Japan-Bangladesh Joint Seminar on Advances in Bridge Engineering ISBN: 984-32-2520-6
Dhaka, Bangladesh. 10 August 2005

Highway bridge specifications and recent development of steel-concrete composite bridges in Japan

Masatsugu Nagai*

Department of Civil and Environmental Engineering, Nagaoka University of Technology
1603-1, Kami-tomioka, Nagaoka 940-2188, Japan

Abstract

Highway Bridge Specifications in Japan is introduced, which covers all the national roadway bridges. After shifting the technical standards based on specifications to those based on performance in 2002, next revision is now under consideration. Shift to LSD with partial safety factor format, explicit statement of lifetime, strengthening specifications for enhancing durability, addition of provisions that meet newly developed composite girder bridges with very simple transverse stiffening system and so on are expected. In order to reduce the bridge construction cost, new technology has been developed and being used, and they are introduced in detail. For further reduction of the construction cost, the importance of introduction of innovative design concept is emphasized.

1. Introduction

This paper deals with three topics. The first one is Highway Bridge Specifications in Japan (JHBS)[1)] and the second one is recent development of steel-concrete composite bridges for reducing the construction cost and enhancing durability. Finally, future subjects for further reducing the construction cost are presented.

Design Specifications for Highway Bridges was revised in 2002. The basic concept is to shift the technical standards based on specifications to those based on performance. In addition, several provisions were added in order to meet new requirements for constructing economical bridge systems. The next revision is now under consideration. Since the work for revision has just started, at the present moment, the contents of new version is not clear. However, shift from Allowable Stress Design method (ASD) to Limit State Design method (LSD) with partial safety factor format is expected.

* E-mail: nagai@nagaokaut.ac.jp

The new bridge technology developed for reducing the construction cost is explained. Under the leadership of Japan Highway Public Corporation (JH), the revival of continuous composite girder bridges and the structural reform from multi-girder to two- or three-girder bridge system with very simple stiffening system have been made. Based on economical evaluation made by JH, when the span length is from 30 to 60 meters, these newly developed steel-concrete composite girder bridges are the most competitive solution and have been widely used now in Japan. For attaining further reduction of construction cost, since the newly developed bridge system is too simple to reform, it is recommended to incorporate the design innovation.

2. Design specifications for highway bridges

The Design Specifications for Highway Bridges in Japan (JHBS)[1)] was issued from Japan Road Association (JRA) around 100 years ago and have been revised many times. Recent main revision was made in 1993 and 1996. In 1993, specifications related to live load was revised in order to meet the increasing size of vehicle and the improvement of durability. In 1996, after the Hyogo-ken Nanbu earthquake, the seismic design method was revised. JHBS covers all the national roadway bridges whose span length is less than 200 meters. Besides the above Specifications, there are a number of guidelines, such as Specifications for steel, composite and concrete structures issued by Japan Society of Civil Engineers (JSCE), and have been used as a reference. For long-span highway bridges such as the Honshu Shikoku Connecting Bridge Project, Design Specifications issued by the Honshu Shikoku Bridge Authorities are available.

JHBS consists of 5 parts; Common rules for design, Design of Steel bridges, Concrete bridges, Sub-structures and Seismic design. Basically, stability of the structures has been checked based on the Allowable Stress Design method (ASD). Fatigue problems have not been dealt with except for designing the steel deck plate. However, in view of increasing fatigue damage in steel bridges, Guidelines for Fatigue Design was newly issued in 2002. In the 2002 edition, performance based design concept was also introduced.

The next revision of the Design Specifications for Highway Bridges is now under consideration. Introduction of Limit State Design method (LSD) is expected, in which ultimate, serviceability and fatigue limit states of the bridge will be checked by employing the partial safety factor format.

Hereafter, we introduce the revision of the Specifications made in 2002 and an outline of the next revision now under consideration.

2.1 Recent revision of specifications for highway bridges

The design standards were revised in 2002. The basic concept is to shift the existing technical standards based on specifications to those based on performance, and to give consideration for improving durability of the bridges. In addition, new provisions were added to meet requirements for designing newly developed economical bridge system, which will be introduced later in this paper.

2.2 Revision in the common section

The followings are main revised items.

1. Performance required for designing a bridge has been clearly indicated.
2. Required items for materials and regulations on wire rope and parallel strand have been added.
3. Required performance for bearing shoes and expansion joints have been defined and their design procedures have been also prescribed.
4. Installation of water-preventing layer between asphalt pavement and concrete slab has been obliged, and checking items for enhancing durability of the slab have been listed.

2.3 Revision in section on steel bridges

The followings are the main revised items.

1. Design code for checking fatigue strength has been added in order to enhance durability. In view of increasing fatigue damage in steel bridges, fatigue check has been obliged.
2. Available upper limit of the plate thickness has been increased from 50 to 100 millimeters, including weathering steel. In Japan, in order to reduce the construction cost, instead of multi-girder system, construction of two-girder bridge has been increasing. This results in the use of larger thickness of the lower flange plate exceeding 50 millimeters. To meet this requirement, upper limit of the available thickness has been increased.
3. Use of tension-type bolt connection has been increasing. New specifications on tension-type bolt connection has been added.
4. As mentioned in above 2), construction of two-girder bridge has been increasing. In this bridge system, instead of RC slab, pre-stressed concrete (PC) slab has been used to meet the wide span. Hence, specifications on PC slab have been added.
5. Since a thick plate exceeding 50 millimeters is welded, detecting inner defect at the welding points becomes very important. Hence, the regulations on non-destructive testing such as ultrasonic testing of welds have been strengthened.
6. In view of increasing fatigue damage in steel deck plate, regulations on fabrication of the steel deck plate have been added.

2.4 Revision now under consideration

Discussions on next revision have started. First meeting was held on July 2004. Final revised version is expected to issue in 2007. New revised version may consist of 3-level document; Level-1 is basic of design (definition of required performance), Level-2 is standard specifications (measures to satisfy the required performance) and Level-3 is reference materials (theory, technical information and examples etc.) .
Although not finalized at all, the issues would be

1. Introduction of limit state design with the partial safety factor format which meets ISO
2. Clear definition of performance of bridge and its component
3. Specifications related to maintenance of existing bridges
4. Specifications for durability and explicit statement of lifetime of bridges
5. Specifications for composite structures and members
6. Specifications for new structural type such as steel girders with less stiffeners
7. Specifications for structural analysis and modeling

2.5 Design code for steel and composite structures by Committee of Steel Structures of JSCE

Committee of Steel Structures of JSCE has just started the project to publish Standard Specifications for Steel and Composite Structures. It is based on LSD and partial safety factor format will be employed. Design code for steel structures was issued in 1987 and revised in 1997. These versions were based on LSD. Design code for composite structures was also issued in 1989, however, it was incorporated in Guidelines for Performance-Based Design of Steel-Concrete Hybrid Structures and was issued by Committee of Structural Engineering of JSCE in 2002.

New Standard Specifications for Steel and Composite Structures consists of 5 parts; Basic planning, Performance-based Design, Fabrication, Maintenance and Seismic design, and will be published in 3 or 4 years, which includes latest research fruits. Furthermore, the design format will meet ISO format.

3. Recent development of steel-concrete composite bridges

In order to reduce the bridge construction cost, instead of multi-girder system, recently the bridge with two or three main girders has been increasing. It is natural to consider, when we design plate girder bridges, that the employment of smaller number of girder leads to economical solution. In such system, since the slab span becomes wider, pre-stressed concrete slab or steel-concrete composite slab with higher durability is inevitable. This practice is completely different from that of European engineers. They have been using RC slab until the span length reaches 8 or 10 meters.
In the followings, newly developed composite I-girder and box-girder bridges are introduced. Regarding the economical evaluation of various types of bridges, we followed the estimation made by JH.

3.1 I-girder bridges

For bridges with a width from 10 to 11 meters (2-lane), PC slab is supported by two girders and, for bridges with the width around 18 meters (3-lane), PC slab is supported by two or three girders. These are shown in Figure 1. The main girders are connected with small-sized rolled cross beams only installed at a distance from 5 to 10 meters. The main role of the cross beam is to support the erection facilities and to prevent lateral torsional buckling instability of the main girder at intermediate supports. This bridge system is very simple, which has a slab, two or three I-girder and small-sized rolled cross beams.

By employing this system, fabrication cost is drastically reduced and painting area is also reduced, resulting in the reduction of construction cost and enhancement of the ease of inspection and maintenance. It has been reported, when the span length is from 30 to 60 meters, this type of bridge is very competitive and, in many competitions, it beats the strong competitor, PC box girder bridges. However, depending on the site conditions, segmental PC box girder bridges sometimes beat the composite two I-girder bridges.

3.2 Box girder bridges

When the span length exceeds 60 meters or so, it has been reported that PC box girder bridges having the web of concrete or of corrugate steel become competitive. To compete with this solution, a two-box girder bridge system with narrow width box section was developed. It will be applied to the bridge with a relatively wide width. If we employ a box section with narrower width, thicker flange is requisite, which leads to less number of longitudinal stiffeners mainly used for preventing buckling instability of the steel plate subjected to compressive force. By this means, we can reduce labor cost for fabrication.

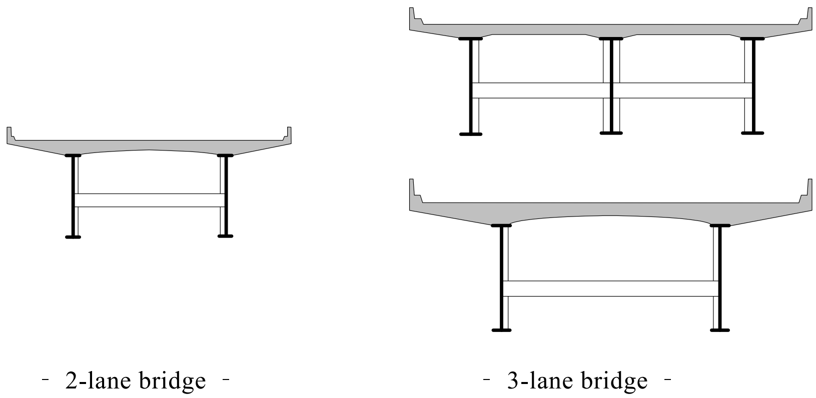


Fig. 1. I-girder bridge

This bridge system is also simple. It has a slab, two box girders with thick flange plate and cross beam at supports only. Intermediate cross beams are removed. Figure 2 shows the cross section.

When the bridge width is relatively narrow, for example the bridge with two-lane, a top-opened box girder bridge shown in Figure 3 has been constructed. At the erection stage, since the slab is not installed, the bridge has an open section, hence, safety against lateral torsional buckling instability has to be checked carefully. After casting concrete slab, closed section with high torsional rigidity is obtained. When steel-concrete composite slab is used, if the bottom steel plate in composite slab is attached atop the upper steel flange in advance, high torsional rigidity is ensured, and no possibility of lateral torsional buckling is predicted during construction.

At the present moment, when the span exceeds 60 meters, it has been evaluated that these bridges are less competitive compared to PC box girder bridges.

3.3 Development of competitive steel solutions for longer-span bridge

As explained above, it has been reported, when the span length exceeds 60 meters, that PC box girder bridges, PC box girder bridges with steel corrugated web plate and PC box girder bridges suspended by diagonal cables from relatively lower tower (so called extradosed-type PC bridges) are very competitive (see Figure 4). This evaluation on economics is made by JH, and its judgment has a strong influence on selecting bridge type in Japan. In fact, if the span exceeds 60 meters, we can see many PC bridges in a new highway bridge construction. For example, when the span length is from 60 to 100 meters, PC box girder bridges with web of concrete or of corrugated steel and, when the span length exceeds 100 meters, PC box girder with corrugated steel web, hybrid truss girder (upper and lower chord members are concrete and web member is steel truss) and extradosed PC box girder bridges have been constructed.

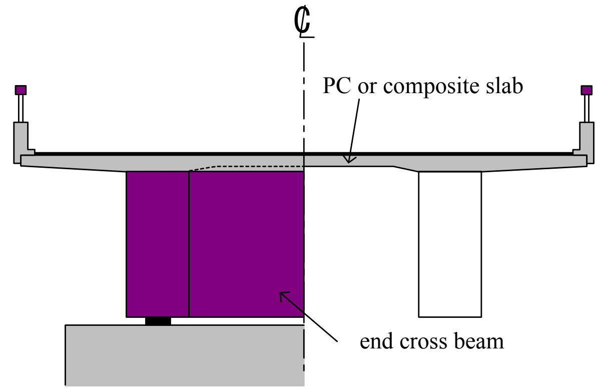


Fig. 2. Two-box girder bridge

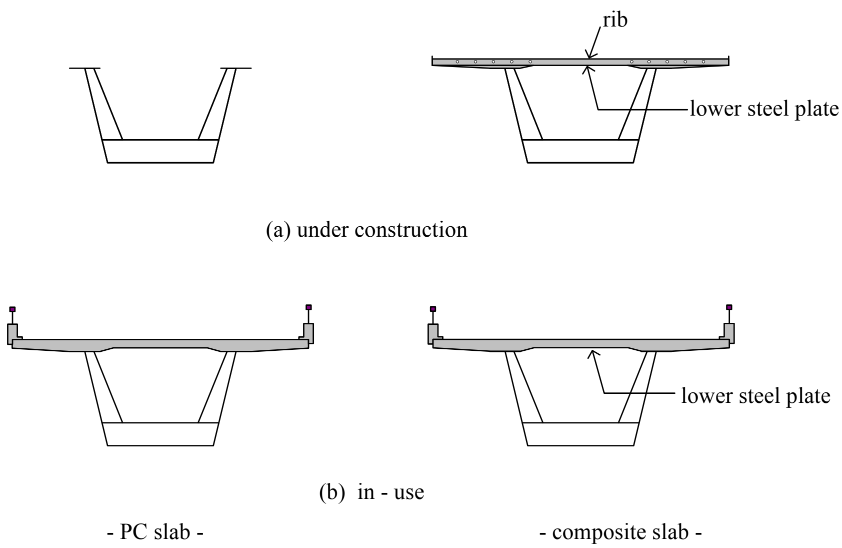


Fig. 3. Top-opened single box girder

A composite truss girder bridge and box girder bridge with steel deck are steel solutions against the above. However, except for the construction site with very bad soil condition, these types have not been realized.

To compete with above PC bridges with a span exceeding 60 meters, the composite two I-girder bridge is recommended, in which lower two steel flanges are connected with concrete slab at intermediate supports. This type of bridge shown in Figure 5 has been called “double composite girder bridges”, and a lot of examples can be seen in Germany. However, if elastic design method is adopted, the effectiveness of this type of bridge will not be obtained. Because, at intermediate supports subjected to hogging bending moment, the yield moment of the “double composite type” and “conventional type” will be nearly the same (see Figure 6). In order to utilize this system efficiently, taking into account the fact that buckling instability of compressed thin web plate is prevented by concrete slab, ultimate bending strength should be full plastic moment, which is 30 to 40% higher than yield moment.

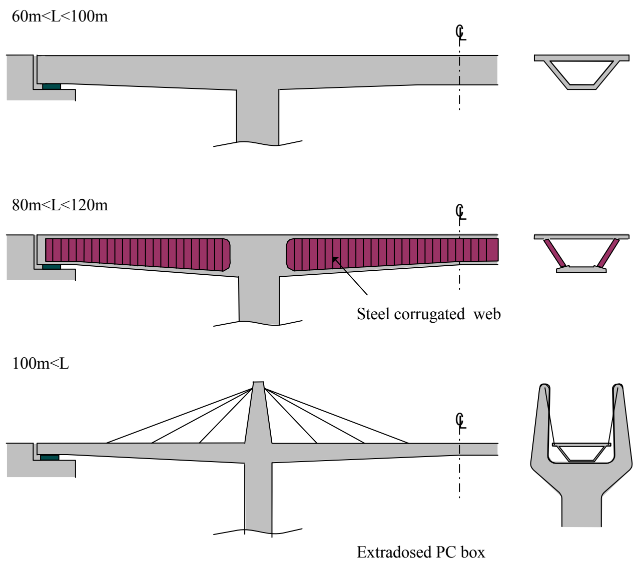


Fig. 4. Competitive PC bridge solutions

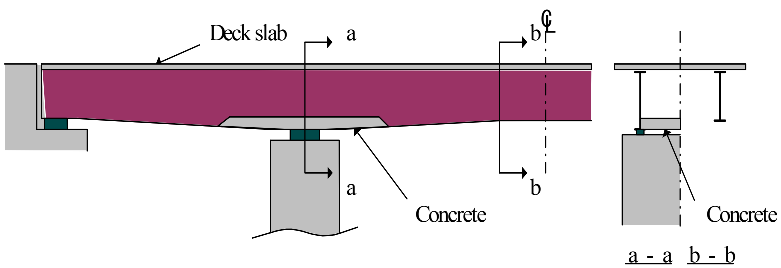
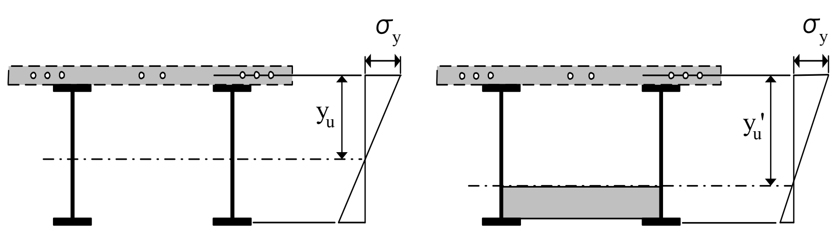


Fig. 5. Double composite girder bridge



$W = I/y_u \cong I'/y_u'$

I: moment of inertia of cross section

σ_y: yield point of reinforcing bar

Fig. 6. Comparison of yield moment

Furthermore, since both open and closed sections are used, safety against aerodynamic instability has to be examined. Even though there is a lot of subjects to be resolved, the structural characteristics and economical evaluation of this type of bridge is now under survey by our research group sponsored by the Japan Iron and Steel Federation.

4. Future subjects

The revival of continuous composite bridge together with structural reform from complicated to simple had been carried out from 1995 to 2000 under the leadership of JH. From this research project, economical solutions for the bridge with a span length from 30 to 60 meters has been developed, namely, continuous composite two-I-girder bridge with a simple transverse stiffening system. So far, construction of this type of bridge has been limited to bridges owned by JH. Recently, in spite of the fact that some parts of design procedure violate the provisions stipulated in JHBS for national roadway bridges, the adoption has been gradually increasing. This verifies an economical advantage of this type of bridge.

In my opinion, since a newly developed bridge system is very simple, we will face difficulty in developing further simple bridge system. Hence it is recommended to incorporate design innovation. The followings are design innovations to be considered.

4.1 Thin web with large aspect ratio without horizontal stiffeners

Normally, buckling strength of the web is estimated under the condition that four sides are simply supported. Identification of the degree of rotational constraint obtained from flange plate and vertical stiffeners at four sides of the web is very difficult, so that the simply support condition has been commonly used. However, it is clear, when the composite girder is subjected to sagging bending moment, that fixed condition is expected at the upper side of the web, and enhances the buckling strength of the web. Based on this fact, we can use more slender web compared with web thickness stipulated in JHBS.

We carried out the experimental research[2)] and the new web design method[3)] was proposed. A maximum aspect ratio is set to be 3.0, which is larger than the maximum aspect ratio of 1.5 stipulated in JHBS. In addition, relatively thin web can be used. For example, in case of the web (yield point = 355MPa) with a height of around 3,000 millimeters and without horizontal stiffeners, JHBS requires a minimum thickness of 23 millimeter. However, we used the thickness of 18 millimeters at the design of actual bridge of JH. This resulted in less steel weight and the reduction of the fabrication cost.

4.2 Evaluation of ultimate strength by 3D finite element analysis

When estimating ultimate strength of the girder or bridge system under bending, shear and combined bending and shear, computer calculation, that is to say, elasto-plastic finite displacement analysis using solid and/or shell element, will give us precise strength. Because, conservative assumptions related to the boundary conditions can be avoided.
Introduction of computer-aided design “Design by Analysis” to the practical design is the future subject to be examined. Precise estimation of ultimate strength will lead to more economical solution.

4.3 Introduction of compact section design

Based on ASD, maximum strength is yield point of the material or buckling strength of the member, which has been stipulated to be less than yield point.

When the composite girder is subjected to sagging bending moment, as has been stipulated in ASSHTO-LRFD[4)] and EC[5)], if PNA (Plastic Neutral Axis of the composite section) falls in the concrete slab or compressed web height-to-thickness at full plastic moment is less than specified values, plastic moment is expected, and it is around from 30 to 40% larger than the yield moment.

PNA of most of recent composite two I-girder bridges is predicted to fall in the concrete slab. Furthermore, since the relatively high depth of the girder has been used, crash of the concrete slab before reaching plastic moment of the section can be avoided. Hence, introduction of compact section is important.

4.4 Double composite 2-I-girder bridges

The double composite girder bridge was explained. At intermediate supports, when the full plastic moment is expected, the ultimate bending strength will be full plastic bending moment throughout the bridge length. This behavior is also seen at the design of the rolled beam. This makes possible to design the bridge with less steel volume.

5. Codification of design innovation

In order to obtain economical solutions with high durability, which can reduce the construction cost, the structural reform from multi-girder to two-girder system was proposed by JH. The two-I-girder bridge requires relatively thick lower flange plate exceeding 50 millimeters and wide span concrete deck. To meet these requirements, in 2002, JHBS allowed using maximum plate thickness up to 100 millimeters and pre-stressed concrete slab.

The lower lateral bracing members were removed and, instead of cross bracing members and/or large-sized cross beams, small-sized shape-steel cross beams at a distance from 5 to 10 meters were recommended. However, above structural simplifications violate the related regulations stipulated in JHBS.

In the former chapter, innovative design methods leading to further reduction of construction cost were proposed. However, these means also violate the provisions in JHBS. In the next revision, specifications for new structural type and composite structures will be added, and the design by analysis will also be discussed.

6. Concluding remarks

JHBS was introduced, which covers all the national roadway bridges with a span length less than 200 meters in Japan. Revision in 2002 and revision now under consideration were also introduced. In the revised version in 2002, shift to technical standards based on performance was made and new provisions meeting design procedures for newly developed simple structural form were added. The content of revision now under consideration is not clear at this moment. However, the shit from ASD to LSD with partial safety factor format is expected.

Reduction of construction cost is a key factor for promoting public works. To cope with the subjects, JH carried out structural reform from multi-girder to two- or three-girder system depending on the number of vehicle lanes. In addition, continuous composite girder design was revived and very simple transverse stiffening system was also employed. To push the construction of such bridge system, JH established their own design manual, in which several provisions violate JHBS. However, the validity of new design procedures had been confirmed through analytical and experimental researches.

Hence, these provisions should be included in JHBS. Finally, in order to attain further reduction of construction cost, incorporating design innovation explained is recommended and inevitable.

References

1. Japan Road Association (JRA): Specifications for Highway Bridges, 2002 (in Japanese)
2. Ohgaki, K., Kawaguchi, Y., Isoe, A., Takahashi, S., Kawashiri, K. and Nagai, M, "Experimental study on stiffening design method for main girder of composite two plate-girder bridges, " Jour. of Structural Engineering, JSCE, Vol.44A, pp.1229-1239, 1998 (in Japanese)
3. Expressway Technical Center: Design and construction manual for continuous composite two girder bridges with PC slab, 2002 (in Japanese)
4. AASHTO: AASHTO LRFD Bridge design specifications, The third edition, 2004
5. CEN: Eurocode 3: Design of steel structures, Part 1-1: General rules and rules for buildings (prEN 1993-1-1: 2003), 2003