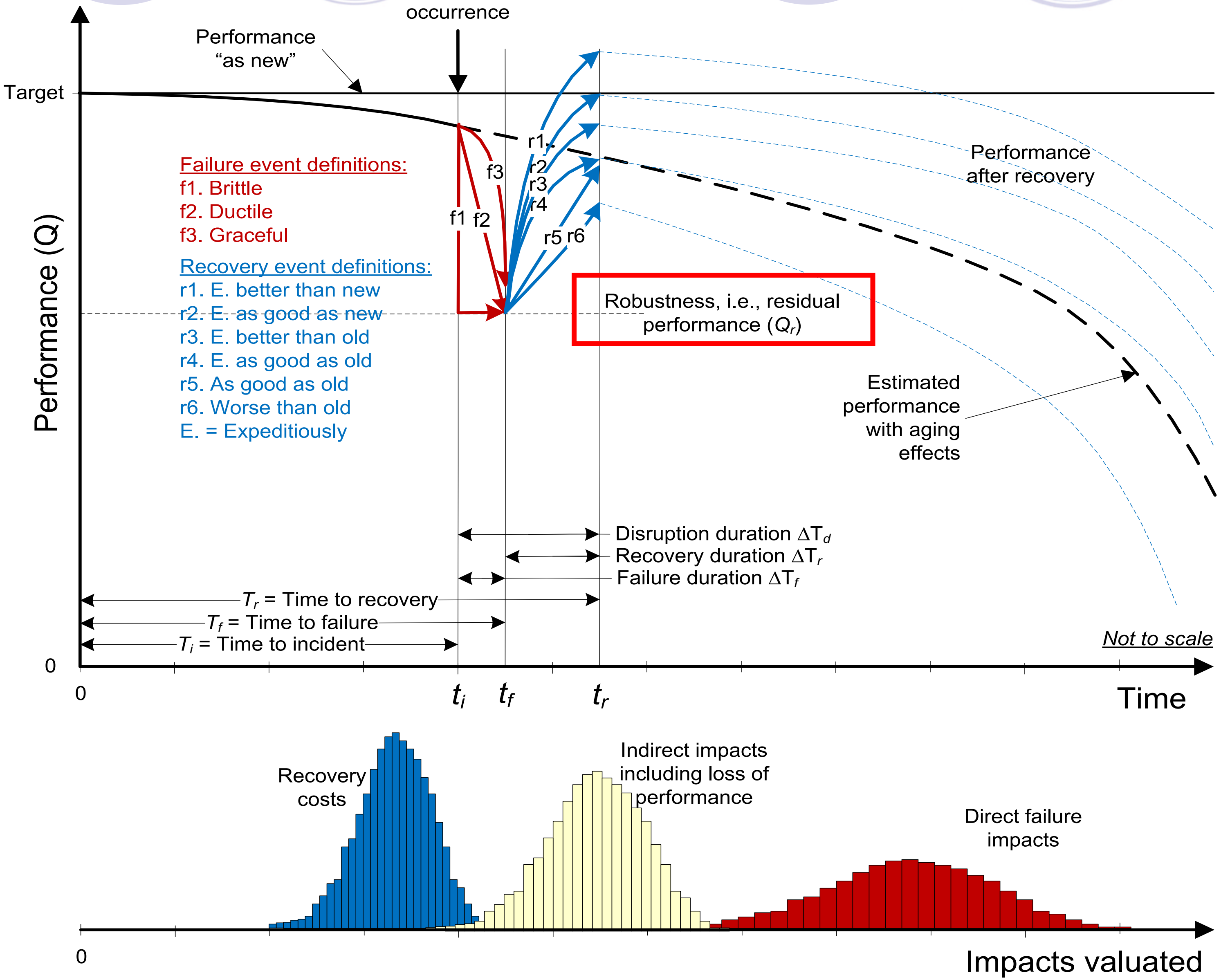
- **Strategy to cope with BDBE (Beyond Design Basis Event) in Infrastructure Design**
  - From Limit State Design to "Anti-catastrophe"-oriented Design
  - From "Large Ductility" to "Collapse Control"
  - Functionalities in BDBE is different from those in DBE.
  - Validation with Qualitative Evaluation supported by Accountability (Legitimacy, Governance)

Discussion of “Anti-Catastrophe”

- “Anti-Catastrophe”-oriented design was a proposal from structural engineers as lessons from the disasters by 2011 Tohoku Earthquake.
- Structural engineers are primarily responsible for the performance of infrastructures against Design Basis Events (DBE).
- Structural engineers believe that they can contribute to avoid catastrophic situation of our society by adding new features for Beyond DBE to infrastructures by their engineering based considerations.
- AC is close to “resilience” or “robustness” but considers more severe damage and social context.

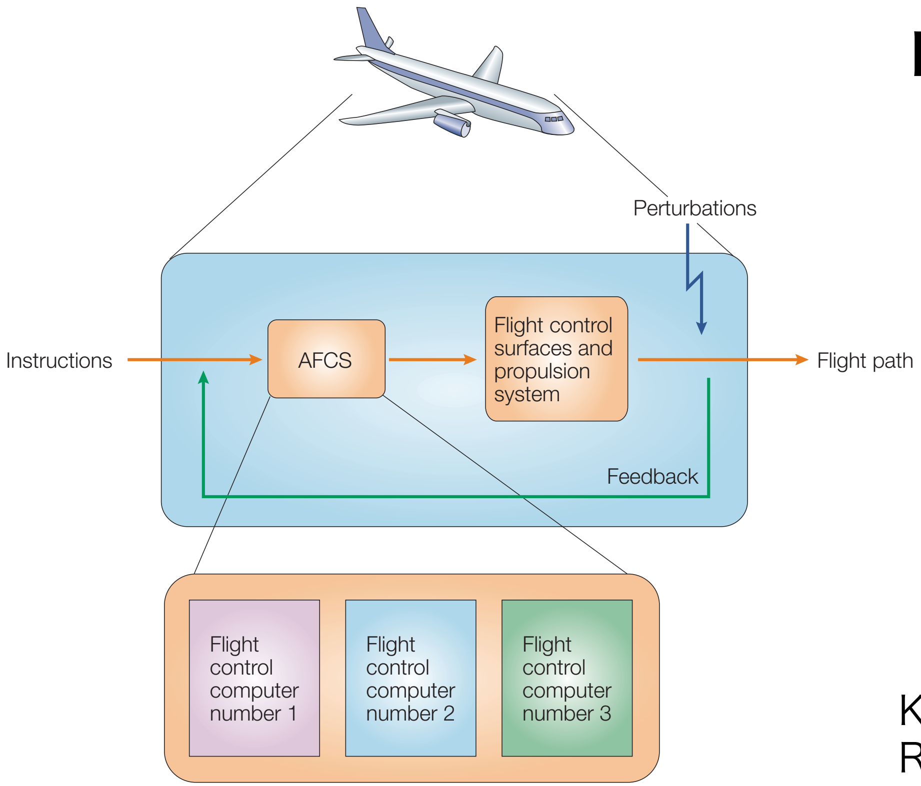
Honda, R, Akiyama, M, Kataoka, S., Murono, Y., Nozu, A. and Takahashi, Y., Seismic Design Method to consider “Anti-Catastrophe” Concept, Proc. Of 16th WCEE, 2017

Infrastructure (building or lifeline) system performance over time (Ayyub, 2015)



Robustness

- **Robustness** enables the system to maintain its functionalities against external and internal perturbation.

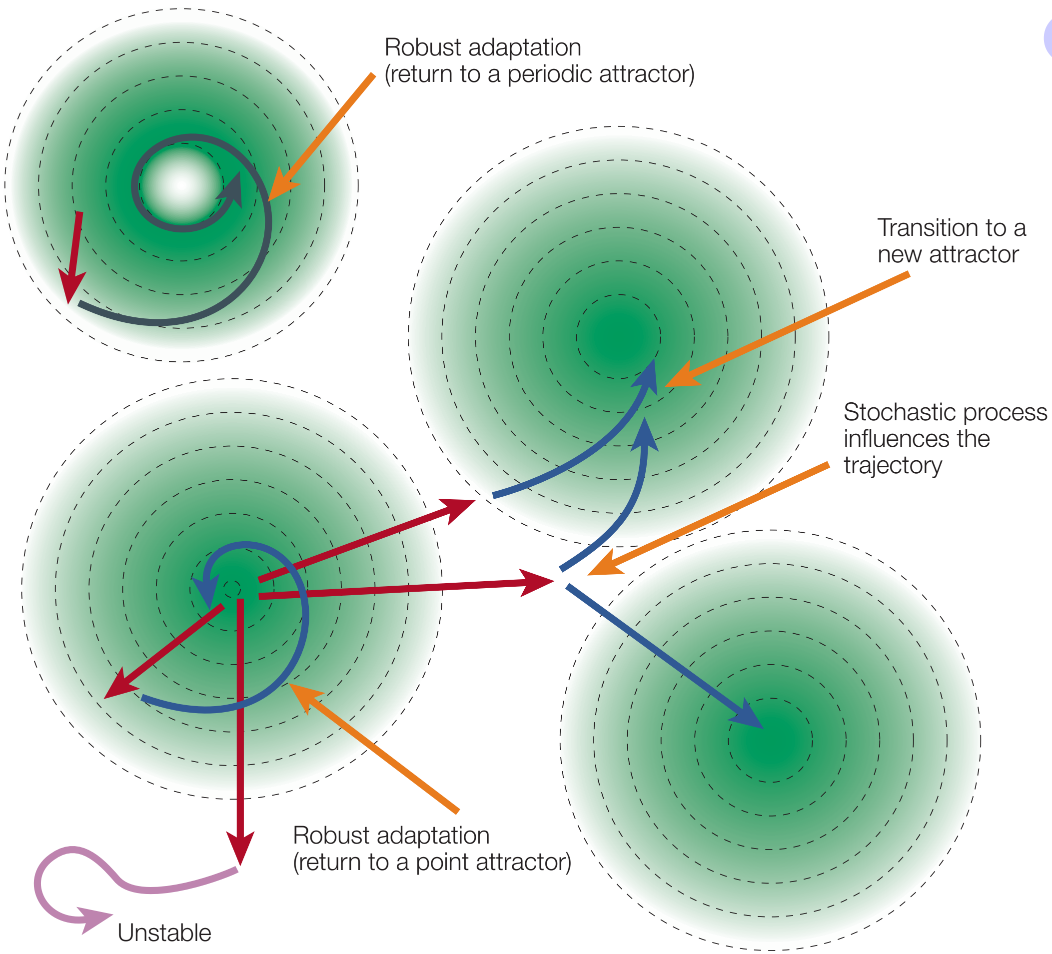


Properties of Robustness

- System Control
  - Negative Feedback
  - Positive Feedback
- Fail-safe (Redundancy and Diversity)
- Modularity
- Decoupling

Kitano, H., Biological Robustness, Nature Reviews: Genetics, Vol. 5, pp.826-837, 2004

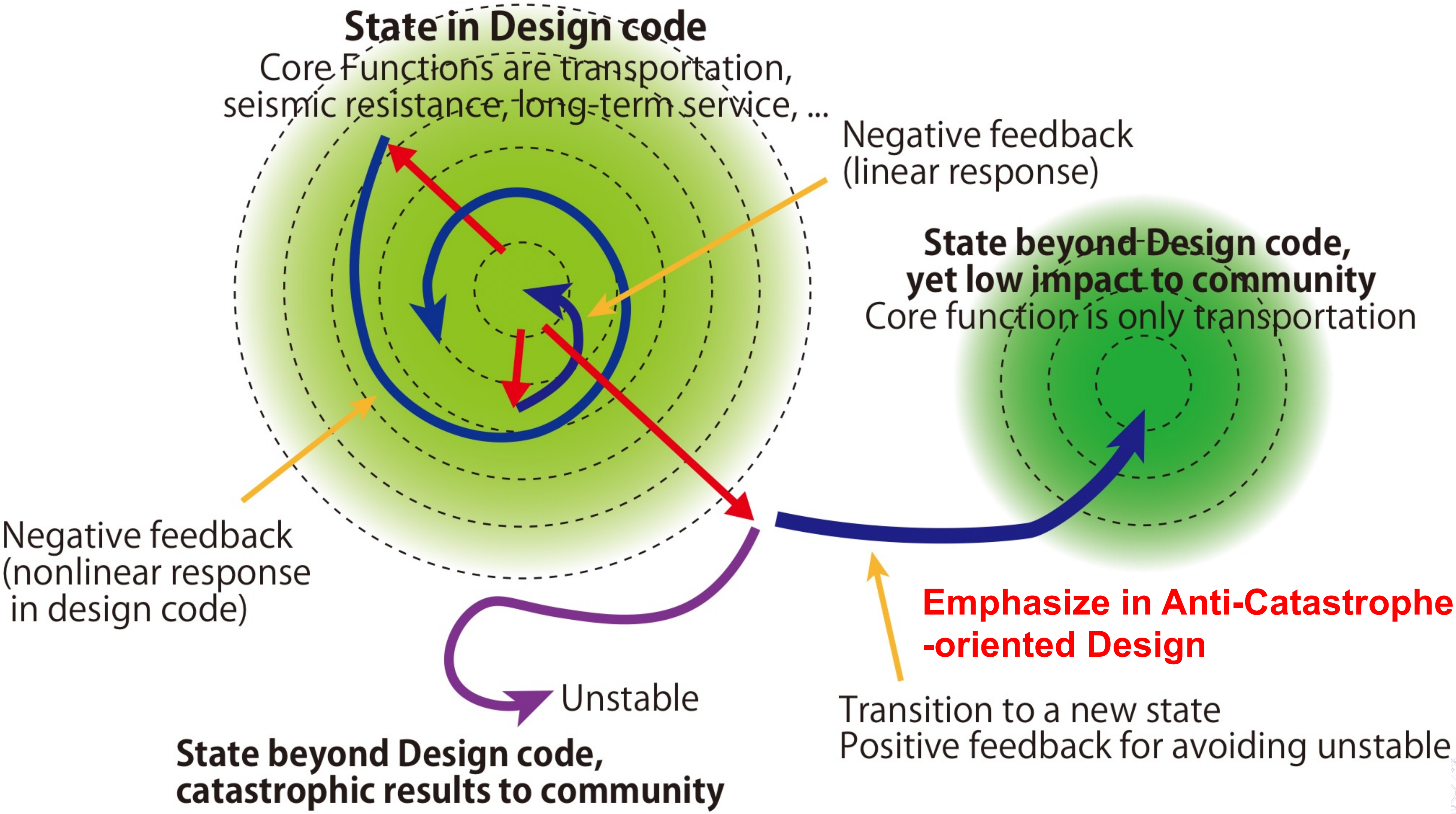
Robust reactions of the system : to stay or to change



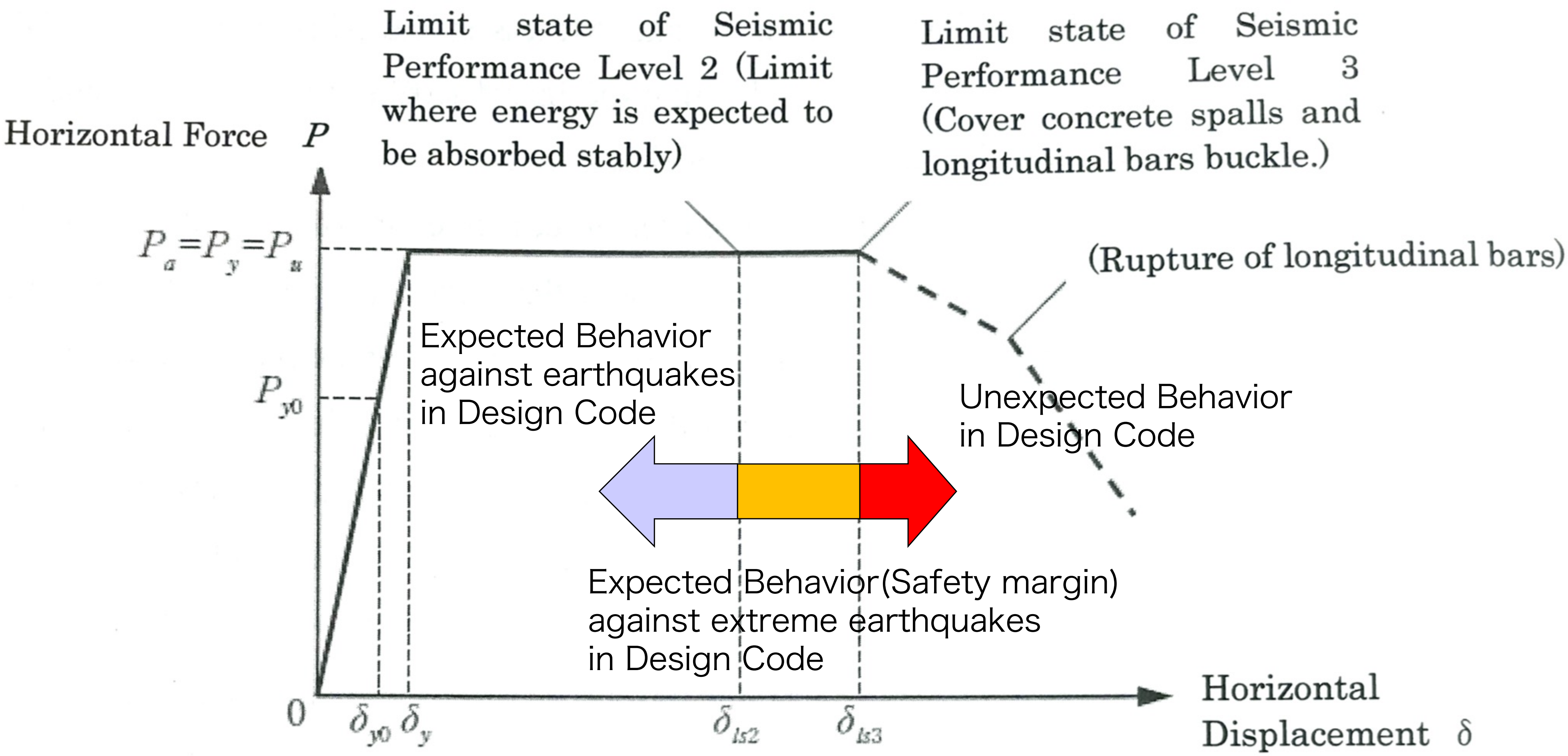
- Robustness allows changes in the structure and components of the system owing to perturbations, but specific functions are maintained.

Kitano, H., Biological Robustness, Nature Reviews: Genetics, Vol. 5, pp.826-837, 2004

Robust reactions of the system
: to stay for DBE or to change for BDBE

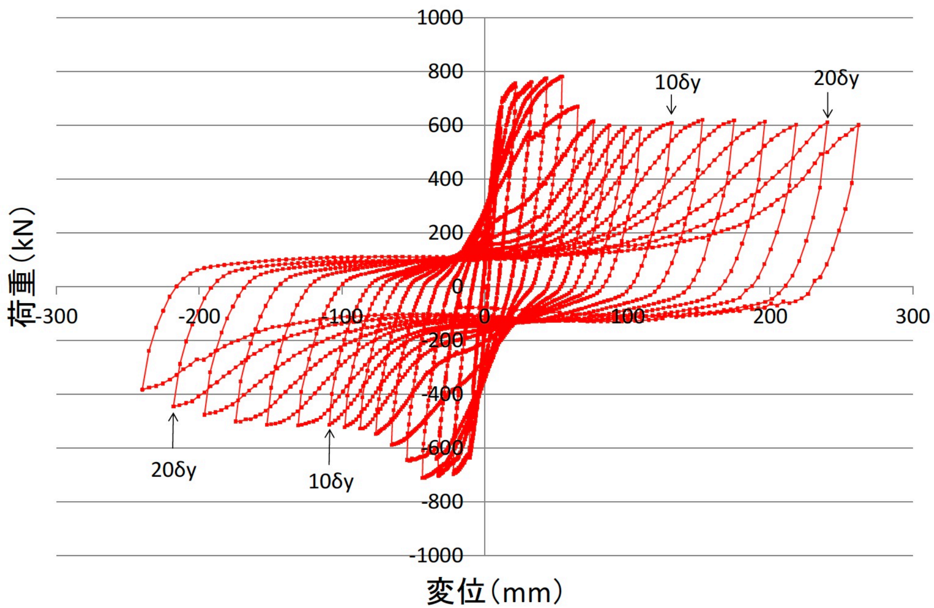


Relationship between the Horizontal Load and Horizontal Displacement of a Flexural-Failure Type Reinforced Concrete Pier

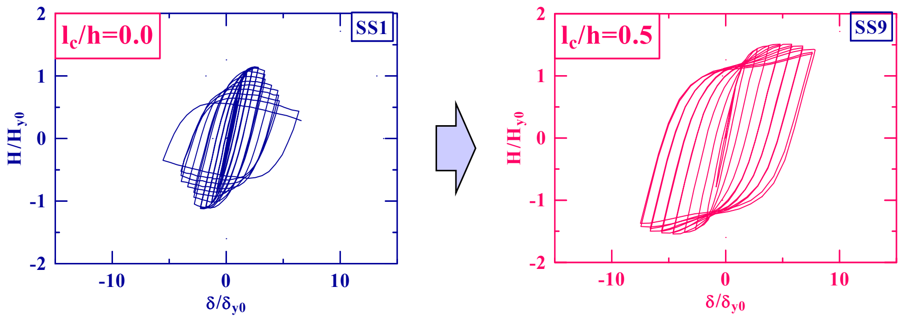


Comments added to the Figure in Specifications for Highway Bridges, Vol. V, Seismic Design (Japan Road Association 2014)

Structural Engineering Strategy after 1995 Kobe Earthquake



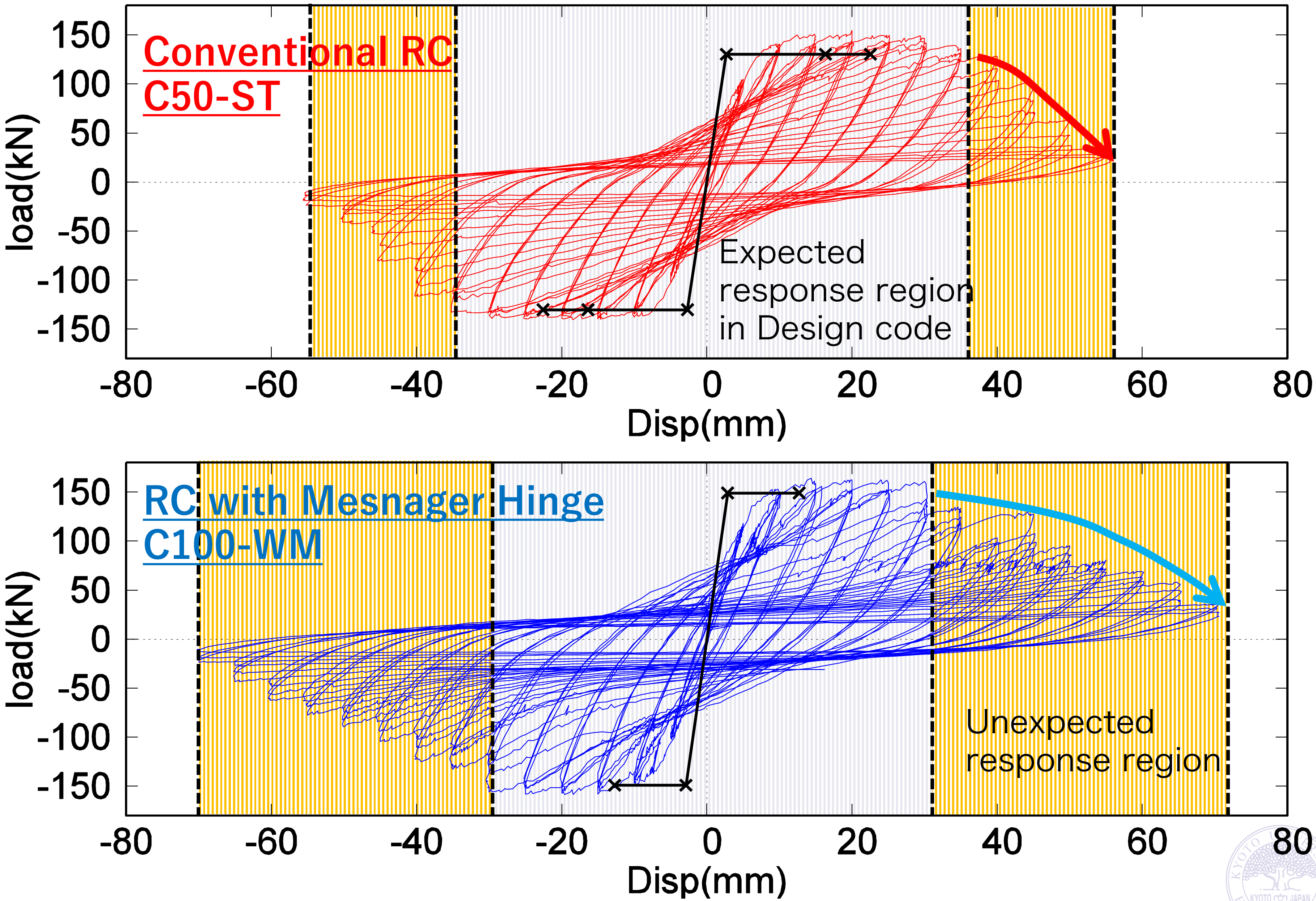
RC column with spiral rebar
(East Japan Railway Company)



Steel column with infill concrete (Usami, Nagoya Univ.)

- Larger ductility, better performance of structures against very severe earthquakes
- To enable to express the performance quantitatively, deterioration cannot be accepted.

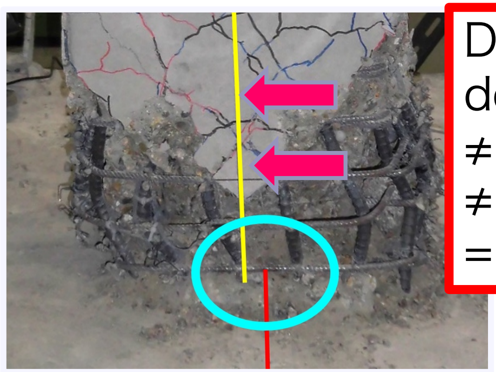
Large Ductility, Yet Fragile



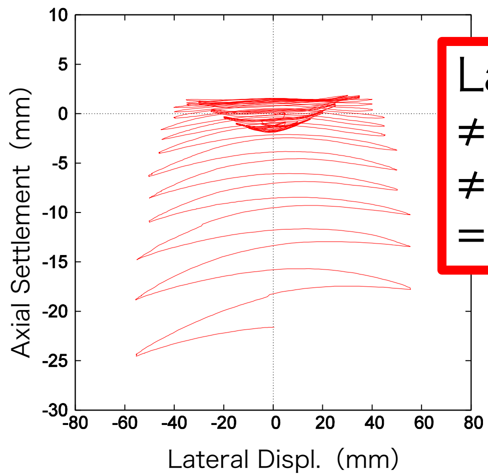
Goto, Takahashi 2018: Development of RC columns with Mesnager Hinge

Large Ductility, Yet Fragile

Conventional RC
C50-ST

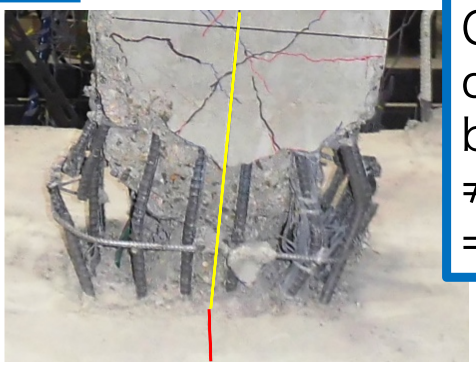


Discontinuity of deformation
≠ Plastic hinge
≠ Structural hinge
= Destruction

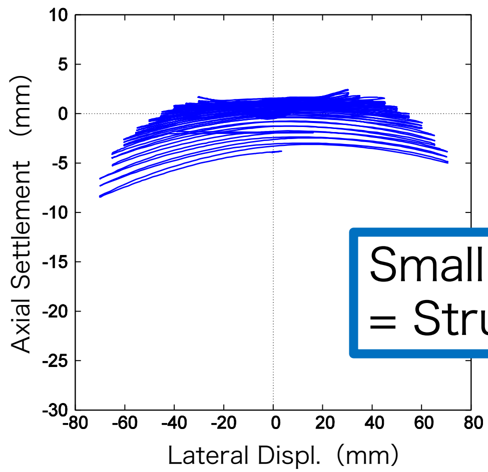


Large settlement
≠ Plastic hinge
≠ Structural hinge
= Destruction

RC with Mesnager Hinge
C100-WM



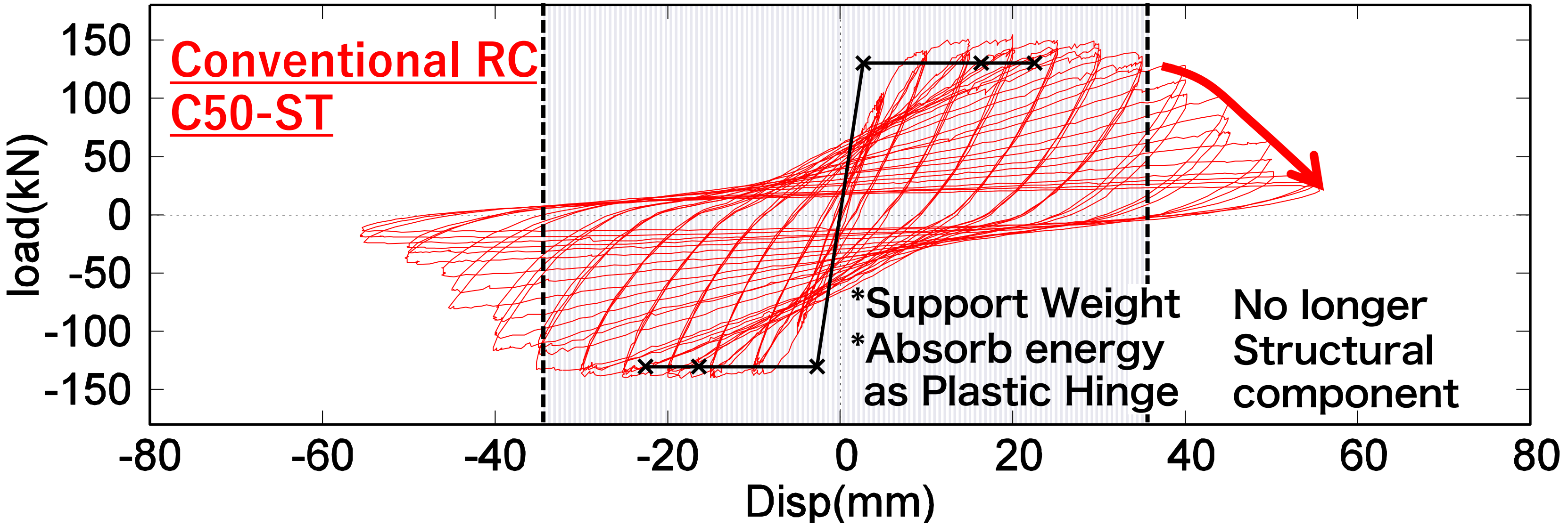
Continuity of deformation, but buckling rebars
≠ Plastic hinge
= Structural Hinge

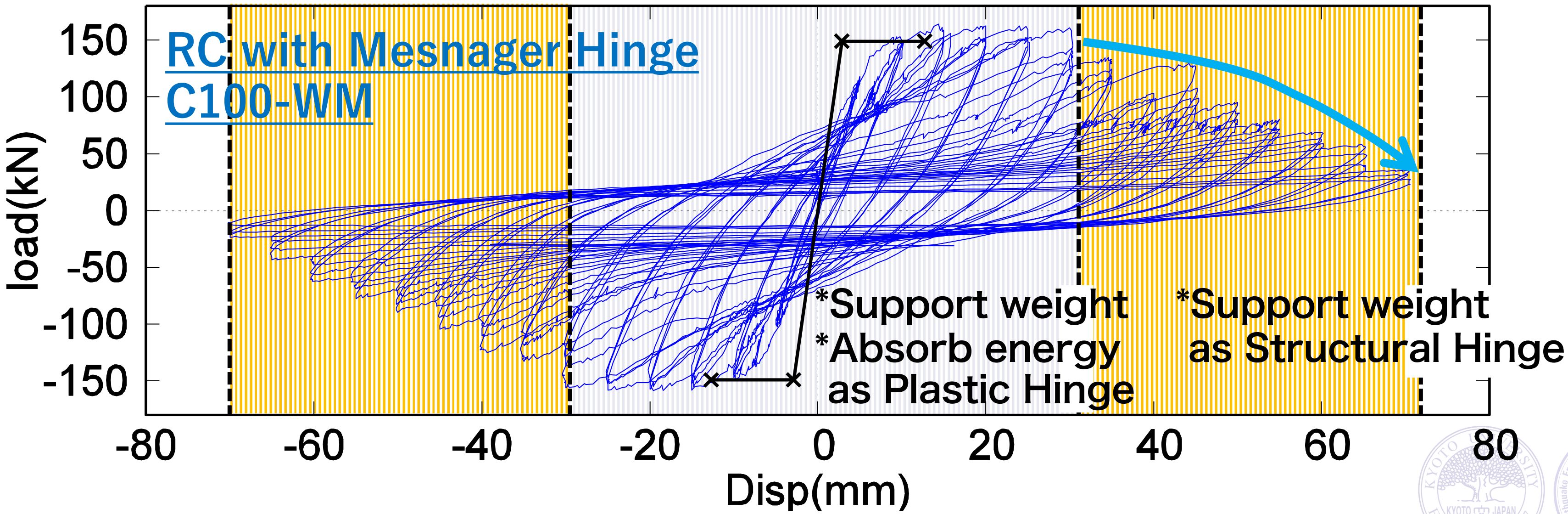


Small settlement
= Structural hinge

Goto, Takahashi 2018: Development of RC columns with Mesnager Hinge

Change Functionality of Structure

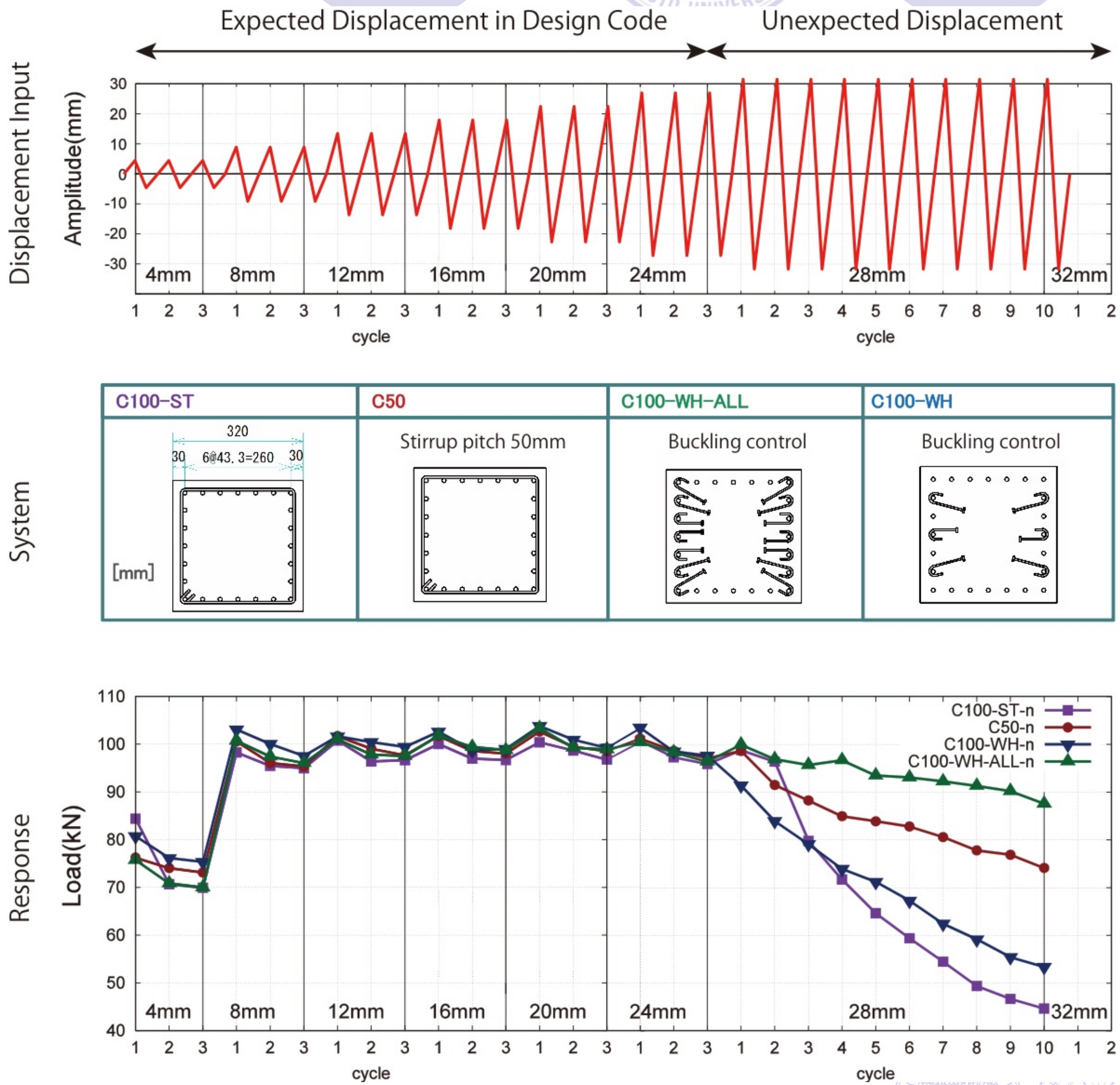




Goto, Takahashi 2018: Development of RC columns with Mesnager Hinge

(Quantitative) Collapse Control

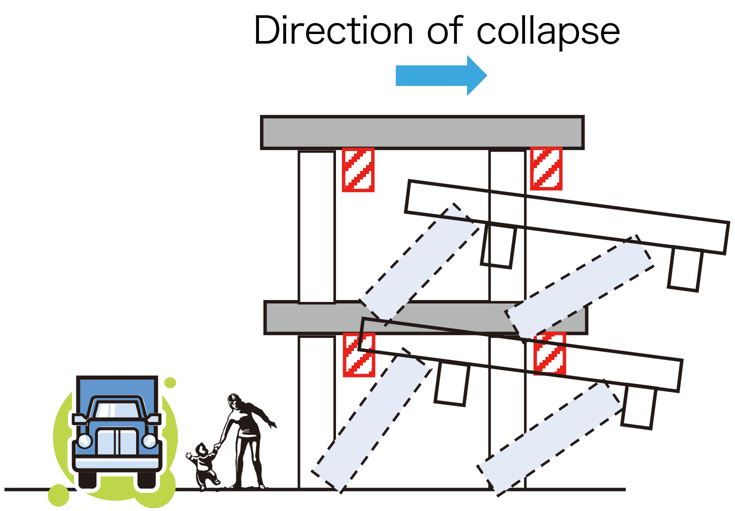
- RC columns with same sectional size.
- All columns are satisfied with Japanese design code.
- Different structural details show different load deterioration.

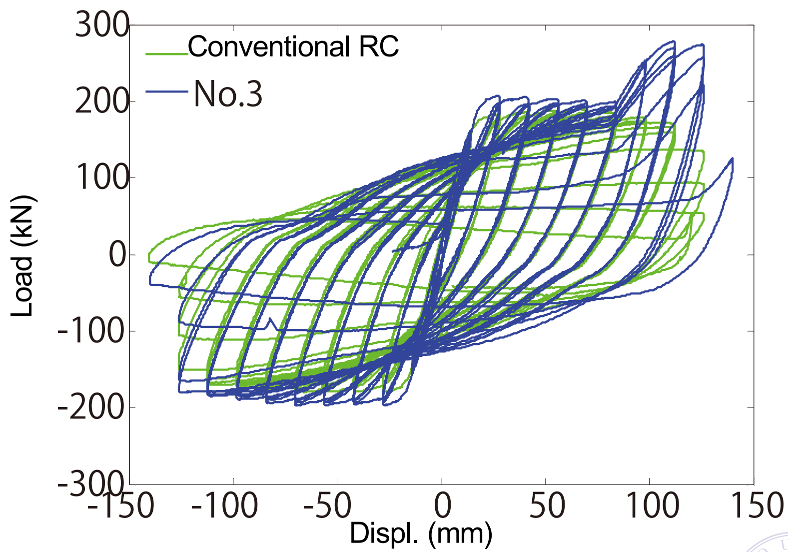


Uemura, Takahashi 2018: Cyclic Loading Tests of RC Columns with Bond-Slip Connectors on Longitudinal Bars, fib congress

(Quantitative) Collapse Control

- Control the direction of collapse
  - To prevent loss of life
  - To avoid interrupting emergency transportation
  - To reserve access routes or space for recovery process





Toyooka et al. 2018: Cyclic loading test of a viaduct column equipped with the collapse direction control device, Proc. of JSCE Earthq. Eng.

Future Discussions in Structural/Earthquake Engineering

- Discussion on how to develop next-generation infrastructure in developed countries who have a lot of existing non-conforming infrastructure
- Discussion on infrastructure performance during recovery process
  - Qualitatively, but predictable collapse behavior
  - Quick recovery of core functionality
  - Prepare for monotonically increase of seismic performance in the future