No. 65 August 2022

STEEL CONSTRUCTION TODAY & TOMORROW

https://www.jisf.or.jp/en/activity/sctt/index.html

Feature Article

Towards Highly Resilient and Longer-lasting Steel Bridges

Published Jointly by

The Japan Iron and Steel Federation

Japanese Society of Steel Construction

Bridge Technologies of Hanshin Expressway Wangan Route and Structural Plans for Osaka Wangan Expressway Western Extension Project

by Hidesada Kanaji
Corporate Executive Officer
Hanshin Expressway Company Limited

Hidesada Kanaji (Dr. Eng.): After graduating from the Graduate School of Engineering, Kobe University, he entered Hanshin Expressway Company Limited in 1988. He successively held various technology-related posts in this company and assumed his current position as Corporate Executive Officer in 2022.

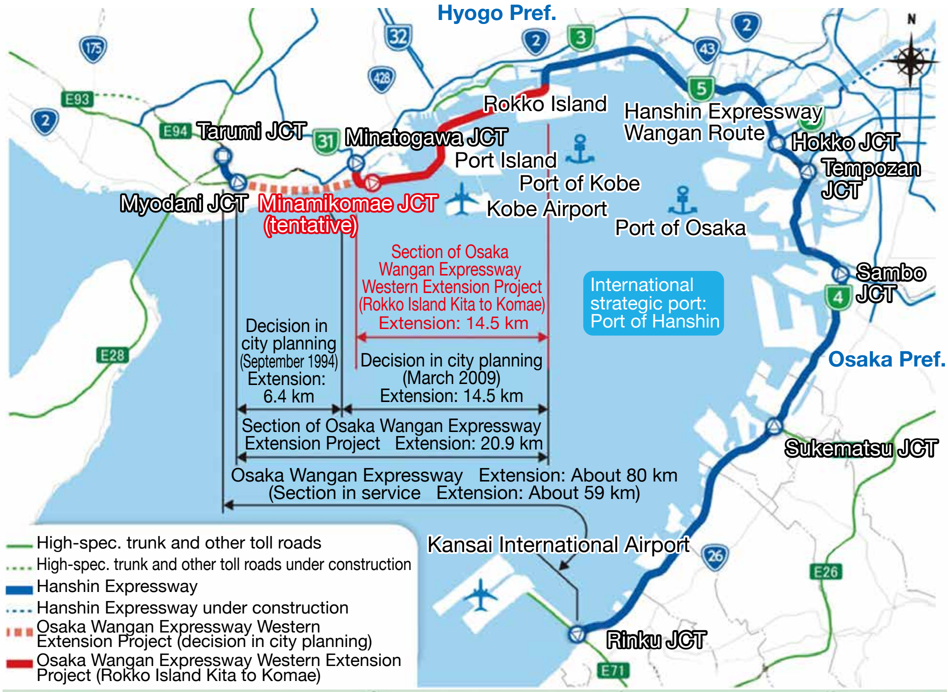
Hanshin Expressway Wangan Route and Osaka Wangan Expressway Western Extension Project

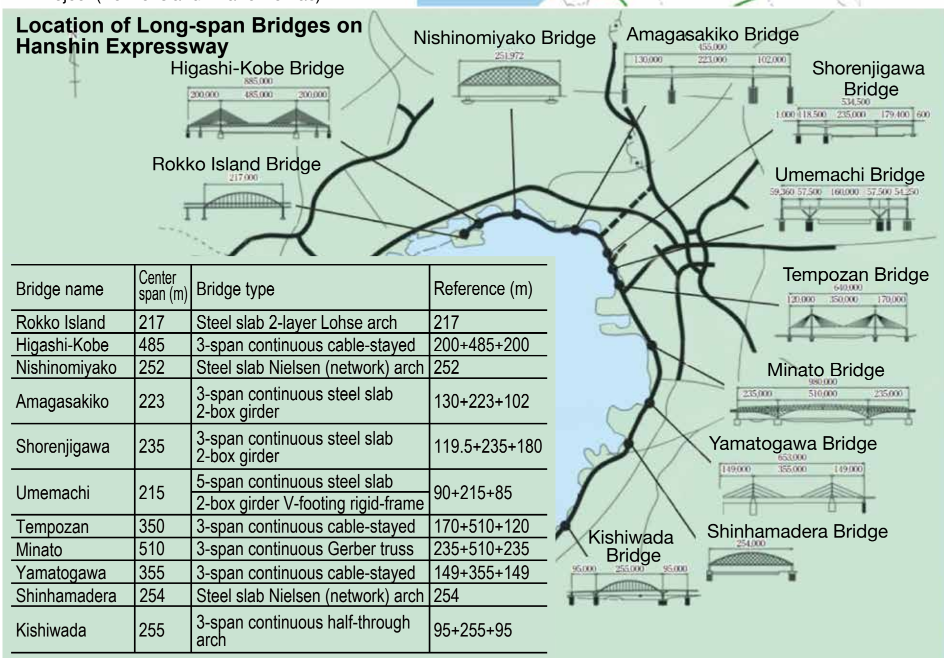
The Osaka Wangan Expressway is a trunk line with a total extension of about 80 km, which runs along the coastal area (*wangan*) of Osaka Bay. It connects with the Honshu-Shikoku Connecting Expressway at Myodanicho in Kobe City, passes through a reclaimed area between Kobe and Osaka and finally connects with the Kansai International Airport at Matsubara in Izumisano City. It is positioned as an expressway that serves as a trunk line for the Kansai Region, one of the representative economic zones of Japan, particularly as a trunk line in the coastal area covering international ports in the Kansai Region. (Fig. 1)

Construction of the Osaka Wangan Expressway started in July 1970 with a starting point at the Minato Bridge and the route was put into service in July 1974. Then, the route in service was extended one after another, and prior to the opening of the Kansai International Airport in September 1994, the Osaka Wangan Expressway that connects the airport with Rokko Island opened to traffic in April 1994. Because the expressway was constructed by Hanshin Expressway Company Limited, it is called the Hanshin Expressway Wangan Route.

The route of the Osaka Wangan Expressway Western Extension Project covers a 14.5 km-long section from Rokko Island to Nagata-ku in Kobe City. While the implementation of the extension project had been delayed due to the influence of the Great Hanshin Earthquake of 1995, the extension project was designated as a national public works project

Fig. 1 Hanshin Expressway and Osaka Wangan Expressway





Bridge name	Center span (m)	Bridge type	Reference (m)
Rokko Island	217	Steel slab 2-layer Lohse arch	217
Higashi-Kobe	485	3-span continuous cable-stayed	200+485+200
Nishinomiyako	252	Steel slab Nielsen (network) arch	252
Amagasakiko	223	3-span continuous steel slab 2-box girder	130+223+102
Shorenjigawa	235	3-span continuous steel slab 2-box girder	119.5+235+180
Umemachi	215	5-span continuous steel slab 2-box girder V-footing rigid-frame	90+215+85
Tempozan	350	3-span continuous cable-stayed	170+510+120
Minato	510	3-span continuous Gerber truss	235+510+235
Yamatogawa	355	3-span continuous cable-stayed	149+355+149
Shinhamadera	254	Steel slab Nielsen (network) arch	254
Kishiwada	255	3-span continuous half-through arch	95+255+95

in 2016, and then in 2017 the method of merging public works and toll-road project was introduced to the extension project, and it was decided for this extension project to participate in the government-controlled port-harbor project in 2018. Currently, the Osaka Wangan Expressway Western Extension Project is steadily being promoted toward the earlier opening of the full-length route to traffic.

Bridge Technologies Applied in the Construction of Hanshin Expressway Wangan Route

• Truss Bridges

The Minato Bridge is a representative long-span bridge on the Hanshin Expressway. It is a Gerber truss bridge having a center span length (L) of 510 m, the world's third longest, and a total length of 980 m (Photo 1). At the stage of project planning, many bridge types were compared for the construction of the Minato Bridge—Gerber truss bridge, arch bridge, cable-stayed bridge and suspension bridge, but the bridge types other than the Gerber truss type were shelved by taking into account the support of the bridge on the soft ground of reclaimed land or by worrying about the occurrence of uneven sinking between supports on the soft ground.

A specific feature in the construction of the Minato Bridge lies in that a great amount of 80 kgf/mm^2-grade high-strength steel (HT80) was applied as a means to reduce the steel weight of the bridge.

• Cable-stayed Bridges

The Yamatogawa Bridge (L=355 m) is a cable-stayed bridge, the first of its type in Japan with a center span surpassing 300 m. It is a three-span continuous cable-stayed bridge composed of one column tower and employing one fixed support from the aspect of seismic design, a rare seismic design not found in current bridge construction. The bridge clearance of the cable-stayed Tempozan Bridge (L=350 m) is very high, about 50 m, and the bridge adopts a long-period structure by the use of a flexible tower with two fixed supports in the tower section. In the construction of these two bridges, extensive R&D was promoted on wind-resistant design to pursue high wind-resistant stability by the use of a flap structure and a flat hexagonal-section structure with splitter plates and fairings.

It is the Higashi-Kobe Bridge (L=485 m) that is cited as the compilation of cable-stayed bridges of the Hanshin Expressway Wangan Route (see Photo 2). In its construction, rationalized structure and structural aesthetics were thoroughly pursued, which thus led to the adoption of an H-shaped tower with long columns installed on the horizontal member and harp-type multi-cables. In terms of seismic design, extensive attempts were made to apply a long-period structure called the all-free system in which all supports are movable, and a vane-type oil damper was adopted as a safety device for the long-span bridge, the first of its kind in Japan.

• Arch Bridges

Diverse kinds of arch bridges were constructed one after another, including a spandrel half-through arch bridge—Kishiwada Bridge (L=255 m), four basket-handle type Nielsen Lohse (network arch) bridges—Shinhamadera Bridge (L=254 m), Nakajimagawa Bridge (L=157 m), Kanzakigawa Bridge (L=148 m) and Nishinomiyako Bridge (L=252 m) and a double-deck Lohse bridge—Rokko Island Bridge (L=217 m).

• Seismic Retrofitting

The type of bridge that has been extremely difficult to retrofit since the Great Hanshin Earthquake (1995) was the long-span bridge. For the Minato Bridge in particular, because of its huge steel weight peculiar to a truss bridge, conventional seismic retrofitting such as additional steel plate reinforcement and concrete filling could not be applied. Given this situation, new seismic retrofitting measures were worked out—the base-isolation structure

Photo 1 Minato Bridge

Photo 2 Higashi-Kobe Bridge

and response-control structure, which thus led to the adoption of base-isolation floor framing and response-control braces. The fundamental factor that facilitated the adoption of such measures is a damage-control design worked out based on past seismic damage experience.

These seismic retrofitting concepts have since been applied effectively in the shear panel of the main tower at the Tempozan Bridge that treats displacement in the direction perpendicular to the bridge axis and the cable damper at the Higashi-Kobe Bridge that controls the bridge axis-direction movement of the main girder.

Fig. 2 Concept of Structural Plans

Concept item for structural plans	Design consideration			
Network in the event of disasters	Considerations to unexpected design conditions	Inspection applicability	Repair applicability	Effective use of new technologies
Creation of landscaping	Urban landscaping	Continuity of routes	Innovativeness/ Developability	Harmonization with society and nature
Long-term maintenance	Securement of durability	Reliable maintenance	Mitigation of traffic obstruction	Construction quality

Structural Plans for Osaka Wangan Expressway Western Extension Project

• Concept of Structural Plans

The highway section of the Osaka Wangan Expressway Western Extension Project is composed mostly of bridge structures at both the land and sea areas, among which is a long-span bridge with a main span length of about 600 m that straddles the route at the Port of Kobe. In the selection of the bridge type to be applied in the extension project, a basic policy was formulated in which the selection be made by working out the concept of structural plans based not only on the design/construction and maintenance of the bridges in service mentioned above but also past seismic experience, and at the same time comprehensively taking into account the performance and economic advantage that conform to this concept (refer to Fig. 2).

• Shinko-Nadahamakoro Bridge (tentative name)

For the bridge type that conforms to the proposed concept of the structural plan, three plans for the bridge type were drafted for the Shinko-Nadahamakoro Bridge: single cable-stayed bridge, continuous cable-stayed bridge and continuous suspension bridge. While the span length of the planned Shinko-Nadahamakoro Bridge will reach 650 m, it was judged that the possibility is high for the construction of a multi-span continuous long-span bridge when taking into account the recent trend in bridge technologies. Meanwhile, it was considered that a center span of 600-m class will exceed the common span range applicable by the use of truss, arch and other bridges and that the adaptability of these bridges to the proposed structural plan concept is low from the aspect of seismic resistance and maintenance.

Finally, the continuous cable-stayed type was selected for the Shinko-Nadahamakoro Bridge (Fig. 3). Specifically, while its cost (initial and lifecycle costs) is high, the cable-stayed bridge was evaluated comprehensively as an excellent bridge type from such aspects as high maintenance/landscaping performance, sufficient redundancy to resist seismic motion and ground displacement and high inspection/restoration performance.

• Kobe-Nishikoro Bridge

As a bridge type that conforms to the proposed concept of the structural plan, two plans were drafted for the Kobe-Nishikoro Bridge—1-main tower cable-stayed bridge and 2-main tower cable-stayed bridge. In the case of constructing the 1-main tower cable-stayed bridge, while its span length will reach 480 m, a world-class length for cable-stayed bridges, it was judged that the construction of 1-main tower cable-stayed bridge would be highly feasible when taking into account the recent trend in bridge technologies.

Regarding the truss, arch and other bridge types, the span length of 480 m is not cost effective for these types and it was judged that their adaptability to the proposed concept of structural plans is low in terms of seismic resistance and maintenance. Further in the case of adopting the suspension bridge, it would be required to install anchorages in the sea area, which would bring about great influence due to circumjacent land changes, and it was further judged that the adaptability of the suspension bridge to the proposed concept of the structural plan is low.

To these ends, because the bridge construction site is not located in the center portion of sea space, the 1-main tower cable-stayed bridge was evaluated as the bridge type for Kobe-Nishikoro Bridge from the perspective of excellent landscaping performance in terms of asymmetrical space and high adaptability to the proposed concept of the structural plan (Fig. 4). Meanwhile, the position of installing the tower of the 1-main tower cable-stayed bridge will be located on a site where the risk of uncertain fault can be mitigated.

Fig. 3 Shinko-Nadahama Koro Bridge (continuous cable-stayed bridge)

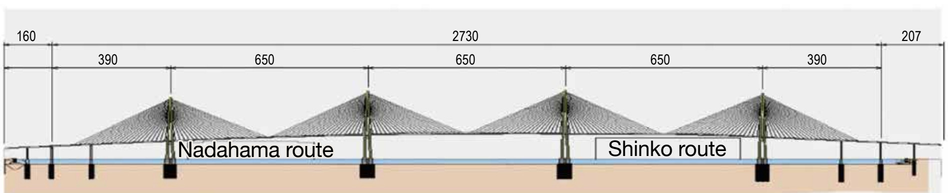
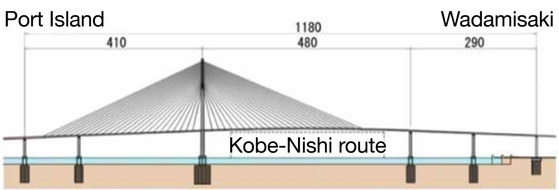


Fig. 4 Kobe-Nishikoro Bridge (1-main tower cable-stayed bridge)



Activities of the Research Committee on Steel Bridges with Higher Resilience and Longer Service Life (2nd Term)

by Kazuo Tateishi
Chairman of the Research Committee on Steel Bridges with Higher Resilience and Longer Service Life (Professor, Nagoya University)

Kazuo Tateishi: After finishing the master course at the Tokyo Institute of Technology, he entered East Japan Railway Company in 1988. Then, he served as associate professor at the Tokyo Institute of Technology and The University of Tokyo in 1997. He assumed his current position as professor of the Graduate School of Engineering, Nagoya University in 2003.

Towards Social Infrastructure with Higher Resilience and Longer Service Life

Recently, phenomena such as large-scale earthquakes, wind and flood damage and other natural disasters have occurred almost every year, jeopardizing human lives and lifestyles. The importance of providing measures against disasters is now being emphasized more than ever before. Social infrastructure is required to be resilient and continue to deliver flexible performance sufficient to resist a massive earthquake deemed likely to occur in the near future and wind and flood damage expected to become more and more devastating. Meanwhile, how to cope with the aging of many structures that form lifelines is an imminent issue and how to extend the service life of those structures, new and old, is now a matter of growing concern.

In the field of steel bridges, there is also a rising need for the provision of countermeasures against large-scale damage and for the recovery of function of obsolete structures, with two key points—higher resilience and longer service life. Bridge engineers are required to make contributions toward the protection of human lives and the maintenance of the national economic vitality by solving these emerging tasks.

In order to solve these tasks, it is important to prepare more resilient and longer-life structures than ever before and at the same time to appropriately maintain these structures. The technologies that accurately meet these needs are wide-ranging. For example, it is necessary to establish technology that can surely guarantee the diverse performances required for steel bridges. In addition, these technologies are important: design technology that takes into account ease of renewal, technology that allows sure and effective maintenance, and technology that is conducive to recovering and improving bridge functions by means of repair and function reinforcement.

Research Committee on Steel Bridges with Higher Resilience and Longer Service Life (1st Term)

The Japanese Society of Steel Construction (JSSC) has promoted the activities of various research committees involved in research on steel bridges for more than 20 years since 1997 based on the assignment of research from The Japan Iron and Steel Federation (see Table 1). JSSC has made contributions toward solving diverse tasks that meet the needs of the times by tackling many problems facing steel bridges, accumulating research attainments and reflecting them in various kinds of standards and specifications.

Table 1 Chronology of Research Committees on Steel Bridges

FY	Research Committee	Working Group
1997-1999	Research Committee on Next-generation Civil Engineering Steel Structures	• Working Group on Design of Rationalized Steel Bridge Girders • Working Group on Seismic Design Method for Steel Bridges • Working Group on Application of High-performance Steel Products for Steel Bridges
2000-2002	Research Committee on the Performance-based Design of Steel Bridges	• Working Group on Safety and Applicability of Steel Bridges • Working Group on Corrosion Protection and LCC for Steel Bridges • Working Group on Seismic Resistance of Steel Bridges • Working Group on Higher Performance of Steel Bridges
2003-2005	Research Committee to Improve Steel Bridge Performance	• Working Group on Rationalized Design Methods • Working Group on Improvement of Steel Bridge Durability • Working Group on Seismic Design Guidelines for Steel Bridges • Working Group on Weathering Steel Bridges
2006-2008	Research Committee to Improve Performance and Reliability of Steel Bridges	• Working Group on Rationalized Structure and Design for Steel Bridges • Working Group on Fatigue Strength of Steel Bridges • Working Group on Seismic Design Guidelines for Steel Bridges • Working Group on Weathering Steel Bridges
2009-2012	Research Committee on Improvement of Structures and Design Method for Steel Bridges	• Working Group on Rationalized Structure and Design for Steel Bridges • Working Group on Fatigue Strength of Steel Bridges • Working Group on Seismic Design Method for Steel Bridges • Working Group on Weathering Steel Bridges
2013-2014	Research Committee on Improvement of Structures and Durability of Steel Bridges	• Working Group on Rationalized Structure and Design for Steel Bridges • Working Group on Fatigue Strength of Steel Bridges • Working Group on Maintenance for Weathering Steel Bridges
2015-2017	Research Committee on Steel Bridges with Higher Resilience and Longer Service Life (1st Term)	• Working Group on Rationalized Design • Working Group on Fatigue Strength • Working Group on Corrosion and Durability
2018-2019	Research Committee on Steel Bridges with Higher Resilience and Longer Service Life (2nd Term)	• Working Group on Rationalized Design • Working Group on Fatigue Strength • Working Group on Corrosion and Durability

Fig. 1 Road Map to Attain Respective Research Tasks of the Committee on Steel Bridges with Higher Resilience and Longer Service Life

Tasks	~FY2014	FY2015	FY2016	FY2017	FY2018	FY2019
① Subtask 1 Working Group on Rationalized Design	Verification of load-carrying capacity of column and un-stiffened plate	Presentation of load and resistance factor for column and stiffened plate and presentation of constitutive law for seismic analysis that can deal with cyclic loading		Revision of *Specifications for Highway Bridges*: Introduction of load and resistance factor design method	Presentation of example of application of SBHS (steel for bridge high-performance structure) member in seismic design	
② Subtask 2 Working Group on Fatigue Strength	Expansion of design fatigue class	Collection of load rating data and its trial analysis Effect on fatigue life improvement including that by the use of high-strength steel (experiment, analysis and design method)		Preparation of load rating manual (draft)	Structuring of design, inspection and rating systems; Organization of manual for bridge assessment Standardization of effect on fatigue life improvement	
	Trial for and arrangement of fatigue life improvement	Collection of information on detective method for fatigue crack, proving of repairing and reinforcing methods for fatigue crack		Guideline for maintenance and corrosion diagnosis data	Preparation of guideline for crack repair and service life prolongation methods	
③ Subtask 3 Working Group on Corrosion and Durability	Surveys of task submitted by Ministry of Land, Infrastructure, Transport and Tourism	Assessment of practical bridge data and examination of reliability improvement measure		Maintenance and corrosion diagnosis	Preparation of handbook on design and maintenance and its reflection in standards	
Interdisciplinary tasks in above-mentioned three subtasks **Steering Conference**	Survey and assessment of practical example of corrosion of bridge	Examination about steel bridge corrosion diagnosis technology ① Interdisciplinary assessment of attainments of each working group→Proposal of attainments to society ② Tackling with the research task that supplements the niche between fields (between subtasks and different fields) ③ Creation of research theme for future		Preparation of corrosion map and corrosion-protection manual	Technical data on steel bridge having high corrosion resistance	

The Research Committee on Steel Bridges with Higher Resilience and Longer Service Life was established in 2015 as a research organ that took over these research activities and in light of the need for the higher resilience of steel bridges as a countermeasure against natural disasters and for the longer service life for aging bridge structures. In the three-year research activities (1st term) aimed at the greater resilience and longer service life of steel bridges, the Research Committee achieved definite achievements such as the rationalized assessment of load-bearing capacity of steel bridges and steel product members, long-lasting technology as a means to treat the fatigue and corrosion of steel bridges, and assessment and repair technologies useful for appropriate maintenance.

Research Committee on Steel Bridges with Higher Resilience and Longer Service Life (2nd Term)

During the period of activities by the Research Committee, the Kumamoto Earthquake occurred in 2016 and the periodic inspection of bridges was legally required to be carried out. Triggered by these events, steel bridges have faced emerging tasks such as the damage control, and easy and reliable maintenance.

Given such a situation, the Research Committee on Steel Bridges with Higher Resilience and Longer Service Life (2nd Term) was established with the purpose of putting into practice the higher resilience and longer service life of steel bridges by contributing to the revision of technical standards and specifications through accumulation of research achievements (Fig. 1). The Committee is composed of three working groups as shown in Fig. 2. The committee members cover those from wider fields—not only research organizations but also highway/railway companies, The Japan Iron and Steel Federation, Japan Bridge Association and The Japan Civil Engineering Consultants Association. Its specific feature lies in that the committee takes a proactive approach to reflect research results in practical bridge construction works.

♦♦♦

The Research Committee on Steel Bridges with Higher Resilience and Longer Service Life promoted its 2nd-term research activities mainly in the period from 2018 to 2019 while at the same time reexamining its 1st-term research activities. In the following pages, the research achievements of each of the three working groups—Working Group on Rationalized Design, Working Group on Fatigue Strength and Working Group on Corrosion and Durability—are outlined.

Fig. 2 Outline of Research Committee on Steel Bridges with Higher Resilience and Longer Service Life and Its Working Groups

Research Committee on Steel Bridges with Higher Resilience and Longer Service Life
Chairman: Kazuo Tateishi (Nagoya University); Vice Chairman: Yoshiaki Okui (Saitama University); Jun Murakoshi (Tokyo Metropolitan University); 27 managers and committee members

Working Group on Rationalized Design
Chief: Yoshiaki Okui (Saitama University);
Deputy Chief: Takao Irube (FaB-Tec Japan Corporation);
Secretary-general: Takeshi Miyashita (Nagaoka Institute of Technology);
21 committee members and observers

Working Group on Fatigue Strength
Chief: Kengo Anami (Shibaura Institute of Technology);
Secretary-general: Takeshi Hanji (Nagoya University);
22 committee members and observers

Working Group on Corrosion and Durability
Chief: Eiji Iwasaki (Nagaoka University of Technology);
Secretary-general: Tetsuhiro Shimozato (Ryukyu University);
40 committee members and observers

Report of the Working Group on Rationalized Design

—Experiments towards Rationalized Design and Load Rating in Maintenance—

by Yoshiaki Okui
Chief of the Working Group on Rationalized Design, Research Committee on Steel Bridges with Higher Resilience and Longer Service Life (Professor, Saitama University)

Yoshiaki Okui: After graduating from the Graduate School of Science and Engineering, Saitama University, he joined Kawasaki Heavy Industries, Ltd. in 1985. Then he served as associate professor at Saitama University in 1993 and visiting researcher at Delft University of Technology in Netherlands in 1996. He assumed his current position as professor at Saitama University in 2009. His areas of expertise cover structural engineering and bridge engineering.

In the 2nd-term research, the Working Group on Rationalized Design of the Research Committee on Steel Bridges with Higher Resilience and Longer Service Life promoted research focusing on the following themes:

- Ultimate and serviceability limit strengths of single-rib compressive stiffened plates
- System redundancy in load rating
- Examination towards the wider application of composite girders
- Local-global coupling buckling of columns
- Examination of elastoplastic parameters of steel products applicable to seismic analysis

Outlines of the achievements from research on three themes—the first, second and fourth—are introduced in the following article.

Ultimate and Serviceability Limit Strengths of Single-rib Compressive Stiffened Plates

Both ultimate limit strength (ULS) and serviceability limit strength (SLS) of single-rib stiffened plates were investigated using numerical analyses. The single-rib stiffened plates with large aspect ratios are a structural element that is showing increasing application in narrow-width box girder bridges. While it is well known that ULS of single-rib stiffened plates is higher than that of standard stiffened plates specified in the *Specifications for Highway Bridges of Japan Road Association (JSHB)*[1], its predominance is not taken into account in the current version of *JSHB*. Furthermore, the property of recently developed "Steels for Bridge High Performance Structure" (SBHS) is not properly assessed in the specifications in current use. In this research, we aimed at clarifying probabilistic information about the load-bearing capacity of single-rib stiffened plates considering these aspects.

The deterministic elastoplastic finite element analysis (FEA) and finite difference approximation (FDA) were employed to estimate probability parameters of ULS and SLS. The residual stress and initial out-of-plane displacement were considered as initial imperfection, and they were treated as random variables. The peak compressive stress was adopted as ULS, while the compressive stress obtained when the out-of-place displacement reached the limit value of manufacturing tolerance was assigned to SLS.

As examples of numerical results, Figs. 1 and 2 show the 5% fractile values of ULS and SLS, respectively. In both figures, the vertical axis is ULS and SLS normalized using the yield stress σ_y, and the horizontal axis stands for the width-to-thickness ratio parameter R_r of sub-panels in a stiffened plate. They also show the numerical results of stiffened plates with 2-3 longitudinal stiffeners obtained in the 1st-term research. In addition, experimental results for bridge high performance steel SBHS500 and normal steel SM490Y are plotted in Fig.1.

In 2021, the wide stiffened plate with more than 4 longitudinal stiffeners was studied. In 2022, it is scheduled to propose a design method by incorporating all results (ULS, SLS, narrow stiffened plate with a single rib, intermediate stiffened plate with 2-3 ribs, wide stiffened plate) and a design code for *JSHB* as well.

Fig. 1 Ultimate Limit Strength (5% Fractile) of Compressive Stiffened Plates

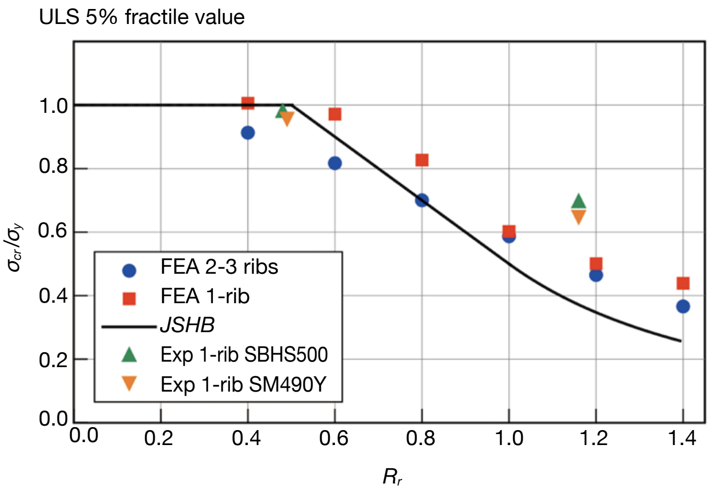
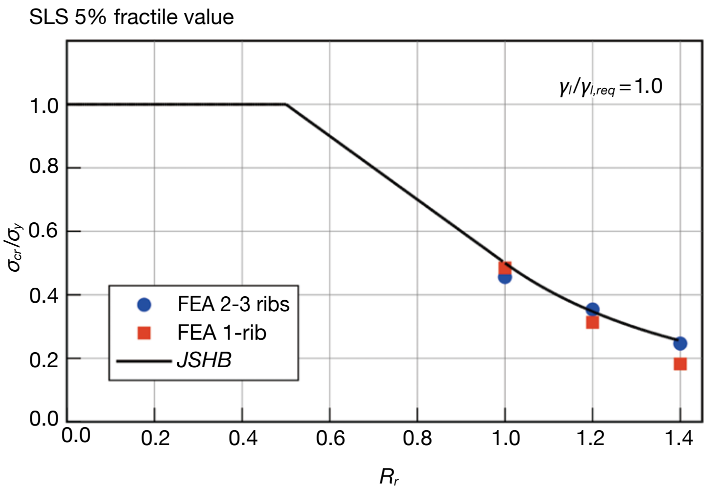


Fig. 2 Serviceability Limit Strength (5% Fractile) of Compressive Stiffened Plates



System Redundancy in Load Rating

A system factor of load rating for existing bridges was investigated. In this study, the system factor ϕ_s is multiplied to member capacity C to reflect the system redundancy when calculating a rating factor RF. The following general expression is assumed to estimate the rating factor:

$$RF = \frac{\phi_c \phi_s C - \gamma_D D}{\gamma_L (L+I)} \qquad (1)$$

where

γ_D and γ_L: Dead load factor and live load factor

D, L, I: Dead load effect, live load effect, dynamic load allowance

C: Member capacity

ϕ_c: Condition factor

In bridge design practices, the ultimate state of a member is regarded as the ultimate state of the whole bridge system, but in most bridges, the bridge system possesses a load-carrying capacity higher than that of the single bridge member. The system factor is used to maintain an adequate level of system safety.

In order to evaluate the system factor, both linear elastic and nonlinear finite element analyses (FEA) were carried out, and the system factor ϕ_s was calculated from the difference between the ultimate-state live load factors using:

$$\phi_s = 1.0 + \frac{L+I}{C}(\lambda - \lambda^*) \qquad (2)$$

where

λ, λ^*: Ultimate-state live load factors obtained from nonlinear FEA and linear elastic FEA, respectively

Because system redundancy results from changes in stiffness due to plastic behavior cannot be considered, λ^* obtained from linear elastic FEA does not involve the system redundancy. On the other hand, λ from nonlinear FEA reflects the system redundancy. Hence, when the rating factor *RF* is calculated based on Equation (1) and using the system factor in Equation (2), it has become possible to calculate a rating factor *RF* that takes into account the effect of system redundancy.

As a case study, the system factor was calculated for the three bridges shown in Table 1. While these three bridges were designed in accordance with the former design standard that adopted the allowable stress design method, the system factor was calculated based on the current version of *JSHB*. As an example of FEA, Fig. 3 depicts the strain distribution of the concrete deck and the effective stress distribution of steel girders at the ultimate state in A Br. shown in Table 1.

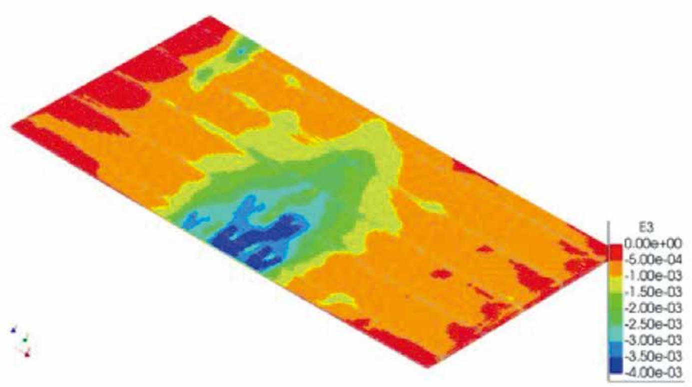
Fig. 4 shows the system factor obtained from Equation (2) and the live load factor at the limit state obtained from the nonlinear FEA. G1 stands for the outer girder, and G2 for the inner girder. As the number of main girders increases, the system factor becomes larger. In the 3-span continuous plate girder N Br., the ultimate live load factor for negative bending moment case "M_{min}" becomes lower than that for positive bending moment case "M_{max}", and the system factors became nearly 1.0. The standard approach for load rating is arranged as the "Bridge Evaluation Manual" by incorporating these results and the achievements attained in the 1st-term research.

Local-global Coupling Buckling of Columns

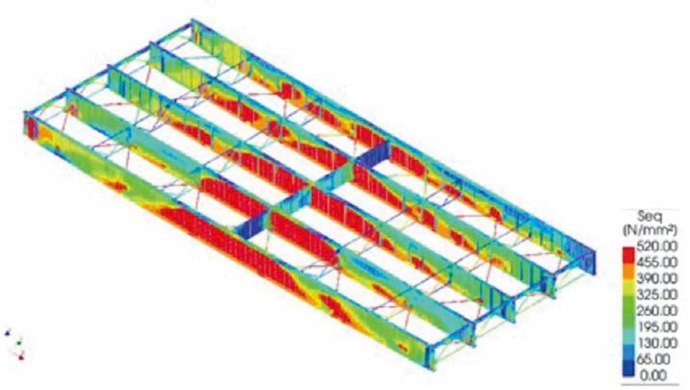
In the 1st-term research, two compressive loading tests were conducted for long columns with non-stiffened box-section. The dimensions of both test specimens reflected the cross section of actual truss bridges. Furthermore, the dimensions of two test specimens were settled in accordance with *JSHB* so that global buckling occurred in the one specimen and local-global coupling buckling took place in the other one. In the 2nd-term research, first nonlinear FEM analysis was conducted to reproduce the loading tests.

Fig. 5 shows the comparison between the test and analytical results for the specimen using bridge high-performance steel SBHS500. The peak load-carrying capac-

Fig. 3 Nonlinear FE Analysis of A Br. at the Ultimate State[3)]



(a) Strain distribution of concrete decks



(b) Effective stress distribution of steel girders

Table 1 Outline of Model Bridges for Case Study

Model name	A Br.	B Br.	N Br.
Type	Composite simple-span plate girder	Composite simple-span plate girder	Non-composite 3-span continuous plate girder
Span length (m)	34.4	39.3	3@28.0
No. of girders	5	3	4
Construction year	1971	1983	1975

ity could be obtained within a margin of 6% compared to the experimental results obtained by introducing the measured initial displacement and residual stress of specimens into the FEM analysis.

Since it was found that the buckling strength can be predicted by using the developed FE models, the design equation for the local-global coupling strength for columns was examined by means of FE analysis. Fig. 6 shows examples of the parametric study results, in which the circles stand for the FEA results and the blue and violet curves indicate the design strengths of the current version of *JSHB*. It can be seen from the study results that the buckling strength decreases owing to the local-global coupling effect as the width-thickness ratio parameter R of the plate that composes the non-stiffened box-section increases. Meanwhile, *JSHB* underestimates the coupling buckling strength especially for R=1.5.

We proposed Equation (3) as a design equation for local-global coupling buckling strength σ_{cr} :

$$\sigma_{cr}/\sigma_y = \chi\rho_{crg} \quad (3)$$

where ρ_{crg} is the reduction rate for column buckling strength specified in *JSHB*, and χ stands for the coupling effect, and is given in the following expression:

$$R = 0.4541R^3 - 1.3015R^2 + 0.7094R + 0.8927 \quad (4)$$

Fig. 7 illustrates a comparison between the proposed equation and the analytical results. Although the slightly safety-side assessment was made, the proposed equation and the analytical result showed a favorable correspondence.

References

1) Japan Road Association: Specifications for Highway Bridges—I Common, II Steel Bridges and Steel Product Members, Maruzen, 2017 (in Japanese)
2) Research Committee on Steel Bridges with Higher Resilience and Longer Service Life (II): Advanced Design and Verification Technologies for Steel Bridges, JSSC Technical Report No. 119, 2020 (in Japanese)
3) Okui, Y., Denda, D., Kumaki, K., Sakuma, S: A proposal for evaluation method of system redundancy and system factors in load rating of steel bridges, J. of Struct. Eng., JSCE, Vol.68A, pp.1-10, 2022 (in Japanese)

Fig. 4 System Factor ϕ_s and Ultimate Live Load Factor λ Obtained from Nonlinear Finite Element Analysis

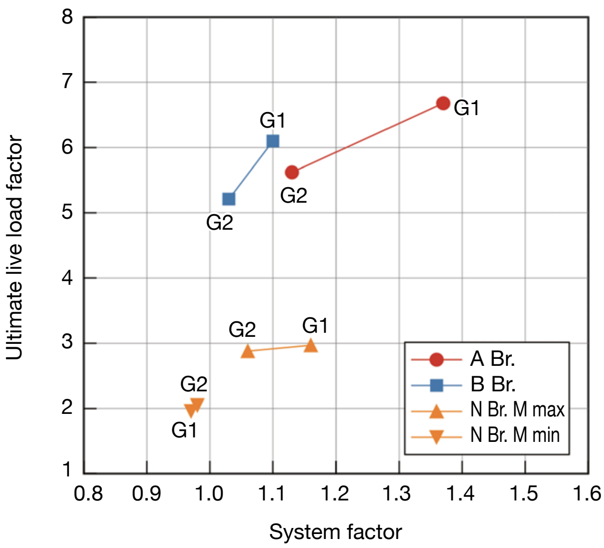


Fig. 5 Comparison between Experiment and FE Analysis of Box Column Buckling Test for Bridge High Performance Steel (SBHS500, R=0.9, λ=0.6)

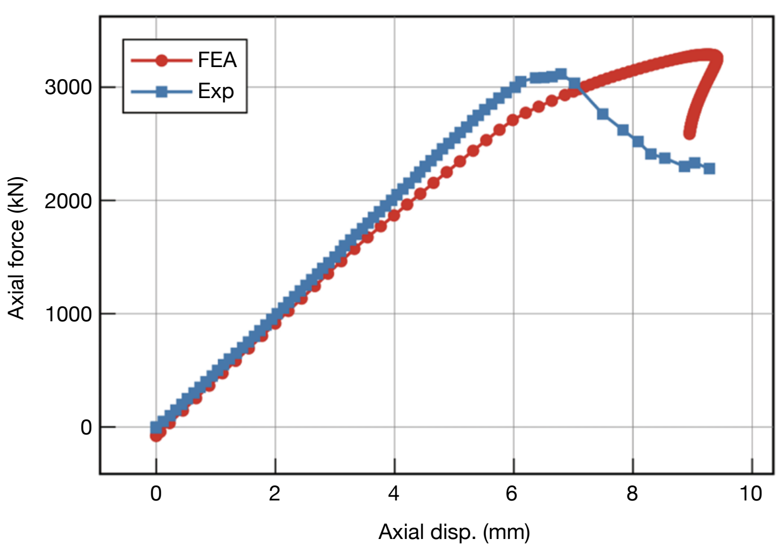


Fig. 6 Design Buckling Strength (Solid Curve) and Nonlinear FEA Results (Circle Mark) with Various Width-to-Thickness Ratio Parameters *R* and Column Slenderness Parameters λ

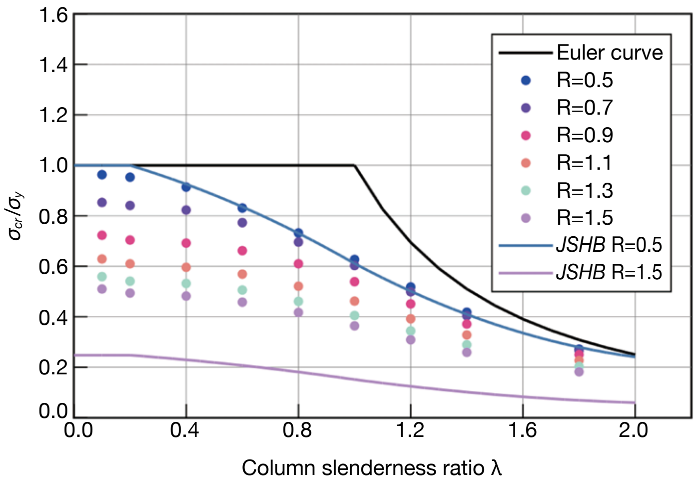
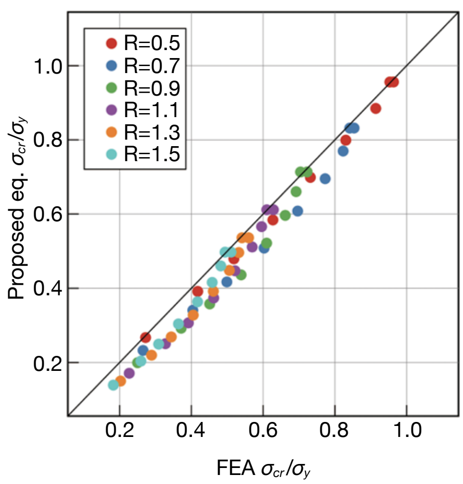


Fig. 7 Comparison between Proposed Design Equation and FEA Results



Report of the Working Group on Fatigue Strength

—Improvement of Fatigue Strength and Verification of Detection and Repair Technologies—

by Kengo Anami
Chief of the Working Group on Fatigue Strength, Research Committee on Steel Bridges with Higher Resilience and Longer Service Life (Professor, Shibaura Institute of Technology)

Kengo Anami: After graduating from the School of Engineering, Tokyo Institute of Technology in 1993, he served as research associate at Lehigh University in the US in 2001 and as associate professor at Shibaura Institute of Technology in 2008. He assumed his current position as professor at the Department of Civil Engineering, Shibaura Institute of Technology in 2014. His areas of expertise cover steel structures and their maintenance.

In order to tackle two major propositions imposed on steel bridges—higher resilience and longer service life, the Working Group on Fatigue Strength of the Research Committee on Steel Bridges with Higher Resilience and Longer Service Life promoted research and surveys with the aim of contributing to two propositions from the perspective of welded joint fatigue. Specific activities were promoted in view of the following two tasks:

- Quantitative evaluation method for the effect of weld toe treatment on the improvement of fatigue strength from the perspective of improving the fatigue strength of welded joints
- Effective and rational maintenance (effect of inspection and repair/reinforcement) from the perspective of the maintenance of steel bridges

An outline of the achievements of the Working Group on Fatigue Strength is as follows:

Quantitative Evaluation Method for the Effect of Peening Treatment on Fatigue Strength Improvement

Diverse approaches have been proposed as the method to improve the fatigue strength of welded joints by means of weld toe treatment. As for the peening treatment that improves fatigue strength by introducing compressive residual stress, an object of this research, many approaches have been proposed and extensive research has been promoted. As a result, this peening treatment has been put into practical use in bridges, centering on the existing bridges, but fatigue strength classes after peening treatment have not yet been established in Japan.

Noticing the application of peening treatment in newly-built or existing bridges, the Working Group promoted the examination of fatigue strength class after peening treatment, part of which is introduced below:

• Settlement of Fatigue Strength Classes of Welded Joints after Peening Treatment

In steel bridges, out-of-plane gusset and cruciform welded joints are joint forms that frequently pose fatigue-induced problems. Targeting these joints after three kinds of peening treatments—ultrasonic impact treatment (UIT), hammer peening on base metal (HP) and air-type needle peening (PPP), the Working Group experimentally examined the effect of peening treatment on fatigue strength improvement and evaluated the dependency of the effect of peening treatment on steel strength and stress ratio. At the same time, the Working Group analyzed the existing fatigue test data available in Japan and abroad.

As a result, it was confirmed that steel strength (yield strength) and stress ratio strongly affect the fatigue strength improvement by peening treatment, and then the Working Group proposed the fatigue design curve after peening treatment shown in Fig. 1. Fig. 2 shows ex-

Fig.1 Fatigue Design Curve of Peened Welded Joints

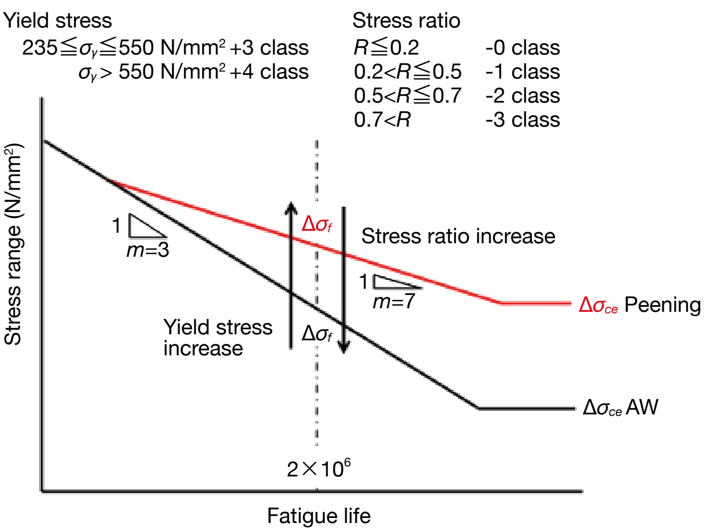
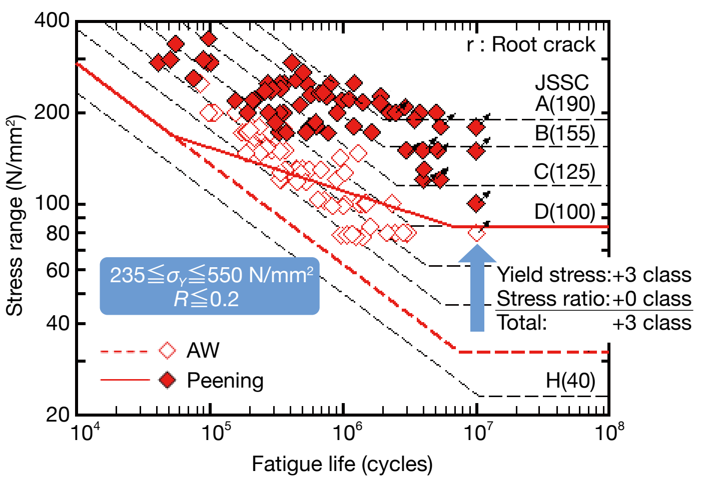


Fig.2 Comparison between Proposed Design Curve and Fatigue Test Results (Out-of-plane Gusset Welded Joints)



amples of fatigue design curves obtained by improving fatigue strength at 2 million cycles by 3 class, which is the sum of the influence of steel strength (yield stress: +3 class) and stress ratio (±0 class). The slope of design curve is proposed to be 7. Meanwhile, when the stress range is extensive, the effect on fatigue strength improvement becomes unavailable, and accordingly in the stress range that surpasses the point where the as-welded design curve and the peening curve intersect, a fatigue design curve similar to the as-welded fatigue design curve is applied in the figure.

• Examination of Precautions That Take into Account New Bridge Design

Regarding precautions for peening treatment at the stage of new bridge construction, the Working Group examined the stress ratio, blast treatment after peening treatment and working of compressive force occurring during bridge construction. In this connection, the result of examination of the influence of the pre-compressive loading on the peening effect is introduced in the following:

The plate-bending fatigue test (R=0.5) was implemented employing an out-of-plane gusset joint specimen as shown in Fig. 3 to which pre-compressive loading was applied. Fig. 4 shows the change in residual stress at the position 2 mm from the weld toe of the air-type needle peened specimen. As seen in the figure, the level of reduction of residual stress introduced by means of peening increased due to the increased pre-compression loading. In this examination, setting the level of pre-compression loading as a parameter, the fatigue test (R=0.5) was implemented after introducing pre-loading to examine the effect of pre-loading on the fatigue strength improvement by peening (the case of pre-compressive loading at 5.8 kN is shown in Fig. 5). The examination results showed that, as the level of pre-compressive loading increases, the effect of all 3 peening methods on fatigue strength improvement decreases.

Future plans call for further examination (including additional fatigue testing under R=0) of the relationship between the reduction of the rate of fatigue strength improvement and the pre-loading level, and incorporation of the effect of pre-compressive loading in the proposed design curves introduced above.

Effective and Rational Maintenance

Aiming at the effective and rational maintenance of steel bridges, the Working Group promoted the following examinations: (1) applicability of non-destructive method to detect fatigue crack without removing steel paint was examined; (2) focusing on the 2 typical countermeasures for the fatigue crack in steel bridge, namely (stop hole+splice plate) and (stope hole applied to weld bead), the rational repair/retrofit design method and quantitative evaluation method of effects of the countermeasure were discussed. In this section, examination of (stop hole+splice plate) is introduced.

In the activities of the Working Group on Fatigue Strength introduced in *Steel Construction Today & Tomorrow* No. 54 (August 2018), two methods to forecast the stop hole periphery stress that governs the reinforcement effect were explained: a method employing the cracking length and the splice plate structure as a parameter and another method employing the stress occurring at the upper surface of the splice plate. Aiming at establishing a rational splice plate design method, the Working Group examined the estimation of the fatigue strength of stop holes under the

Fig. 4 Reduction of Residual Stress due to Pre-compressive Loading

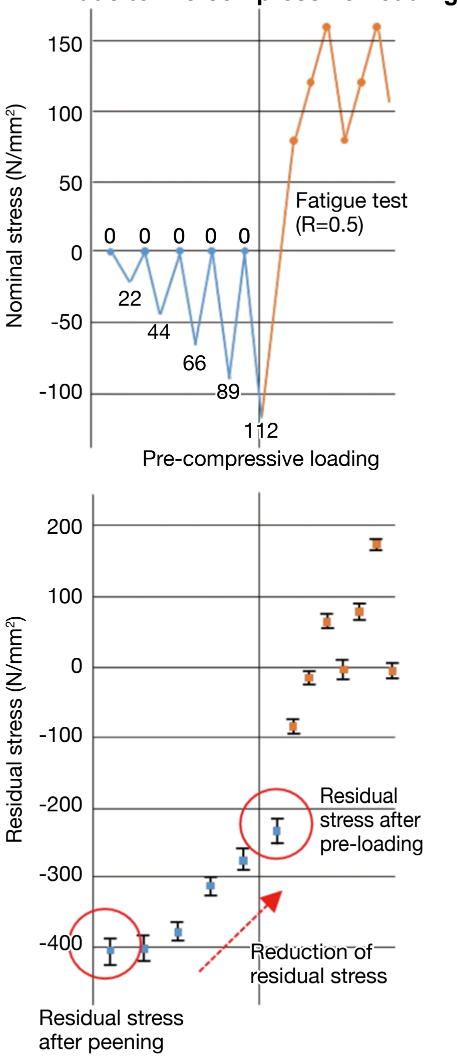


Fig. 3 Compressive Loading prior to Fatigue Test

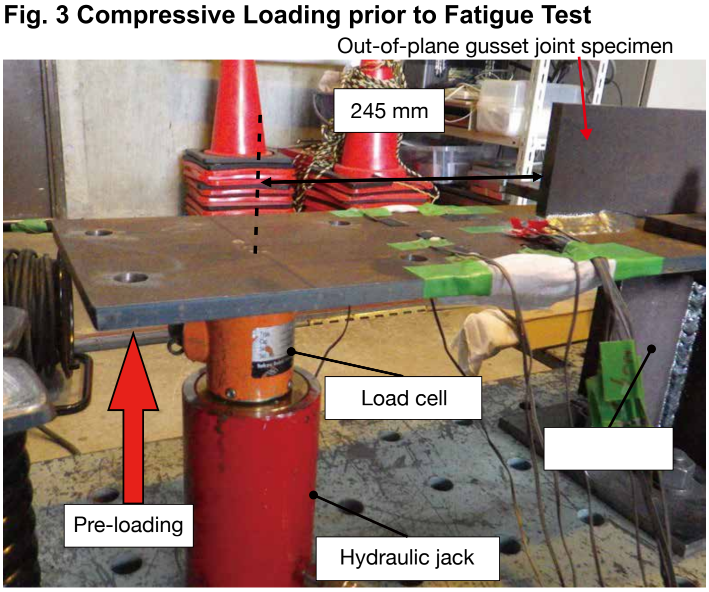
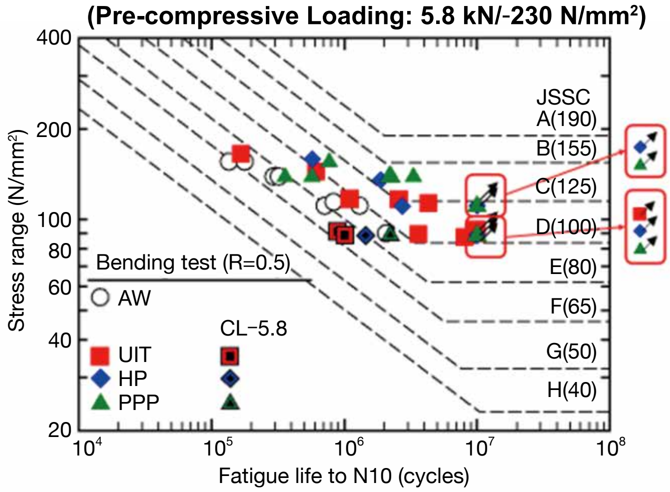


Fig. 5 Fatigue Test Results (Pre-compressive Loading: 5.8 kN/-230 N/mm²)



splice plate and a simple structural analytical approach for the stress at the stop hole periphery applicable in practical design, which are introduced in the following:

• Fatigue Strength of Stop Hole under Splice Plate

In accordance with the results of estimated stresses at the stop hole periphery, the tension fatigue test was conducted employing fatigue test specimens in which the splice plate thickness was changed so that the crack initiates from the stop hole periphery and from the area near bolt hole due to fletching (refer to Fig. 6). The fatigue test results are shown in Fig. 6. In the test, most specimens caused fracturing due to fletching in the neighborhood of the first bolt, and the fatigue strength of the specimen was equivalent to that of a high-strength bolt friction joint that caused similar fractures. Currently, the tension fatigue test is underway employing a specimen that can take into account the tensile residual stress due to welding.

Capitalizing on the results of both tests, it is planned to confirm the fatigue strength class of the stop hole under the splice plate and to make proposals towards the establishment of a rational design method for splice plate reinforcement.

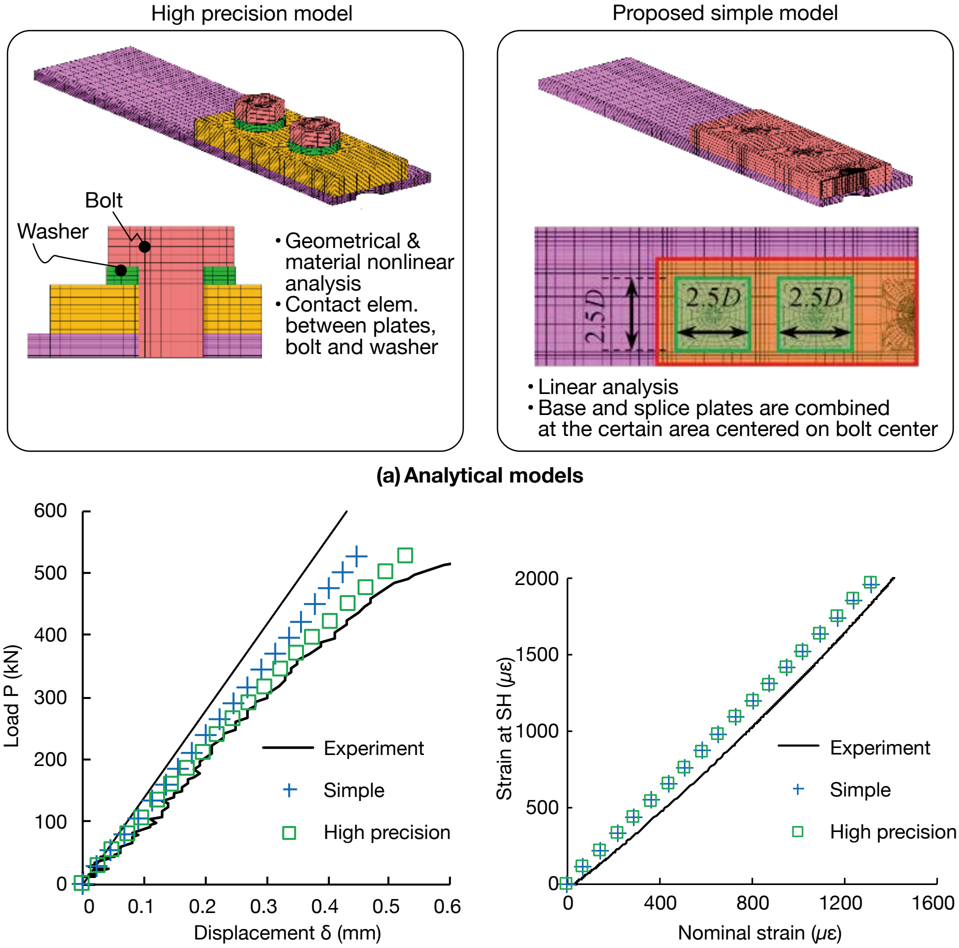
• Simple Model to Forecast the Stress at Stop Hole Periphery

In the activities of the Working Group on Fatigue Strength introduced in *Steel Construction Today & Tomorrow* No. 54 (August 2018), it was explained that the stress at the stop hole periphery and the behavior of the splice plate structure can precisely be shown by structuring the advanced high-precision FEM model shown in Fig. 7 (a). In this connection, if a simple FEM model were structured that can forecast the stress at the periphery of the stop hole under the splice plate within an elastic range, it is considered that this simple model will expand the possibility to design rational splice plates even for practical applications.

Currently, targeting the fatigue test specimen shown in Fig. 6, examinations are underway of several modelling approaches, which has led to the proposal of a simple model employing the solid element (Fig. 7).

The proposed model is a linear model that shares the nodes of the splice plate and the base plate within a rectangular range with a bolt center of 2.5D (D: bolt diameter). While slight differences are found in the load-displacement relationship between high-precision and proposed simple models, the stress at the stop hole periphery in both the high-precision and proposed simple models well coincide each other and is also well correlated with the experiment results.

Fig. 7 Proposed Simple Analytical Model

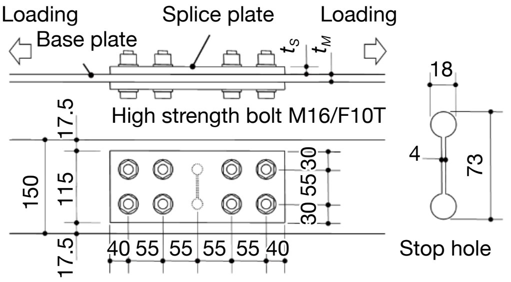


(a) Analytical models

(b) Relationship between load and displacement

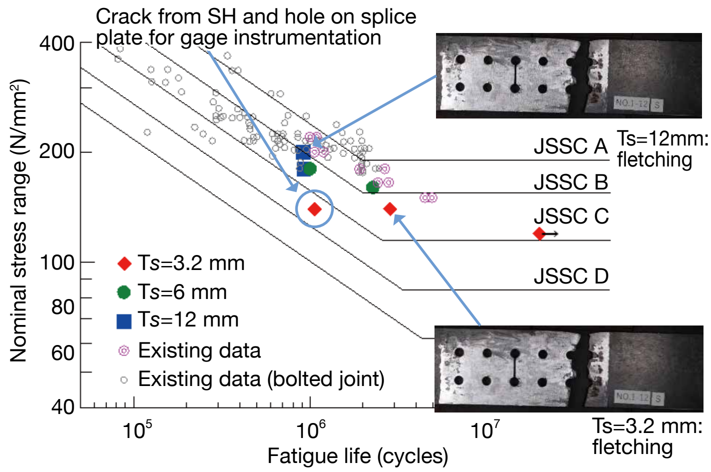
(c) Relationship between nominal strain and strain at stop hole

Fig. 6 Fatigue Tests for Stop Hole under Splice Plate



Base plate thickness:12 mm	
Splice plate thickness Ts	
12 mm (Expect fletching fatigue)	6 mm
3.2 mm (Expect fatigue from SH)	

(a) Fatigue test specimen



(b) Fatigue test results

Report of the Working Group on Corrosion and Durability

—Tasks of Applying Weathering Steel Bridges and Corrosion Repair Method for Steel Bridges—

by Eiji Iwasaki
Chief of the Working Group on Corrosion and Durability, Research Committee on Steel Bridges with Higher Resilience and Longer Service Life (Professor, Nagaoka University of Technology)

Eiji Iwasaki: After finishing the doctoral course at the Graduate School, Nagaoka University of Technology in 1990, he served as associate professor of Nagaoka University of Technology. He assumed his current position as professor, Graduate School of Nagaoka University of Technology in 2012. His areas of expertise cover structural engineering, steel structure engineering and structural analysis.

Noticing the technology conducive to reducing corrosion-protection costs and preventing corrosion-induced deterioration and damage to steel bridges, the Working Group on Corrosion and Durability of the Research Committee on Steel Bridges with Higher Resilience and Longer Service Life promoted examinations focusing on the following themes:

- Application of weathering steel in bridge construction that allows the minimization of lifecycle cost (LCC) in an appropriate corrosion environment and maintenance technology for weathering steel bridges
- Structural improvement and corrosion-protection material application technology as a means to improve the corrosion resistance and durability of steel bridges
- Measures to maintain and recover the corrosion resistance of steel bridges

In the survey of and research on the application of weathering steel bridges, the Working Group tackled the judgement on applicability or inapplicability of weathering steel bridges and the improvement of weathering steel bridge maintenance technology. Specifically, the Working Group promoted the following research and surveys—analysis of soundness levels based on periodic inspection data, the proposal of implementing periodical inspections, the effect of anti-freezing agent (deicing salt) spraying on weathering steel bridges, and the judgement of corrosion conditions of weathering steel bridges and of measures to cope with the occurrence of unusual corrosion.

As for measures to improve the corrosion resistance and durability of steel bridges, the Working Group tackled the judgement of the strength to resist the corrosion damage and measure to repair damaged bridges, structural improvement and methods to apply corrosion-prevention materials, and measures to maintain/recover corrosion resistance and its inspection method. Specifically, the Working Group promoted the following research and examinations: strength diagnosis for girder end and high-strength bolt friction joints, the method to repair corrosion-induced thickness reduction and the effect of repair methods on strength improvement, and methods to improve corrosion resistance. Developmental research on a steel bridge inspection simulator employing the corrosion map was also promoted.

Part of the specific activities of the Working Group on Corrosion and Durability are introduced in the following:

Evaluation of Applicability of Weathering Steel Bridges in Anti-freezing Agent Spraying Areas

While a few examples have been reported in which corrosion due to the scattering of anti-freezing agents has occurred in weathering steel bridges constructed in cold snow-fall areas, quantitative examinations of corrosion occurrence have scarcely been made. Then, we made surveys of the sprayed amount of anti-freezing agent on the road (refer to Photo 1), the amount of air-borne salt on the bridge girder and the amount of the reduction of the thickness of exposed steel members.

Survey results made clear that regarding the sprayed amount of anti-freezing agent on the road S (kg/m/day/lane) and the airborne salt on the girder C (mdd=mg/dm^2/day), a certain relationship of S=kC can be obtained[1]. In this relationship, k shows the contribution ratio of flying of the anti-freezing agent sprayed on the road to the girder section. Fig. 1 shows the contribution ratio of flying of the anti-freezing agent to a parallel bridge with no difference in el-

Photo 1 Road surface on the Kochi Expressway in Winter

evation. The spraying amount S on the road (4 lanes, each 2 for inbound and outbound) where 53 kg of anti-freezing agent is annually sprayed is 53 kg/m/365 days/4 lanes or 0.036 kg/m/day/lane. Because the contribution ratio of flying to the upper surface of flanges k is within a range of 2~5 as shown in the figure, it can be obtained that the flying amount to the upper surface of lower flange C is 0.072~0.18 mdd.

The practically-measured flying amount of anti-freezing agent on the bridge installed on this 4-lane road amounted to 0.113 mdd on the outside area of the inbound lane and 0.248 mdd on the outside area of the outbound lane, and thus it can be considered that the approximate flying amount on the girder can be calculated by the use of this flying contribution ratio. In addition, the above-mentioned examination showed that there is a correlation between the airborne salt amount and the corrosion-induced reduction in the thickness of steel test pieces. (Refer to Fig. 2)

Improvement in the Objective Evaluation of Rust Appearance of Weathering Steel Bridges

Weathering steel bridges suppress the development of rusting by forming an adhesive rust layer on their surface. However, there are cases in which the adhesive rust is not formed depending on the bridge installation environment and the specific property peculiar to the weathering steel cannot be demonstrated. To this end, it is necessary to evaluate the soundness level of rust conditions. Then, based on transparent-adhesive-tape tests, we structured a binary classification AI that is applied to determine whether or not the rust that occurred requires special care to be paid in maintenance. (Refer to Photo 2)

In order to confirm the classification accuracy of the AI, 8 kinds of data sets were prepared that are composed of the training data and the data used for evaluation (Table 1). In the table, the data means the transparent-adhesive-tape test data, C means the rust that requires care in maintenance and S means the rust that does not require care in maintenance.

While the amount of data and the ratio of C to S are changed for every data set, AI was structured for which the classification accuracy surpassed 90% for every data set. AI that showed the highest classification accuracy of 95.6% was that for data set 2-7, with which the correct evaluation result for rust appearance was obtained.

Meanwhile, there were cases of incorrect evaluation such as the case in which C was judged as C. How to reduce the case of undesirable evaluation is a future task in terms of practical applications.

Photo 2 Sample of transparent adhesive tape test

Diagnosis of Strength at Corroded Bolted Joints

High-strength bolted joints are the typical structural section where corrosion is liable to occur, and various countermeasures are applied according to the level of corrosion-induced deterioration—repainting, replacement of bolt and reinforcement and replacement of splicing plates. Therefore, in order to appropriately and rationally maintain high-strength bolted joints, it is required to understand and evaluate the sliding strength that meets the corrosion condition of each structural member (base plate, splicing

Fig. 1 Contribution Ratio of Flying of Anti-freezing Agents k

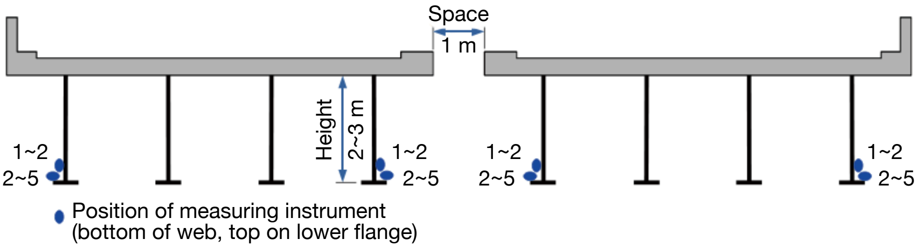


Fig. 2 Amount of Flying Deicing Salts and Corrosion Loss of Plate Thickness

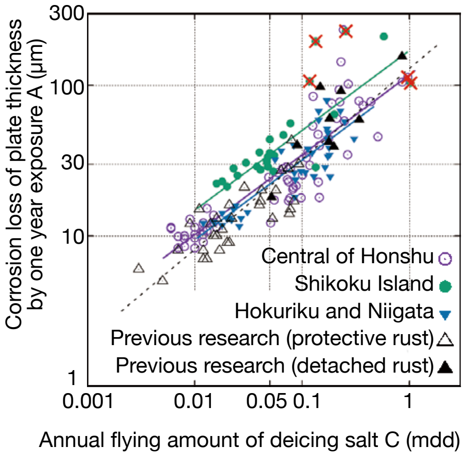


Table 1 Binary Classification Data Sets and Classification Accuracy

Data set	Number of training data		Number of data for evaluation	Classification accuracy (%)
	C	S		
2-1	20	140	160	91.9
2-2	60	420	160	93.1
2-3	100	700	160	94.4
2-4	140	980	160	94.4
2-5	220	1540	160	92.5
2-6	220	220	160	93.8
2-7	1540	1540	160	95.6
2-8	1540	3080	160	93.8

plate, high-strength bolt).

Taking into account these situations and notifying the high-strength bolt and splicing plate, examinations were made of the method to evaluate the tightening axial force and the sliding strength that conform with the thickness reduction form of the high-strength bolt and the splicing plate in which corrosion-induced thickness reduction occurs[2]. Examination results showed that the residual tightening axial force of corroded bolts can be evaluated with an accuracy of ±15% based on the corrosion form and the thickness reduction amount, which led to the proposal of the flow to evaluate the retained sliding strength of corroded splicing plates. (Refer to Fig. 3)

Development of Steel Bridge Inspection Simulator Employing Corrosion Map

One of the specific advantages brought about by the use of steel bridges lies in that their corrosion can be recognized immediately and visually, but corrosion characteristics (corrosion condition, corrosion factor, corrosion form, etc.) are diverse. Accordingly, high-level corrosion inspection skills are required such as continued accumulation of knowledge, on-site visual approach based on experience, capability to effectively implement inspections, and understanding of not only the serious corrosion that involves traffic regulation but also the specific features of the structure that is likely to cause corrosion.

Given such situations, we developed a steel bridge inspection learning software employing 3D corrosion maps prepared by means of the collection and analysis of corrosion examples[3]. In order to verify the validity of this software system, hands-on learning and questionnaire surveys with the participation of engineers were carried out and the results thus obtained were examined. (Refer to Fig. 4)

In the conventional learning method, a corrosion map was used that was prepared by arranging the corrosion records of bridges with different construction environments and lapse of application years to a record. In the newly-developed learning method, a 3D-CG corrosion map is used that was prepared based on respective bridge inspection data. Compared to the conventional method, this learning system employing the 3D-CG corrosion map was successfully evaluated as a system that is valid in effectively learning knowledge about corrosion inspections.

Fig. 3 Diagnosis of Strength at Corroded Joint Section

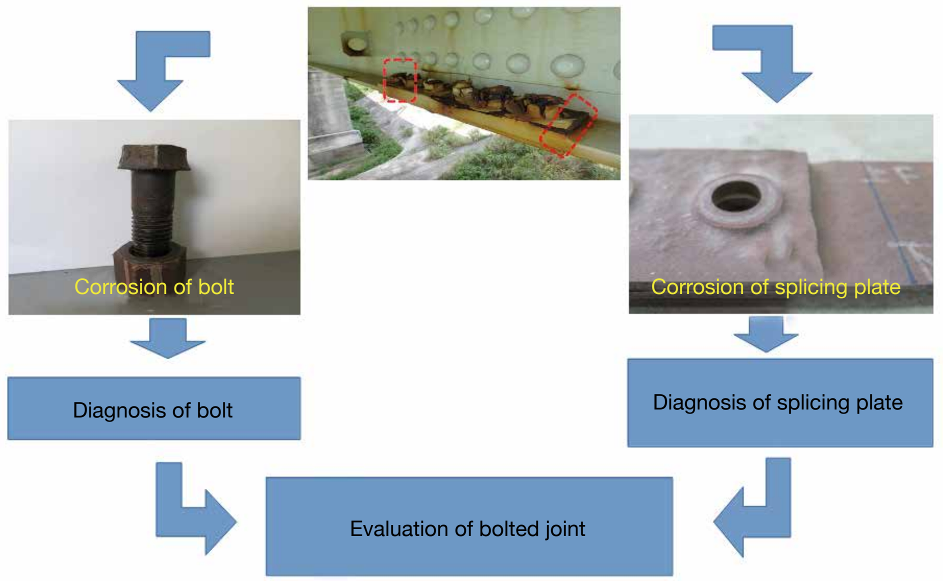
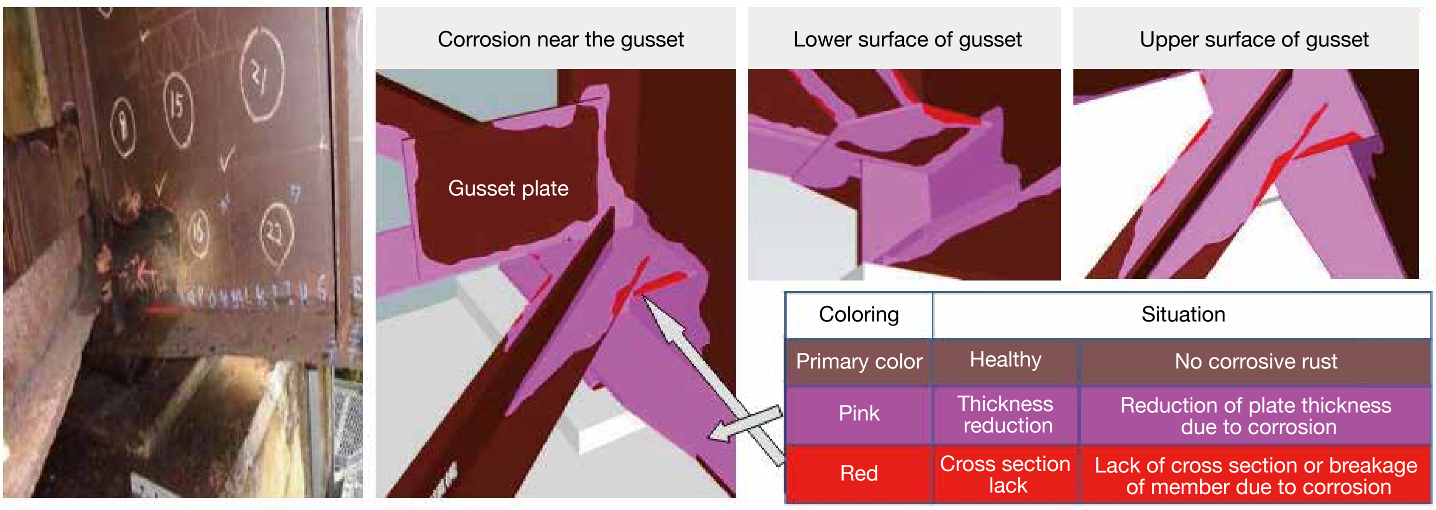


Fig. 4 Corrosion Inspection Simulator



Coloring	Situation	
Primary color	Healthy	No corrosive rust
Pink	Thickness reduction	Reduction of plate thickness due to corrosion
Red	Cross section lack	Lack of cross section or breakage of member due to corrosion

References

1) Eiji IWASAKI, Ryuichirou NAKASHIMA, Hiroshi TAWADA and Ikki ISHII: EVALUATION OF APPLICABILITY OF WEATHERING STEEL BRIDGE IN DEICING SALT SPRAYING DISTRICTS, Doboku-Gakkai-Ronbunsyuu A1, Vol.74, No.3, 440-457, 2018 (in Japanese)

2) Shuhei YAMASHITA, Tetsuhiro SHIMOZATO, Masayuki TAI, Tasunori ARIZUMI and Tetsuya TABUKI: CORROSION BEHAVIOR OF SPLICED PLATE AND SLIP RESISTANCE IN HIGH STENGTH BOLTED CONNECTIONS, Doboku-Gakkai-Ronbunsyuu A1, Vol.74, No.3, 359-375, 2018 (in Japanese)

3) Yasushi NAGASWA, Tetsuhiro SHIMOZATO, Masayuki TAI, Yoshiaki TAMAKI and Yusuke HIWA: DEVELOPMENT OF LEARNING SYSTEM FOR CORROSION INSPECTION OF STEEL BRIDGE USING 3DCG, Doboku-Gakkai-Ronbunsyuu H, Vol.75, No.1, 35-47, 2019 (in Japanese)

SBHS
—High-performance Steel for Bridges Originated in Japan—

by Masahide Takagi
Chief Manager, Research Group on Steel Products for Bridges
The Japan Iron and Steel Federation

Masahide Takagi (Dr. Eng.): After receiving his Master's degree at the Graduate School of Engineering, Osaka University, he entered Nippon Steel Corporation in 1994 and has since been engaged in technical development and promoting the application of steel products for bridges. He concurrently serves as a member of the Research Group on Steel Products for Bridges at The Japan Iron and Steel Federation.

Outline of SBHS

It is said that the origin of iron bridges in Japan is the Kurogane Bridge constructed in 1868 in Nagasaki Prefecture (the Japanese term Kurogane means iron). Since then, iron and steel materials applied in bridge construction have evolved from cast iron and wrought iron to steel and at the same time incessantly followed the path towards higher performance in conformity with the needs of the times.

Two motivating forces behind the steady development of steel products for bridges are cited: the progress of steel product manufacturing technology and the growing need for higher-performance steel products. SBHS (Steels for Bridge High Performance Structure) is a high-performance steel product destined for bridge construction and originating in Japan. Triggered by the project to develop high-performance steel products in the U.S., SBHS has been developed capitalizing on joint efforts among universities (incl. research institutions), steelmakers and bridge fabricators[1]. Currently, it is accepted that SBHS is the steel product positioned as the forefront in the advancement of steel products destined for common application to steel bridge construction.

Table 1 shows an outline of SBHS specified in JIS (JIS G 3140), and Table 2 shows the comparison of the properties of SBHS and conventional structural steel for bridge use. SBHS is produced by reflecting the advanced steel product manufacturing technology available in Japan, applied with the aim of improving the diverse performance offered by steel bridges as infrastructure. Further it guarantees tensile strength, fracture toughness, weldability, workability, weather resistance performance and other properties higher than those of conventional steel products.

A specific feature in the production of SBHS is the standard use of the ther-

Table 1 Digest of SBHS Standard (JIS G 3140)

Designation	Plate thickness (mm)	Yield strength (N/mm²)	Tensile strength (N/mm²)	Charpy absorbed energy*	Cracking parameter P_{CM}(%)
SBHS400 SBHS400W**	6≦t≦100	≧400	490～640	≧100J@0℃	≦0.22
SBHS500 SBHS500W**		≧500	570～720	≧100J@-5℃	≦0.20
SBHS700 SBHS700W**	6≦t≦50	≧700	780～930	≧100J@-40℃	≦0.30
	50<t≦75				≦0.32

*Sampling direction: Perpendicular to rolling direction
**W: Specifications of weathering steel (Prescription of composition range: Cu, Cr and Ni)

Table 2 Comparison of Characteristic Properties between SBHS and Conventional Steel (SM, SMA) (Example in 50 mm-thick steel plate)

		490 N/mm²-grade steel		570 N/mm²-grade steel		780 N/mm²-grade steel	
		SBHS400 SBHS400W	Conventional steel (SM490Y/SMA490W)	SBHS500 SBHS500W	Conventional steel (SM570/SMA570W)	SBHS700 SBHS700W	Conventional steel (HT780*)
Strength	Yield point (N/mm²)	≧400	≧335	≧500	≧430	≧700	≧685
	Constant yield point	○ (6-100 mm)	△ (≧ 40 mm)	○ (6-100 mm)	△ (≧ 40 mm)	○ (6-75 mm)	△ (≧ 40 mm)
Workability Weldability	Excellent toughness	○ (≧100J@0℃)ᴵ	△ (≧47J@ 0℃)ᴵᴵ	○ (≧100J@ 5℃)ᴵ	△ (≧47J@-5℃)ᴵᴵ	○ (≧100J@-40℃)ᴵ	△ (≧47J@-40℃) ᴵᴵ
	Reduction of preheating temperature	○ (No preheating)	△ (Preheating temperature: 80℃ or more)	○ (No preheating)	△ (Preheating temperature: 80℃ or more)	○ (Preheating temperature: 50℃ or more)	△ (Preheating temperature: 100℃ or more)
Corrosion resistance	Weathering steel spec.	○ (SBHS400W)	○ (SMA490W)	○ (SBHS500W)	○ (SMA570W)	○ (SBHS700W)	–

○: Response with common specifications △: No response with common specifications
I: Sampling direction: Perpendicular to rolling direction II: Sampling direction: Rolling direction *: HBS G 3102

mo-mechanical control process (TMCP), an original steel plate manufacturing technology from Japan. TMCP is a technology that appropriately controls the rolling temperature and cooling speed of steel plates and makes the microstructure of steel fine (Photo 1), which allows for the improvement of the mechanical properties of steel plates such as high tensile strength and improved fracture toughness. In addition, TMCP brings about further advantages—for example, higher tensile strength is attained by the addition of small amounts of alloying elements, and thus weldability is improved (see Fig.1).

In the development of SBHS application technology for bridge construction, an important task has been how to maximize steel bridge performance with the effective use of improved properties of steel products mentioned above.

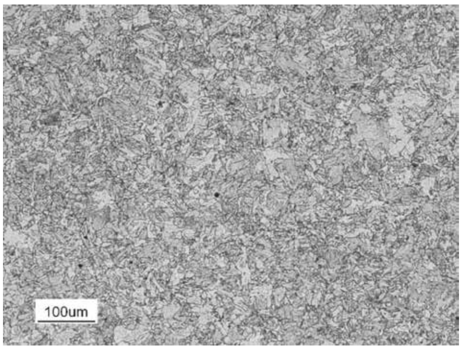
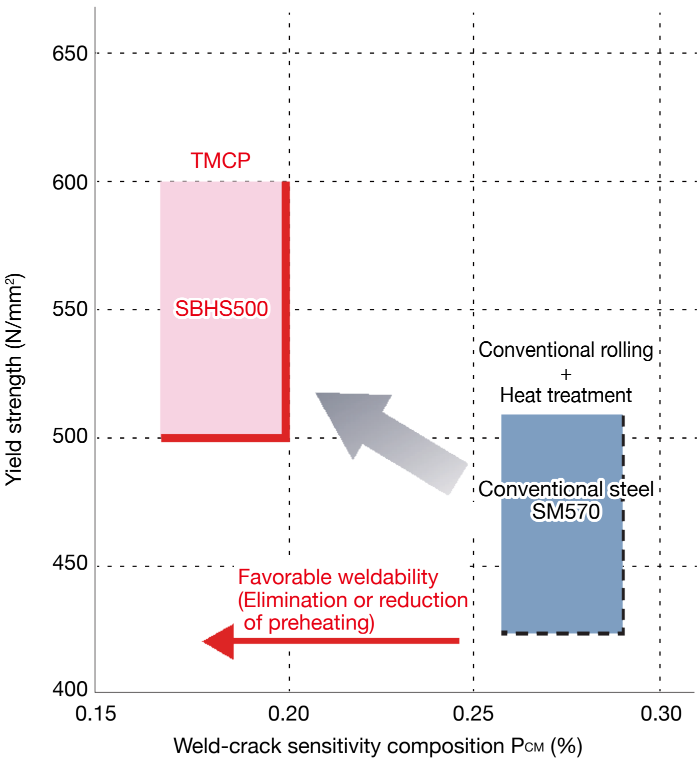


Photo 1 Microstructure of SBHS

Fig.1 Relationship between P_{CM} and Yield Strength



Application Advantages of SBHS

In conventional steel products, as the strength required increases, the workability such as weldability lowers, thereby causing the difficulty in fabrication of steel structures. In contrast, in SBHS, because the addition of the alloying elements that adversely affect weldability can be reduced due to the application of TMCP, the weldability is improved by a great margin compared to that of conventional steel plates with an identical level of tensile strength. Furthermore, welding materials have been developed that can conform with various welding methods and fully secure the specific performance required for welded joints, and steel member fabrication techniques have been prepared that allow for the application of high-strength steel plates in various structures.

Diverse advantages are expected to be brought by the use of SBHS—not only an economic advantage available by means of the lightweight construction of bridge structures but an improvement in safety, reliability and durability required as the infrastructure. For example, not only can heavy-thick steel members be used by changing on-site joint from bolt joint to weld joint by the optimized use of favorable weldability peculiar to SBHS but the thickness of the plates to be applied can also be reduced due to no bolt hole-related reduction of cross-sectional area, and further the durability can be widely improved by eliminating the bolt joint-induced uneven member surface that might serve as a defect in terms of corrosion protection. To this end, expectations are high for the effective use of specific properties of SBHS to make a steady contribution towards the improvement of the overall performance over the life cycle of bridges.

Practical Application of SBHS in Bridge Construction

The bridge to which SBHS was first applied is the Tokyo Gate Bridge (Photo 2) with the main span composed of a truss-box hybrid structure. It was

Photo 2 Tokyo Gate Bridge

Photo 3 Ground assembly of large blocks by means of on-site welding

opened to traffic in 2012 in the mouth of the Port of Tokyo. In the bridge, diverse technologies were introduced to promote rationalized construction. Specifically, large-block truss structures were assembled by means of on-site welding at an on-site yard, and the bridge was constructed employing a large-block erection method (see Photo 3). It is reported that the specific property of not only high strength but also ease of application of on-site welding peculiar to SBHS greatly contributed towards labor saving in construction and the reduction of construction cost.

Table 3 shows the main application record for SBHS. Since the first application with the Tokyo Gate Bridge, SBHS is showing increasing adoption in ways that are conducive to realizing rationalized bridge structures and larger-scale bridges in diverse bridge types such as space-truss (see Photo 4), arch, rigid-frame and box-girder bridges, which has thus led to the contribution of economical construction of bridges and the enhancement of their reliability.

Incorporation of SBHS in Technical Standards for Bridges

It was in 2008 that SBHS and its welding materials were standardized in Japanese Industrial Standards (JIS G 3140 and others), so it was standardized at a relatively early stage of SBHS development. However, it took a long time until SBHS was incorporated in the technical standard for bridges (*Specifications for Highway Bridges*). This is attributable to the fact that it was not allowed for bridges to see the deterioration of safety from the application of new materials, and thus it was required to verify whether or not bridges constructed using new materials possessed sufficient safety from a wider perspective, including those not specified in the technical standard.

In the development of SBHS, with the cooperation of the university and other related organizations, the Research Group on Steel Products for Bridges accumulated useful data pertaining to strength characteristics such as material property, load-bearing capacity and fatigue strength as the structural member and further the workability through the systematic welding tests, and at the same time compiled a track record of application to practical construction, such as the Tokyo Gate Bridge. The goal of the Research Group was to demonstrate the reliability of SBHS.

Specifically, in the experiment of buckling strength, in order to prove no lowering of the strength attributable to the difference of material properties and the dispersion of strength not only in the plate elements such as outstanding plates and simply supported plates that compose the structural member but in the structural members such as columns and girders that compose the bridge, some research institutions conducted systematic material tests and diverse kinds of full-scale fracture tests that take into account the initial imperfections at the stage of member manufacture over several years. These endeavors successfully verified that SBHS offers sufficient safety in bridge construction.

The steady accumulation of this data was highly assessed, which led to the incorporation of SBHS400 and 500 in the 2017 version of the *Specifications for Highway Bridges*[3]. The preparation of the technical standards showed that SBHS, which until now was imagined as a steel material destined for special-purpose bridges, could be applied in the construction of general-purpose bridges.

Future Prospects

A trial calculation was made for the case of applying SBHS400 and 500 in the construction of a 3-span continuous composite twin I-girder bridge with an average span of 60 m and a 3-span continuous composite narrow box-girder

Photo 4 Nagata Bridge (space-truss)

Table 3 Record of Applications of SBHS

Year	Bridge name	Structure type	Steel grade (t_{MAX})
2006	Rinkai Chuo Bridge, Tokyo Port Seaside Road	Box girder	BHS500 (59 mm)
2006–2009	Tokyo Gate Bridge Tokyo Port Seaside Road	Truss-box hybrid Box girder	BHS500 (50 mm)
2009	Nagata Bridge	Space truss	SBHS500 (67 mm)
2009	Inba-shosuiro Bridge	Box girder	SBHS500 (59 mm)
2011	Shin-Miyagawa Bridge	Truss	SBHS 400W (22 mm)
2012	Otagawa-ohashi Bridge	Arch	SBHS500 (67 mm)
2012	Takatsuki JCT Bridge, Shin-Meishin Expressway	Bridge pier	SBHS500 (57 mm)
2012	Asakegawa Bridge, Shin-Meishin Expressway	Arch	SBHS500 (86 mm)
2014	Nutanohara Bridge	Rigid frame	SBHS500W (27 mm)

bridge with an average span of 80 m, the common bridge types in Japan. It was reported from the calculation results that the steel weight could be reduced by about 5~6% and the construction cost by about 2% in the case of applying SBHS400 and 500 compared to the case of applying conventional steel products (refer to Figs. 2-4)[4].

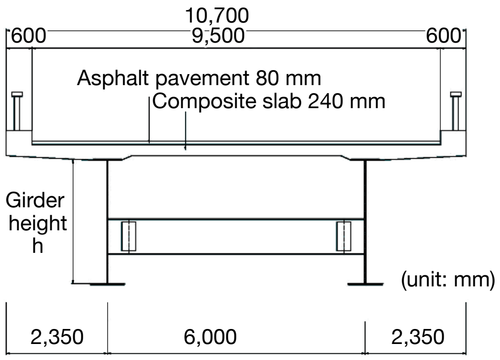
The application of high-performance steel products such as SBHS allows for the reduction of the amount of steel products to be applied and it will be feasible to rationalize bridge construction and reduce the construction cost due to the effective use of improved weldability and lightweight bridge construction. In addition, the reduced steel weight and labor saving in construction will serve as an effective means for reducing CO_2 emissions, which has become as important as ever.

SBHS is an advanced steel product that meets the Japanese steel industry's initiative toward solving environmental issues through the supply of eco-friendly steel products. In light of this, the Research Group on Steel Products for Bridges is exerting every effort toward promoting the application of SBHS.

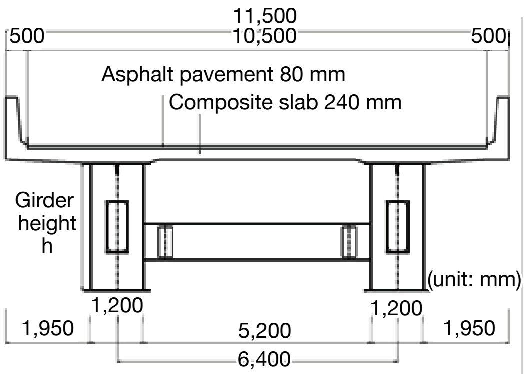
References

1) Chitoshi Miki, Atsushi Ichikawa, Takashi Kusunoki and Fumimaru Kawabata: Proposal of New High Performance Steels for Bridges (BHS500, BHS700), Journal of the JSCE, No.738, I-64, pp.1-10, July 2003 (In Japanese)
2) (e.g.) Katsuyoshi Nozaka, Yoshiaki Okui, Masato Komuro, Takeshi Miyashita, Kuniei Nogami, Masatsugu Nagai: Experimental Study on the Strength of SBHS I-girder, Journal of Structural Engineering, Vol. 59A, pp. 70-79, March 2013 (In Japanese)
3) Japan Road Association: Specifications for Highway Bridges, II Steel Bridges and Steel Members, November 2017 (In Japanese)
4) Masahide Takagi, Masashi Kato, Masahiro Matsushita, Hiroshi Iki: A study on Effective Utilization of SBHS for Steel Highway Bridge based on a Trial Design, Bridge & Foundation Engineering, pp. 35-40, January 2020 (In Japanese)

Fig. 2 Bridges subjected to Trial Calculation

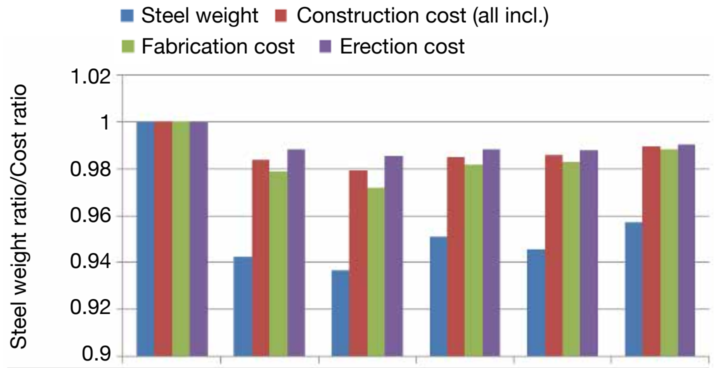


Composite twin I-girder
(average span: 60 m)



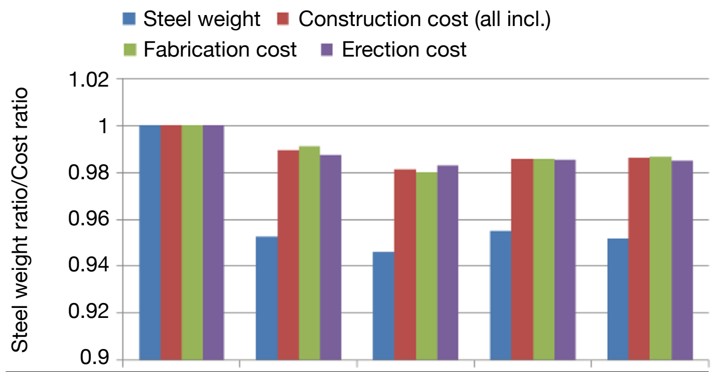
Composite narrow-box girder
(average span: 80 m)

Fig. 3 Calculation Results for I-girder



	Case 1	Case 2	Case 3-1	Case 3-2	Case 3-3	Case 3-4
Girder height (mm)	2,900		2,700	2,600	2,550	2,500
Steel grade	SM	SM+SBHS				
Min. web thickness	14 mm	15 mm	14 mm		13 mm	

Fig. 4 Calculation Results for Narrow-box Girder



	Case 1	Case 2	Case 3-1	Case 3-2	Case 3-3
Girder height (mm)	2,900		2,700	2,600	2,550
Steel grade	SM	SM+SBHS			
Min. web thickness	14 mm	15 mm	14 mm		13 mm

FY 2021 AJSI Webinar: Energy-Efficient and Environmental Transition towards Sustainable Steel Industry

The Japan Iron and Steel Federation (JISF) concluded a memorandum with the ASEAN Iron and Steel Council (AISC) in fostering interaction concerning the environment, standardization and trade in May 2014. In the field of the environment, with the cooperation of the Ministry of Economy, Trade and Industry, the JISF has started up a public-private collaborative scheme called the ASEAN-Japan Steel Initiative (AJSI). The purpose of this initiative provides the platform for exchanging knowledge and experiences to contribute to energy saving and environmental protection in the ASEAN countries. In addition, the AJSI aims to encourage technology transfer from Japan to the ASEAN steel industry. To make them realize, the JISF focuses on three main activities of Steel Plant Diagnosis, Technologies customized List and Public and Private Collaborative Workshop.

On February 24, 2022, as a part of AJSI, the JISF held the online seminar "FY 2021 AJSI Webinar: Energy-Efficient and Environmental Transition towards Sustainable Steel Industry" targeting Indonesia, Singapore, Thailand, the Philippines, Vietnam, Malaysia and Myanmar, to which a total of more than 200 persons from the government, steelmakers and others in those nations participated.

For the ASEAN steel industry, which has been impacted by the COVID-19 as with other nations, the webinar covered examples of short-term energy efficient and environmental protection measures that are currently in high need and simple in practical use. Moreover, the JISF introduced the outline of the online Steel Plant Diagnosis conducted for the first time. In addition, the webinar provided information about medium to long-term energy efficient, and environmental initiatives and measures. The AISC expressed gratitude for the contribution of the past AJSI activities in the ASEAN steel industry, and also showed the view that it would be meaningful to discuss the solutions to the stagnation of energy saving and environmental protection initiatives by the Corona disaster with Japan.

The JISF, jointly with the Japanese government, is determined to continue to supply support for energy efficiency and environmental protection to the ASEAN steel industry through the activities of AJSI in the future.

Presentation at the SEAISI Online Event

At the South East Asia Iron and Steel Institute (SEAISI) Sustainability & Construction Fortnight e-Event held on November 26, 2021, Takehiko Tagami, a member of JISF's Committee on Overseas Market Promotion, gave a presentation titled "Market Development of Steel Structures in Japan: Standardization, Building Codes and Steel Products." The presentation was delivered at the request of the Sub-Committee on Steel Application in Construction Sector of SEAISI to which JISF participates as an observer.

This SEAISI's event is annually held at the year-end. The online event in 2021 was held in two parts: ASEAN iron and steel sustainability topics at 1st week (15-19 Nov.) and sustainable construction including related presentation from Japan at 2nd week (22-26 Nov.). In the Japan's presentation, Takehiko Tagami addressed the background of growth and trends of steel construction markets in Japan, the relationship among government, academia and industry for application of steel structures, and Japan's building codes and its management system. In addition, he introduced the effort for the development of advanced steel products for construction such as steel product for earthquake-resistant buildings and their applications.

STEEL CONSTRUCTION TODAY & TOMORROW

Published jointly by
The Japan Iron and Steel Federation
3-2-10, Nihonbashi Kayabacho, Chuo-ku, Tokyo 103-0025, Japan
Phone: 81-3-3669-4815 Fax: 81-3-3667-0245
URL https://www.jisf.or.jp/en/index.html

Japanese Society of Steel Construction
3F Aminosan Kaikan Building, 3-15-8 Nihonbashi, Chuo-ku, Tokyo 103-0027, Japan
Phone: 81-3-3516-2151 Fax: 81-3-3516-2152
URL http://www.jssc.or.jp/english/index.html

Edited by
Committee on Overseas Market Promotion, The Japan Iron and Steel Federation
Chairman (Editor): Keiji Ando

Published three times per year, **STEEL CONSTRUCTION TODAY & TOMORROW** is circulated to interested persons, companies and public organizations to promote a better understanding of steel products and their application in the construction industry. Any part of this publication may be reproduced with our permission. To download content (PDF format), please go our website at: https://www.jisf.or.jp/en/activity/sctt/index.html. We welcome your comments about the publication and ask that you contact us at: sunpou@jisf.or.jp.