TECHNICAL DEVELOPMENTS IN STRUCTURAL ENGINEERING WITH EMPHASIS ON STEEL BRIDGES IN JAPAN

Yozo FUJINO\(^1\) and Yutaka KAWAI\(^2\)

\(^1\)Fellow of JSCE, Distinguished Professor, Institute of Advanced Sciences, Yokohama National University
(240-8501 Yokohama, Kanagawa, Japan)
E-mail: fujino@ynu.ac.jp

\(^2\)Fellow of JSCE, Dept. of Civil Eng., Nihon University (1-2-1, Izumi-chou, Narasino, Chiba 275-8575, Japan)
E-mail: yutaka-kawai@mue.biglobe.ne.jp

Key historical events and technological developments in the field of structural engineering with emphasis on steel bridges for the past 50 years are reviewed in order to evaluate the present problems from four different perspectives, namely analysis, material, structural design, and measurement. The current state and future prospects are discussed to bring in a new future outlook on structural engineering field.

**Key Words:** civil steel structures, steel bridges, structural engineering, technological developments, review, prospect, structural material, analysis, sensing, monitoring

1. **INTRODUCTION**

Structural engineering has been an essential and important technology for infrastructures through every stage of their life cycle, such as planning, structural design, construction, maintenance, demolition, and removal stage.

There are some scales to measure the vigorousness of research and development activities in the structural engineering field. The number of technical papers published in the related scientific societies may be an effective index from the academic viewpoint. The transition in the number of papers published in the Journal of JSCE (Japan Society of Civil Engineers); the Journal of JSCE (Japan Society of Civil Engineers); Structural Engineering & Earthquake Engineering; Ser. I and Ser. A, and Journal of Structural Engineering (Vol. A) is shown in Fig.1 together with the total number of papers published in all the divisions of the Journal of the JSCE. The figure shows that the total number of papers rapidly increased from the 1980s and reached a peak at the start of this present decade. In the 1980’s, the number of papers related to structural engineering published in the Journal of JSCE was saturated at around 100. However, the total number of papers concerning structural engineering did not cease to grow; instead, some papers shifted to the Journal of Structural Engineering that was divided into specific departments in 1985. The total number of papers published in the two major journals increased to the maximum at the start of the 2000s and has gradually decreased since then.

Taking into consideration that the main subjects of the research and development of structural engineering are deeply related to construction practices, the need for R&D in the field of construction may lead to an increase in the number of papers. Recently, many infrastructure construction projects have been exposed to severe social criticism and their necessity and validity of execution were questioned. Thus, the promotion of civil infrastructures based on national consensus and scientific basis has been discussed\(^1\).

![Fig.1 Number of published papers related to structural engineering.](image-url)
The current status and future outlook of the related research and development in structural engineering should be reviewed again in this regard.

Several reviews of current status or future prospects of technologies for steel structures have been published in many specific technical publications. The authors have reviewed the 50-year history of technical development in Japanese steel bridges, as a representation of infrastructures, together with major social events in Japan and transition in structural engineering both in Japan and in rest of the world. In this paper the present issues of structural engineering are identified and the outlook into the future is discussed and elaborated by adding fresh topics to the authors’ previous paper.

2. HISTORY OF STRUCTURAL ENGINEERING IN STEEL BRIDGES

Structural engineering is an essential technology in every stage of the life cycle of infrastructures. It consists of the following four basic technologies:
- structural analysis technology,
- structural material technology,
- structural design technology including design criteria, and
- measurement technology.

In the present paper, the history of steel bridges in Japan is reviewed following these four kinds of basic technology.

The main steel bridge construction projects in Japan are shown in Table 1 and Table 2 together with the social events and the history of the abovementioned four basic technologies. In the following section, the history of structural engineering in Japan is reviewed and discussed at every decade.

(1) Developments before the 1950s

The first iron bridge in Japan was Kurogane Bridge, which was designed by Forgel, Dutchman, and manufactured in 1868 by Nagasaki Seitetsusho, the former name of Mitsubishi Heavy Industry. Almost all iron bridges in the Meiji period (1868-1912) were made of imported materials. Since the beginning of Taisho period (1912-1926), many steel railway bridges were constructed by using domestic steel. The commonly used method for connecting structural members was the riveted connection. After Mitsubishi Nagasaki Zosenkou first applied coated welding electrodes to the connection method for boiler parts in 1914, coated welding electrodes were produced by domestic firms around the beginning of World War II (1941). However, riveted joints were the most popular connection method for structural components and welded steel structures were adopted for only limited objectives, where the main required performance of steels was strength. There had been no unified standards of bridge design; the design specification for steel highway bridges was first drafted in 1939. At that time, highway bridges were classified into first-class bridges (national highway) and second-class bridges (prefectural road), and the design vehicle loads were specified as 13-tonf and 9-tonf, respectively. The provision, in which the loading magnitude ratio of the front wheel to the rear wheel is prescribed as 1:4, has been followed till the present specification. As the New Road Act was enforced in 1952, the competent administrative agency was shifted to the Ministry of Construction (currently Ministry of Land, Infrastructure, Transport and Tourism or MLIT). Furthermore, the design specifications for steel highway bridges were established in 1952, and the design vehicle load magnitude for the first-class bridges was raised up to 20-tonf.

Regarding the technical field of concrete bridges, the first standard specification for reinforced concrete was published by JSCE in 1931. After that, all standard specifications concerning the required quality and testing methods for structural concrete used in civil infrastructures have been established by JSCE. The standard specifications for reinforced concrete were revised in 1936 and 1940. Following the establishment of the standard specifications for concrete without reinforcement in 1943 and the standard specifications for concrete in 1949, the JSCE has periodically revised them until now. Their applications are used for not only bridges but also for other civil structures. This may be the reason for the difference in the technical history between concrete bridges and steel bridges, where the standard specifications for structural materials have been established as JIS (Japan Industrial Standard).

(2) Developments in the 1950s

In this decade, steel structures were highly developed and spread along with the rapid progress of steel manufacturing and assembling technologies.

In 1950, several kinds of domestically produced coated electrodes were developed and applied to various steel structural products and the coated electrodes for mild steels were standardized in JIS (JIS Z 3211).

Concerning the steel bridge engineering field, Honkyu Bridge (Hyogo) was constructed as the first all-welded steel girder bridge in 1952. After that, welding method had been the main joining technique for steel bridge fabrication. Incidentally, the first prestressed concrete bridge, Chosei Bridge (Ishikawa), was constructed in the same year. Builders were challenged to use new technologies in making
new types of bridges in this decade.

Since the production of high-grade steel structur-
als using imported materials and home production of
high-strength steel began in the 1950s, the use of
high-strength steel overseas increased. Under these
circumstances, Japan’s first high-strength steel
bridge that used a total weight of around 1,000 tons
of 490N/mm² class high-strength steel was con-
structed. This bridge utilized riveted joints in com-
bination with welded joints. Following that, the first
all-welded high-strength steel bridges in Japan,
lizuka Bridge (Tokyo) and Shin-Kita Bridge (Osaka),
were constructed in 1954. It was the start of the
general use of all-welded high-strength steel bridges.

The number of constructed steel bridges is not so
large as shown in Fig.2[10]; however, the growth of the
number of bridges rapidly increased in the latter half
of this decade.

In the field of structural design technology, several
important design specifications, such as Design
Specifications for Steel highway Bridges (1956),
Design Specification for Arc Welded Steel Railway
Bridges (1956), Specifications for Welded Highway
Bridges (1957), and Design and Construction Speci-
fications for Composite Highway Bridges (1959),
were published. Design specifications that were ap-
plicable to all-welded steel structures had been up-
dated regularly.

The JSCE published the Standard Specifications
for Concrete in 1949 as the technical standard for
concrete bridges. It was subsequently revised in 1951
and 1958, because the material technology of con-
crete improved rapidly at that time.

In the field of material technology, starting from
the adoption of 490N/mm² class high-strength steel
for naval vessels of the Defense Agency, domestic
productions of the coated electrodes for 490N/mm²
high-strength steel began. At that time, imports of
automatic welders, such as the submerge arc welders,
and argon gas shielded welding technology was in-
troduced in the USA. Such active technology de-
velopments in the field of welding engineering led
the JWES (Japan Welding Engineering Society) to
join the IIW (International Institute of Welding) in
1953, and started international research and devel-
opment activities with industrial circles.

On the measurement technology, domestically
produced portable ultrasonic flaw detectors for
welds inspection were marketed in 1952; however, at
this time the criterion for acceptable defect level was
not yet established, and more research was required
before flaw detectors could be used for a wide range
of welded steel structures. On the other hand, in 1954
industrial films for X-ray flaw detection were pro-
duced and placed on the market by a domestic film
maker. After that the inspection cost by X-ray flaw
detection decreased due to widespread use.

The testing method and its criterion for the tech-
nical certification of welders (JIS Z 3801; welding
performance qualification) were established in 1954
and after that, the skill certification examinations for
arc welding and gas shield welding were carried out.
These certification examinations contributed greatly
to the improvement of the quality and reliability of
welded structures. In 1955, a sectional meeting was
organized at the Japan Industrial Standard. The
JWES that was in charge of this meeting established
the Welding Engineering Standard (WES).

To meet the demand for higher-strength steels,
Japanese steel makers developed the 590N/mm² class
high-strength steel (2H steel), which was a Mn-Si
steel produced with direct quenching and tempering
process. After that, the ultra-high-strength steel
(CARILOY T-1 steel) was developed in the USA.
This completes the historical development of the
high-strength steel available in the market today.

The decade is distinguished by the start of the
shipbuilding boom that caused mass consumption
of electrodes. It was followed by the increasing trend
in large-size ships as a result of the nationalization of
the Suez Canal (the so-called first ships export boom;
1955-1957). According to the statistics of Lloyd’s
Register, Japan was ranked first in the production
volume of shipbuilding in 1957. Judging from such
industrial circumstances, the development in steel
production and weld engineering was mainly pro-
pelled by the needs of the shipbuilding industry. The
bridge engineers transferred the technology to the
steel bridges construction, which still had a limited
market.

In 1953, the largest composite girder bridge (Fu-
nagata Bridge, Yamagata) at that time was con-
structed. The bridge used rigid shear connectors
consisting of steel blocks that were popular at that
time. Afterwards, stud dowels started to be used
widely for shear connectors of various steel-concrete
composite structures when the stud welders, the
technology for which was adopted by a Dutch man-

![Fig.2 Number of constructed bridges by year.](image)
| Year  | Events | Analysis | Material | Design (Codes) | Measurement & Monitoring |
|-------|--------|----------|----------|----------------|-------------------------|
| 1950s | 1952   | First All Welded Steel Bridge (Honkyu-Bridge) | 1952 Start at Practical Use of 50kgf/mm² Class HT(High Tensile Strength Steel) | 1950 JSCE Standard Specifications for Concrete Structures | 1950 MOT National Transportation Research Institute & Kyowa Electronic Instruments Co Ltd Successful Trial of Strain Gauge |
|       | 1952   | First PC Bridge (Chosei Bridge) | 1955 Production of 60kgf/mm² HT(Japan Steel Works, LTD) | 1951 JSCE Standard Specifications for Concrete Structures: Revised | 1950 Japan Meteorological Agency (JMA) Type-50 Seismometers |
|       | 1953   | Largest Scale Composite Girder Bridge (Funaga Bridge) | Commercial Production of Weathering Steel Started | 1955 JSCE Prestressed Concrete Design and Execution Manual | 1953 SMAC Type Seismometer (Strong Motion Accelerometer Committee) |
|       | 1953   | 50kgf/mm² Class High Strength Steel Bridge (Sagami Ohashi Bridge) | 1959 SM50 50kgf/mm² HSS Specified in JIS | 1956 Specifications for Steel Highway Bridges | 1955 Sperry Colt Resonance Tuning-Fork Type Gyro |
|       | 1954   | First Orthotropic Steel Deck Bridge (Nakazato Bridge) | 1960 Specification for Design of Welded Railway Bridge (Draft) | 1956 Specifications for Arc-welded Steel Railway Bridges | 1959 JMA Type-59 Seismometers |
|       | 1958   | Kanogawa Typhoon | 1961 JSCE Prestressed Concrete Design and Execution Manual: Revised | 1957 Specifications for Welded Steel Highway Bridges | 1960 Maitain Invention of Laser |
|       | 1959   | First Continuous Composite Girder Bridge (Kema Bridge) | 1964 Specifications for Welded Steel Highway Bridges | 1958 JSCE Standard Specifications for Concrete Structures: Revised | 1961 JMA Type-61 Seismometers |
| 1960s | 1959   | <Isewan Typhoon> Biggest Victims | 1959 Design & Execution Manuals for Composite Highway Bridges | 1964 Specifications for Welded Steel Highway Bridges: Revised | 1962 First Commercial Production of Foil Strain Gauge |
|       | 1959   | First Cable Stayed Bridge (Katsuse Bridge) | 1964 Specifications for Reinforced Concrete Highway Bridges: Revised | 1964 Specifications for Reinforced Concrete Highway Bridges | 1970 Corning Inc.(USA) Low-loss Optical Fibers |
|       | 1960   | Tsunami caused by Chilean Quake | 1968 Specifications for Prestressed Concrete Highway Bridges | 1970 Specifications for Highway Bridges: Revised | 1970 Design Standards for Railway Structures (Steel Bridges) |
| 1970s | 1962   | First Long Span Suspension Bridge (Wakato Ohashi Bridge) | 1975 HSBE; 600t/400t Fatigue Testing Machine | 1971 Seismic Design Manual for Highway Bridges: Revised | 1971 Corning Inc.(USA) Low-loss Optical Fibers |
|       | 1964   | Tokaido Shinkansen Opened | 1971 Standards for Design of Shinkansen Network Constructions | 1971 Manual for Painting of Steel Highway Bridges | 1971 Corning Inc.(USA) Low-loss Optical Fibers |
|       | 1964   | Metropolitan Expressway Opened | 1972 Design Manual for Bearing of Steel Bridges | 1971 Design Specification for Super Structures of HSBE: Revised | 1971 Corning Inc.(USA) Low-loss Optical Fibers |
|       | 1964   | Application of 80kgf/mm² Class HSS for Highway Bridge (Hanawa Viaduct) | 1973 Design Specification for Super Structures of HSBE: Revised | 1972 Design Specification for Super Structures of HSBE: Revised | 1971 Corning Inc.(USA) Low-loss Optical Fibers |
|       | 1964   | Tokyo Olympic Game | 1973 Design Specification for Super Structures of HSBE: Revised | 1973 Design Specification for Super Structures of HSBE: Revised | 1971 Corning Inc.(USA) Low-loss Optical Fibers |
|       | 1965   | Meishin Expressway Opened | 1975 HSBE; 600t/400t Fatigue Testing Machine | 1974 HSBE; 600t/400t Fatigue Testing Machine | 1971 Corning Inc.(USA) Low-loss Optical Fibers |
|       | 1969   | Tomei Expressway Opened | 1976 Design Specification for Highway Bridges: Revised | 1973 Design Specification for Super Structures of HSBE: Revised | 1971 Corning Inc.(USA) Low-loss Optical Fibers |
| 1970s | 1970   | Japan World Exposition (Suita) | 1975 HSBE; 600t/400t Fatigue Testing Machine | 1974 HSBE; 600t/400t Fatigue Testing Machine | 1971 Corning Inc.(USA) Low-loss Optical Fibers |
|       | 1970   | Japan's Largest aquaduct bridge (Fujigawa Aquaduct Bridge) | 1975 HSBE; 600t/400t Fatigue Testing Machine | 1974 HSBE; 600t/400t Fatigue Testing Machine | 1971 Corning Inc.(USA) Low-loss Optical Fibers |
|       | 1972   | Sapporo Olympic Game | 1975 HSBE; 600t/400t Fatigue Testing Machine | 1974 HSBE; 600t/400t Fatigue Testing Machine | 1971 Corning Inc.(USA) Low-loss Optical Fibers |
|       | 1972   | Okinawa reverted to Japan | 1975 HSBE; 600t/400t Fatigue Testing Machine | 1974 HSBE; 600t/400t Fatigue Testing Machine | 1971 Corning Inc.(USA) Low-loss Optical Fibers |
|       | 1973   | Kanmon Bridge (Suspension Bridge) | 1975 HSBE; 600t/400t Fatigue Testing Machine | 1974 HSBE; 600t/400t Fatigue Testing Machine | 1971 Corning Inc.(USA) Low-loss Optical Fibers |
|       | 1973   | <First World Oil Crisis> | 1975 HSBE; 600t/400t Fatigue Testing Machine | 1974 HSBE; 600t/400t Fatigue Testing Machine | 1971 Corning Inc.(USA) Low-loss Optical Fibers |
|       | 1974   | Minato Ohashi Bridge (Truss Bridge) | 1975 HSBE; 600t/400t Fatigue Testing Machine | 1974 HSBE; 600t/400t Fatigue Testing Machine | 1971 Corning Inc.(USA) Low-loss Optical Fibers |
|       | 1976   | Ohashi Ohashi Bridge (Arch Bridge) | 1975 HSBE; 600t/400t Fatigue Testing Machine | 1974 HSBE; 600t/400t Fatigue Testing Machine | 1971 Corning Inc.(USA) Low-loss Optical Fibers |
|       | 1976   | Hirado Ohashi Bridge (Suspension Bridge) | 1975 HSBE; 600t/400t Fatigue Testing Machine | 1974 HSBE; 600t/400t Fatigue Testing Machine | 1971 Corning Inc.(USA) Low-loss Optical Fibers |
|       | 1977   | Saigou Ohashi Bridge (Arch Bridge) | 1975 HSBE; 600t/400t Fatigue Testing Machine | 1974 HSBE; 600t/400t Fatigue Testing Machine | 1971 Corning Inc.(USA) Low-loss Optical Fibers |
|       | 1978   | Miyaguni Earthquake | 1975 HSBE; 600t/400t Fatigue Testing Machine | 1974 HSBE; 600t/400t Fatigue Testing Machine | 1971 Corning Inc.(USA) Low-loss Optical Fibers |
|       | 1979   | <Second World Oil Crisis> | 1975 HSBE; 600t/400t Fatigue Testing Machine | Revised | 1971 Corning Inc.(USA) Low-loss Optical Fibers |
|       | 1979   | Three Mile Island Accident | 1975 HSBE; 600t/400t Fatigue Testing Machine | Revised | 1971 Corning Inc.(USA) Low-loss Optical Fibers |
| Year | Events                                                                 | Analysis                                                                                     | Material                                                                                       | Design(Codes)                                                                                     | Measurement & Mentoring                                                                 |
|------|------------------------------------------------------------------------|--------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------|
| 1980s|                                                                        |                                                                                            |                                                                                                |                                                                                                |                                                                                             |
| 1982 | Tohoku Shinkansen Opened                                               |                                                                                            |                                                                                                |                                                                                                |                                                                                             |
| 1982 | JR Maglev Floating Run                                                 |                                                                                            |                                                                                                |                                                                                                |                                                                                             |
| 1983 | Nihonkai-chubu earthquake                                              |                                                                                            |                                                                                                |                                                                                                |                                                                                             |
| 1983 | America in Ruins, The Council of State Planning Agencies               |                                                                                            |                                                                                                |                                                                                                |                                                                                             |
| 1985 | Ohnaruto Ohashi Bridge                                                 |                                                                                            |                                                                                                |                                                                                                |                                                                                             |
| 1986 | Meiko-Nishi Bridge (Cable Stayed)                                      |                                                                                            |                                                                                                |                                                                                                |                                                                                             |
| 1986 | Chemnitz Nuclear Power Plant Accident                                  |                                                                                            |                                                                                                |                                                                                                |                                                                                             |
| 1987 | Privatization of JNR, establishment of seven JR companies               |                                                                                            |                                                                                                |                                                                                                |                                                                                             |
| 1988 | Sato Ohashi Bridge (Suspension)                                        |                                                                                            |                                                                                                |                                                                                                |                                                                                             |
| 1989 | Yokohama Bay Bridge (Cable Stayed)                                     |                                                                                            |                                                                                                |                                                                                                |                                                                                             |
| 1990 | Iikusui Ohashi Bridge (Tuss Bridge)                                    |                                                                                            |                                                                                                |                                                                                                |                                                                                             |
| 1991 | Igachi Bridge (Hybrid Cable Stayed)                                    |                                                                                            |                                                                                                |                                                                                                |                                                                                             |
| 1991 | Higashi-Kobe Ohashi Bridge (Cable Stayed)                              |                                                                                            |                                                                                                |                                                                                                |                                                                                             |
| 1993 | Hokkaido Nansen-Oki Earthquake; M=7.8                                 |                                                                                            |                                                                                                |                                                                                                |                                                                                             |
| 1993 | Tokyo Rainbow Bridge (Suspension)                                      |                                                                                            |                                                                                                |                                                                                                |                                                                                             |
| 1994 | The Great Los Angeles Earthquake; M6.8                               |                                                                                            |                                                                                                |                                                                                                |                                                                                             |
| 1994 | Tsunami Tsusha Bridge (Cable Stayed)                                   |                                                                                            |                                                                                                |                                                                                                |                                                                                             |
| 1995 | Great Hanshin-Awaji Earthquake; M=7.2                                 |                                                                                            |                                                                                                |                                                                                                |                                                                                             |
| 1997 | Tokyo Bay Aqua-Line Opened                                             |                                                                                            |                                                                                                |                                                                                                |                                                                                             |
| 1998 | Akashi Kaikyo Ohashi Bridge (Suspension)                               |                                                                                            |                                                                                                |                                                                                                |                                                                                             |
| 1998 | Chidorinosawagawa Bridge (First Composite Bridge with PC Deck Slab)   |                                                                                            |                                                                                                |                                                                                                |                                                                                             |
| 1998 | Meiko Chuo Ohashi Bridge (Cable Stayed)                                |                                                                                            |                                                                                                |                                                                                                |                                                                                             |
| 1999 | Sato-uchi Shimanami-Kaido (All Routes of HSBJ Completed)               |                                                                                            |                                                                                                |                                                                                                |                                                                                             |
| 1999 | Yumemai Ohashi Bridge (First Floating Turnable Bridge)                |                                                                                            |                                                                                                |                                                                                                |                                                                                             |
| 2000s|                                                                        |                                                                                            |                                                                                                |                                                                                                |                                                                                             |
| 2000 | First Hybrid Rigid Frame Truss Bridge (Tatobani Bridge)                |                                                                                            |                                                                                                |                                                                                                |                                                                                             |
| 2001 | First Use of "Asset Management" in Priority Policy of MILT             |                                                                                            |                                                                                                |                                                                                                |                                                                                             |
| 2001 | Imabeppugawa Bridge (Steel Twin-Girder Compound Rigid-Frame Bridge)    |                                                                                            |                                                                                                |                                                                                                |                                                                                             |
| 2001 | Bigawa Bridge, Kigawa Bridge (Steel-PC Mixed Extradosed Bridge)        |                                                                                            |                                                                                                |                                                                                                |                                                                                             |
| 2001 | Terrorist Attacks Upon the United States; World Trade Center Building Collapsed |                                                                                            |                                                                                                |                                                                                                |                                                                                             |
| 2003 | Sanriku-mami Earthquake; M=7.9                                        |                                                                                            |                                                                                                |                                                                                                |                                                                                             |
| 2003 | Miyakojima Earthquake, M=2.4                                          |                                                                                            |                                                                                                |                                                                                                |                                                                                             |
| 2003 | Yokosuka Earthquake, M=0.1                                           |                                                                                            |                                                                                                |                                                                                                |                                                                                             |
| 2004 | Niigata-ken Chuetsu Earthquake; M6.8                                  |                                                                                            |                                                                                                |                                                                                                |                                                                                             |
| 2007 | Collapse of I-35W Mississippi River bridge                            |                                                                                            |                                                                                                |                                                                                                |                                                                                             |
| 2008 | MILT Proposal for the Preventive Maintenance of The Road Bridge        |                                                                                            |                                                                                                |                                                                                                |                                                                                             |
| 2008 | 2005 Dassault Systems (French) Acquired ABAQUAS (USA)                  |                                                                                            |                                                                                                |                                                                                                |                                                                                             |
| 2007 | Application of Carbon Fiber Sheets for Repair of Asari Bridge (Chuo Expressway) |                                                                                            |                                                                                                |                                                                                                |                                                                                             |
| 2006 | Specified of SBHS (High performance Steel for Bridges) in JIS          |                                                                                            |                                                                                                |                                                                                                |                                                                                             |
| 2010s|                                                                        |                                                                                            |                                                                                                |                                                                                                |                                                                                             |
| 2010 |                                                                         |                                                                                            |                                                                                                |                                                                                                |                                                                                             |
ufacturer, were largely produced domestically.

On the technology of structural analysis, various numerical calculation methods suitable for electronic computers were developed. In this period, FORTRAN, the first high-level computer language, was developed in 1957.

The remarkable event in this field was the publication of Stiffness Method by M. J. Turner, R. W. Clough, H. C. Martin, and L. J. Topp, who took an active part in the aircraft industry, in 1956. It was the basic general idea of the Finite Element Analysis, which is the essential analytical tool for structural engineering. In 1958, the first Conference on Electronic Computer Application (ASCE Structural Division) was held and it accelerated the progress of the structural analysis method by computers. The technical papers presented at the conference consisted of two types of studies. One was the study related to the problems that had been solved theoretically but required extensive calculation time. Another was the study to improve the efficiency of practical structural design.

The representative study of the former was the development of solvers for simultaneous equations, and computers were expected to be numerical analyzers. On the other hand, the research subject that dealt with the development of smart machines, termed as Artificial Intelligence (A.I.), was organized by J. McCarthy et al. at the Dartmouth Conference in 1956. After that, various applied researches were carried out in many scientific fields with the progress of computers. However, it was not until 1979 that bridge researchers and engineers became interested in A.I. to develop bridge maintenance systems.

On the measurement technology, the first domestically produced strain gauges and static strain measuring instruments resulted from the research conducted by the former Transportation Research Institute (Ministry of Transportation) in 1950. SMAC strong motion seismometer that is essential to seismological observation was developed in 1953.

In the 1950s, technological developments were mainly on the structural materials and structural analysis; these were followed by the design and measurement technologies.

(3) Developments in the 1960s

The 1960s was an era of extremely active investment on infrastructures in anticipation of the 1964 Tokyo Olympic Games. It was the start of the “age of infrastructures mass production”, and the number of constructed bridges increased every year as shown in Fig.2. The first cable-stayed bridge, Katsuse Bridge (Kanagawa), which was completed in 1960, was the first modern suspension bridge in Japan, Wakato Ohashi Bridge (Fukuoka) was constructed in 1962. It was the starting age of long span bridges. Furthermore, various transportation infrastructures, such as Tokaido Shinkansen, Tokyo Metropolitan Expressway, Meishin Expressway, and Tomei Expressway, were opened followed by the rapid completion of infrastructures in Japan. However, partly because these infrastructures were constructed rapidly in time for the opening year of the Tokyo Olympic Games, structural deteriorations due to aging were found later on.

At this time, technical investigations on the construction of Honshu-Shikoku Bridges started. In 1961, the former Ministry of Construction and the former Ministry of Transportation (the present MLIT) jointly commissioned JSCE to solve the technical problems. The JSCE Committee on Technical Investigation of Honshu-Shikoku Bridges started the investigation. It was concluded that the construction of 1,500m of center span class suspension bridges was technically possible and the construction method of underwater foundations at a depth of 50m under rapid tidal current would be found by the following technical investigations. In the same year, the committee on Honshu-Shikoku Bridge organized by the former Japan Railway Construction Public Corporation (JRCC) concluded that the design of railway suspension bridges with center span of 600m-1,500m combined with highway bridges were feasible and met the traveling requirements of trains. This made the plan for combined railway and highway suspension bridge more feasible. In 1967, the committee organized in JSCE published the final report on the feasibility of construction plans of all the four bridge routes. Afterwards, the former Ministry of Construction and the former Ministry of Transportation jointly decided, in their final research report on the construction cost and time, that the bridge section at the strait crossing span would be a double deck section consisting of highway on the upper deck and railway on the lower deck, and the planning design was conducted in line with the JSCE committee policy.

On the development of material technology, the 580N/mm² class high-strength steel that has been increasingly used on bridge structures, and the weathering steel (SMA50, SMA58) were standardized as JIS in 1966 and 1967, respectively. In this decade, high-strength steels and weathering steels became increasingly popular in steel bridge fabrication.

In the design technology field, the design specification for welded structures, in both highway bridges (1960) and railway bridges (1964) were updated by taking into account newly developed technology. Until then, wind-resistant design for bridge struc-
tures had been conducted for individual bridges. Since numerous long span bridges were scheduled to be constructed in the Honshu-Shikoku Bridge project, the wind-resistant manual of Honshu-Shikoku Bridge and its commentary were published in 1964 as Japan’s first wind-resistant design standard for bridges\(^3\) to ensure the unified safety design against wind stability of different bridges. Hitherto, almost all studies on the wind-resistant bridge design have been carried out in the wind tunnels owned by aircraft engineering research institutions. The first large-scale wind tunnel facilities were established in the University of Tokyo in 1964\(^4\) and it led to further studies on wind-resistant bridge design together with the progress in various long span bridge projects.

In 1964, the Design Specification for Reinforced Concrete Highway Bridges and the Design Manuals for Piled Foundations were published. Furthermore, the Design Specifications for Prestressed Concrete Highway Bridges were published to cope with the increase in applied spans. Consequently, the main design specifications for highway bridges had been completed in this decade.

In the analysis technology field, R. W. Clough began to use the term Finite Element Method (FEM) in 1960. The first large-size electronic computer was developed domestically in 1962 and various kinds of extensive numerical calculations became common in practice. In 1967, the most popular text book for students who intended to learn FEM was published by O. C. Zienkiewicz\(^5\) and it accelerated the progress of numerical analysis in structural engineering.

At this time, Zienkiewicz published some advanced papers on iso-parametric elements and non-linear analysis together with B. Iron and R. Owen. In addition, Finite Strip Method (FSM) was proposed by Y. K. Cheung in the latter half of the 1960s, and the technical paper on the analysis of plate bending using Boundary Element Method (BEM) was published by Jaswon and Matini. Several numerical analysis methods that made the best use of the finite element method were developed and used in practice in this decade.

(4) Developments in the 1970s

Following the period of high economic growth of the latter half of the 1950s and the 1960s, public investment had a temporary slump in the 1970s as a result of industrial restructuring caused by the two oil crises. However, the construction of steel bridges continued to increase for over 40 years until the latter half of the 1990s.

In 1970, the Honshu-Shikoku Bridge Authority was established and the basic investigation plan was prescribed by the former Ministry of Construction and Ministry of Transportation. It became the start of the strait-crossing bridges era. In 1973, the Ministry of Construction and Transportation approved the implementation plan of the Honshu-Shikoku Bridge Authority, and determined the simultaneous start of construction of three routes: Kobe-Naruto route, Kojima-Sakaide route, and Onomichi-Imabari route. Immediately after that, however, the construction work was postponed indefinitely in accordance with the government measures for curbing overall demand caused by the oil crisis in 1973. In 1973, construction of only three bridges in the Kojima-Sakaide route (Ohnaruto Bridge, Innoshima Bridge, and Ohmishima Bridge) was started\(^6\).

In this decade, research and development works on construction techniques for long span bridges were aggressively conducted. Their results successfully contributed to the completion of the representative bridge types suitable for long span bridges, such as truss bridges (Minato Ohashi Bridge; 1974, Oshima Ohashi Bridge; 1976), arch bridges (Saigou Ohashi Bridge; 1977) and suspension bridges (Kannon Bridge; 1973).

In the field of material technology, no notable progress in steel making and welding engineering were made in this decade; however, the design specifications and manuals were improved steadily to utilize the developed steel and welding processes.

On the analysis technology, several general purpose analysis programs, such as seismic response analysis programs (e.g., SHAKE and FLUSH) and general-purpose FEA programs (e.g., NASTRAN and ABAQUS) were released commercially. At this time, however, these programs could be operated only on large-scale computer systems that were quite expensive, and their applications to structural engineering were limited only to the highly complicated structural problems.

In the technology field of artificial intelligence (A.I.), diagnostic expert system; MYCIN\(^7\) was developed for medical use. It was in the latter half of the 1980s that the same type of expert system was applied for the structural diagnosis of deteriorated civil structures.

Concerning design technology, several separate design specifications were published individually for every specific technical field, which might have caused some problems in the practical application due to their inconsistencies. Therefore, in 1972 these separate specifications were systematized and integrated into the unified design specifications for highway bridges. It was Japan’s first Specifications for Highway Bridges that consisted of Part I: Common design principles and Part II: Steel bridges. Afterwards, Part III: Concrete bridge was added in 1978, and in 1980 Part IV: Substructure and Part V:
Seismic design were published to complete the design specification in the present format. In Part I, common items for the other parts, such as loads and materials, were combined. The applicable bridge span was revised from 150m to 200m. In Part II: Steel Bridges, the following five design specifications were combined: design specifications for steel highway bridges, construction specifications for steel highway bridges, specifications for welded steel highway bridges, design and construction manuals for composite highway bridges, and design and construction manuals for high-strength friction grip bolt connections of steel highway bridges.

(5) Developments in the 1980s

As was in the 1970s, research and development remained focused on the progress in construction technology of longer bridge span mainly for offshore bridges\(^5\). Of special interest was the Akashi Kaikyo Bridge project that was restarted after being postponed due to financial crisis. The project was restarted after altering the original plan of a combined railway and highway bridge to a modified plan of highway bridge. For this purpose, various research and development works were carried out to solve the practical technical problems for the construction of the suspension bridge with the largest center span in the world. In this process, numerous important results in the related specific engineering fields were obtained to design and construct securely the longest span suspension bridge in aspects such as wind-resistance, seismic design, and fatigue design.

In the material technology field, 800N/mm\(^2\) class high-strength steel that contributed to weight reduction of structural members and 580N/mm\(^2\) class high-strength steel for power transmission towers were standardized in JIS\(^9\).

Concerning the technology for structural analysis, the application of supercomputers for construction engineering was introduced\(^{20}-^{23}\). The first conference of AAAI (American Association of Artificial Intelligent) was held in 1980 and following that, the research on A.I. became very active. In 1982, the neural network system, which was the most basic method of A.I. research, was developed, and the A.I. evolved with the progress in speed and capacity of computers\(^{24}\). In the bridge engineering field, expert systems that operate the high-level inference techniques such as decision making in a complicated design and execution planning were studied from the latter half of the 1980s. This was conducted to preserve and transfer abundant knowledge and experience from senior bridge engineers who would soon retire.

On the design technology, integration of design specifications for highway bridges was made. The previous version of Part I: Common design principles and Part II: Steel bridges published in 1972 was revised to introduce the latest related technologies. Part IV: Substructures and Part V: Seismic design was published in 1980.

Part V: Seismic design, known formerly as Seismic Design Manuals for Highway Bridges published in 1978, was further revised to include the latest knowledge obtained from the research and development project, conducted in 1977 by NILIM and MLIT, and the experiences from the Miyagi-Oki Earthquake in 1978. In this specification, the provision of verification for deformation performance against earthquakes was introduced to prevent brittle failure of bridge piers and abutments.

In the material technology field for concrete structures, the JSCE Standard Specifications for Concrete Structures introduced the limit state design method for design. Furthermore, the Construction Manuals for Concrete Bridges and the Design Manuals for Concrete Bridges were published in 1984 and 1985, respectively. This indicates the widespread and rapid increase in concrete bridges in this decade. On the other hand, early deterioration of concrete structures due to salt damage and alkali-aggregate reaction were recognized as a serious durability problem. Several investigations were carried out to develop countermeasures for this damage by both public and private research organizations, and as a result, Countermeasure Manuals for Salt Damage and Alkali-Aggregate Reaction Control Measure were published in 1984 and 1989, respectively.

The high-standard highway network plan was proposed in the 4th comprehensive national development plan in response to the report of the Road Council in 1987. According to this report, the Shin Tomei Expressway was included in the high-standard highway network, and it was to begin construction. The specifications of this highway were more advanced than those of the other general highways. The ratio of cost of structures, such as bridges and tunnels, to the cost of road extension was presumed to be more expensive\(^{25}\) for better road alignments. To address this issue, various research and development works, including the introduction of technologies from abroad, were conducted to reduce construction costs. As a result, several new types of structures, such as minimized girder bridges and long span deck slabs, and new construction technologies, such as field welding for full sections, were employed. These technologies are now popular in bridge engineering.

(6) Developments in the 1990s

The 1990s were marked by the completion of representative long-span suspension bridges of
Honshu-Shikoku Bridges, such as Akashi-Kaikyo Bridge and Kurushima-Kaikyo Bridges, and the representative cable-stayed bridges, such as Ikuchi Bridge, Higashi-Kobe Bridge, Tsurumi Tsubasa Bridge, Meiko-Chuo Bridge, and so on. Constructions of the long span bridges using the world’s latest technologies were concentrated in this decade.

On the other hand, the bubble economy that continued for about 18 years collapsed in 1993. Recession caused by many factors, so-called the lost decade, started until 2002. As a result, the national financial condition declined; however; infrastructure improvement was forced to progress steadily under such a condition. In 1997, an internal cabinet of ministries on reduction of public works expenditure was organized, and it enacted an action agenda in 1997. In the same year, the action plans of 16 government agencies related to public works were released based on the action agenda. However, it should be mentioned that construction market condition at that time was not so bad compared to the present situation where economic recession is commonly felt worldwide. In the bridge engineering field, R&D on design and construction of bridges were continued in an extension of technical developments on reduction of construction cost of the New Tomei Expressway project.

In the design technology field, the Specifications for Highway Bridges were revised again to introduce various results of investigations conducted after the 1980 revision. In this revision, some contents in Part I: Common design principles were reviewed. Contents in Design and Construction Manuals for Reinforced Concrete Deck Slabs of Highway Bridges published in 1984 were introduced in Part II: Steel bridges and Part III: Concrete bridges.

Furthermore, contents in the Design Manuals for Steel Pipe Sheet Pile Foundations were introduced in Part IV: Substructures. In Part V: Seismic design, seismic coefficient method, and modified seismic coefficient method were consolidated and they were redefined as seismic coefficient method, and the verification method for seismic deformation capacity of reinforced concrete piers was revised to verification method of horizontal load bearing capacity. Accordingly, the Design Manuals for Concrete Highway Bridges and the Construction Manuals for Concrete Highway Bridges were revised in 1994 and 1998, respectively. For the steel bridges, the Wind-resistance Design Manual was published in 1991. The standard wind-resistance design method addressed problems in design and construction of long span bridges by integrating the past research results. Furthermore, an improved version of the Painting Manual for Steel Highway Bridges was published. In the same year, a large-scale wind tunnel facility, in which wind tunnel tests using the full bridge model of 1/100 scale Akashi-Kaikyo Bridge were carried out, was installed at Public Works Research Institute. It successfully contributed to the progress in wind-resistance design of long span bridges.

Concerning railway bridges, Design Standards for Railway Structures and Commentary was revised in 1992. This means all design and construction standards for bridges including various manuals were completed in this decade.

In 1991, JSCE Standard Specifications for Concrete Structures: Test Methods and Specifications was published. This specification has been revised every two or three years because related specifications increased and some of them were integrated, revised or abolished, so that new research results and new technologies can be included in the specifications without difficulties.

The most shocking event for civil engineers in this decade was the catastrophe of the Hyogo-ken Nambu Earthquake (the Great Hanshin-Awaji Earthquake Disaster) that occurred in 1995. Most road structures and bridges in Hanshin districts were severely damaged. The recovery works for these structures were conducted using temporary specifications with respect to restoration of highway bridges, which were enacted by the earthquake countermeasures committee in the same year. After that, the Specifications for Highway Bridges were revised based on the temporary specifications in 1996. Part I: Common design principles, Part II: Steel bridges, and Part III: Concrete bridges were reviewed generally. In Part IV: Substructures, verification by seismic horizontal load carrying capacity method that was applied initially only to reinforced concrete piers, was also applied to structural members of substructures and foundations. Part V: Seismic design, incorporated the required performance check based on the importance of the bridge, and the level of two-step seismic verifications, such as seismic method and seismic horizontal load carrying capacity coefficient method. Furthermore, verifications by seismic horizontal load carrying capacity method were applied not only to reinforced concrete piers but also to steel piers, foundations, bearings, and bridge unseating prevention systems.

GIS (Geographic Information System) as a database information management system contributed greatly to understanding the extent of seismic damage, rescue operation, and reconstruction planning of the Hyogo-ken Nambu Earthquake. It led to various experiments on application of GIS for infrastructures in the wide range of life-cycle from planning stage to maintenance stage. Simulation of data such as real time mapping and presentation of time-series were made possible with the progress in computer engi-
neering, and advanced use of computer mapping system was rapidly extended to works, which paper mapping could not easily cover.

R&D on structural design and construction planning using A.I. (as an expert system), whose development started in the latter half of the 1980s, had been actively expanded to structural diagnosis technology. However, in the early 2000s the number of research declined due to difficulties in structuring the knowledge database.

Concerning analysis technology, numerous general purpose structural analysis programs, such as MSC/NASTRAN, FINAS, ANSYS, ADINA, SAP, MARC, ABAQUS, ASKA, DYNA3D and PISCES, were released and used by structural engineers as well as researchers. They greatly contributed to the progress in research and design works as essential tools for the so-called numerical experiments.

(7) Developments after the 2000s

The 2000s could be called the era of technical developments for the reduction of construction cost.

It was said that the Heisei depression ceased due to economic recovery by export-led demand in 2002.

The period of this recession, however, was the longest in Japan economic history, and continuously Japan fell into the second recession (so-called global financial crisis) without any booming market. This economic stagnation might continue for the next 20 years.

Under such economic circumstances, new action agenda on the cost reduction of government public works was announced in 2000, and the new action plan was released based on the agenda in the following year. In the same year, the restructuring program on public works expenditure was established by MLIT in addition to the action agenda and plans. The restructuring activities were started by reviewing the following : acceleration of the project; optimization at every stage of planning, design, and maintenance; and optimization of procurement. The restructuring program is aimed at a 15% reduction of the total construction cost from the 2000 level for the next five years starting from 2003. To achieve this target, R&D agendas were concentrated on construction cost reduction.

As a result, new kinds of steel and concrete hybrid structures were developed, such as the continuous steel truss bridge rigidly connected to reinforced concrete piers (Tarodani Bridge; 2000), composite rigid frame for continuous girder bridge (Imabepu-gawa Bridge; 2001), continuous PC-steel composite extra-dosed bridge (Ibigawa Bridge, Kisogawa Bridge; 2001).

On the other hand, to reduce future maintenance cost, research on the minimization of infrastructure life cycle cost was started by recognizing infrastructure as assets. In this study, the asset management method was highlighted. The term “asset management” was used for the first time in infrastructure management technique including bridges as the priority measures formulated by MLIT in 2001.

In the bridge engineering field, Bridge Management System (BMS) was utilized as the general maintenance technique for bridge structures. In this research field, AI (expert system) was evaluated as a useful diagnosis technique for structural performance.

Revision of the existing specifications for the purpose of construction cost reduction and introduction of performance-based specifications to conform to overseas demand had been strongly requested. Therefore, all the Parts of Specifications for Highway Bridges were revised in 2002 as the first step to introduce performance-based specifications. In each Part, the grounds of the former specifications-based design were expressed as the design requirements and the former design specifications were considered as compatible specification.

From this version, to ensure structural endurance, the provision for fatigue design of steel structural members was introduced in Part II: Steel bridges. Also, the maximum limit of chloride ion concentration for corrosion of reinforcing steel bars and its estimation formula released in the 1999 JSCE Countermeasure Manuals for Salt Damage of Highway Bridges were introduced.

To be consistent with the revision of Specifications for Highway Bridges, the 1990 Painting Manual for Highway Bridges was revised in 2005 and remade as the Painting and Corrosion Protection Manual for Highway Bridges that covers diversification of corrosion prevention systems.

Similarly, Wind-Resistant Design Manual for Highway Bridges was also revised in 2007.

In addition, to meet the demand of internationalization of technical standards for steel structures, the Standard Specifications for Steel and Composite Structures (Part I: General Provision, Part II: Structural Planning and Part III: Design) and subsequently Part IV: Seismic Design were published by JSCE in 2007 and 2008, respectively. These specifications were the first JSCE standards that introduce the use of performance-based design method adopting limit-state design.

Under such circumstances, a steel truss bridge on Highway Route I-35W, Minneapolis, collapsed in 2007. The primary cause of the incident was design error on the gusset plates. However, the incident served as a warming that maintenance of aging bridges was important and indispensable to ensure the safety of existing bridges, and this should also be the lesson for Japan. With the fracture of the diagonal...
structural member of the Kiso-River Bridge caused by corrosion, the Advisory Council on preventive maintenance for bridges was organized at MLIT in 2008. The council recommended five countermeasures to realize the preventive maintenance of highway bridges based on the present condition of the bridges’ integrity.31)

On the other hand, it is noteworthy that after 2000 there were 109 big earthquakes with an intensity of over 5 on the Japanese seismic intensity of seven and they caused extensive damage. They include The 2000 Western Tottori Prefecture, 2001 Geiyo, 2003 Tokachi-Oki, 2004 Chuetsu, 2008 Iwate-Miyagi Nairiku, and 2011 Tohoku-Pacific Ocean Earthquake (Great East Japan Earthquake). Among 109 major earthquakes, 49 occurred after the Great East Japan Earthquake on March 11, 2011, a massive 9.0-magnitude, near the northeastern coast of Japan. It created extremely destructive tsunami waves, and it hit the Pacific coast of east Japan, especially Sanriku coast, tens of minutes after the earthquake. The earthquake and tsunami had caused extensive and severe damage, including an official death toll of 15,882 and 2,888 missing as of May 2013. Now, structural engineering is expected to contribute to rebuild Japan in many ways.

3. THE PRESENT ISSUES AND FUTURE OUTLOOK OF STRUCTURAL ENGINEERING

The aforementioned history of structural engineering concerning steel bridges is summarized and the prospective R&D of structural engineering will be reviewed in the following section.

Figure 3 shows the progress of investment in highway construction32) together with the number of published papers related to structural engineering. This figure shows that variation in the number of published papers is somewhat related to the variation in the amount of investment. The trend reveals that structural engineering related to civil infrastructures might progress with developments of construction projects as the driving force. If such a relation continues in the future, the increase in the number of published papers representing the R&D activities may not be expected because the amount of investment in the new highway construction slowed down or began to decrease.

Studying from another viewpoint, R&D on structural engineering had been active when any of the following four significant changes occurred: (1) development of new material with higher performance, (2) development of new analysis technology with higher accuracy or higher efficiency, (3) variation in social and economic condition, and (4) variation in natural condition due to the largest recorded typhoon, flood, earthquake, etc.

In the 1950s, the developments on steel production and welding technologies progressed remarkably when the changes (1) and (2) occurred due to the second shipbuilding boom. In this period, the steel bridge market was still so small that driving forces to develop new materials (steels) and analysis technologies alone were not strong enough. However, all welded steel bridges and high-strength steel bridges benefited from the results of the shipbuilding boom. The transitions in steel consumption in the shipbuilding market33), steel building market34), and steel bridge market35) are compared in Fig. 4. Details of the transition in steel consumption in steel bridges, shown as red line in Fig. 4, are depicted in Fig. 5. Figure 4 shows that the shipbuilding and steel building markets had been the dominant markets for steels in about 20 years from 1955 to 1973, which was called the high-growth period of Japanese economy. These markets had strong needs to develop new technologies on materials and analysis, and their results in structural engineering were introduced in
In the 1960s, improvement of transport infrastructures increased rapidly to achieve the big national project of the Tokyo Olympic Games. As a result, materials, analysis and design technologies have progressed linking each other in structural engineering.

In the steel bridge development, the market expanded from the latter half of the 1960s to the 1980s and recorded the maximum steel bridge weight of 900,000 tons constructed in a year. As the market expanded, the R&D required by the steel bridge market had to be carried out independently with the assistance of research results from other specific technologies. Consequently, various technical committees organized in JSCE and JSSC have been actively conducting research and investigation works related to bridge engineering. This period can be considered as the independence era of Japan in steel bridge engineering.

Another notable driving force of R&D is the infrastructure loss due to catastrophes, especially, natural disasters such as earthquakes and typhoons. Natural disasters had been creating the need for various R&D effort in the fields of seismic-resistant and wind-resistant engineering for both civil and architectural structures. In the future, the components of technologies related to disaster prevention and disaster mitigation are expected to progress every time a new disaster occurs due to global climate change.

Referring to the abovementioned summary, structural engineering in the steel bridge development had progressed focusing mainly on mechanics, such as material technology, structural mechanics, dynamics, and fluid mechanics, under technical restrictions of their peripheral technologies or legal restrictions.

The bridge engineers should strive to obtain the best solution against challenges found in the construction projects when required by any national bridge construction projects with national consensus. In this era, human resources, material and financial resources could remain constant but not necessarily adequate. Since the beginning of the 2000s, the improvement of transportation infrastructures has declined as a result of the prolonged global recession, and the steel bridge market also has declined rapidly. Figure 4 shows the comparative changes in steel consumption in the shipbuilding, steel building, and steel bridge market. The figure reveals that the shipbuilding market, which included international strategic commodities, showed a recovery trend after hitting the bottom in 1987. On the other hand, steel building and steel bridge markets, which were both domestic infrastructures, continued to decrease steadily without hitting the bottom. The market of steel bridge in particular seems to regain its 1950’s consumption level.

From the viewpoint of steel consumption, it should be recognized that the needs in the steel bridge market alone could not drive R&D on new materials and analysis technology fields. Moreover, if the construction projects are exhausted, the need for R&D from the projects may disappear in the future.

In the past, construction plans of infrastructures were prepared by their owners, such as national and local governments. Engineers or researchers performed their duties only by developing or providing assistance passively for given R&D subjects to achieve the project’s goal. In other words, structural engineering in the steel bridge field was only required to focus on technology development to construct economic structures of good quality under given conditions. However, the given condition is now vanishing.

Concrete, as the main structural material in the engineering field, needs continuing R&D in the future since various technical issues need to be answered. For example, performance of structural concrete may be improved. Technical development to improve concrete performance in combination with other structural materials is in progress. Some problems related to durability such as salt damage and freeze/thaw damage still remain to be answered. This is in contrast to the steels, where the related technologies have already attained full growth.

The amount of concrete consumption has a tendency to decrease as shown in Figure 6. Until 1988, majority of the fresh concrete had been supplied for civil engineering usage. Afterwards, the demands for concrete mainly come from architectural construction. Furthermore, the private demand for architectural use exceeds 50% market share after 2005. It is noticeable that only the shipment volume of fresh
For private architectural use did not decrease [37].

In Fig. 7, the change in the number of published papers in the Journal of JSCE (Divisions V and E) together with that of the Journal of Concrete Engineering are shown. Notice that the number of published papers concerning concrete engineering has not declined. In contrast to steel, the main demand for concrete has been domestic private facilities and infrastructures. Therefore, the need for R&D for new structures or revision of specifications can be more easily produced with few administrative restrictions.

Now that the construction plans are decreasing or vanishing, structural engineers should consider what kinds of infrastructures are necessary or insufficient for people (taxpayers) to live safely and securely without impact on the environment. In this process, engineers should ask themselves which subjects in the present structural engineering are incomplete. They should also determine learn the limit of their potential for development when employing engineering mechanics as the only main technology.

In 2005, the Advisory Committee on Structural Engineering, Mechanics-Structure Liaison Committee in Science Council of Japan, published [2] a research report in which structural engineering was redefined as the scientific techniques required in the life cycle process of a structure, such as planning, design, construction, maintenance, and dismantling/recycling, in order to contribute to building a safe and secure society. In other words, the tangible contribution of structural engineering to society is recognized. Structural engineering has the responsibility to provide comprehensive counseling on the structures, to prevent erroneous decision related to the environment when planning and measuring the structures. Here again, it is recognized that engineering mechanics is still essential although not the main technology anymore in structural engineering.

Not only overseas but also within the country, PPP (Public Private Partnership) and PFI (Private Finance Initiative) will be adopted in increasing number of construction projects. Social infrastructure development projects subjected to PPP or PFI require new infrastructure development techniques that combine socioeconomic needs and the need for structural engineering to break away from conventional structural engineering methods.

It might be a chance to shift from “structural engineering” to “structural science”.

In the design and manufacturing field that relates closely with the steel bridge engineering field, decision making under multiple conditions outside of engineering expertise has been required. This is an important issue that structural engineering needs to resolve. Furthermore, structural engineering is entrusted with the mission to clarify the criteria of modern society and citizens' demand and to construct reliable structures with academic base. In this sense, defining the criteria for steel bridge engineering by means of specifications (Specifications for Highway Bridges) may be unwise. From structures' life cycle viewpoint, actions after completion of bridges such as maintenance should be considered in the design process according to the 2002 revised version of Specifications for Highway Bridges. The concept of structural engineering in steel bridge has been adjusted to that of the Science Council of Japan. However, regardless of the aforementioned active life extension measures [31], it has been pointed out that no expected visible result has been produced yet because of difficulties in R&D on this issue and due to lack of engineers in related fields [38]. Since maintenance engineering requires abundant experience and knowledge of past structural damage and repair works, it is favorable that bridge inspections and structural assessments of bridges are supported by NPO (Non-profit Organization) or volunteers who mainly come from the baby boom generation. However, from the long-term viewpoint, it is desir-
able to establish the knowledge data base and expert system that would replace the skilled engineers. Hence, structural engineering remains to play an active part in bridge engineering. Furthermore, considering the decrease in population due to declining birth rates and the unpopularity of engineering disciplines among students, inspection and measurement by engineers may not be necessarily a sustainable technique. To this end, maintenance engineering should aim at labor saving or full automation by relying on the latest technologies in materials, measurement techniques, and AI as much as possible.

In material technology, the introduction of smart materials will be most suitable for structural engineering in the future. To create smart materials or smart structures, one needs to install or embed controlling elements (sensors and actuators) in the structures. There are two methods to realize smart materials or smart structures: one is by designing smart material composition itself; namely, by assembling and composing atoms or molecules or their aggregates; and the other method is by embedding (or attaching outside) sensors and actuators in the material. For steel bridges, the most promising method would be attaching smart materials on structural members or placing them as parallel members at the weakest section of time-dependent strength.

In measuring technology field, it is expected to combine expert system for structural integrity assessment with health monitoring technology using high-precision sensors or smart materials and data acquisition technology that collects and transmits large monitoring data to computers securely through wireless communication.

The future outlooks of steel bridges are envisaged by reviewing the technical history of steel bridges. The result indicates that conventional expertise, mainly mechanics, remain an important technology. However, we should observe closely new development and trends in material technology, measuring technology, and A.I. technology that have progressed in other engineering fields, and we should incorporate their results. Smart structures are required by society and realizing it will be one objective.

From now on, infrastructure technologies held by enterprises and local governments, such as high-speed railways, expressways, and water and sewage engineering, are required to infiltrate foreign markets as a packaged technology. Korea and China have entered the overseas infrastructure market, and price competition in this field may become an obstacle. To compete with them, offering Japanese specific software and hardware technologies will be absolutely essential. As mentioned before, the current issue in Japanese infrastructure is to provide countermeasures against natural disasters and increasing deterioration of infrastructures. Therefore, their related technologies may yet become the world’s top-level technologies, and they will be effective measures for active advancement into overseas markets and to develop new related technologies.

Considering the present situation of the construction market, we should be able to define the criteria of structures required by modern society and to offer suitable structures with sound scientific basis as pointed by the Science Council of Japan. This can be achieved by introducing the latest technological developments in the other engineering fields that are related to civil structures, such as economics, sociology, environmental engineering, communication engineering, chemical engineering, and so on.

4. CONCLUDING REMARKS

The history and future of structural engineering in Japan are carefully reviewed by taking a general view of the steel bridge history.

The new future outlook of structural engineering field is summarized as follows:

1) Since 2000, R&D effort to reduce construction cost have been continued under national financial constraints. Furthermore, R&D needs to reduce the increasing maintenance cost of numerous existing infrastructures aiming to be sustainable ones.

2) In the present condition, R&D needs to cope with the decreasing number of construction projects and conventional engineering-mechanics-based research topics. From now on, while expertise related mainly to engineering mechanics will remain important, developing smart structures and materials may be one promising solution. This can be achieved by actively introducing results developed in material, measurement, and AI technology fields from other industries outside the steel bridges industry.

REFERENCES

1) Joint proposal of JSCE, JGS, and JCI: The emergency recommendation: Proposal-1; Promotion of Social Infrastructure Development based on scientific basis and consensus building, Proposal-2; Concrete global warming countermeasures from the construction engineering field, Masanori Hamada-Chairman of Civil Engineering- Architecture Committee, Toru Kondo, President of JSCE, Akira Asaoka, President of Japanese Geotechnical Society, Kenji Sakata, President of Japan Concrete Institute, 2010.1 (in Japanese).

2) Science Council of Japan: The emergency recommendation regarding present issues in structural engineering-design criteria and computer addicts society, Liaison Council on
Mechanics-Structure, Advisory panel on structural engineering, 2005.8 (in Japanese).
3) Fujino, Y. and Kawai, Y.: Technological developments in the structural engineering with emphasis on civil steel structures, *Journal of Structural Engineering, Vol. 57A*, pp. 1-15, 2011.3 (in Japanese).
4) Japanese Society of Steel Construction : Locus of Steel Structures, 2008 (in Japanese).
5) Japan Bridge Association : History of Steel Bridge Technology, 2010.5 (in Japanese).
6) Fujitaira, M.: History of Technical Standards for Highway Bridges, Gihodo Syuppan, 2009.4 (in Japanese).
7) Science Council of Japan: Progress of welding and joining technologies and their outlook for the 21st century, Liaison council on artificial object design and production, Advisory panel on joining engineering, 2002.10 (in Japanese).
8) Tanaka, G., Shindo, T. and Toda, M.: On the fabrication and erection of all-welded highway bridge of Honkyubashi Bridge, *Journal of the Japan Welding Society (Journal of JWS), Vol. 21*, No. 9, pp. 236-246, 1952.9 (in Japanese).
9) Nishigaki, Y., Komommae, R., Okuda, Y. and Torii, K.: The durability study on the Japan’s first PC bridge-Chosei Bridge, *Proceedings of Annual JCI Convention, Japan Concrete Institute, Vol. 24*, No. 2, pp. 607-612, 2000 (in Japanese).
10) Tamakoshi, T., Nakasu, K., Ishio, M. and Takeda, T.: Research on the life estimation of highway bridges, Technical Note of National Institute for Land and Infrastructure Management, No. 223, 2004.12 (in Japanese).
11) Hattori, T. and Kato, S.: Changes in utilization of computer in structural engineering field, *Journal of Architecture and Building Science*, pp. 113-116, 1970.2 (in Japanese).
12) The Japanese Society for Artificial Intelligence HP: History of Artificial Intelligence, http://www.ai-gakkai.or.jp/jsai/whatsai/AllHistory.html (in Japanese).
13) Akiyama, H.: History of wind-resistant design specifications, *Bridge and Foundation, Vol. 32*, No. 8, pp. 61-64, 1998.8 (in Japanese).
14) Hirai, A., Okauchi, I. and Miyata, T.: On the wind tunnel test for full span suspension bridge model (the fourth report), *Proceedings of the 20th Annual Conference of the JSCE*, pp. 351-352, 1965 (in Japanese).
15) Zienkiewicz, O. C., Taylor, R. L. and Heinemann, B.: *The Finite Element Method*, 1st Edition, 1967 (7th edition as of 2010).
16) Japan Bridge Engineering Center : Progress in Honshu Shikoku Bridges, Committee on Editing of Honshu Shikoku Bridges, Committee on Estimation of Utilization of Super Computer - in Construction Companies, JSCE, No. 421/VI-13, pp. 43-52, 1990.3 (in Japanese).
17) JSCE Subcommittee on nonlinear analysis; Committee on structural engineering, *J. Struct. Mech. Earthquake Eng., JSCE, No. 453/VI-17*, pp. 11-22, 1992.9 (in Japanese).
18) Science Council of Japan: Vision and strategy in R&D of Artificial Interagency, Liaison council on multimedia communication network, 15 advisory panel, 2005.6 (in Japanese).
19) Aramaki, E.: Planning of new Tomei-Meishin expressway, *J. Struct. Mech. Earthquake Eng., JSCE, No. 444/VI-16, pp. 1-9, 1992.3 (in Japanese).
20) Express Highway Research Foundation of Japan (EHRF): Research report on economy of steel bridges, 2000.3 (in Japanese).
21) Suzuki, S. and Yamada, I.: Achievements and future in wind-resistant design technology for long span bridges, *Wind Engineers, Japan Association for Wind Engineering, Vol. 32*, No. 4, pp. 448-455, 2007.10 (in Japanese).
22) Matsumoto, M., Morikawa, H., Takada, S. and Hanakawa, K.: Systemization of factor analysis for earthquake victim and seismic diagnosis used by GIS in Hyogoken Nambu Earthquake, *Proceedings of the Special Conference on Han-Shin Awaji Earthquake Disaster, Vol. 2*, pp. 227-234, 1997 (in Japanese).
23) Ozawa, K.: Asset Management for infrastructures, *Annual Journal of Civil Engineering in the Ocean, JSCE, Vol. 22*, pp. 1-4, 2006.7 (in Japanese).
24) Kobayashi, K. and Ueda, T.: Perspective and research agendas of infrastructure management, *J. Struct. Mech. Earthquake Eng., JSCE, No. 744/IV-61*, pp. 15-27, 2003.10 (in Japanese).
25) The Advisory Council on Preventive Maintenance of Highway Bridges (MLIT) : Proposals for Preventive Maintenance of Highway Bridges, 2008.5 (in Japanese).
26) MLIT : Transition of Investment for Road, http://www.mlit.go.jp/road/ir/ir-funds/pdf/data1.pdf (in Japanese).
27) The Shipbuilder’s Association of Japan : Shipbuilding Statistics 2010 (in Japanese).
28) Committee on Architecture of the Japan Iron and Steel Federation : Statistics related to structural-steel frames for building, 2010.3 (in Japanese).
29) Japan Bridge Association: Statistics of Steel Bridges, 2009.10 (in Japanese).
30) Ministry of Economy, Trade and Industry: Statistics of shipment volume of fresh concrete, 1971-2005 (in Japanese).
31) Ouchi, M.: History and future of infrastructure investment estimated from consumption amount of cement-concrete materials, *Journal of JSCE, Vol. 91*, No. 7, pp. 52-53, 2006.6 (in Japanese).
32) Nishikawa, K.: Life time and maintenance of highway bridges, *J. Struct. Mech. Earthquake Eng., JSCE, No. 501/I-29*, pp. 1-10, 1994.10 (in Japanese).
33) Seki, H.: Research perspective on maintenance, *J. Struct. Mech. Earthquake Eng., JSCE, No. 557/V-34*, pp. 1-14, 1997.2 (in Japanese).
34) Ministry of Internal Affairs and Communications : Administrative evaluation and monitoring for maintenance and renewal of infrastructures- counsel recommendation on maintenance of highway bridges, 2010.2 (in Japanese).
35) Wu, Z., Xu, B. and Harada, T.: Review on structural health monitoring for infrastructure, *Journal of Applied Mechanics, JSCE, Vol. 6*, pp. 1043-1054, 2003 (in Japanese).
36) Todoroki, A.: Trend of structural health monitoring technology, *Proceedings of the Japan Society of Mechanical Engineer*, Vol. 8, pp. 139-140, 2005 (in Japanese).
43) Fujino, Y.: Maintenance and application of sensing technologies towards prevention of infrastructure disaster, *Proceedings of the Annual Conference of Railway Technical Research Institute*, 2007 (in Japanese).

44) Fujino, Y.: Efforts for safe and secure issues in urban space viewed from sensing technology, *System/Control/Information*, Vol. 50, No. 10, pp. 70-73, 2007 (in Japanese).

45) Fujihashi, K., Miyamoto, M., Okutsu, K. and Okutsu, M.: Sensing technology with optical fiber addressed disaster prevention field, *NTT Technical Journal*, pp. 52-56, 2007.9 (in Japanese).

46) Mita, A.: Deterioration of structures and health monitoring, *EXTEC*, Express Highway Research Foundation of Japan, No. 87, pp. 39-40, 2008 (in Japanese).

47) Konishi, S.: Status-quo and perspective of research and development in maintenance technology of railway structures, *J. Const. Manage. Eng.*, JSCE, Vol. 64, No. 4, pp. 369-380, 2008.10 (in Japanese).

48) Culshaw, B.: The smart bridge of the future, *Journal of Advances in Science and Technology*, Vol. 55, pp. 187-198, 2008.9.

49) Nagayama, T., Spencer, Jr. B. F. and Fujino, Y.: Smart sensor middleware development for dense structural vibration measurement, *J. Const. Manage. Eng.*, JSCE, Vol. 65, No. 2, pp. 523-535, 2009.6 (in Japanese).

*(Received September 17, 2013)*