BRIDGE INSPECTION STANDARDS IN JAPAN AND US

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Abstract

Element-level bridge inspection has been developed in Japan and the US respectively. Conventional maintenance / rehabilitation urgency rating needs a diagnosis given by qualified engineers and is somehow subjective. In addition to that, the element data recording of damage state rated in an objective manner is a new trend. The present paper compares the histories and concepts of bridge inspection program in both countries and highlights some of the element-level inspection results in Japan. The results show that the accumulation and big data mining of objective element-level data has a huge potential to improve bridge management and design / inspection standards.

Introduction

Bridge inspection is primarily conducted to assess the structural safety and related maintenance urgency for individual bridges. Accordingly, bridge inspection demands a comprehensive engineering (or subjective) judgment for structural safety and maintenance urgency at the structural member level or component level or bridge level. However, recently collecting objective / scientific damage rating at element level has been widely accepted both in Japan and the US and executed in addition to the conventional inspection standards.

For example, the amendment of Road Law was approved in Japan in May 2013, clarifying that it is an obligation for all road administrators to inspect structures with consideration of preventive maintenance. It also empowers Minister for Land, Infrastructure, Land, Transport and Tourism to investigate road administrators' statuses for highway maintenance for the sake of technology development. In the US, MAP-21 (Moving Ahead for Progress in the 21st Century Act) was enacted in 2012. While the conventional national bridge inspection standards with a 0-9 scale rating continue to be executed for structural components of all bridges on public roads, now States are required to collect element level condition state data set of bridges on the National Highway System. With these backgrounds, both Japan and the US have established element-level bridge inspection standards these days, respectively. However, the definition of 'element' in bridge inspection is different between Japan and the US. It is not a problem of which is better or which is worse. It should be important to make the definition of element and data recording structure meet the aims of element level inspection, which may vary with bridge owner by bridge owner.

Accordingly, the present paper considers what should be considered to set out

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the definition of ‘element’ or unit of condition rating or data collection structure in inspection. The present paper first reviews expected outputs from big-data mining in bridge inspection data in the era of scientific element level bridge inspection. Ministry of Land, Infrastructure, Transport and Tourism bridge inspection protocols and US NBIS (National Bridge Inspection Standards) are compared, pointing out the difference in the definition and unit of components and elements in bridge inspection (MLIT, 2004). Secondly, the details in MLIT’s ‘finite’ element level damage rating protocol are reviewed, in which the MLIT protocol is comprised of damage appearance ratings for ‘finite’ elements and maintenance urgency ratings for structural members., where the definition of ‘finite element’ will be explained later. Finally, the present paper shows some highlight scientific facts that are found out in the data of MLIT `finite’ element level bridge inspection and discusses the potentials of MLIT’s finite element level bridge inspection on promoting data-driven bridge maintenance and R&D in bridge engineering.

Brief histories of Element-level Bridge Inspection in Japan and the US

Bridge inspection protocols depend on the aims of inspection. Table 1 shows expected scientific / engineering achievements and administrative achievements in bridge inspection. The primary concern of bridge inspection is to secure the structural safety for passengers moving under and on bridges. Conventional bridge inspection programs both in MLIT and the US are stipulated mainly for evaluating the urgency for maintenance or other actions from the viewpoint of safety. In Japan, a model bridge inspection manual developed in 1988 by Public Works Research Institute (PWRI) of then Ministry of Construction and used to be recommended (legally non-binding). A single rating indicator was assessed for each structural member in each span, accounting for the extent of damage and the urgency of maintenance simultaneously. In the US, the Silver Bridge spanning the Ohio River collapsed in 1967 and NBIS was enforced in 1971. Inspection is mandatory for all bridges on public roads. Inspection frequency is two years in principle. States have collected overall condition data for components at the bridge level, where components are defined as superstructure, substructure, deck, and culverts. States also shall conduct monitoring the bridge when a critical finding is found during an inspection. NBIS was updated several times, learning bridge collapses and major failure events.

In 1990s-2000s, the importance of preventive maintenance was realized in both Japan and the US, respectively, for better bridge management. Table 2 shows the number of bridges and vehicle shares by owner in Japan. MLIT has and operates as many as 20,000 bridges on designated sections of national highways. The Japanese road network was intensively developed during the rapid economic growth of the 1970s, and the number of road bridges has now reached approximately 700,000 (bridge length ≥ 2 m). As shown in Figure 1, it is predicted that the number of bridges older than 50 years will account for almost half of bridges in 15 years. Fatigue in steel piers and deck plates, chloride ingress in prestressed concrete beams, alkali silica reaction (ASR) in concrete structures, and fatigue failure of concrete in reinforced concrete decks were widely reported. MLIT raised a preventive maintenance initiative and ordered National Highway Offices to implement the present once-in-5-year bridge inspection protocol in 2004 (MLIT, 2004). Maintenance urgency rating for structural members is included, but damage appearance rating for more detailed units is also recorded. Damage appearance ratings are introduced because of expecting a scientific achievement of No. 2 in Table 1, data-driven systematic preventive maintenance. However, it is also designed to achieve data-driven updates and improvements in design specifications and inspection protocols as well as the understanding of needs in bridge preservation technology, corresponding to the expected scientific achievements Nos. 3 and 4 in Table 1.

Because preventive maintenance is required to reduce future maintenance costs, MLIT started a subsidy program in 2007 for local governments to establish long-term bridge maintenance programs. As a result, prefectures now have bridge inspection programs that follow the MLIT protocol and sometimes with some changes. Namely, bridges on arterial routes that carry a large part of traffic are now inspected periodically. However, some municipalities still do not inspect their bridges. Some conduct but inspection protocol and quality are not standardized.

In the US, several states started improving their bridge inspection program to obtain condition data for structural elements for bridge management system use. CoRe element data collection guide was developed in AASHTO for bridge owners to aim at better bridge preservation programs and performance-based budgeting. Most states started to follow it (AASHTO 2002). MAP-21 was enacted in 2012 and now all states will need to collect element level inspection data for bridges on NHS, following the reporting system of AASHTO Manual for Bridge Element Inspection (AASHTO, 2013). FHWA is also directed under MAP-21 to study cost-effectiveness, benefits and feasibility of collecting element-level data for non-NHS.

Summary of Bridge Inspection Protocol in Japan

Maintenance Urgency Rating

In both Japan and the US, bridge inspection protocols are comprised of the part for assessing structural safety and the part for collecting quantitative and objective damage data for elements. In terms of the structural safety part, there is no big difference in philosophy between the MLIT protocol and the US NBIS, except for the unit of assessment.

In the MLIT protocols, bridges with a span longer than 2 m are inspected once in every five years. Hands-on visual inspection is required. Tools and devices may be used with a limited amount to determine such as fatigue crack in steel members. For each structural member in each span, the condition is translated into either of the following maintenance urgency ratings:

- A No repairs needed.
- B No immediate repairs needed.
- C Repair needed
- E1 Emergency action is necessary from the viewpoint of structural safety

and stability

E2 Emergency action is necessary because of other factors.

M Repairs needed in the course of the regular maintenance work

S Further detailed investigations needed

Maintenance urgency ratings are diagnosis given by experienced engineers in a subjective manner, recommending to bridge owners the needs for action by the time of the next inspection. Engineers are required to interpret the maintenance urgency for each member, taking into account the damage appearance ratings in finite elements in the structural member, specific characteristics of the damage such as the direction of crack, the location of damage in the structural member, the function of the structural member, likely causes / sources of damage, interactions with other damage at other structural members and components in the bridge, earlier remedial work history, the deck / slab coating system, the drainage system, environmental factors such as traffic volume, deicing salt dumping volumes, the distance from the sea etc and so on. No numeric criteria like crack width and length are specified for maintenance urgency ratings.

In the US, each bridge is divided into four major parts for assessment: deck, superstructure, substructure and culvert. Inspectors give either of 0-9 ratings in a subjective manner of interpretation for damage. The rating scale for each part ranges from 0-9 depending on the severity of damage and urgency of action. Namely, four indices describe the extent of damage as a whole bridge.

Figure 2 shows a schematic diagram of deterioration curves. Deterioration rates have a huge variety and the variety increases with increase in the extent of damage. Figure 3 shows an example of test result for the fatigue of concrete in RC deck slabs. Wheel loading tests were conducted for two specimens, where a wheel subjected to a given axel load moved back and force on the specimen until the specimen collapsed. The test specimens were cut out of two different existing bridges and their crack widths and densities in concrete are very similar to each other. However, Specimen A in Figure 3 did not collapse at a wheel movement of 200,000 cycles while Specimen B collapsed at a wheel movement of 20,000 cycles, with 1/10 of the durability compared to Specimen A. This should be because some cracks had already penetrated through the entire depth of deck slab before the experiment as indicated by efflorescence marked with the red circle in Figure 3. As also well known, other factors such as water coming from the deck slab surface can accelerate the evolution of fatigue crack in deck slab concrete. Figure 4 shows cracks in steel members. The influence of cracks on the safety of bridges depends on crack locations and directions. Namely the maintenance urgency rating for cracks cannot be easily standardized as a function of crack widths and lengths and it should mislead engineers to set out any numeric criteria for maintenance urgency ratings such as a function of crack widths and other numeric parameters. Engineer's diagnosis on site should go first.

(Finite) Element-Level Damage Appearance Rating

Preventive maintenance has been promoted in both Japan and the US in recent years to reduce the future rehabilitation cost. Data-driven management has been expected to help bridge administrators seek a preferable timing and preventive remedial measure to provide for individual bridges. Quantitative distributions of different extents of damage within components are required to estimate future maintenance costs more precisely, because preventive maintenance is sometimes conducted span-by-span or portion-by-portion. In addition to bridge management use, the importance in data objectivity has been widely recognized to examine the long-term bridge performance and improve bridge design. However, the maintenance urgency rating does not necessarily equal the extent of damage appearance. It involves a subjective prediction by engineers regarding the time evolution in existing damage and related degradation in structural safety, calling for taking into account various factors such as the possible causes of damage.

Accordingly, an element-level data collection with scientific / objective damage condition ratings is required to capture the type and distribution of distress in components and monitor the exact extent of present damage at each distress and at the time of the inspection. Both element-level data collections in Japan and the US record objective, not subjective, standardized condition states for specific defects. However, as illustrated in Figure 5, there is a notable difference in the definition of ‘element’ and the data recording philosophies / structures between Japan and the US.

As specified in the AASHTO manual (AASHTO, 2013), elements in the US are breakdowns of components that are directly related to the load capacity such as the group of girders, the group of columns, the group of abutments, the group of fixed bearings and the group of movable bearings in a bridge. In addition, secondary components such as protective coating systems, wearing surfaces, and joints are also set out. The data structure is summarized as follows:

- Category of element
- Specific defects
- Damage ratings: good, fair, poor, and severe for each category of defect
- Quantities of each category of defect in feet, area, or each for enumerated elements for each category of defect and each damage extent.

Elements defined in the MLIT protocols are subdivided portions of individual structural members at individual spans. For example, as shown in Figure 5, every single girder for each span is subdivided into several parts at the position of floor beams in a span. Figure 6 illustrates examples of element categories and finite element meshing for damage appearance ratings in the MLIT protocol. In Figure 6, a line from dot to dot or an area from panel to panel is a finite element. Hereafter, ‘element’ in Japan will be referred to as ‘finite element’ in this paper in comparison of `element’ in the US, because the geometry of elements and the inspection data structure are analogous to those of finite element analyses.

Figure 7 illustrates the data recording structure, in which:

- Individual damage ratings for 13 defect categories at maximum for each finite element. For example,

- ✓ A finite element of a steel beam has damage appearance ratings for #1 Corrosion, #2 Cracking, #3 Looseness / Falling, #4 Rupture, and #5 Deterioration of corrosion-proofing function, respectively
- ✓ A finite-element of a concrete beam has damage condition ratings for #6 Cracking, #7 Peeling and exposure of reinforcing bars, #8 Leakage and free lime, #9 Falling out of place, #10 Damaged concrete reinforcement, and #12 Lifting, respectively.

- Damage conditions are from "a" being no damage and "e" being the worst. Even the existence of no damage shall be recorded.
- Furthermore, in relation to the damage category #6, cracking, crack patters are also categorized as also shown in Figure 7.

As also shown in Figure 7, when choosing a span and an element category, you can see the layers of finite element damage rating maps as many as specified defect categories --- big data processing friendly.

Data objectivity is thought of crucial and a reference manual is published by NILIM, MLIT, to keep the data objectivity, showing sample photographs of each damage category of each damage rating. Inspectors are requested to record the existence and extent of damage as precisely as possible in a digital manner, 'a' being no damage and 'e' being the worst. They have to assign the damage appearance rating of 'a' to 'e' sort of automatically with no subjective translation, comparing sample photographs and some numeric criteria like crack width on the reference with what they see and measure on site. It is also worth noting that MLIT, in practice, has awarded the maintenance urgency rating inspection and damage condition rating inspection, separately. Both ratings are cross-checked by bridge administrators as sort of a quality assurance system.

Because data objectivity is secured and the distributions, categories, and ratings of damage at finite elements are digitized and clustered, MLIT's finite-element level inspection is expected to cover all aspects listed in Table 1.

Big Data Mining on the MLIT's Finite Element Level Bridge Inspection Database

To examine the effectiveness of the design for MLIT's finite element-level inspection protocol, some highlight findings processed from a big data of MLIT's finite element level bridge inspection are shown below. Since 2003 the finite-element level bridge inspection has been implemented for as many as 20,000 bridges under the jurisdiction of the national government. Most bridges have been inspected twice following the same finite element level inspection protocol and some bridges have been inspected three times. Damage appearance rating data obtained in FY2006-2010 are mainly used below.

Figures 8 and 9 are examples of showing the potential of the promotion of data-driven preventive maintenance using the finite element level inspection. Figure 8 shows the ratio of the number of spans with any damage at designated finite elements to the number of all finite elements inspected in terms of steel I-beam bridges. Figure 8 deals with corrosion of I-beam. Because of the finite element inspection, a tendency in the distribution of damage extent in a girder or a span can be understood. Span-ends and outside girders are susceptible to damage compared with span-centers and inner girders. This may be attributed to the water that comes through expansion joints and stay around girder-ends and the supply of chlorides from the sea brought by wind or deicing salt from the road surface to outside girders. Because finite-element data is likely to show the difference in the distribution of distress in a structural member, we can expect to grasp the needs of new and better preventive maintenance techniques. For example, based on such findings, NLIM and MLIT highway offices have proposed a zone painting manual.

Figure 9 shows a stochastic transition in corrosion of steel girders. Using two batches of finite element data that covers 10 years, the change in damage condition rating for corrosion of the same finite elements is counted and the transition probabilities are calculated from a to a, b, c, d, e, respectively, from b to b, c, d, e, respectively, from c to c, d, e, respectively, and so on, resulting in a stochastic time evolution in corrosion of bridge girders with years. In this calculation, finite elements that were applied to some remedial work in the past such as the refurbishment of surface coating system were discarded. Different deterioration tendencies within a span and within a girder are found out, which should get involved in bridge management systems to limit the extent of overestimation or underestimation of deterioration in estimating the future total maintenance costs for bridges.

Figure 10 is an example of showing the potential of data-driven improvement of design specifications using finite element-level bridge inspection. Figure 10(a) describes the numbers of spans with specific crack patterns in post-tension PC T-beams. Crack patterns are categorized into twenty different identities in inspection as illustrated in Figure 10(c), where only major patterns are shown in the illustration. The result shown in the left-hand side of Figure 10(a) is based on all inspection results (3,874 spans in total), while the right-hand side of Figure 10(a) is only based on initial inspection results out of all inspections (136 spans in total), where in MLIT new bridges are inspected within two years after putting in service using the finite element level bridge inspection protocol. The data clearly shows that cracks evolve with years. Cracks along PC cables such as patterns #2 and #20 or along stirrups such as pattern #10 may indicate the corrosion of cables and reinforcement. Structural details of PC tendons and cover depths have been changed for almost the last twenty years and we would like to follow the inspection results to figure out the effectiveness of such changes. Figure 11(b) shows the comparison in crack patterns between post-tension and pre-tension PC beams. Cracks of Patterns #2 and #4 especially appear more in post-tension girders. More stringent construction quality controls can be required for post-tension beams.

Meanwhile, the existence of cracks with pattern #1 indicates that some flaw could exist in design practice. For example, the present design standards in Japan do not incorporate residual stresses accumulated during construction such as thermal stresses during concrete casting into stress calculations, while usually residual stresses due to welding are involved in setting the strength curve of steel beam and columns. Long-term loads such as shrinkage and creep of concrete and the related restrained stresses due to the existence of reinforcement bars may be necessary to be examined. Cracks can give adverse effects on the long-term durability of concrete structures and violate the presumptions / theories to calculate stresses in cross-sections and strengths of prestressed concrete beams.

Figure 11 is an example of the potential of developing a more logical inspection protocol by conducting a big data analysis on the finite element level bridge inspection data. Figure 11 shows the number of steel I-beam spans and box-beam spans with or without any crack by age and by average daily large vehicles. Crack tends to appear either when a bridge is older than 20-30 years or when carrying more than 10,000 large vehicles a day. The result indicates that further analyses may clarify the needs for the introduction of special inspection programs by age and type of distress.

In conclusion, the results highlighted above show the effectiveness of finite element level bridge inspection to aim at all achievements listed in Table 1.

Concluding Remarks

We are seeing the advent of the use of big data in bridge inspection. Both Japan and the US just have changed laws in terms of bridge inspection and adopted finite element or element level inspection. Both countries are now considered to face a significant challenge to use the big data of bridge inspection wisely. To conduct data mining, data collection protocol should be carefully designed to make the data structure harmonize with big-data mining. The present paper shows that the MLIT's finite element level bridge inspection protocol is likely to do a good job in this regard. This paper especially points out potentials that finite-element level damage rating can be useful to figure out scientific facts that backup data-driven preventive maintenance, data-driven technology development in maintenance, and data-driven improvement / development in design specifications and inspection standards, with examples.

Data collection strategies can change with bridge administrators / owners' needs as summarized in Table 1 and there is no guidance for relevant assessment units (definition of 'element') and data collection structures. Accordingly, the authors hope to continue to exchange and share with each other between Japan and the US the information on:

- Benefits of detailed data collection such as best practices in the data-driven management of individual bridges or the data-driven coordination of network-level bridge preservation programs.
- Examples of things to be improved in design and construction based on scientific fact findings from the data
- Examples of data-driven technology development in bridge inspection and maintenance (e.g. Clarifying development targets and needs for non-destructive testing tools)

References

AASHTO (2002). Guide for Commonly Recognized (CoRe) Structural Elements,

CORE-1-I1. AASHTO, Washington, DC.
AASHTO (2013). Manual for Bridge Element Inspection, 1st Edition. AASHTO, Washington, DC.
Ministry of Land, Infrastructure, Transport and Tourism (2004). Bridge Inspection Manual.

Table 1. Relationship between aims of periodical bridge inspection and Japan and US bridge inspection standards

Expected scientific / engineering achievements	**Expected administrative achievements**	Ratings	Inspection units
1. Preservation of bridges - Leading to maintenance or other actions - Sending to detailed inspection	Securing safety for passengers under and over bridges	Maintenance urgency rating (Subjective)	Components in NBIS or Members in MLIT protocol
2. Data-driven systematic investment in preventive maintenance at network level and bridge level, respectively	Better funding scheme and performance measurement in management	Damage appearance rating (Objective)	Elements in AASHTO manual or Finite-elements in MLIT protocol
3. Data-driven "kaizen" or continuous updates in design specifications, inspection standards, retrofit guidelines etc	Technology development		
4. Data-driven technology development for maintenance			

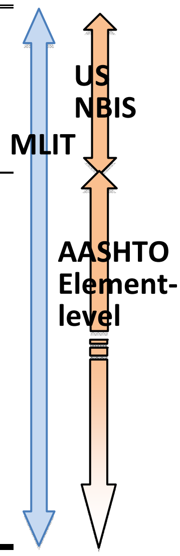


Table 2. Bridge Inventory in Japan (As of April 2013)

	Number of road bridges*	**Average 24-hour traffic numbers**** [**Large vehicle** / **total**]
National Expressways (Owned by MLIT and operated by expressway companies)	7,246 (1.1%)	9,068 / 27,884
National Highways --- Designated Sections (Owned and operated by MLIT)	**20,763 (3.1%)**	**3,326 / 16,641**
National Highways --- Other Sections (Owned and operated by Prefectures)	30,200 (4.4%)	1,127 / 8,120
Prefectural Roads	100,152 (14.7%)	568 / 4,941
Municipal Roads	521,173 (76.7%)	
Total	**679,534 (100%)**	---

*As of April 2013 ** Based on the 2010 road traffic census data

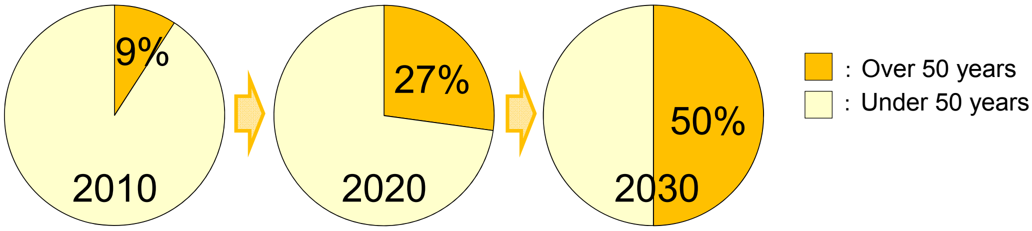


Figure 1. Percentages of bridges older than 50 years at present, in 10 years and in 20 years.

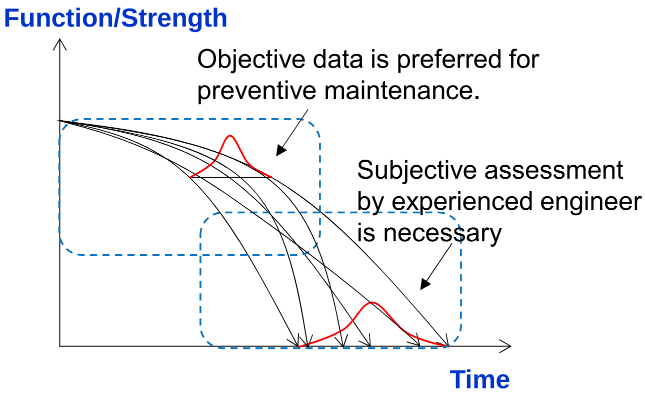


Figure 2. Schematic diagram of deterioration curves, showing the variation in deterioration rate becomes larger with increase in deterioration

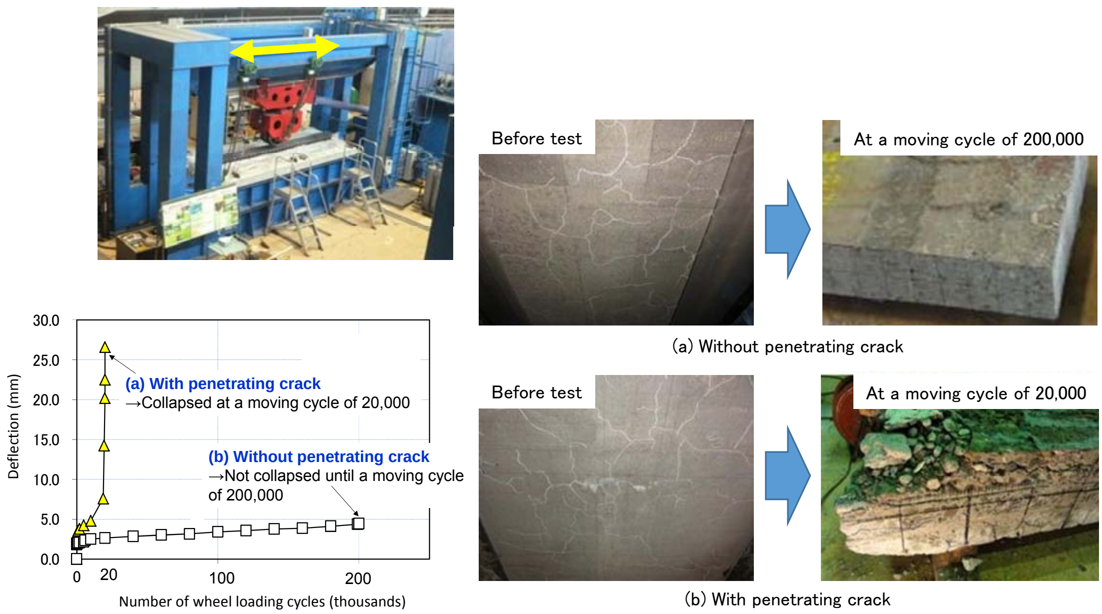


Figure 3. Example of moving wheel loading tests for fatigues in RC deck slabs having similar damage appearance states

Figure 4. Cracks at different positions in steel superstructures

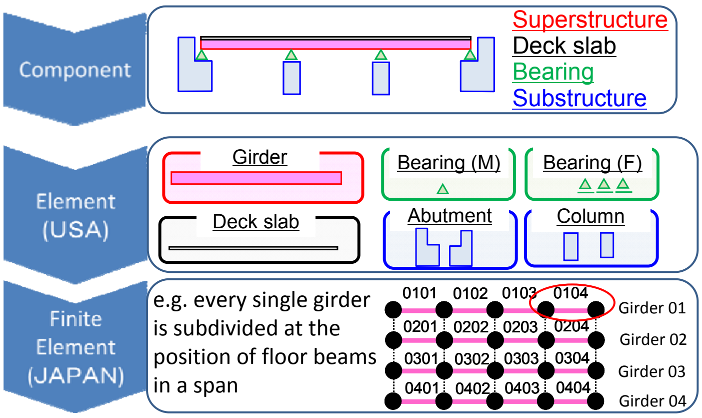


Figure 5. Difference in definition of ‘element’ in inspection between MLIT (Japan) and the US

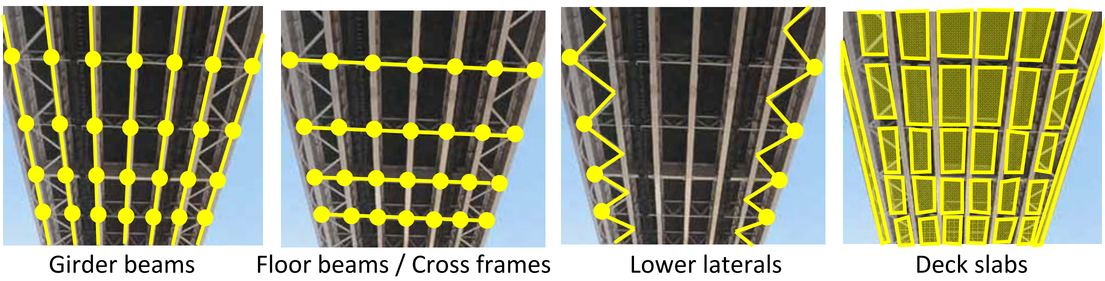


Figure 6. Examples of element categories and finite element meshes in the MLIT’s finite element level bridge inspection

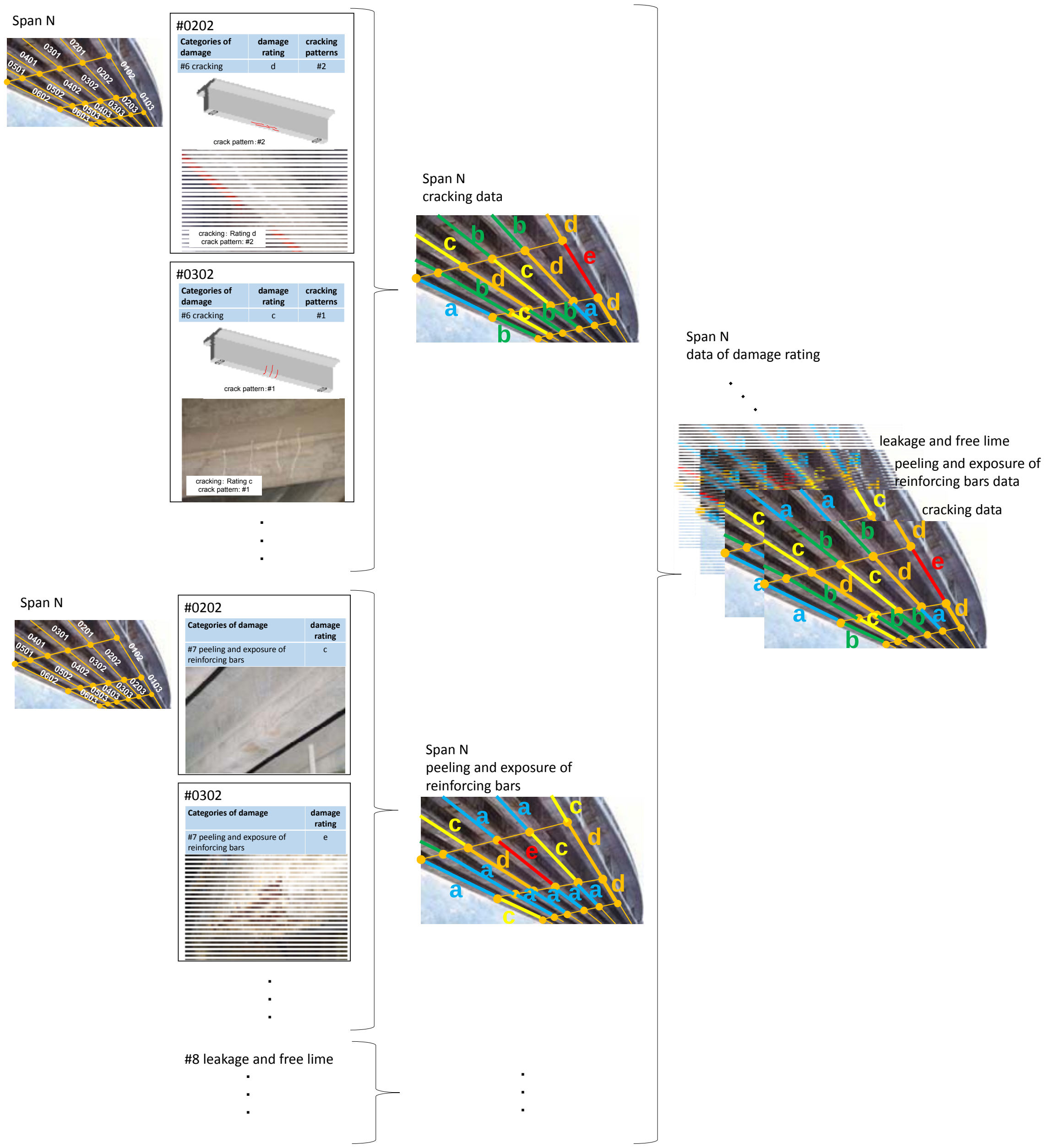


Figure 7. Data structures in finite element level bridge inspection of MLIT

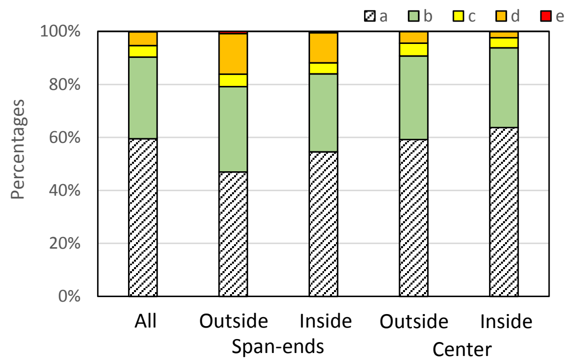


Figure 8. Percentages of finite elements in terms of corrosion in steel beams of steel I-beam bridges (“a” being no damage and “e” being the worst)

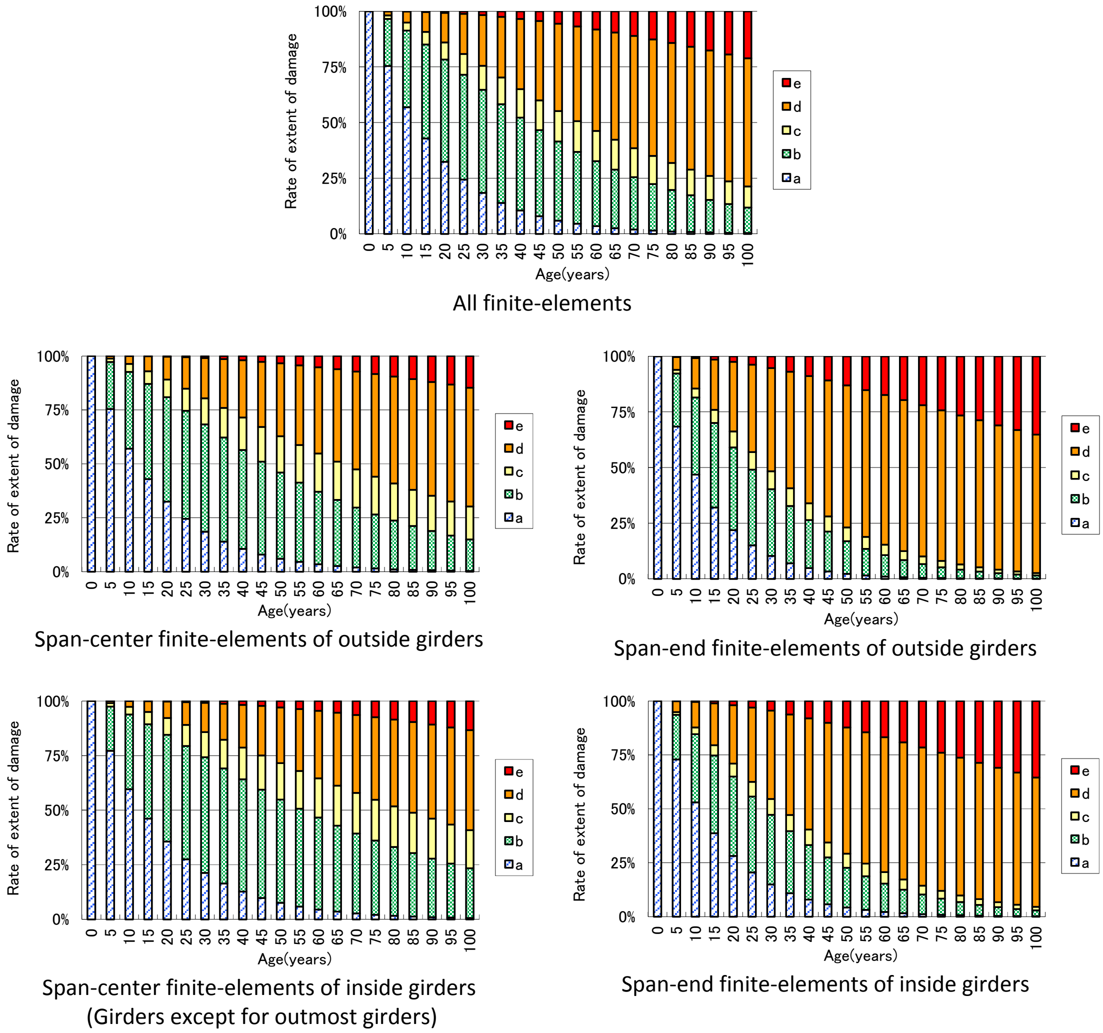
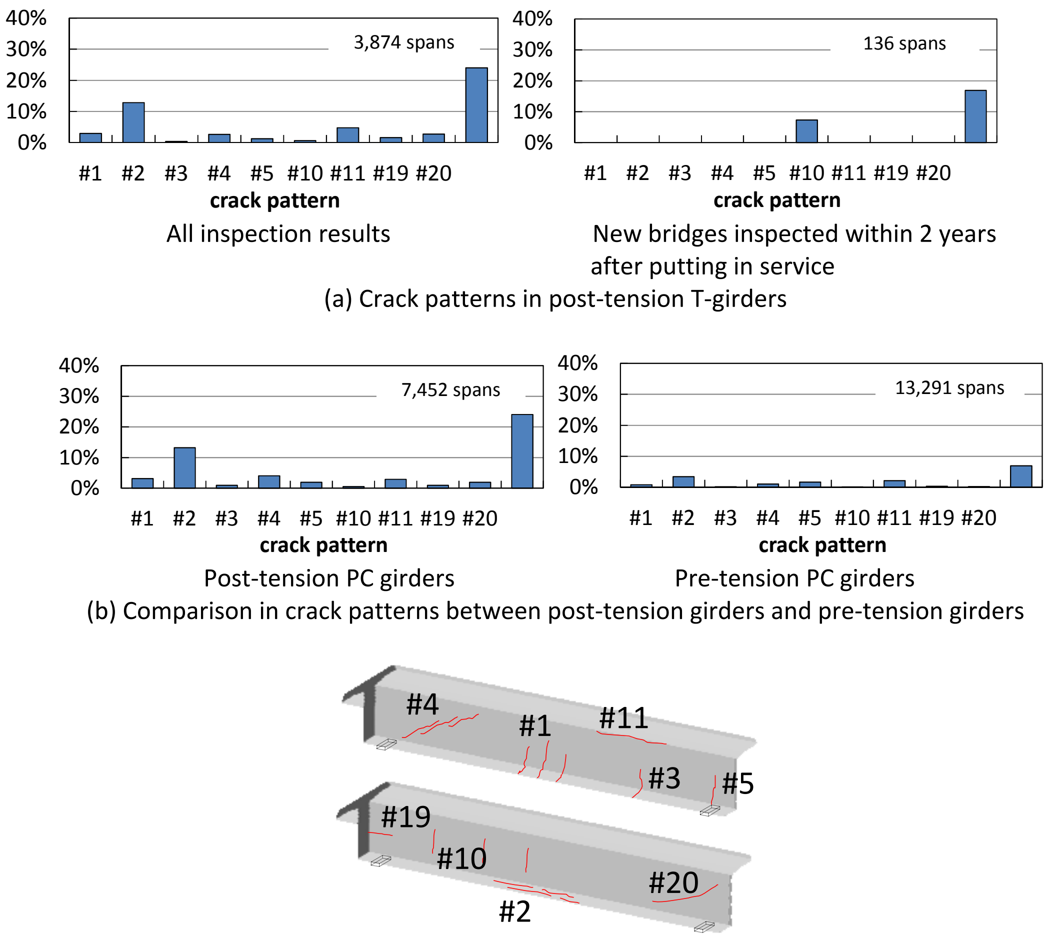


Figure 9. Stochastic time evolution in corrosion with years on steel beams of steel I-beam bridges (Based on the inspection data from FY2009 to FY2013)



(a) Crack patterns in post-tension T-girders

(b) Comparison in crack patterns between post-tension girders and pre-tension girders

(c) Crack patterns in MLIT's inspection manual

Figure 10. Number of spans with one or more finite elements having individual patterns of crack regarding PC beams.

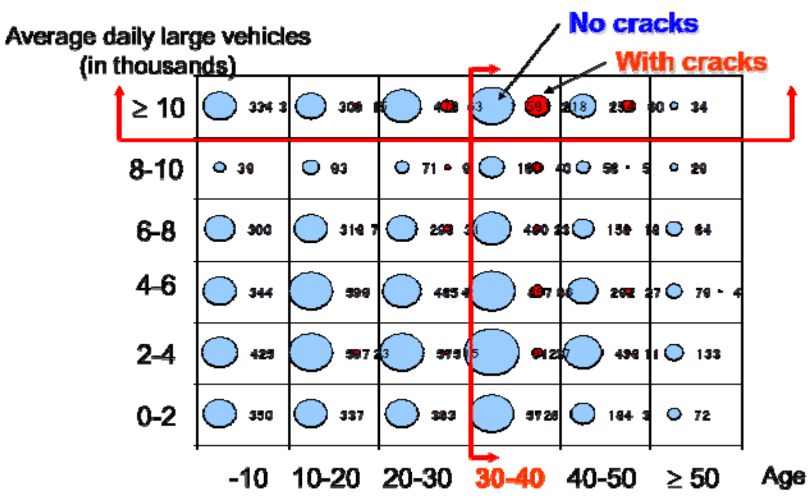


Figure 11. Number of spans with crack detected in steel I-beams and box-beams by age and average daily large vehicles