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Current practices and future directions of steel design in Japan

Eiki Yamaguchi†

Department of Civil Engineering, Kyushu Institute of Technology, Tobata, Kitakyushu 804-8550, Japan

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Abstract. Four design codes/regulations for steel structures in Japan are briefly reviewed. Some of them employ the limit state design concept while the others are still based on the allowable stress design concept. The process for revision is now in action. The directions in the development of structural design codes are also reported herein. It is noted that a current trend in this development is to employ the performance-based design concept that has been successfully implemented in some seismic design codes.

Key words: Japanese design codes; steel structures; allowable stress design; limit state design; performance-based design.

1. Introduction

Various design codes for steel structures are available in Japan. In this paper, those for highway bridges, railway structures and steel buildings are briefly introduced. In addition, Design Code for Steel Structures Part A, a model code of JSCE (Japan Society of Civil Engineers), is also reviewed The application of this Code is not restricted to specific structures, i.e., it may be used for the design of general steel structures.

Some structural design codes in Japan have employed the limit state design concept while the others are still based on the allowable stress design concept. They do not necessarily conform to international standards such as ISO2394 (ISO 1998). Under these circumstances, many of the codes are currently being reviewed for revision. A trend in the development of design codes is to employ the performance-based design concept that has been successfully implemented in some seismic design codes.

2. Design Specifications for Highway Bridges

2.1. Overview

Design Specifications for Highway Bridges were published about 100 years ago. Since then, it has been revised every several years. The current Specifications (Japan Road Association 2002) consist of 5 parts: Design and Common Rules, Steel Bridges, Concrete Bridges, Sub-Structures and Seismic

†Professor, E-mail: yamaguch@tobata.isc.kyutech.ac.jp

Fig. 1 Collapse of a steel bridge due to earthquake

Design. While the Specifications are written basically in allowable stress design format, the limit state design format is employed partially in Concrete-Bridges and Seismic–Design Parts.

The 1995 Hyogo-ken Nanbu Earthquake, also known as the Kobe Earthquake, caused much damage to civil infrastructures, and an example is shown in Fig. 1. The investigation in the aftermath of the earthquake revealed that very large seismic loads were indeed applied to the structures and that it would be prohibitively expensive to construct the structures that do not undergo any damages under such large seismic loads. Then the design concept has been inevitably changed to the so-called “damage-tolerant” design against extreme earthquake that does not necessarily take place during the service life of a highway bridge.

In the past, fatigue cracks were not expected to occur in highway bridges. However, in recent years, many fatigue cracks have been found in highway bridges, possibly due to overloading. A typical fatigue crack is presented in Fig. 2. Fatigue design is therefore considered essential in highway bridges these days.

Fig. 2 Fatigue crack at the top of a vertical stiffener in steel bridge

Table 1 Matrix for seismic performance

Design ground motion		Bridge category A	Bridge category B
Level 1		Seismic performance 1	
Level 2	Type 1 Type 2	Seismic performance 3	Seismic performance 2

These two issues, i.e., seismic design and fatigue design, are reviewed in the following sections.

2.2. Framework of seismic design

A matrix for seismic performance is summarized in Table 1. The constituents of the matrix include design ground motions, bridge categories and seismic performances. In general, the combination of a design ground motion and a bridge category yields the target seismic performance of a structure to be designed. In order to assess the seismic responses of a structure, static analysis will do if its behavior is simple; otherwise nonlinear dynamic analysis is required.

2.2.1. Design ground motion

Two levels of ground motion should be considered in design:

Level 1: Ground motion that takes place during the service life of a bridge with high probability

Level 2: Ground motion that takes place during the service life of a bridge with low probability but at large intensity

Furthermore, the design ground motion of Level 2 is sub-divided into two types:

Type 1: Seismic loads due to the ground motion at a plate boundary such as the 1923 Kanto Earthquake that has repeated large amplitudes over a long time duration

Type 2: Seismic loads due to the ground motion at an intra plate boundary such as the 1995 Hyogo-ken Nanbu Earthquake that has extremely high intensity in a short time duration

2.2.2. Bridge category

Bridges are categorized into two groups:

Category A: Standard bridges

Category B: Very important bridges

2.2.3. Seismic performance

Once the level of ground motion and the category of a bridge are specified, the target performances of a bridge is established as one of the following:

Seismic Performance 1: No damages in the bridge in the aftermath of seismic event

Seismic Performance 2: Damage is limited in the bridge so that its function can be recovered promptly

Seismic Performance 3: Damage in the bridge is not fatal

2.3. Fatigue design

Steel-Bridges Part of Design Specifications for Highway Bridges states that fatigue effects shall be considered and suggests the use of Fatigue of Steel Bridges (1997) and Guideline for Fatigue Design of

Steel Highway Bridges (2002).

As most of the fatigue damages in steel bridges start in welded joints, the fundamental requirement for fatigue design is the selection of an appropriate joint. Guideline for Fatigue Design of Steel Highway Bridges (2002) contains a list of the joints that may be used for highway bridges.

The first step of the fatigue design, except for orthotropic steel decks, is the evaluation of stress ranges due to vehicle loads. The basic vehicle load is 200 kN/axis, which is then adjusted by several factors such as impact and stress-evaluation method. If the maximum stress range is smaller than the constant-amplitude cut-off limit, fatigue problem is negligible. Otherwise, cumulative damage due to heavy vehicles passing through the bridge needs to be assessed for the period of design service life of a bridge, using fatigue-life curves. The amplitude cut-off limits and the fatigue-life curves are specified in the Guideline for Fatigue Design of Steel Highway Bridges (2002). Note that the guideline also provides a set of simple rules; the satisfaction of those rules exempts a bridge from any fatigue design.

In general, fatigue damage in orthotropic steel decks is considered to be prevented through proper structural details. To this end, the Guideline for Fatigue Design of Steel Highway Bridges (2002) specifies structural details and does not require direct evaluation of stress ranges. However, in recent years, more fatigue cracks are found in orthotropic steel decks than expected (Yuge *et al*. 2004), and thus, fatigue design of orthotropic steel decks has become one of the on-going research subjects that attract many bridge researchers and engineers.

2.4. Issues for revision

Discussion on the next revision of the current set of design codes started at the end of 2002. The directions of the next revision have been discussed so far. The followings are some of the possible issues in the revision (Fujino 2003):

a) Introduction of LRFD format
b) Strengthening of specifications on the maintenance of existing bridges
c) New specifications for composite structures and members
d) Explicit statements on lifetime of bridges
e) Clear explanation on performance of bridges and components
f) Strengthening of specifications on durability
g) Strengthening of specifications on new structural types such as steel girders with less stiffeners and PRC

3. Design Standard for Railway Structures and Commentary (Steel and Composite Structures)

3.1. Overview

Design Standard for Railway Structures and Commentary (Steel and Composite Structures) was first published in 1912. Several revisions were made since then, and the latest version became available in 1992 while the unit was converted to the SI-Unit in 2000 (Ministry of Land, Infrastructure and Transport 2000). Up to the previous version published in 1983, the Standard was based on the allowable stress design concept while the current version has adopted the limit state design concept. It is noted however that some railway companies still use the old version of the Design Standard based on the allowable stress design in practice.

A technical committee has been set up to work on the next revision, aiming to introduce the performance-based design concept to the Standard.

Another seven standards for railway structures are also available, each of which is designated for a specific type of structure or seismic design. The per formance-based design has been implemented to some extent in the seismic design standard already.

3.2. Limit state design

Three kinds of limit states have been introduced:

(a) Ultimate limit states:
A structure or a member fractures, buckles, undergoes large deformation, etc. Typical phenomena are yielding under tension and buckling under compression.

(b) Serviceability limit states:
A structure or a member ceases to be functional due to excessive cracking, deflection, vibration, etc.

(c) Fatigue limit states:
A structure or a member fractures due to repeated loads.

Verification equations take the following form:

$$\gamma_i \frac{S_d}{R_d} \leq 1.0 \tag{1}$$

$$S_d = \sum \gamma_a S(\gamma_f F_k) \tag{2}$$

$$R_d = \frac{R(f_k / \gamma_m)}{\gamma_b} \tag{3}$$

where

S_d denote the design values of loads effects; R_d the design values of resistances;
F_k the representative values of loads;
f_k the characteristic values of material properties;
γ_i the factors for structures;
γ_f the factors for loads;
γ_a the factors for structural analysis;
γ_m the factors for material properties; and
γ_b the factors for design methods

4. Steel buildings (Kohno 2003)

Design codes, standards and recommendations are available for steel buildings. They are categorized to two groups: one is of legal codes and the other is of those published by various professional organizations such as Architectural Institute of Japan (AIJ). The legal codes are issued by either the national or a local government.

4.1. National design regulations

The national law for structural design was enacted in 1919 and the enforcement orders were issued in

Fig. 3 Building damaged by earthquake

the following year. The allowable stress design was employed with dead loads and vertical live loads. After the 1923 Kanto Earthquake, the law was revised by the introduction of horizontal loads with the seismic coefficient of 0.1. The legal framework of seismic design for buildings changed considerably in 1980, after which elasto-plastic analysis has become necessary against large seismic loads as well as the allowable stress design based on elastic analysis for modest seismic loads. The revision on the law of standards for buildings was made in 1998, and the performance-based design concept was introduced. Although the performance-based design tends to require more consultation with clients, the necessity of such a design approach is justified if the damages of buildings during the 1995 Hyogo-ken Nanbu Earthquake, such as that shown in Fig. 3, are considered.

4.2. Difference in design in terms of building heights

Legal difference in the design procedures of steel buildings exists between high-rise and low-rise buildings. Herein a high-rise building is defined to be a building taller than 60 m. The design of a low-rise building can be carried out by compliance with legal codes, and the building permission is issued by local authorities. On the other hand, the design of a high-rise building must be conducted by qualified specialists, which is required by Ministry of Land, Infrastructure and Transport.

5. Design Code for Steel Structures Part A; Structures in General

5.1. Overview

There are standards, specifications and guidelines for the design of conventional steel structures such as highway bridges, railway bridges and buildings. In recent years, new types of steel structure tend to increase. To deal with this situation, Committee on Steel Structures in JSCE set up a subcommittee, which published Design Code for Steel Structures Part A in 1987. The Code has employed the limit state design. To incorporate research advances on steel structures, the Code was revised in 1997, and it was translated into English (Subcommittee on Design Code for Steel Structures 1997). Since the Code covers a variety of steel structures, loads are not given specifically. Instead, a generic method on the assessment of design loads is presented.

5.2. Contents

The table of contents of the Code is given as follows:

Chapter 1	General provisions
Chapter 2	Materials
Chapter 3	Load cases and load combinations
Chapter 4	Structural analysis
Chapter 5	Strength of materials and structural members
Chapter 6	Verification of limit states
Chapter 7	Provisions for structural member
Chapter 8	Provisions for connection
Chapter 9	Provisions for framed structure
Chapter 10	Provisions for plate structure
Chapter 11	Provisions for seismic design

As may be seen in the above, verification equations and structural details are separated for a clear-cut presentation; i.e., all the verification equations are given in Chapter 6 while structural details are presented in other chapters. Three kinds of limit states, i.e., ultimate limit states, serviceability limit states and fatigue limit states, are employed.

5.3. Verification equations

The following format has been adopted for verification equations in this Code:

$$\sum_{i=1}^{n} \frac{S_{di}}{R_{di}} \leq 1.0 \qquad (4)$$

where
S_{di} denote the design values of load effects; and
R_{di} the design values of resistances

The design values of load effects are computed as

$$S_{di} = S_{di}(\nu F_k) \qquad (5)$$

where
ν denotes a safety factor; and
F_k the representative values of loads

Only one safety factor ν has been utilized in this Code and is supposed to represent various ambiguous aspects encountered in design practices collectively. Eq. (5) indicates that ν is applied to the loads, making the physical meaning of the safety factor very clear, even when nonlinear structural analysis is conducted. In 2003, the Committee on Steel Structures in JSCE set up a sub-committee to revise this Code so as to adopt the performance-based design concept.

6. Directions in development of design codes

6.1. Basis of Structural Design for Buildings and Public Works

In Japan, structural design codes have been developed for specific structures traditionally and each has evolved in its own way. Therefore, while each design code is good in a sense that it has been optimized for specific structures, the codes thus developed may not be consistent with each other. Possible lack of consistency among domestic design codes and also with international standards initiated Ministry of Land, Infrastructure and Transport to conduct research, which resulted in the publication of "Basis of Structural Design for Buildings and Public Works" in 2002 (Ministry of Land, Infrastructure and Transport 2002). This is intended to serve as the "Code for Code Writers", and its table of content is given as follows:

1. General
    1.1. Scope
    1.2. Basic requirements of design
2. Limit states
    2.1. General
    2.2. Ultimate limit states
    2.2. Serviceability limit states
    2.3. Restorability limit states
3. Actions
    3.1. Definitions
    3.2. Classification of actions
    3.3. Treatment of actions
    3.4. Load combination
4. Seismic design
    4.1. Seismic performance
    4.2. Method of indicating ground motion levels
5. Method of verifying performance

Chapter 1 presents the basic requirements of structural design: the design working life is specified, and the fundamental performance requirements of safety, serviceability and restorability are ensured for the specified period. Chapter 2 prescribes the associated limit states to be verified: ultimate limit states, serviceability limit states and restorability limit states. Fatigue limit states, durability limit states and fire resistance limit states may be included in ultimate limit states, and serviceability limit states as appropriate. Restorability limit states are the limit states regarded as being located between serviceability limit states and ultimate limit states, and it refers to the states beyond which the repair of a structure is no longer a practical choice from the viewpoint of cost and time. The chapter regulates that the limit states shall be selected according to the purposes of the structure to be designed.

Chapter 3 recognizes three actions: direct action, indirect action and environmental action. The environmental action is included for the verification of serviceability and safety. Chapter 4 states that specified seismic performance shall be explicitly indicated and the ground motion level corresponding to the required performance shall be specified. In Chapter 5, it is recommended that the verification method considering reliability, such as the method of partial factors, should be incorporated into the technical standards related to design in an appropriate form.

6.2. Code Platform Version 1: Principles, Guidelines and Terminologies for Structural Design Code Drafting Founded on the Performance-Based Design Concept

National Institute for Land and Infrastructure Management, Ministry of Land, Infrastructure and Transport, has entrusted JSCE to issue this Code. The project started in 2001 and it was completed in 2003 (Committee on Fundamental Study of Comprehensive Design Code 2003). As the name implies, this is a comprehensive design code, providing a fundamental framework for drafting structural design codes of the performance-based design concept. The table of contents is given as follows:

1. Definition of terminologies
2. General
   2.1. Scope
   2.2. Framework of design codes
3. Performance requirements of structures
   3.1. Objectives of a structure
   3.2. Performance requirements
   3.3. Performance criteria
4. Verification procedures
   4.1. Allowable verification procedures
   4.2. Verification approach A
   4.3. Verification approach B
5. Structural design report

Some of the key features are as follows (Honjo *et al.* 2003):

(1) A glossary of terminologies is provided in accordance with the usage of widely accepted international codes such as ISO2394 (ISO 1998) and the performance-based design codes and guidelines developed recently in Japan.
(2) It is emphasized that the limit state design is one of the most appropriate methods for the performance-based design.
(3) The performance requirements of structures are described by three levels: objectives − performance requirements − performance criteria.
(4) Each performance criterion is specified by a combination of three factors: a) limit states of a structure, b) actions/environmental influences and their combinations, and c) time. The significance of a structure should also be taken into account in specifying the performance criteria.
(5) Two verification approaches are specified. In verification approach A, there are no restrictions on the method to be used in the performance verification. However, a designer is requested to prove that the designed structure would satisfy all the performance criteria. In verification approach B, a designer would verify performances of structures based on a design code of lower hierarchy (for example, a design code for specific structures) specified by the owner of the structures.

7. Conclusions

In Japan, some of the modern steel design codes have employed the limit state design concept while the others are still based on the allowable stress design concept. However, most of them described herein are currently in the process of revision, and are being developed towards the performance-based design, into which the limit state design is incorporated.

Several studies of the performance-based design concept for steel structures have been conducted (Japan Society of Steel Construction 2001, Subcommittee on Fundamental Study of Performance-Based Design for Steel Structures 2003). Yet, the understanding of the performance-based design concept does not seem to be adequate, especially among practitioners. It is therefore the author's belief that while the revision of a design code is being discussed, the education of engineers and students for the emerging new design concept is also very important, and must be taken care of systematically on a national basis.

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