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Development of design and theory of bridge structures in modern Japan *

近代日本の橋梁設計技術および、構造解析理論の発達について

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Abstract, This paper describes the development of bridge technology in modern Japan from the viewpoint of the diffusion of knowledge of design and theory of structures introduced from western countries. In the first half of Meiji Era (1868-1912) most of iron bridges were imported from western countries or designed and fabricated by foreign engineers hired by Japanese government. From the end of 19th century to the beginning of 20th century design and theory of structures had been started to diffuse, which was greatly supported by the publications on bridge engineering in Japanese language. In this study the process of the development of design and theory of bridge structures has been clarified and studied by examining the publications on bridge engineering.

1. Background and the purpose of the study

Knowledge of design and theory of bridge structure had been developed behind technology of erection and fabrication. Early experience of iron bridge was made by the construction of the railway bridges on the line of Osaka and Kobe and several road bridges in Nagasaki, Osaka, Yokohama and Tokyo. These bridges were imported from England or designed and fabricated by hired foreign engineers and technicians in Japan and the involvement of Japanese engineers was limited. At the end of 1870s iron plate girders were fabricated for the first time in Japan at Shimbashi Works of the Department of Railway to replace the timber girder bridges on the line between Shimbashi and Yokohama. First design experienced by Japanese engineer was the Kamogawa River railway bridge with 50 feet span plate girders on the line of Kyoto and Otsu, which work was commenced in 1878.

Knowledge of design and theory of structures is the most essential factor to compose the bridge technology. It is not exaggerated to say that the development of bridge technology is completed by the master of knowledge of design and theory of structures. Examining the process of learning the design and theory of structures is important for the study of the history on the development of bridge engineering in modern Japan.

Most studies in past on the history of bridge technology focused on the development of material, technology of fabrication and erection, standards and specification, systems and planning as urban design. On the contrary viewpoints of structural design, strength of materials and theory of structures were relatively few.

* Keywords; Theory of structures, Bridges, Modern Japan, Publications.

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In the important sources, "History on Railway Bridge in Japan" [1], "History on Civil Engineering in Japan" [2] and "History of Industry in Meiji Era (Civil Engineering)" [3] which supply basic information for the study on modern bridge engineering history, change of bridge structures, specifications, materials, fabrication and erection methods, organizations and systems are described, however design technology and theory of structures are not mentioned. "History of Road in Japan" [4] describes the change of strength of material and theory of structures even though few pages are allocated.

The purpose of this paper is to study on the development of bridge technology in modern Japan by clarifying the process of introduction and diffusion of design and theory of bridge structures in modern Japan.

First of all the development of theory of structure in western countries is to be clarified. The situation in Japan who introduced the knowledge is studied, which includes development of mathematical knowledge required for the introduction of western engineering knowledge. Then design and theory of bridge structure is studied by examining the publications[5] on bridge engineering in Japan, which has been tried in only a few studies.

2. Development of theory of structures in Europe

A lot of iron railway bridges had been constructed in 19th century according to the progress of the Industrial Revolution in western countries. Railway lines were extending rapidly to replace canal transportation and new industrial material had been developed and iron had been taken over by wrought iron and later by steel. Need of bridge construction due to the demand of transportation became stimulation to the development of theory of structures. When Japan opened her door to western countries in the middle of 19th century graphical methods of analysis for trusses had been already developed and theory for analysis of statically indeterminate also had been being established [6] .

(1) Early theory of structures

Leonard Euler (1707-1783) announced the theory of buckling of long column in 1757. Charles Augustin Coulomb (1736-1806) also announced the results of his research on theory of structures at the turn of 18 to 19th century. Thomas Young (1773-1829) announced the result of the research on physical properties (Young's Ratio) in 1807. It is possible to say that conditions and circumstance had been matured at the beginning of 19th century for the following development of theory of structures and strength of materials in 19th century.

From 18th century to the first half of 19th century France was the leading county of theory of structures, where science (mathematics) was applied promptly to practical engineering matters. This was enabled by the existence of Ecole des Ponts et Chaussees established by bridge engineer, Perronet in 1747 and succeeded to Prony and Ecole Polytechnique established by Monge in 1784 where famous engineers such as Fourier, Lagrange, Poisson took active part.

In the beginning of 19th century Claude Louis Marie Henri Navier (1789-1836) of France contributed to the development of theory of structure. Navier published "Resume des Leçons", first textbook of theory of structures in 1826 and established the basis of modern theory of elasticity and the application to practical problems. Navier had already shown theory of statically indeterminate structures such as continuous beams, arches and frames in the textbook. "Resume des Leçons" which had been written based on his note of lectures from 1819 at Pont et Chaussees and had been revised until version 3 in 1864 exerted a strong influence on the development of theory of structures in 19th century.

(2) Development of materials and theory of structures

The development of materials also exerted an influence on the development of theory of structures. In the latter half of 18th century iron was appeared for structural use for the first time and this new material started to diffuse for structures with the traditional materials, mason and timber. At the beginning of 19the century wrought iron started to be applied to structural use on the favor with the puddling process invented by Henry Cort in 1784 which converted pig iron into reliable malleable iron.

The superiority of structural characters of iron and wrought iron to timber and mason exerted an influence on the development of theory of structures by changing the way of application and type of structures themselves.

For the design of iron arches with far lighter dead weight than that of stone arches member forces of arch ribs and horizontal reactions to bearings were required to calculate more accurately. Application of wrought iron to bridge members expecting to bear not only compression but also tension force required the elastic analysis.

Theory responded to this requirement was studied by Moseley, Pole, Robert Stephenson (1803-1859) and Isambard K. Brunel (1806-1859) who belonged to the first generation of railway construction in U.K.

Moseley educated in France, advanced county of theory of structures and was familiarized with the theory of Coulomb and Navier published "The Mechanical Principles of Engineering and Architecture" in 1843 which was the first substantial textbook of strength of material written in English. Mosley was also a pioneer of engineering education with Robison, Willis and Rankine in 19th century.

Following Navier, Saint-Venant showed practical theory of continuous beams in the textbook of his lecture in 1838. This was the only practical theory until B. P. E. Clapeyron (1799-1864) applied his theory to Pont d'Asnieres, continuous girder bridge with five spans over the river Seine. In U.K. Navier's theory was introduced by Moseley and applied to the Britania bridge of four span continuous box girder by Stephenson and Fairbairn[7].

Famous "Theorem of the Three Moments" emerged in 1857 after Clapeyron studied the application of Navier's theory of continuous beams to Pont d'Asnieres mentioned above. Bresse, Mohr, Winkler and Heinrich Müller-Breslau (1851-1925) also contributed to the development of the theory of continuous beams.

Regarding the theory of arches, Navier shown basic theory of elastic analysis of two-hinged arch in "Resume des Leçons" and the achievement was followed by Carl Culman (1821-1881), Mohr, Winkler and Heinrich Müller-Breslau.

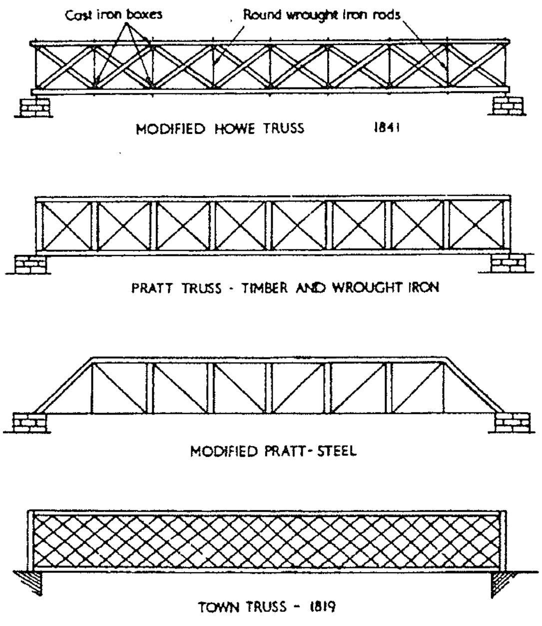


Fig.1 Truss types in the North America[8]

(3) Structural analysis of truss

Truss was the most popular bridge structure characterized bridge construction in 19th century. Trusses were being constructed all over the world including Japan according to railway construction in the second half of 19th century. Wrought iron truss had been started to fabricate in the middle of the century and the theory of structural analysis for truss was also started to develop.

The development of modern truss started in USA as timber frame structures (Fig.1). From the end of 18th century carpenters had already built timber trusses in the shapes of combination of arch and truss or the transformations. Wernwag who had immigrated from Germany constructed a lot of frame structures of the combination of arch and truss.

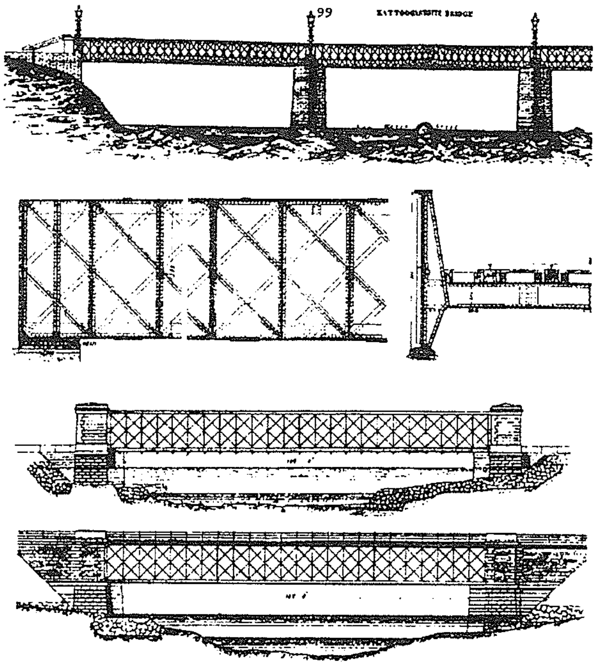


Fig. 2 Wrought Iron Trusses developed in Europe[11]
150ft. truss of Katagustota bridge, Ceylon 1858 (upper), 150ft. truss of Mosel Bridge at Koblenz 1858(middle) and 200ft. truss of Brenner railroad 1865(bottom)

Table 1 Development of theory of structures in Europe and North America

Year	Development of Theory of Structures	Related Events
18th C.	57 L. Euler announced theory of buckling of long column	47 Ecole des Ponts et Chaussees 80 Ecole Polytechnique 96 Finlay's suspension bridge
19th C.	07 T.Young proposed "Young's Ratio". 08 Navier published "Resume des Leçons" 29 Poisson announced concept of "Poisson Ratio" 43 Moseley published "Strength of Materials" 57 B. Clapeyron announced "Theorem of Three Moment". 62 Graphical methods of analysis of truss by Ritter. 72 Graphical methods of analysis of truss by Cremona 73 Graphical methods of analysis of truss by Bow 74 Graphical methods of analysis of truss by Culman and Levy. 75 Analysis of statically indeterminate structures established. 77 W. Ritter announced theory of stiffened suspension bridge. 77 J. Rayleigh announced "Theory of Sound". 88 Melan annouced elastic behaviour of suspension bridge.	18 ICE established by Telford 24 Smart got patent of lattice 47 Accident of Dee railway bridge 48 Warren got patent of truss 49-50 Stephenson constructed box girder at Menai and Conway. 49 J. A. Roebling constructed Niagara suspension bridge. 56 Bessemer invented Converter for steel making process 67 Martin invented furnace for steel. making process. 74 Eads Constructed first steel bridge in USA. 83 Brooklyn suspension bridge. 90 Forth Railway bridge
20th C.	01 Theory of Moiseieff 10 Theorem of V. Karman Engessor-Karman	21 Rolled H shape steel 37 Golden Gate suspension bridge. 40 Accident of Tacoma-narrows bridge

(Note; Edited by authors)

Burr constructed a huge scale of timber truss at Susquehanna, Pennsylvania in 1814[9) . In 1820 Town got a patent of so called "Town Truss". Hereafter a lot of types of truss had been conceived by Howe, Jones, Linville and Whipple [10) . Truss structure had been also developed in Europe (Fig.2).

In UK truss structure had been adopted as frames or members of machines such as Watt engines or ships at the end of 18th century. In Germany truss was erected as frames of roof structure of Munich National Theater completed in 1823. Smart got a patent of lattice in a shape of figured cloth grid composed of diagonals of flat bars in 1824

By the beginning of 19th century truss had been changed to present shape from the combination of arch and truss or the transformations. Lattice structure was analyzed by beam theory regarding as plate girder with web plate composed of numerous diagonals. In early stage lattice was not accepted well by leading engineers such as I. .K. Brunel and Robert Stephenson. First substantial adoption of lattice for bridges was railway bridges on the line of Dublin and Drogheda railway in 1840.

In UK Warren got a patent of "Warren Truss" in 1848 and first substantial truss was erected at London Bridge station in 1850. In 1852 truss was erected over the River Trent on the line of Great Northern Railway at near Newark and Crumlin Viaduct with the total length of 1,700ft was erected in 1857 crossing the valley of the Ebbw River. Double warren trusses including Belah Viaduct[12) had been erected by Thomas Bouch (1823-1880) on South Durhamand Lanchashire Union railway. Construction of trusses had been spread rapidly from the middle of 19th century according to railway construction, which had enforced the development of graphical methods of analysis of truss.

Graphical methods of analysis was firstly studied by William John Macquorn Rankine (1820-1872) and J. C. Maxwell (1831-1879) and followed by the study of simple truss of Bow in 1873. The development of graphical methods of analysis was also contributed by the studies of Ritter in 1862, Cremona and Culman in 1872 and Levy in 1874[13) . These studies on graphical methods as well as algebraic method were motivated by strong need of huge number of truss construction for railways.

(4) Analysis of statically indeterminate structures and dynamic behaviour.

For the analysis of statically indeterminate truss or frame structures C. A. P. Castigliano (1847-1884) of Italy, Levy of France and Mohr of Germany proposed several numerical formulas of analysis in addition to graphical methods of analysis. Müller-Breslau had developed the theorem of influence lines for statically indeterminate structures based on "Reciprocal Theorem" introduced by Betti (1823-1892) and Maxwell.

After the analysis of statically indeterminate frame structures had been established around 1875, theory of structure had been developing rapidly by the studies of Mohr, Müller-Breslau and other structural engineers. "Principle of Least Work" was introduce by Castigliano for the statically indeterminate structures such as rigid frames and suspended structures [14), 15) .

Regarding the construction of modern suspension bridge, Finlay's Jaycob's Creek suspension bridge in 1796 was followed by Menai suspension bridge by Telford in 1826, Niagara suspension bridge in 1855 by John Roebling and Brooklyn bridge in 1883 by John and his son Washington Roebling, Both Menai suspension bridge and Clifton suspension bridge designed in 1829 and completed in 1869 were based on the theory of unstiffened suspension bridge developed in 1823 by Navier.

For analysis of suspension bridge Rankine (1858), A. Ritter (1862, 1879) and W. Ritter (1877) proposed theories of stiffened suspension respectively. Against this proposal of analysis theories, Roebling adopted experimental solution based on past experience for the design of Brooklyn suspension bridge. During and after Brooklyn bridge was constructed analysis of the elastic behaviour of suspension bridge was studied by Frankel and Du Bois in 1882, Levy in 1886 and Joseph Melan in 1888.

The study of Du Bois was introduced in the book "Bridge Structure (Application of Theory)" [16) published in Japanese language in 1897, but it mainly described analysis of truss and theory of suspension was not mentioned.

Study on the dynamic behaviour of structures had been already started by the end pf 19th century. The accident of railway bridge designed by R. Stephenson over the River Dee in 1847 became the beginning of the study. After this accident experimental study on the influence due to dynamic loading was carried out[17)

Development of analysis of dynamic behaviour of structures relied on the study by John W Rayleigh (1842-1919) who was a physicist with research result " Theory of Sound " in 1877. This study was the basic theory to support the development of dynamic behaviour of structure in the early 20th century following the study of 19th century. Dynamic behaviour of suspension bridge induced by strong wind was interested for scientific study but full understanding the behaiviour was given the study after the famous accident of Tacoma narrows suspension bridge in 1940. However in the construction of Niagara suspension bridge stay cables were applied for increase the rigidity to anti vibration of deck and this shows the empirical understanding of the influence of vibration in 19th century[18) .

3. Knowledge of mathematics in Japan before Meiji Era.

Theory of structures and design methods developed in western countries had been introduced rapidly from the beginning of Meiji Era (1868-1912) according to the practical need of railway construction and other engineering such as manufacturing of machinery. For the introduction of theory of structures basic engineering knowledge was required, among which most essential basic knowledge was mathematics. Western mathematics, geometry and algebra was started to learn as measurement technology for the purpose of navigation.

In early bridge engineering books published in Japan most pages were allocated for truss structures by mentioning both graphical methods and algebraic method [19, 20), 21)].

At the end of 19th century when almost 30 years had passed since the opening of the door to foreign countries, Japanese engineers started to be involved in practice of bridge design. In contemporary bridge engineering books trigonometrically function had been adopted for the analysis of truss member force as shown in Fig. 3[22)] .

Next we move to algebraic method for calculation of member forces,

Member force of $AC = V' \times \sec\beta$

Member force of $BC = V \times \sec\alpha$

Member force of $BC = V \times \tan\alpha$

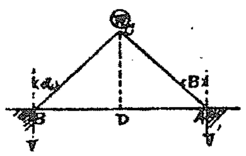
Where, V and V' are reaction of bearings.

This example shows truss of single triangle. In the case of trusses composed of multi triangles, same principle can be applied.

Fig. 164

次ニ代數的應力論ニ移ラン

第百六十四圖



V及V'ヲ両支點ノ反動トセバ

ACノ應力＝V'×secβ

BCノ應力＝V×secα

BAノ應力＝V×tanα

コハ單一ナル三角構桁ナルモ縱令ヒ若干ノ三角形ヲ連續セリト雖モ蓋シ此原理ニ外ナラザルナリ

Fig.3 Figure from early textbook published in Japan language.
Calculation of member forces of warren truss.
(Source : Ref.No.22, p.9. Authors' translation)

Since knowledge of mathematics was indispensable for learning theory of structures of bridges, it is useful to examine the knowledge of mathematics in Japan before they introduced advanced western engineering technology.

At the beginning of 16th century mathematics had risen at the cities in northern Italy such as Venice and Genoa responding to practical necessity of trade and commercial activity, which was based on Arabic mathematics. Mathematics for trade and commercial activity was succeeded to science to develop. At the end of 16th century decimal and logarithm were discovered and method of calculation had got rapid progress.

In Japan, at the beginning of 17th century when commercial activity had been active under the stable Tokugawa Shogunate, mathematics had risen based on Chinese mathematics of commerce[23)] .

Mathematics had been developing for commerce in Japan as well as China and Europe. This was mentioned in Japanese commercial mathematics book "Jinbou-Ki" principal mathematics book published at the beginning of 17th century[24)]. Kouwa Seki (1642-1708) was principal mathematician in 17th century.

Mathematics for commerce had been diffused in Japan through education system of "Terakoya", private school for common people. The level of diffusion of mathematics in Japan at the middle of 19th century is seemed to have been ranked relatively high in all over the world[25)] This must be one of the most important conditions to introduce and accept the theory of structures developed in western countries.

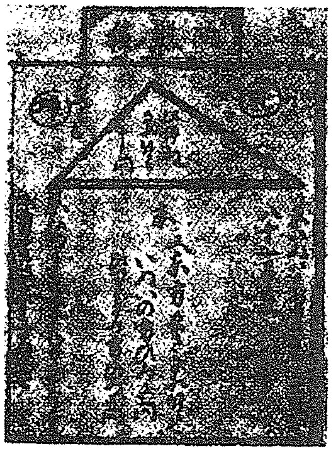


Fig.4 Question appeared in "Jinbou-Ki", 1796 version
A+B=81, A+C=72, where length of three sides of a triangle are A, B and C respectively. Then, calculate A, B and C.
(Source, Ref. No.24, p.137. Authors' translation)

Popular Japanese mathematics books adopted for textbooks in the first half of 19th century were "New Mathematics" (Minoru Hasegawa) explaining algebra and geometry published in 1830 and famous traditional Japanese commercial mathematics book, "Jinbou-Ki" mentioned above.

Mathematics that had risen due to the need of commercial activity was succeeded to the study of science in Europe. On the contrary commercial mathematics had not been developed for science and technology in Japan but was being treated as hobby at most in except for commerce.

Through Edo Era (1600-1868) common people had elementary knowledge of mathematics as a part of basic knowledge of so called "reading, writing and abacus (calculation)". On the contrary samurai people did not because they were educated that upper class people should not be involved commercial activity nor touch money. Mathematics for commerce was not recognized as a subject of study at all by samurai people.

In the first half of 19th century western knowledge was introduced from Netherlands. Disadvantaged knowledge such field as medicine was learned well but mathematics was not because mathematics was not recognized behind the western knowledge. It was understandable that translated books on medicine were published but not on mathematics. Samurai people were not interested in mathematics until the middle of 19the century. This means that mathematics, as a field of science was not studied at all in Japan before Meiji Era.

It was at Nagasaki Navy Training Centre established in 1855 that western mathematics was substantially learned for the first time.

American naval fleet composed of 5 steamers headed by Commodore Perry visited Japan in July 1853 to establish the diplomatic relations to Japan. The steamers gave strong impression to Japanese people and made Tokugawa government to recognize the importance of fleet of steamers for diplomatic strategy. Two years later, the government got a paddle steamer of 729 ton and 150-horse power with three masts from Netherlands. This ship, the first Japanese naval ship arrived Nagasaki in June 1855, which was called "Kanko-Maru". For the training of navigation Tokugawa government invited officers belong to the West India fleet of Netherlands navy for instructors and the trainees were young samurai people mainly from Tokugawa government. This was the first experience for samurai people to learn western mathematics as well as other subjects of natural science and technology such as navigation, machinery, surveying etc[26] .

Table 2 Books on western mathematics published in Japan in the middle of 19th century.

Year	Published mathematics books
1855	*Nagasaki Naval Training Centre was established.*
1857	"Methods of Western Mathematics", (S. Yanagawa.).
1862	*Mathematics Dept. was established in Research Centre of Western Publications. ("Bansho-Shirabesho")*
1871	"Textbook of Mathematics" (Kohei Kanda), "Calculation Book" (Shizuka Hanai), "Self-learning of Western Mathematics" (Kanichi Hashizume), "Western Calculation Method" (Chojiro Ishikawa), "Learning of Calculation" (Yasunori Yoshida), "Fraction of Western Mathematics" (Kishi, Yamada), "Proportion of Western Mathematics" (Kishi), "Collection of Questions" (Sekiguchi),
1872	"New Book of Mathematics", (Chikayama. Takahashi), "Algebra of Western Mathematics" (Kazunori Shima), "Learn of western Mathematics" (Chorin Kawakita),
1873	"Shortcut to Western Mathematics" (Nushito Tanegashima), "Quick Learning of Western Mathematics", (Fumisuke Miwa),

Note, Translated and edited by authors referring to ref. No.23, pp.165-177.

Once the importance of mathematics was recognized a lot of books on western mathematics in Japanese language were published from the middle of 19th century to the latter half of the century[27), 28)]. In 1857 Shunzo Yanagawa (1832-1870) published the first western mathematics book "Methods of Western Mathematics". Mathematics Department was established in the Research Centre of Western Publications (Bansho-Shirabesho) and Kohei Kanda (1830-1898) was in charge of mathematics and published "Textbook of Mathematics" in 1871 referring to "Practical Arithmetic" by C. Davies publishes in New York. In the same year "Self-learning of Western Mathematics" by Kanichi Hashizume, "Western Calculation Method" and "Quick Learning of Mathematics" by Chojiro Ishikawa, "Learning of Calculation" by Yasunori Yoshida, "Fraction of Western Mathematics" by Kishi and Yamada, "Proportion of Western Mathematics" by Kishi and "Collection of Questions" by Sekiguchi were published. And in 1872 "New Book of Mathematics" by Chikayama and Takahashi, "Algebra of Western Mathematics" by Kazunori Shima and "Learning of western Mathematics" by Chorin Kawakita were published.

The publication of mathematics books mentioned above were the evidence of the existence of basic knowledge based on the Japanese mathematics. This means that mathematics was rediscovered by the introduction of western mathematics. This "rediscovery" was the first step of introduction of western science and technology including modern bridge engineering.

4. Publication of bridge engineering books in Japan[29) 30) 31)]

When Japan opened her door to foreign countries, "Theorem of Three Moments" had been already announced by Clapeyron and graphical methods of analysis of truss had been developing by Ritter et al.

To introduce the western knowledge, books were imported and hired western instructors such as J. A. L. Waddel (1854-1938) adopted these books for textbooks of their lectures. In the first half of Meiji Era western publications by Müller-Breslau, F. Bleich and others were the only written source of western knowledge for Japanese engineers. From the middle of the century Japanese publications had started to be published and been baring an important role for the diffusion of introduced knowledge. Therefore the trend of publication of bridge engineering books in Japan is very important indicator that shows the development of bridge engineering in Japan.

(1) First half of Meiji Era, 1868-1890

"General Description on the Methods of Embankments and Bridges" [32)] and "Drawings of Embankments and Bridges" [33)] in Japanese style binding were the first bridge engineering books in Meiji published in 1871. As it is read "This book describes the traditional methods of construction commonly used in the age of former government" in the preface of the first book, these books describe the bridge engineering before western knowledge had been introduced and show the starting point of bridge engineering in Japan.

In most engineering fields, imported books were adopted for the textbooks of lectures in early year of Meiji. Before the Imperial College of Engineering, "Kobu-Daigaku" was established in 1873 engineering education had been executing at Nagasaki Ironworks, Yokosuka Ironworks, Yokohama Ironworks, Railway Department and Lighthouse

Department respectively using the textbooks imported from UK or France.

In the Lighthouse Department established at Yokohama in 1868, engineering education was started in 1870 and continued until the function was succeeded to the Imperial College in 1874. The curriculum covered drawing, mathematics, construction and survey and measurement etc (Source, History on Japan lighthouse, by Lighthouse Department of Japan Coast Guard.). A lot of engineering publications and education materials were imported mainly from UK[34].

In Yokosuka Ironworks (shipyard), engineering school "Kou-Sha" was established and subjects of shipbuilding including strength of materials as well as language were lectured. Engineering books were imported mainly from France.

Before engineering books started to be published by the hand of Japanese, substantial engineering education was required. In 1873 the Imperial College of Engineering had been established as mention above and this function was succeeded to the Imperial College, Tokyo in 1877. In 1881 Tokyo Technician School, now Tokyo Institute of Technology had been established. These newly established schools and college had been producing educated engineers under the instruction of foreign teachers. After 1890s, graduates of these schools and colleges gradually took over the positions of instructors and publications on bridge engineering in Japanese language started to be appeared.

(2) Latter half of Meiji Era, 1890-1910

One of the early bridge engineering books written in Japanese was a part of volumes in series book, "Lecture Book of Civil Engineering" (Dobokugaku-Kogiroku)[35] published from 1890 to 1896 composing of 15 volumes in total in the size of B6. This book was a record of lectures which covers whole subjects of civil engineering. Bridge engineering was involved in "General on Bridge Engineering", "Bridge Foundation", "Piles", "Arch and annex", "Timber Bridge" in volume 4, "Erection of Timber Bridge" in volume 12 and "Strength of Materials" in volume 15.

In "General of Bridge Engineering" in volume 4, general and basic information on bridge engineering was described in 92 pages. Loading, tensile strength of wrought iron, comparison of the property between steel and wrought iron and difference of structural details between British way and American way are discussed. Most of the examples in the book were refer to British experience. "Strength of Materials"[36] in volume 15 of "Lecture Book of Civil Engineering" was written by Yorihiko Ishibashi and composed of 21 chapters and the total pages are 939. In this volume materials and theory of structures are mainly described.

In 1893 Takegoro Okada, an engineer of Tokyo Metropolitan Government published "Theory of Bridges"[37] which was the result of lectures. In this book basic methods of analysis of truss and calculation methods of pin joints are explained and 400 Kan per Tsubo (455 kg/m^2) of design load regulated in 1886 was showed as well as design load recommended by Waddel.

In 1896 "Civil Engineering, Bridge"[38] was published. This book was substantial bridge engineering book composed of two volumes with 125 pages in volume 1 and 205 pages in volume 2. This book mainly describes strength of material but design practice such as connection of riveting, eye bar connection, pin connection and stiffeners are also described even though limited pages are allocated.

In 1894 "Handbook of Design of Road Bridge"[39] was published in Toyama prefecture. This book is not substantial bridge engineering book such as "Strength of Materials", "Lecture Textbook of Civil Engineering" by Ishibashi and "Theory of Bridges " by Okada mentioned above but a practical book for common engineers in charge of small timber bridges. This book is a kind of design manual to supply conversion tables of units of length, weight, area and volume, unit weight of timbers commonly used numerical formulas and other useful design information.

In 1897 Ishibashi translated and published "Design Example of Iron Structures" in two volumes[40]. The original book was "The Practical Designing of Structural Iron Works" published by Henry Adams in 1894. The numbers of pages are 178 in volume 1 and 125 in volume 2 respectively showing examples of plate girders, lattices, riveting with 14 drawings. This book supplemented information on the practical aspect of bridge engineering since his book "Strength of Materials" mentioned above focused theoretic aspect of structures.

Ishibashi also published "Drawings of Iron Bridges"[41] in 1897. In this book he explained principal iron bridges in USA, UK, France, Austria and Italy showing drawings of general views and partially detail drawings.

Suetaro Sakaoka published "Bridge Structures (Application of Theory)"[42] with 369 pages in total in 1898. In this book Sakaoka introduced the theory of Du Bois[43] from his book "Stress of Structures". From the end of the century American way of design was gradually overwhelming the British way in Japan and Sakaoka explained Cooper's view on the comparison of pin connection and rivet connection in a chapter "Advantages of Pin-connected Truss". Cooper's view was typical contemporary American thinking on bridge design which had been insisted by Waddel between July 1885 to February 1896 in the discussion on Japan Mail[44].

In 1898 Rokuo Uchida published a book of drawings on railway structures entitled "100 feet Steel Truss Girder and Other Structures with 24 Drawings"[45]. This book includes the drawings of standard truss designed by C. A. W. Pownall (1849-?) with spans of 100 and 200 ft, standard plate girder with spans of 12 and 15 ft., Hirakawa railway bridge in Aomori, Gosekigawa river railway bridge and railway related facilities such as Apt type rail, stations, rail points, turn tables, water tanks and pile driving machines. Most drawings are in the size of A2 and author's explanation and notes were in English.

In 1902 Hikosaburo Kanai, an engineer of Tokyo Metropolitan Government published "Waddel's Design Specification for Iron Bridges"[46] which was an translated book from design specification recommended by Waddel. Even though this was a small book like a pamphlet in the size of A5 with only 36 pages, the book was useful for design practice. Since design specification had not been published yet, this book including design loads and allowable stresses at the end of the volume must have been valuable for bridge engineers.

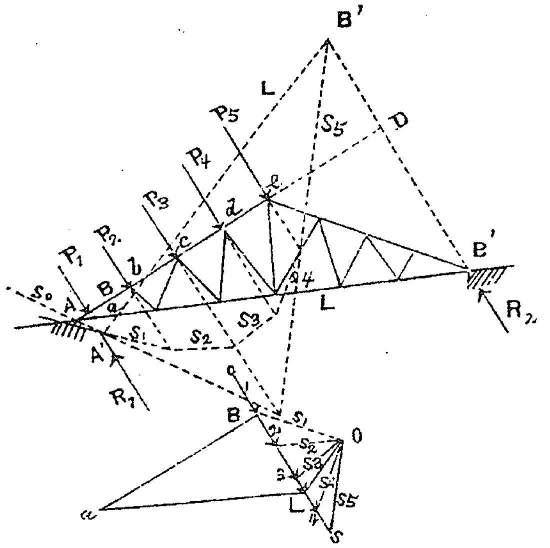


Fig.5 Analysis of Roof Truss (1898)
(Source; Ref.42), p.94.)

In 1908 Kanai published "Bridge (Civil Engineering)" [47] edited for the textbooks of Kogyokusha Technical school. General information such as classification of bridge structures, materials and design loads were mentioned at general remarks, then theory of analysis was explained for plate girder and truss respectively in total pages of 438.

Isami Hiroi published an English book "Plate Girder Construction" [48] in 1888 while he was in USA. This book was written based on his experience of design at Edge Moor Iron Company where he belonged to since he had left for USA in 1883. This book was practical book describing from basic knowledge on beam theory to practical knowledge such as design loads, structural analysis, determination of cross sections, structural details, connections, calculation of girder weight for transportation and estimation. This book was not written only for Japanese engineers but this could be recognized as one aspect of technical level of Japanese engineering at the end of19th century. Hiroi also published an English book on statically indeterminate structures, "The Statically Indeterminate Stress in Frames Commonly used for Bridges" in 1905.

(3) Taisho to Showa Era, 1910-1940

"Modern Bridge Engineering (volume 1)" [49] written by Kenichi Nakamura in 1912 and revised in 1925 describes design method of timber and iron plate girders. At the end of the volume extractions from the regulation on road structures issued in 1919 and the regulation on the construction of Japan National Railway issued in 1920 are refer to. In 1926 "Modern Bridge Engineering (volume 2)" [50] was published. Volume 1 describes only plate girders but volume 2 deals with the method of analysis on truss structures.

From the beginning of Showa Era (1926-1989) number of publications on bridge engineering had rapidly increased, which had produced several conspicuous trends of the publication of bridge engineering books. First trend was the publication of books on statically indeterminate structures. "Stress Calculation of Statically Indeterminate Structures under Static Loading" (Matazaemon Kimura, Taiyo-Do Shobo) in 1927, "New Theory of Structures" [51] in 1928, "Theory of Rigid Frame" (Yaku Miura, Maruzen) in 1929, "Collection of Theorem on Rigid Frames" (Matazaemon Kimura, Karasuma-Shoten) in 1930 and "Theory of High Rise Frames" (Shizuo Saka, Bunkei-Sha) in 1930 were published respectively.

Second trend was the publication of practical books. "Collection of Theorem on Rigid Frames" mentioned above, "Strength of Material for Practical Use" (Koichi Uryu, Maruzen) in 1929, "Standard Design Book of Civil Works" (Sho Kobiki, Doboku-Kenkyukai) in 1930 and "Pocket Book on Strength of Material" (Noboku Yamaguchi) in 1930 were published.

Third trend was the publication of reference books based on the past achievements on bridge construction works. The Department of Reconstruction and the Research Centre of Civil Engineering had published reference books. "List on Road Bridges (No.1)" [52] was published in 1925 and "List on Road Bridges (Supplement)" [53] was in 1928. Volume 1 and 2 of "Collection of Design Drawings on Bridges" were published by Department of Reconstruction in 1928 and volume 3 in 1929 and volume 4 in 1939 respectively

(4) Publications on design codes and specifications

First application of design specification was in 1895 when Seiichi Furukawa designed railway bridge of plate girder of rolled I-section[54] using the specification modified from Baker's specification by C. W. Kinder, an engineer for Chinese railway.

In 1909 Cooper E33 load was adopted for standard design load in Japan and from the next year "General Specifications For Steel Railway Bridges" regulated by American Railway Engineering Association in 1910 was recommended to refer for the design of railway bridges.

First official design specification in Japan was "Design Specification of Steel Railway Bridges" which was issued in 1912 as notification No.111. Main part of the contents in the specification conformed to General Specification of AREA. In 1921 Japan National Railway Regulation (Regulation No. 2 of Dept. of Railway) was issued, which regulated design loading of E40 and architecture limits. Regarding fabrication, "Fabrication Specification for Railway Steel Bridges" was issued in 1923 as notification No.168. In the Specification for Steel Railway Bridges issued in 1928, metric system was adopted and impact load was revised and KS loading was adopted

Regarding the specification for road bridges first regulation including design load was issued in 1886 as notification No.13, Ministry of

Interior. In article 29 of chapter 5 design load was regulated as "bridge structures should be strong enough to bear loading of 400 Kan per Tusbo on full bridge surface" (400 Kan/Tsubo = 455kg/m^2 = 93 lb/ft^2). This was the first code of loading for road bridges in Japan

Until the middle of the 19th century design loading of road bridge was not a given condition for design engineering but one of the factors which design engineers should determine as a part of design judgment. In the latter half of the century design load was gradually involved in specification as standard load. In UK, it was recommended to apply 60 to 90 lbs per square feet (293 to 439 kg/m^2) on both pedestrian and carriageway. In France design load for road bridge started to be regulated by the Government from 1850s. In the regulation of 1891 live load was specified as uniform load of 400 kg/m^2 followed by wheel loads of 6 to 16 tons and 0.7 ton of horse. In USA as mentioned before Waddel published a book to show his recommended load, which was introduced in Japan in 1902[55].

The regulation on road structure was issued in Japan when Road Low was established in 1919. (Regulation of Ministry of Interior, No.24, 25) In this regulation design load for automobiles was regulated for the first time. From 3,000 Kan (12.3 tons) to 1,700 Kan (6.38 tons) of automobile load and uniform load from 11 Kan/Shaku (450kg/m) to 15 Kan/Shaku (612kg/m) were regulated. In 1926 "Detailed Regulation on Road Structures (Plan)" was issued and live load was changed to 12 tons for 1st grade bridge, 8 tons for 2nd grade bridge and 3 tons for 3rd grade bridge respectively in metric system and articles on impact load and effect of earthquake were added. In the revised regulation in 1935 architecture limits, road alignment and slopes were regulated. In 1939 "Design Specification for Steel Road Bridge (Plan)" and "Fabrication Specification for Steel Road Bridge (Plan)" were published, which covered from design details to fabrication. The Department of Civil Work of Ministry of Interior published "Specification of Design and Fabrication for Arc Welding Steel Bridge" in 1940.

5. Consideration

(1) Development of design technology.

When Japan opened the door to foreign countries theory of structure had already been developed in western countries to cope with the demand of analysis of trusses, continuous beams and also rigid frames.

In the first half of Meiji Era (1868-1912), overall bridge design depended on western technology. However Japanese had learned theory of structures rapidly, which was greatly supported by the knowledge of mathematics. The knowledge of theory of structures was learned under the instruction of hired western engineers in foreign languages. Construction of railway gave opportunities of practical experience for Japanese engineers.

From the middle of Meiji Era, Japanese gradually started to design bridges by themselves. First generation of Japanese engineers who had been educated by western knowledge started to diffuse their mastered knowledge in Japanese language[56]. This has been clarified in previous chapter by examining the publication of bridge engineering books.

It is possible to say that the development of Japanese bridge engineering had entered into new step at the end of 19th century. Learning of western bridge engineering was carried out substantially from the basic knowledge of theory of structure to practical design technology in Japanese language[57].

On the other hand it was said that bridge engineering was more difficult for Japanese engineers than other subjects of engineering fields, which made them to take more time to learn. This situation was explained by the statement in "History of Industry in Meiji Era (Railway)" mentioned below.

It was bridge, especially superstructure that Japanese had been relying on the hand of foreign engineers for the longest period of all railway related structures. Before British engineer Pownall, an advisor returned to his country in 1896, foreign engineers had been involved in almost all technologies from design to fabrication. Even after 1896, principal part was still relied on foreign countries and it was the end of Meiji Era that Japanese engineers were involved in all part of bridge engineering independently[58]. (Authors' translation)

By virtue of substantial learning of design technology, Japanese engineers were gradually involved in design of bridges from the end of 19th century even though majority was still in the hands of foreign engineers.

In 1903 Hikosaburo Kanai published "Drawings of Actual Examples of Design and Construction for Iron Bridge"[59]. This book was written according to the achievement of the design and construction of Minato Bridge, bowstring truss over the Nihonbashi River designed by Ryuta Hara and completed in 1895. The wrought iron was imported from Belgium and the mechanical property was tested in the laboratory of Yokosuka Shipyard. This publication, a report of the construction of Minato Bridge is an example that shows the full involvement of Japanese engineers in design and construction of the bridge.

From the end of 19th century reinforced concrete was conceived and developed in Europe. At the beginning of 20th century the technology on reinforced concrete was quite new in Japan as well as in Europe.

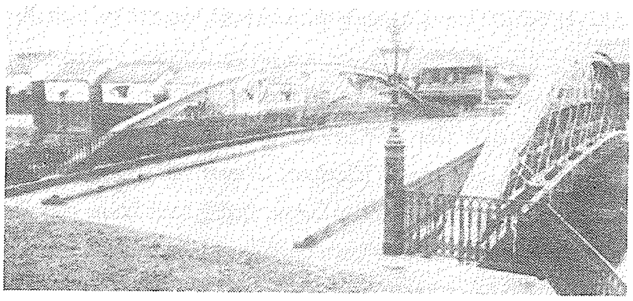


Photo 1. Minato Bridge (1895, Tokyo)
Source; Nihon no Hashi, p.38

Photo 2 Kandagawa River Bridge (Rigid frame structure, 1932)
Source; "Report on the construction of the viaduct between Ochanomizu and Ryogoku", 1933, Ministry of Railway, photogravure.

Japanese engineers were sensitive enough to introduce the new technology without delay and this attitude was supported by the developed knowledge of bridge engineering. The evidence of the existence of the knowledge is again publications.

Few years behind Europe and USA, books on reinforced concrete were published in Japanese language. "Reinforce Concrete" (Shuji Inoue, Maruzen, 1906), "Method of Reinforced Concrete" (Sahiko Sato, Ookura-Shoten, 1907) and "Reinforced Concrete Arch" (Shigematsu Akimoto, HakubunKan, 1909) were published as early publications on reinforced concrete. The existence of these publications shows that Japanese bridge engineering had been developed enough to diffuse new technology quick and efficiently.

By the end of Meiji Era (1868-1912) 43 reinforced concrete bridges in total had been completed and the earliest achievements of reinforced concrete structures were Wakasa Bridge (1903, Kobe), Yamashina Canal Bridge (1903, Kyoto) and Shimadagawa River Culvert (1904, Yonago). The publications of reinforced concrete mentioned above were published as a result of these experience based on the actual construction of the structures.

Generally the development of the knowledge of design and theory of structure and technology of construction such as erection and fabrication had not been achieved at the same time and there were time difference between them. Case of statically indeterminate structure gave another example of the time difference between the development of knowledge of design and theory of structures and actual construction.

It was Taisho Era (1912-1926) that the theory of statically indeterminate structure was introduced. Almost half century had past since the theory was developed in Europe. During Meiji Era no statically indeterminate structures had been constructed because there were no need of the practical construction until the end of Taisho Era (Photo.2). In "History on Railway Bridge in Japan" Keiichi Kubota said as follows.

"*---- recently theory of rigid frame was developed for practical use and structures in which columns and plate girders were rigidly connected were erected at Iidabashi Station and Arayashiki Viaduct of the Central Line. These structures were constructed after the Kanto Great Earthquake and ----*"[60] (Authors' translation)

Famous Castigliano's "Principle of Least Work" was explained for the statically indeterminate structures for the first time in the book "New Theory of Structures"[61] published in 1928.

(2) Motivation of technology introduction

It is possible to point out the existence of strong motivation of catching up to advanced technology in the background of the development of bridge engineering in Meiji Era. This is appeared in the contemporary publications on bridge engineering..

Suetaro Sakaoka who published "Bridge Structures (Application of Theory)" in 1898 said in the preface of his book as common consciousness of Japanese bridge engineers at the end of 19th century as follows.

"*---- it is impossible to expect that present Japanese engineers become authors of complete engineering books which pride even in Europe and USA. It is as if that we expect the appearance of the Golden world. However we are producing well-educated engineers and in the near future it will realize to publish engineering books without any help or instructions of foreigners.*"[62] (Authors' translation)

This description shows common Japanese consciousness on Japanese engineering against that of Europe and USA at the end of 19th century.

From the turn of the century to the beginning of 20th century, construction of both railway and road bridges increased and Japanese peculiar construction methods such as the launching method using their own girders for railway bridges had been conceived and developed. Official specifications for bridge design and construction had been issued from the beginning of this century and hereafter unified design loads had been adopted

Only 30 years after the publication of Sakaoka's book mentioned above, the consciousness on Japanese technology to western technology had dramatically changed. Some of Japanese engineers evaluated their technology was not only at the same level but also in advanced level comparing to western technology. This consciousness, a kind of superiority was shown in an engineering book published at that time. Kenzo Hatanaka said in his book "Development of Various Kind of Bridges and Bridges under the War" in 1944 as follows.

"*40 years has past since Japanese engineers had taken over the design and construction of railway bridges from foreign engineers. For these period Japanese engineers of Railway Department has been devoting themselves and making continuous efforts to the introduction of* *engineering knowledge and the construction of bridges. This engineering accumulation has produced the Japanese peculiar development, which level is not inferior to but superior to the bridge engineering in western countries.*"[63] . (Authors' translation)

Isogoro Iwasaki commented on overall of railway technology in his book "Locomotives and Railways" published in 1942 as followes.

"—— *We are very pleased to know that we have triumphed over the western technology*——"[64]. (Authors' translation)

(3) Change of consciousness to western technology.

Development of design and theory of structure in Japan started in the latter half of 19th century and it was around 1940 that Japanese recognized that they had caught up to western technology.

Consciousness on the western technology had been changing according to the development. From the turn of the century to the beginning of this century Japanese experience of bridge construction had been accumulated due to the increasing demands of construction of railway and road bridges. This accumulation of engineering experience made Japanese engineers to change their consciousness to western technology.

In the early step of the development Japanese engineers had strong consciousness of desire to catch up to western technology due to the inferiority to western technology. Then continuous effort had been made to respond to the domestic demand of bridge construction. The accomplishment of the development made Japanese engineers to have even some superiority to western technology. This process is the typical pattern of the development of bridge engineering in Japan.

However, this "development" means after all the process of introduction; digestion and diffusion of western oriented advanced engineering knowledge in efficient way. The change of consciousness, which had appeared according to the development repeated even after the World War II.

From just after the war to 1960s when the reconstruction of bridges was carried out advanced technology such as materials, welding methods, machines and construction heavy devices and also computer was introduce from western countries. This introduction was motivated by consciousness of desire to catch up with western countries again. From the end of 1960s construction of bridge had been sharply increased supported by the high economic growth. At the same time span and scale of bridges had been increasing dramatically, which was highlighted by the construction of the Honshu-Shikoku bridges.

Through this process Japanese consciousness to western technology had changed again based on their "self-complacent superiority", which reached its peak at the end of 1980s. This pattern of development composes one aspect of distinguished characters of Japanese bridge engineering that may appear in future.

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