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On Longevity and Monitoring Technologies of Bridges - A Survey Study by Japanese Society of Steel Construction -

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ABSTRACT: JSSC, Japanese Society of Steel Construction, has organized a special task committee and conducted a study on the recent development of maintenance, renewal and retrofitting for buildings and bridges of Japan. This paper describes outline of the study by the working group of bridges and consists of two parts. The first part is concerned with the survey on the technologies for the longevity of bridges whereas the second part is specifically concerned with the structural health monitoring technologies reflecting recent developments. In view of the fact that important terminologies such as lifetime and service life have been used differently throughout the world, some fundamental terminologies are reviewed, discussed and redefined in this paper. Furthermore, recent developments on the structural health monitoring technology are reviewed and the results are summarized in a matrix form. Lastly, voices of some local governments, owners of expressways and railroads are taken into account in the form of questionnaire and replies to propose future structural health monitoring system for traffic infrastructures.

1 INTRODUCTION

In recent years, with some exceptions the number of children is significantly decreasing and young people tend to seek easy jobs which do not necessarily require working hard with perspirations in the developed countries in particular and in some developing countries. In this view point, the education of engineers and important traditional technologies that have been acquired through generations are going to be forlorn and these facts are becoming deplorable social problems.

In the world of construction industry, the era of the new construction seems to be ending in most of the developed countries and how to maintain and manage the existing facilities are considered to be one of the most important paradigms. On the other hand, as the socio-economic activities, the scale of the production, consumption and scrap have been significantly increasing and the exhaustion of resources and the destruction of environment are being rapidly accelerated throughout the world. It is needless to say that the construction environment should be drastically changed from the era of scrap to the ecological use of existing stock of infrastructure. Therefore, the structural longevity and elongation of the lifetime of infrastructure should be regarded as increasingly important subjects at the present time and in the future.

According to the white paper of the Government of Japan, the lives of typical infrastructure such as roads and bridges are thought to be 60 years and that of harbors and coasts is 50 years, respectively (MLIT 2002). Furthermore, according to Nikkei Newspaper, the annual cost of maintenance, management, replacement of public infrastructure and restoration from natural disasters of Japan would be doubled from that of 2004 to 2030, namely would become from 5 trillion JPY to 10 trillion JPY. According to the detail of the white paper of Japanese Government, the following facts on the infrastructure are worth mentioning. Assuming the total in-

vestment remains as it is, the figures from those in the year of 2000 will increase or decrease respectively annually to those in the year of 2025 in Japan:

(1) The investment for the maintenance is predicted to increase, specifically, from 3.8 trillion JPY to 6.2 trillion JPY.

(2) The investment for the renewal is predicted to increase, specifically, from 0.3 trillion JPY to 3.7 trillion JPY.

(3) The investment for the newly-built is predicted to decrease, specifically, from 15.9 trillion JPY to 9 trillion JPY.

(4) The stock of the infrastructure will be vastly accumulated.

2 LIFETIME OF BRIDGES

2.1 Definition of Lifetime

It is quite confusing to know that the definition of the lifetime varies considerably from places to places. In this paper, the “lifetime” may be defined as the period of time since structures have started to be in service until they cease to be used for some reasons or the final stage when they are possibly in service any further (JSSC 1991).

2.2 Definition of Expected Lifetime

The expected lifetime may be defined as the period of time in which structures are expected to satisfy the demand performance, to possess the physical load-carrying capacity and to fulfill the serviceability.

2.3 Function and Performance

Performance refers to the structural capacity based on the field inspection data and the structural health assessment taking into account the deterioration of infrastructure. On the other hand, the function implies updated capacities meeting the current standard of the wheel loadings, natural forces such as wind and earthquake excitations, river flow, design traffic flow and so forth.

It is a general practice to decide the maintenance plan based on the field inspection data and the structural health assessment of bridges taking into account their deterioration rate. However, the old bridges built in the past were based on different old codes from now with respect to loads, earthquake-resistant design and river conditions and so forth, thus their function does not correspond to the present design codes. Thus, the judgment on the bridge replacement on the basis of the bridge health assessment alone may lead to wrong decisions. From this standpoint, the final decision requires the functionality in addition to the health assessment as explained in the following. In this paper, the countermeasure such as earthquake-resistance retrofitting is not considered for convenience. However, base-isolation will be regarded as a method to improve the performance in this paper.

2.4 Classification and Concepts of Lifetime

Lifetime may be classified into physical, functional and economic lifetimes (Kato 1983) as shown in Figure 1 and Table 1.

(1) Physical lifetime

It refers to the lifetime of an existing bridge which may have to be renewed by a new bridge upon significant reduction of the load-carrying capacity or by the troubles encountered during the service but deemed difficult to meet these demands by just reforming the present bridge. As shown in Figure 1 (a), it represents the period from the initial state of a bridge to the time when its performance decreases and coincides with the performance corresponding to the serviceability limit. It frequently happens to restore the performance by intermediate repair, retrofitting or replacement works.

(2) Functional lifetime

It refers to the lifetime of an existing bridge which may have to be renewed by a new bridge when the widening of roadway width or the up-grading of the traffic loads are legally demanded but deemed difficult to meet these demands by only reforming the present bridge. As shown in Figure 1 (b), it represents the period from the initial state of a bridge to the time when its demand performance is changed beyond the present performance.

(3) Economic lifetime

It refers to the lifetime of an existing bridge which may have to be renewed by a new bridge when the up-grading the existing bridge is judged much more expensive than building a new bridge. In Figure 1 (c), it represents the period from the initial state of a bridge to the time when its cost for the repair and retrofitting become greater than that for the replacement.

Table 2 shows several examples of physical, functional and economic lifetimes.

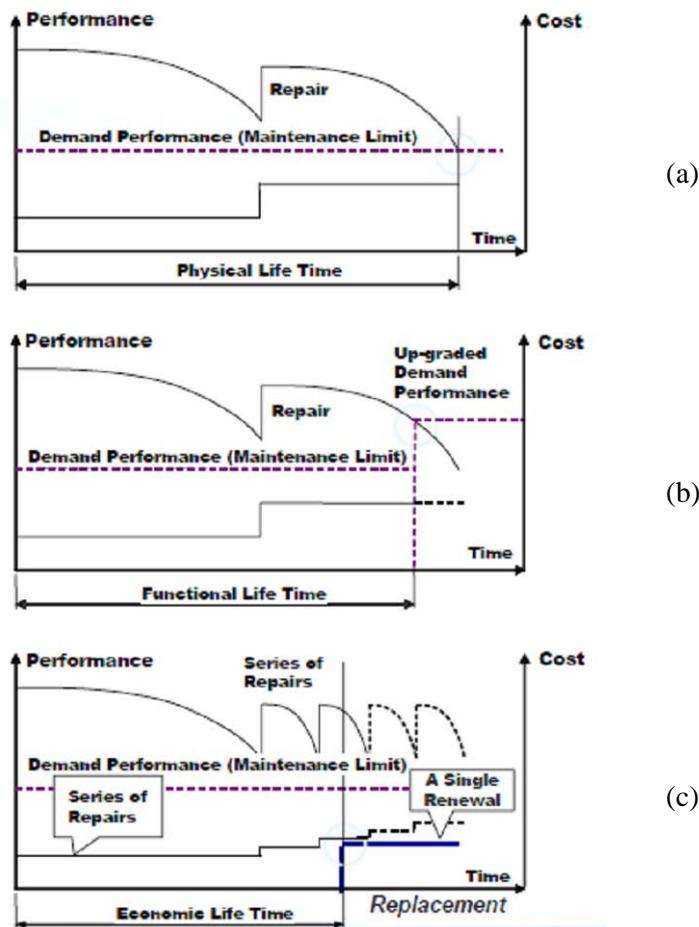


Figure 1. Chronological change of lifetime

2.5 Chronological Change of Reasons for Replacement of Bridges

Figure 2 shows the chronological change of reasons for bridge replacement in Japan (PWRI 1997, BMSG 2004). Figure 2 (a) describes the reasons for bridge replacement during the period of 1977-1986. These reasons may be listed in the order of larger percentage:

- (1) Improvement of road alignment
- (2) Improve the functional obsolescence
- (3) Structural defects such as corrosion
- (4) Insufficient load-carrying capacity

(5) Insufficient earthquake-resistance

Table 1. Comparison of Lifetimes.

Classification of Lifetime	Characteristics	Judgment of Lifetime	Application		Judgment of Economy/Comparison of Cost
			Whole Bridge System	Structural Elements: (Girders, Slabs, etc)	
Physical Lifetime	Limit of Usefulness	Inspection, Structural Health Assessment	No	Yes	No
Functional Lifetime	Difficult to define the index appropriately and point out when	When budget is insufficient, the lifetime will become longer	Yes	No	No
Economic Lifetime	Replacement is deemed cheaper	Comparison of cost and decision-making	Yes	Yes	Yes

Table 2. Examples of physical, functional and economic lifetimes.

	Whole Bridge System	Structural Components (main girders, deck plate, etc)
Physical Lifetime	Traffic suspension, left or scrapped due to insufficiency to carry external load. Lifetime is the same as that of components excluding replaceable ones	Only partial repair is judged to insufficient to meet the bearing capacity and only the replacement is the solution
Functional Lifetime	Narrow road width, road alignment is not good, refitting river flow is planned or aesthetically poor	Road width, road alignment depend on that of the whole bridge system. Partial aesthetic retrofitting may be possible
Economic Lifetime	Replacement is judged better than continual repairs	Replacement is judged better than continual repairs

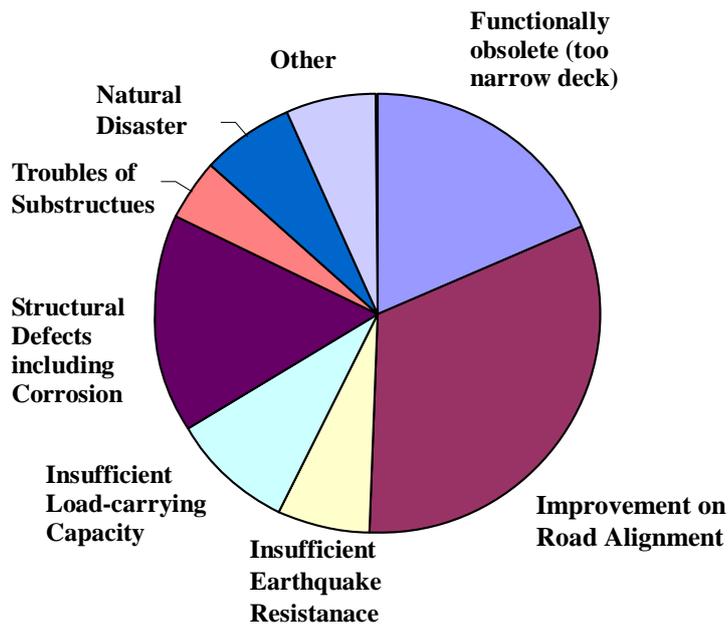
After 10 years, some of the reasons for replacement of bridges have changed as shown in Figure 2. For example, the replacement due to damage corresponds to only 1/5 of the total replacements. Most of the replacements are due to the improvement of road alignment, refit of river flow and widening of road width. The percentage of the improvement of the functionality changed from 57% to 76%.

2.6 Definition of Technology toward Longevity

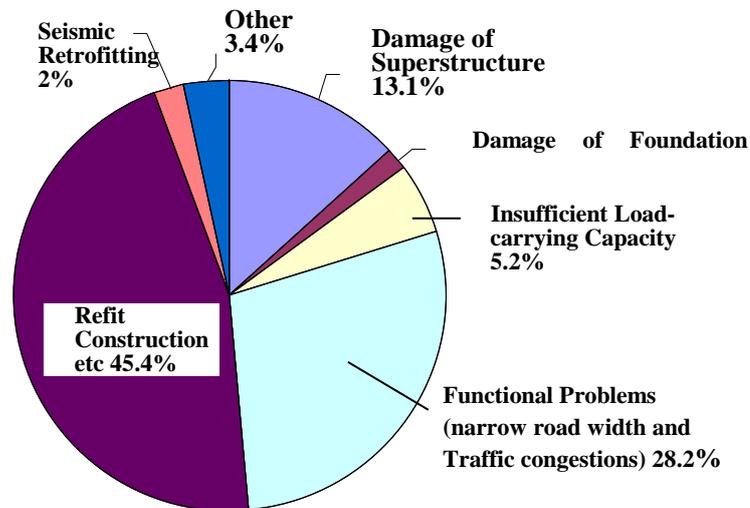
The longevity technology refers to the technology and all methods of management including those for inspection, system, timing, judgment, measure and budget to prolong the lifetime beyond the expected lifetime.

The keywords for the longevity may be summarized as:

- (1) Increase of bridge stocks
- (2) In view of the limitation for budgetary appropriation, the scenario of “renewal of every bridge does not exist any more.
- (3) The national and local governmental principle for the preventive management is supported by the authorized experts.
- (4) The concept of longevity for those newly-built and already existing are different.
- (5) The performance-based specification is encouraged for the longevity by adopting innovative and development technologies.



(a) Reasons of Replacing Road Bridges (1977-1986) (PWRI 1997)



(b) Reasons of Replacing Road Bridges (1996) (BMSG 2004)

Figure 2. Chronological change of lifetime of Japanese roadway bridges

Figure 3 shows the ratio of the bridges with the lifetime over the age of 50 to those under 50 (MLIT 2008). It may be apparent that after the year of 2030, the ratio of bridges over the age of 50 becomes more significant.

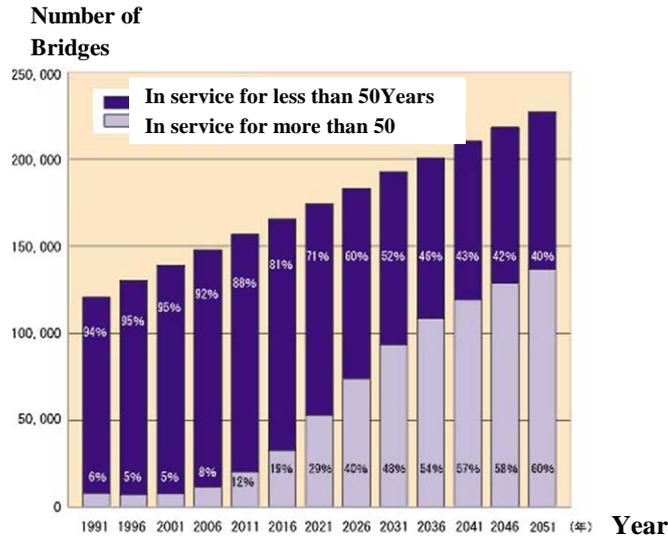


Figure 3. Chronological change of ratio of the bridges with the age over 50 to those under 50.

2.7 Target Lifetime

The target lifetime is not defined by the structures but by the manager.

- (1) It is the matter of consciousness of the managers and the public opinion.
- (2) The limit performance for management varies depending on the demand performance of the time.
- (3) Theoretically, steel structures are considered to be ever-lasting structures.
- (4) The target lifetime may be considered to be 1.5 time of the lifetime of existing structures as shown in Figure 4 (Abe 2008).
- (5) Even at the end of the target lifetime, the structures may not have to be renewed if they possess the sufficient structural health.

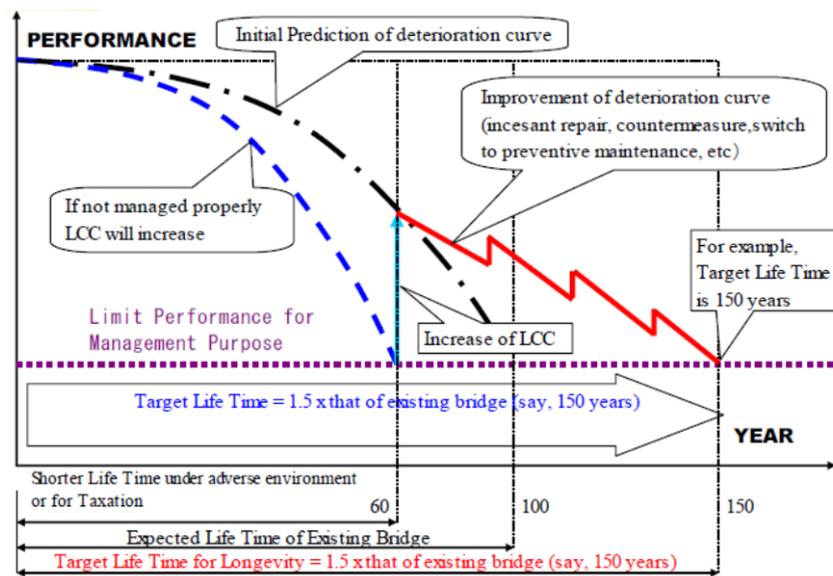


Figure 4. Performance and lifetime of bridges (Abe 2008).

2.8 Management for Longevity

The lifetime can be made longer or shorter than the initially expected one depending on the management method.

2.9 Setting of Basic Parameters for Determination of Lifetime for Steel Bridges

The National Institute for Land and Infrastructure Management, NILIM, showed the statistics of the number of replaced bridge plotted against the year of replacement.

The statistical distribution is assumed to follow the Normal distribution and the parameters are so determined as to minimize the errors between the achieved record and the prediction. Table 3 shows the average lifetime and standard deviation of bridges built from 1920 to 2000 (NILIM 2004).

For those bridges built during the period of so-called “rapid economic progress” from the year 1961 to 1980 the statistics show that the average lifetime is 70 years with the standard deviation of 20 years. Thus, if the normal distribution is assumed and 95% fractile of non-exceedance is assumed, this fractile corresponds to 1.65σ , the longevity of prolonged lifetime of 35 more years can be expected ($20 \times 1.65 = 35$) as shown in Figure 5. While those bridges built in recent years from 1981 to 2000, the average lifetime is 100 years with the standard deviation of 30 years. By the similar token, the longevity of 50 more years may be expected ($30 \times 1.65 = 50$).

If different fractile other than 95% is assumed, the expected average lifetime for steel bridges may be as listed in Table 4. Thus, for recent bridges built after 1980, the expected lifetime may be regarded to be 150 years.

Table 3. Chronological characteristics of replacement of steel bridges (NILIM 2004).

Completed Year	Average Lifetime in Years	Standard Deviation in Years	Remarks
1920-1930	50	10	
1931-1940	40	10	
1941-1950	30	10	2 nd World War
1951-1960	60	20	
1961-1970	70	20	
1971-1980	70	20	
1981-1990	100	30	Scarce data
1991-2000	100	30	Scarce data

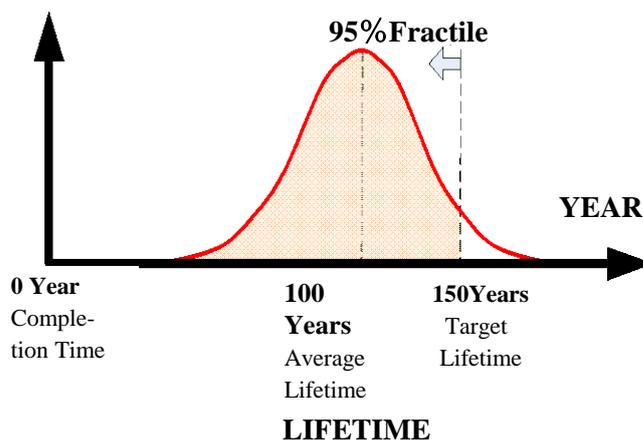


Figure 5. Target lifetime for bridges.

Table 4. Expected average lifetime of bridges for different probabilities of non-exceedance.

Era	Average Life Time	Expected average lifetime of bridges for Probabilities of non-exceedance		
		90%	95%	99%

From 1960's to 1970's	70	96 Yeas	103 Years	117 Years
From 1980's	100	139 Years	150 Years	170 Years

3 PRESENT STATUS OF TECHNOLOGIES FOR LONGEVITY OF BRIDGES

3.1 Change of Social Demand

The philosophy of essential maintenance, namely, "rebuilding bridges when they become older than the lifetime" in the past is nowadays shifting to the philosophy of preventive maintenance and building durable bridges to prolong their service life.

3.2 Type of Damages for Steel Bridges

Most damages are caused by the defective structural characteristics and environmental effects. The most popular damages of steel bridges are considered to be fatigue and corrosion.

3.3 System for Longevity Technology

Figure 6. shows the vision of longevity technology and expected developments of technologies for each step of construction projects.

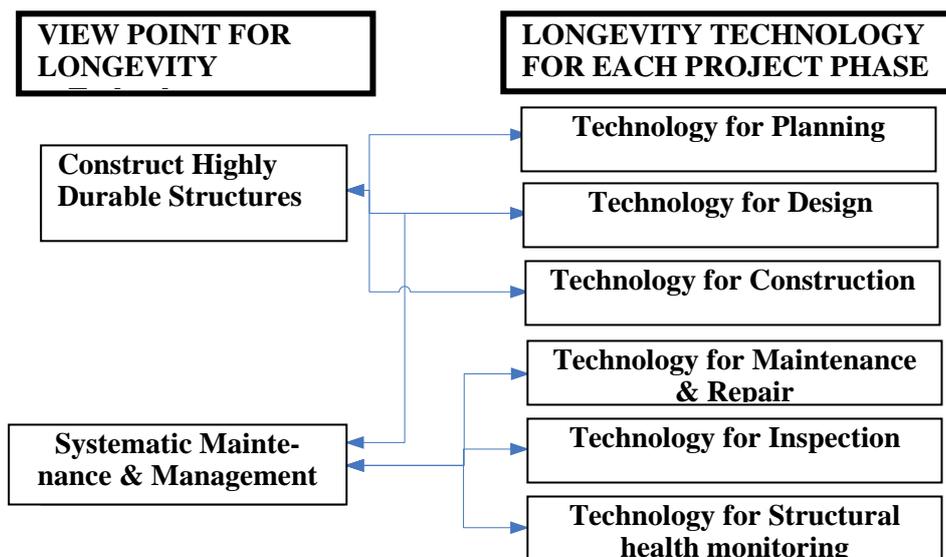


Figure 6. Vision of longevity technology and expected developments of technologies for each step of construction projects.

3.4 Cause of Damages for Bridge Parts and Structural Members

Figure 7 shows the causes of damage of bridge parts and elements of steel bridges. Described here are the locations of damaged steel parts or members, causes of damage and the type of damages. It will be seen that the fatigue and corrosion are the most popular damages for steel bridges.

3.5 Anti-fatigue Technologies

For road bridges, the fatigue design has been introduced in Japan only quite recently. The countermeasure consist of reduction of stress concentration, reduction of residual stresses. Not only in the maintenance but also they should be taken into account at the planning and design steps. Recently, the following two countermeasures are to be noted.

- (1) anti-fatigue steel The steel itself has a desirable characteristics of fatigue-resistance through the adjustment of chemical ingredients and metal texture.

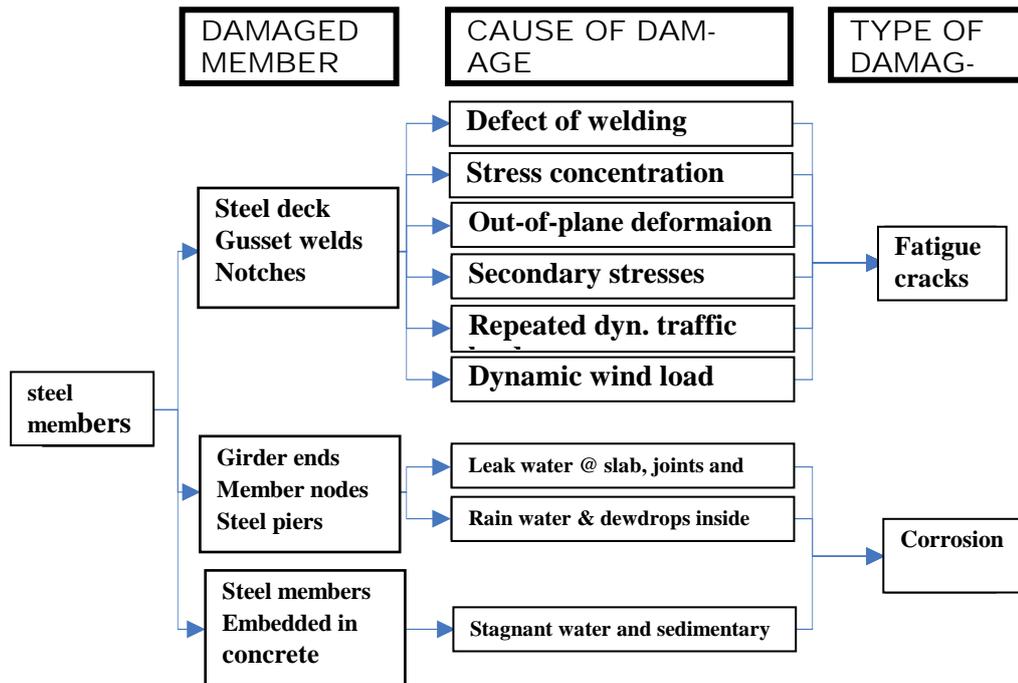


Figure 7. Causes of damage of bridge parts and elements.

- (2) UTI, Ultrasonic Impact Treatment Impact of ultrasonic wave is applied to the weld in order to have the following effects:
 - (a) Tensile residual stresses can be converted to compressive.
 - (b) Reduce the stress concentration by smoothing out the surface of weld.
 - (c) Increase the surface toughness.

3.6 Anti-corrosion Technologies

As has been described above, the corrosion is regarded as one of the most serious problems for steel structures. Not only to those in the area near the sea zone susceptible to salt water but to those cold area where anti-freeze is used inevitably, bridges tend to be corroded much faster than in the other locations. Furthermore, attention must be paid to some specific locations of bridge parts of elements where water tends to be stagnant and pooled or the humidity is easily kept high. Sometimes dewdrops become also harmful unless they dry out. Figure 8 shows an example of dehumidifier used to keep inside a girder dry (Kaneko 1999). Figure 9 also shows an example of dehumidifier used for main cables of a suspension bridge (Kitagawa 2001).

- (1) Improvement of corrosive environment

- (a) This is to dry up inside girder by removing humidity to prevent dewdrops using either dehumidifiers or ventilators.
 - (b) Clean-up technologies: This is to remove the dirt and salt from the surface
- (2) Cathodic protection methods

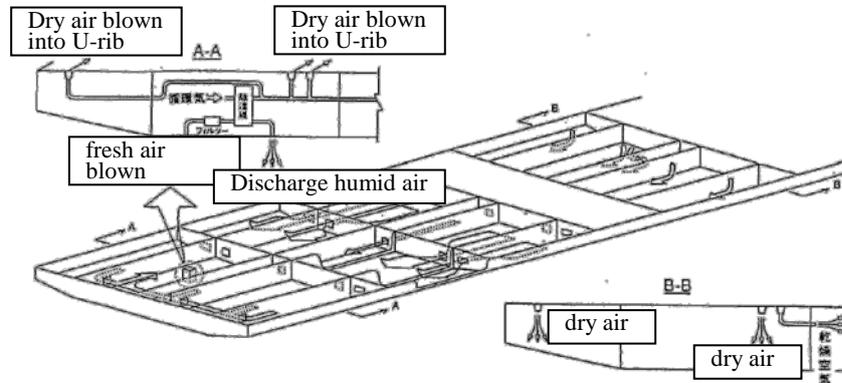


Figure 8. Dry air dehumidifier inside a bridge deck.

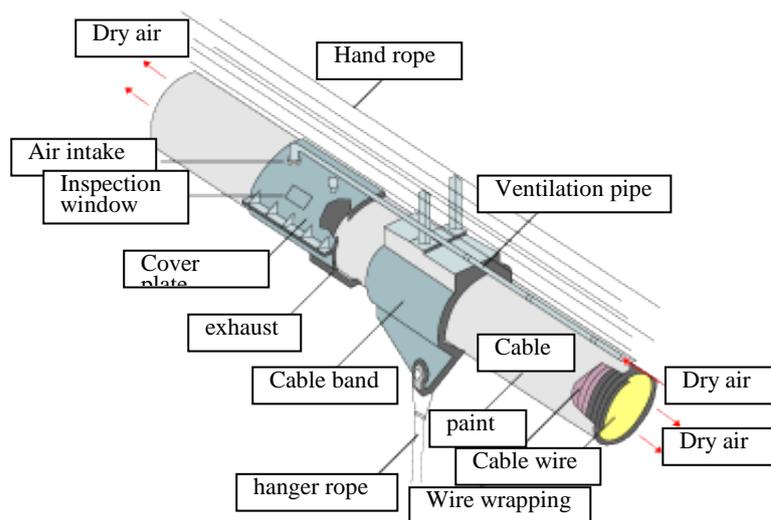


Figure 9. Dry air infusion system for cables.

Because of the severe corrosive environment, corrosion protection should be made, especially for the parts just below the M.L.W.L. when severe local corrosion occurs. For such parts, cathodic protection is generally applied.

- (a) Cathodic protection without external electric power
 - (b) Cathodic protection with external electric power
 - (c) Cathodic protection in the air
- (3) Other anti-corrosion methods
- The other coating methods include (a) painting, (b) organic lining, (c) petrolatum lining and (d) inorganic lining. The inorganic linings include metal linings such as titanium-clad lining (JTS 2000, Nippon Steel 2000), stainless steel lining, thermal spraying using zinc, aluminum and aluminum al-

loys (JAPH 1999). Figure 10 shows an example of cathodic protection without external power source (Ishida 2006).

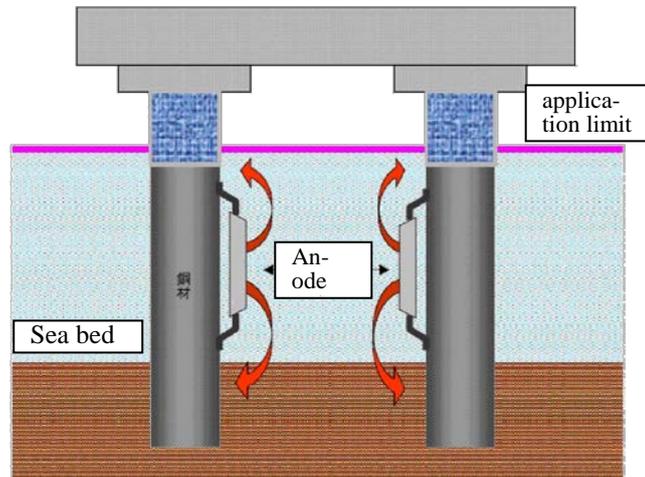


Figure 10. Cathodic protection (without external source power).

3.7 Other Technologies

(1) Technologies for planning and design stages

The assessment is required taking into account LCC considering the construction site and selection of structural type.

(2) Inspection technology

- (a) Anti-fatigue inspection: In the past, the crack inspection was first done by flesh eyes. After confirmation of problems such as peeling-off of painting some detection tests were carried out. However, this method has many shortcomings such as cost, labor, and impossible when eye observation is impossible. → A wireless detection technology may be applied by placing IC tags at the place where cracks are expected to initiate.
- (b) Anti-corrosion inspection: It may be very useful to find out corrosion at the place where eye observation is impossible such as reinforcements in concrete.

4 EXPECTED TECHNOLOGIES FOR LONGEVITY

4.1 Current Attitude of Road Owners

Depending on the demand performance, road owners are interested in the following structural maintenance matters:

- 1) Essential maintenance to repair a great damage.
- 2) Preventive maintenance to repair a light damage
- 3) Up-grading of wheel loads and earthquake retrofitting
- 4) Daily maintenance such as cleaning up road surface, drainage pipes.

4.2 Expected Longevity Technology

Three companies sent their comments: Companies A, B, C and D regarding the present situation and the future issues..

Table 5. Company A

	Present situation	Future issues
Purpose	Lack of engineers/increasing maintenance cost	Education of specialist/ outsourcing/ disclosure of information/ accountability
Inspection	Close inspection once every 5 years/ repeated damage increasing/ Gap between Inspection & repair	Priority in inspection/ remote controlled inspection/ simultaneous check of repeated damage and inspection desirable.
Structural health	Bridge part or whole bridge system? Not well established. Riding comfort more emphasized.	Assessment considering cause of deterioration and structural importance/ demand performance of structures
Maintenance plan	Gap between management level & actual damage level. Prediction of deterioration still not established yet.	Development of reliable investigation and assessment methods/ optimum combination of essential and preventive maintenances
Information management	Gap between prediction and reality. Volume of data too much.	Promotion of data synthesis and its sharing together/ realization of prompt input data at the site and construction of database

Table 6. Company B

	Present situation	Future issues
Purpose	Significant increase of damages/ construction of logic model/ CS (Customer Satisfaction) survey & verification	Maintenance of appropriate management level/ Establish management cycle and accountability
Inspection	Daily & scheduled inspection (frequency depends on routes)/ Check done every year based on logic model	Priority in inspection/ remote controlled inspection/ development of structural health monitoring technology/ re-evaluation of repair/ light repair work during inspection
Structural health	Structural health assessment for each part or component/ instance of damage input into DB	Assessment of structural health of a whole bridge system/ Demand performance of structure
Maintenance plan	Management outcome index is set/ Repair plan is made based on present damage map	Speedy detection of deteriorations by grouping/ development of technology to find the minimum LCC
Information management	Database and AMS already constructed and they are used as maintenance information / It is being applied to support short-term repair plan	History record of repair used for the next inspection/ It is now used as a supporting tool for long-term maintenance plan

Table 7. Company C

	Present situation	Future issues
Purpose	Purpose of maintenance is for the long-term structural health/ Preventive maintenance is for determination of appropriate management level.	200-year lifetime is expected/ heritage of technology and its sophistication
Inspection	Patrol, basics, precise inspection for long-span bridges/ Need for check of paint thickness for the re-painting plan	Grade-up of remote sensing and structural health monitoring/ continue to obtain information on fatigue study for steel bridges
Structural health	Structural health assessment for each part or component/ instance of damage input into DB	Assessment of structural health of a whole bridge system/ Demand performance of structure
Maintenance plan	Annual diagnosis and assessment of	Road users' needs reflected to demand

	structural health on structural components/ quantitative structural health conducted	performance/ determination of management level for each facility (priority rule)
Information management	Database reflecting inspection results/ establish management method for strait-crossing long-span bridges	Effective use of DB/ development of management system for land-based road bridges

Table 8. Company D

	Present situation	Future issues
Purpose	Preservation of safety, serviceability & restorability/ unfortunately, currently only essential maintenance	Education of technology to young engineers/ accountability
Inspection	Regular inspection: once in every two years/ detailed inspection: once in every 10 to 15 years/frequency of inspection differs on type of structures	Education of structural health examination tests to engineers/ structural health monitoring technology/ establishment of important view point and prediction technology of deterioration
Structural health	Assessment on facilities is done depending on management rule/ assessment is based on present degree of deterioration + future deterioration	Objective index is desirably used for judgment of priority/ good balance between the demand performance and the economy
Maintenance plan	Correlation between management level and cost unknown/ maintenance management plan for about 5 years term is used	Feedback is necessary after projects are completed/ establishment of PDCA cycle/ These will make it possible to establish preventive management
Information management	Database of inspection data and maintenance management information has been constructed/ But BMS has not been introduced yet	Effective use of DB and its appropriate renewal necessary to construct BMS

4.3 Several problems to be solved

There are many problems remain yet to be solved. These may be summarized below:

- (1) Difference of management level (demand performance):
Not only the natural environment but also socio-economic environment are to be considered for the determination of lifetime and maintenance management.
- (2) Limitation of budget (evaluation of LCC):
Balancing of cost for maintenance management by essential management and that by preventive maintenance must be established.
- (3) Effective use of data (data sharing):
This is effective when combined with management system and good for accountability.
- (4) Succession of technology:
The education of young engineers and out sourcing are important.
- (5) Effective inspection method (frequency and methodology):
Priority in inspection, remote inspection and structural health monitoring technology are expected to be established.

5 NEEDS FOR STRUCTURAL HEALTH MONITORING AND REQUIRED PERFORMANCE

5.1 Background for Survey by Sending out Questionnaires to Owners of Structures

Attempts were made to communicate with several owners of bridges to find the needs of structural health monitoring by sending questionnaires to them.

(1) Purpose for Surveying

Questionnaires are decided to be sent to know:

- a. What is the needs for structural health monitoring and demand performance?
- b. What is the latest sensors?
- c. What is the latest assessment technology?
- d. What is the applicability of structural health monitoring?

(2) Content of questionnaires and targets

Companies and organizations expected to respond to questionnaire are as follows:

- a. Local governments (4)
- b. Road owners (2 companies)
- c. Railroad companies (4 companies)
- d. Electric power and gas companies (2 companies)

Q1: Questionnaire 1

Question 1 Are there any problems in daily and periodical inspections on the stand point of longevity of bridges or steel structures?

Question 2 Can these problems be solved by structural health monitoring?

Question 3 What kind of structural health monitoring is expected?

Q2: Questionnaire 2

Question 1 What is expected to be detected, for example, cracks and corrosion?

Question 2 What are the objects for measurement?

Question 3 What kind of sensors are used?

6 SURVEY OF STRUCTURAL HEALTH MONITORING TECHNOLOGIES AT THE PRESENT TIME

6.1 Summary of Investigation

An extensive literature survey were conducted to know the technologies available at the present time and future applications.

6.1.1 Purpose and Method of Investigation

The purpose of investigation is as follows:

- (1) to understand the present state of development of structural health monitoring technology
- (2) to construct DB for references on structural health monitoring
- (3) to extract possibilities and problems of application of structural health monitoring toward longevity of steel structures

The methodology of investigation is as follows:

- (1) to collect the information of related books, reports including committee reports, and seminars that are published in Japan

- (2) to collect references on typical international conferences on the structural health monitoring
- (3) to understand the present trend of technologies for structural health monitoring and evaluation of performance
- (4) to classify the existing technologies by summarizing the target of application and methodology in the form of matrix
- (5) to summarize the prospect of application of structural health monitoring technologies after reviewing references

6.1.2 Target references of investigation

The references reviewed are shown in Table 9

Table 9. List of references surveyed

	classification	name	authors/publication	year	
domestic	books	Health structural health monitoring	S.Yamamoto et al	1999	
		Maintenance engineering of infrastructure	JSCE committee on maintenance engineering	2004	
	Symposium and seminars	Report "basic study on advanced structural health monitoring on ships"	JSNA (Japan Ship Technology Research Association)	1998	
		Present status and prospect for maintenance of railroads	Railway Technical Research Institute seminar	2007	
		Workshop on health diagnosis for buildings	Committee of structures, AIJ (Architectural Institute of Japan)	2005	
		Prospect of structural health monitoring of performance implemented by ubiquitous technology	Committee of Information system, AIJ	2007	
		Journal of steel structures and bridges, JSCE	Committee of steel structures, JSCE	2008	
		Seminar on "New inspection and structural health monitoring technologies for steel structures"	Committee of steel structures, JSCE	2007	
		Guideline for structural health monitoring of bridge vibrations	Committee of structural engineering, JSCE	2000	
	Structural health monitoring technologies for concrete structures	Committee of concrete, JSCE	2007		
	Assessment of residual performance and recovery technologies for corroded steel structures	Committee of steel structures, JSCE	2007		
	Periodicals	Structural health monitoring Series	Journal of The Society of Naval Architects of Japan (SNAJ)	1992	
		Special issue "technologies supporting life lines and others"	Journal of JSNDI (The Japanese Society for Non-destructive Inspection)	2006	
	Oversea	Journal	Structural Control; Past, present, and future	Engineering Mechanics, ASCE	1997
			New sensors, Instrumentation and Signal Interpretation	Infrastructure Systems, ASCE	2008
Conference Proceeding		Structural Control and Structural health monitoring	IASCM	2006	
		Structural health monitoring and Intelligent Infrastructure	ISHMII	2007	
		Application of Statistics and Probability in Civil Engineering	ICASP	2007	
		Smart Structures and Materials	SPIE	2006	

6.2 Reference Survey

6.2.1 Summary of references

Totally 136 references were reviewed and summarized by Tables 10 and 11. Although a great number of figures and tables were contained. They are not shown in this paper because of the restriction of page numbers.

Table 10. Content of summary

Study items	Examples of study
Target structures	Long-span bridges, viaducts, high-rise buildings, timber buildings, tunnels, dams, pipelines etc.
Sensors	Optical fibers, piezoelectric materials, AE sensors, accelerometer, wireless measurements, corrosion sensors, etc.
Technologies	System identifications, wave treatments, pattern recognitions, field tests, assessment by NDT, etc
Possibility of implementation	System developments, performance test levels, proof test levels, implementation levels

Table 11. Number of summarized articles.

	Technical papers	State-of-the-arts and commentary	Total
Domestic	50	5	55
Oversea	86	0	86
Total	136	5	141

6.2.2 Representation of matrix

The result of the survey on sensing technologies and assessment methods is tabulated by Tables 12 and 13. The results may be the most conveniently represented by a matrix method as shown in Figures 11 and 12.

Table 12. Sensing technologies and assessment methods.

Classification	Target items	Alternatives
Sensing	Physical quantities for measurement	Deflections, strains, reactions, stresses, accelerations, surface conditions, film thickness, cracks
	Target damages	Corrosion, film deterioration, local deformation, stresses, fatigue, divergent oscillations, material deteriorations
	Target levels	Member level, whole bridge system level
	Target performances	Serviceability, safety, durability
Methods of assessment	Input data	Accelerations, velocities, displacements, strains, external loads, elastic waves, supersonic waves, acoustics
	Output (targets)	(Whole system) Characteristic frequencies, vibration modes, damping coefficients, (Local parts) stiffness, damping factors (Other) damage pattern, time of damage occurrence

Applied structures	Framed structures, buildings, long-span bridges, rail-road tracks
Number of necessary sensors	

Table 13. Matrix Representation of Sensing Technologies

Measured physical quantities	Target of assessment	Sensing methods	Details	Assessment level	Target performance
Displacement	Local deformation	Displacement transducers		Whole system level	Serviceability
		Peak displacement memory sensor		Member level	Safety
	Vibration	Digital camera		Member level	Safety & serviceability
		Laser doppler vibrator		Whole system level	Safety & durability
Strains	Local deformation	Optical fiber	FBG	Member level	Safety & serviceability
			BOTDR	Member level	safety
			OTDR	Member level	Safety & serviceability
			SOFO	Member level	Serviceability
		Peak strain memory sensor		Member level	Durability & safety
		Magnetic strain sensor		Member level	Safety
	Fatigue	Piezoelectric material	Piezoelectric film	Member level	Serviceability
Stresses	Local deformation	EM sensor		Member level	Safety
	Local stress	Slot stress		Whole system level	Safety & durability
Accelerations	Local deformation	Optical fibers	BOCDA	Member level	Safety
		Piezoelectric material	Piezoelectric elements	Member level	Safety & serviceability
		Acceleration sensor		Member level	Durability
			MICA Mote	Whole system level	Serviceability
	Vibration	Optical fibers	FBG	Member level	Safety
	Decrement of rigidity	Piezoelectric material	Piezoelectric elements	Member level	Safety & serviceability
		Oscillation Gyro sensor		Member level	Safety & serviceability
		AE sensors	Smart AE sensors	Whole system level	Safety & durability
Surface state	Corrosion	Piezoelectric material	Macro-fiber composite	Member level	Safety & durability
		Impedance measurement chips		Member level	Safety & durability
		Corrosion environment sensors		Member level	Serviceability & durability
		Corrosion sensors		Whole system level	Safety & serviceability
	Deterioration of paint film	Digital camera		Member level	Safety

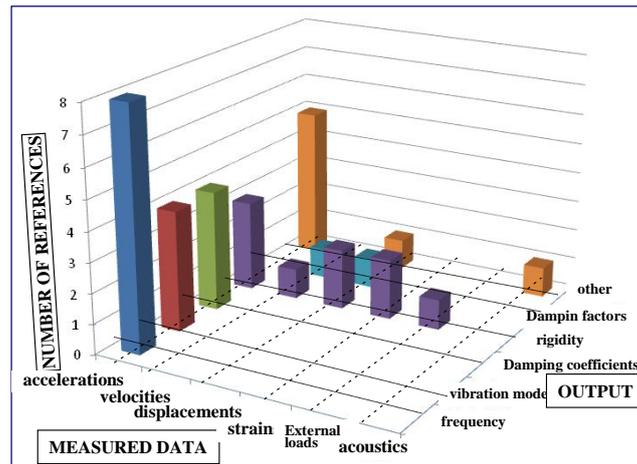


Figure 11. Number of references with respect to measured physical quantities and output.

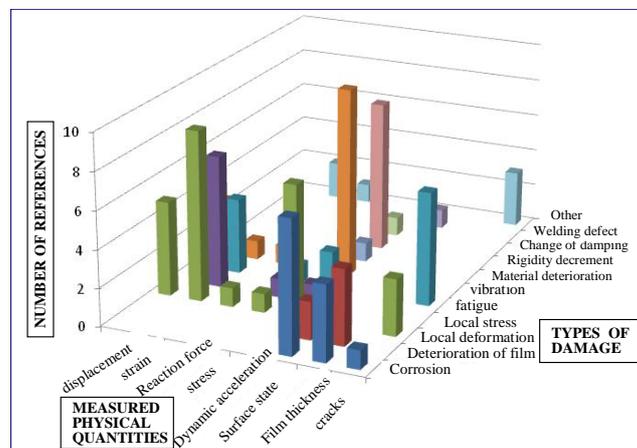


Figure 12. Number of references in the matrix form with respect to measured physical quantities and types of damage.

6.2.3 Sensing technology

The following observations may be made:

(1) Status of developments of sensing technologies

a. Majority of measured physical quantities are strains and accelerations. However, the number of instances of stresses, reaction forces, ph and temperature is quite few.

b. Local deformations and vibrations constitute the majority of the diagnosed damages. The number of instances of direct measurements is quite few for material deterioration and decrement of rigidity target damage.

6.2.5 Examples of advanced technology

Examples of advanced application to measuring diverse physical quantities are cited. Only development of measuring methods other than for strain and acceleration measurements and for real structures

(1) Application of optical fibers to pH and AE measurements to reinforced concrete structures (EBG method) (Habel 2007) See Figure 13.

(2) Stress measurement of prestress tendons by detachable sensors for measuring electro-magnetic permeability (Sumitro 2007). See Figure 14.

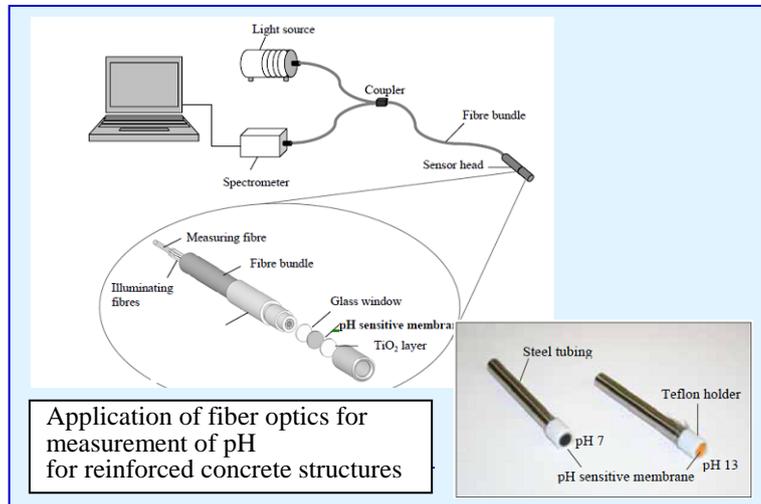


Figure 13. Application of optical fibers to pH and AE measurements to reinforced concrete structures (EBG method) (Habel 2007)

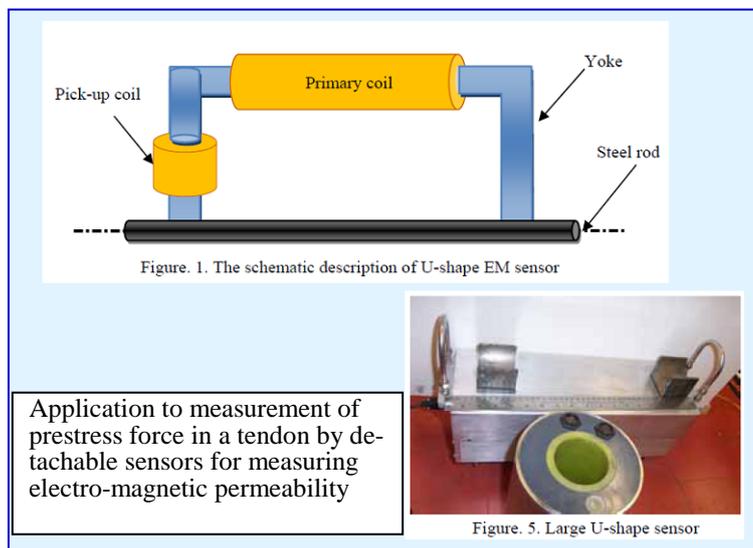


Figure 14. Stress measurement of prestress force in a tendon by detachable sensors for measuring electro-magnetic permeability (Sumitro 2007).

7 CONCLUDING REMARKS

This paper is an English version of JSSC report on the Longevity and Structural health monitoring Technologies of Bridges but limited to only some selected parts of the whole study. The main body of the paper is the summary of the state-of-the-art of the present technologies and the results of discussions among committee members of Longevity and Structural health monitoring Technologies of Bridges of JSSC. It is the authors' great joy if this could serve as a reference of the technologies of longevity and structural health monitoring for steel bridges.

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9 REFERENCES

- Abe, M. 2008. Activity of bridge maintenance toward the age of longevity of bridges. *Report of Seminar. EXTEC*, 84, 61-62 (in Japanese).
- BMSG. 2004. *Guide to management for road bridges*. Bridge Management Study Group, Japan Bridge Engineering Center, JBEC (in Japanese).
- Habel, W.R. et.al. 2007. Fiber Optic Sensors For Long-Term SHM in Civil Engineering Applications, Proc International Conference on Structural Health Monitoring of Intelligent Infrastructure.
- Ishida, Sato, Fujikawa, Sekiguchi and Hashimoto. 2006. Concept of corrosion protection of steel for D-runway –For reduction of LCC-. 2nd Seminar on report of construction of D-runway of Tokyo International Airport (Haneda). 8.1-8.8 (in Japanese).
- JAPH, 1999. *Technological Standard and Commentary of Port and Harbor Facilities*, Japanese Association of Port and Harbor, 1 & 2, (in Japanese).
- JSSC 1991. Study on lifetime of steel structures. *Report of Task Committee on Lifetime of Steel Structures*, 29-30 (in Japanese).
- JTS. Titanium World -In pursuit of its unlimited potentialities and realization of dreams-, 2000. The Japan Titanium Society, <http://www.titan-japan.com>, 7, (in Japanese).
- Kaneko, Mizoue and Naito.1999. Corrosion protection inside a box girder by dry air intake – New Onomichi Bridge-, *Bridge and Foundation*, 33(5), 31-34 (in Japanese).
- Kato, M.1983. Recent topics in maintenance. *Journal of JSCE*. 68(11): 2-5 (in Japanese).
- Kitagawa, Furuya, Nakamura and Suzumura. 2001. Study on corrosion protection performance by dry air intake system for main cables for suspension bridge cables. Proc. JSCE 672(VI50), 145-154 (in Japanese).
- MLIT 2002. White paper of the Government of Japan. MLIT, Ministry of Land, Infrastructure and Transport and Tourism (<http://www.mlit.go.jp/hakusyo/mlit/h14/H14/index.html>) (in Japanese)
- MLIT 2008. Suggestions for preventive maintenance of roadway bridges. *Report of Meeting by experts toward Preventive Maintenance of Roadway Bridges*, MLIT, Ministry of Land, Infrastructure and Transport and Tourism (in Japanese).
- NILIM 2004. Study on estimation of the lifetime of road bridges, *National Institute for Land and Infrastructure Management, NILIM Report*, 223 (in Japanese).
- Nippon Steel 2000. Titanium Clad, Cat. No. TC026, (in Japanese).
- PWRI Bridge Laboratory. 1997. Study on replacement of bridges (III), *PWRI Report 3512* (in Japanese).
- Sumitro, S. et.al.2007. Removable Actual-Stress Sensor, Proc International Conference on Structural Health Monitoring of Intelligent Infrastructure.