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SEISMIC PERFORMANCE CRITERIA OF HIGHWAY BRIDGE DESIGN IN JAPAN AND CALIFORNIA

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The seismic performance criteria in the design codes are a basis of design for earthquake resistance of structures. Comparisons of the seismic performance criteria of highway bridge design were made between Japan and California. Both countries have many common points in the approach to seismic design of bridges, e.g., the performance criteria are similar. However, one major difference is in the manner in which "ordinary" and "important" bridges are defined in the two design codes. Most of the bridges in Japan are considered "important" as opposed "ordinary" in California. This results in significant difference in the practical design.

Key words: *Seismic design, Earthquake engineering, Bridge design, Performance design, Structural design*

1. INTRODUCTION

Suffering from severe earthquake damage to the highway bridges in San Francisco Bay Area (1989) and Los Angeles (1994) followed by the Kobe Earthquake (1995) in Japan, both State of California and Country of Japan have greatly improved the earthquake resistance design of highway bridges. In the earthquake resistance design the purpose is unique even though the conditions in the two countries are different. The differences are in the nature of organizations and the construction practices. This paper examines and compares the difference and similarity of the design standards that have been developed independently.

After studying structural damages of the Kobe Earthquake, Japan published a new version of seismic design codes[1)] in March 2002. The new codes define in clear form the performance criteria for earthquake resistance according to the policy of the performance based design. Also, the California Department of Transportation (called Caltrans thereafter) published the basic policy of seismic design[2)] in January 1999, which defines the performance criteria, and the latest version of the seismic design critera[3)] in December 2001, which specifies the practical design standards. In this paper the study is focused on comparing the performance criteria in both countries, which are a basis of any structural design.

2. SEISMIC PERFORMANCE CRITERIA

The seismic performance criteria of the Specifications for Highway Bridges in Japan[1)] specifies three levels, Performance 1, 2, 3, which are applied to each classification of bridges, ordinary and important bridges, and the level of ground motion as shown in Table 1. They are categorized considering the level of safety, serviceability, and restorability for short term and long term. The details of each Performance are given in the Japanese design codes[1)].

They are similar to Caltrans performance criteria[2)] given in Table 2. It also considers the serviceability and the level of damage (restorability). A slight difference is that the Japanese criteria require Performance 1 for both ordinary and important bridges while Caltrans does only for important bridges and allows Performance 2 for ordinary bridges. This means that Caltrans is a little less severe for ordinary bridges. However, it can be said that the performance criteria in both countries are generally similar. Details of the levels of damage and service are given in Caltrans design policy[2)].

It is interesting to note that the Japanese codes specify two types of earthquake, inland and plate boundary, contrary to Caltrans. This is because Japan has experienced two types of destructive earthquake, Kanto Earthquake in 1923 (plate boundary type) and Kobe Earthquake in 1994 (inland type).

Performance 3 of the codes in both countries intends to save lives but allow major structural damages excluding collapse (Table 1 and 2). However, the practical design in Japan basically tries to repair rather than replace. Any serious damage is considered better to be fixed than removed because the service can resume earlier with less cost.

In Performance Level 2, Japanese code has the requirement to limit the residual displacement less than 1/100 (1%) of the height after the Kobe Earthquake. This came from the experience of the Kobe Earthquake in which the restoration was difficult when the residual displacement was larger than 1/100. Caltrans does not have this requirement in actual design because most of the bridges are ordinary and designed for Performance Level 3, as we will see later, in which the damaged bridges are to be removed. Further the analysis to determine the residual displacement is not so reliable.

Table 1 Seismic Performance Criteria of Japanese Specifications

<table>
<tr><td colspan="2">Ground Motion</td><td>Ordinary Bridges</td><td>Important Bridges</td></tr>
<tr><td colspan="2">Level 1</td><td colspan="2">Performance 1</td></tr>
<tr><td rowspan="2">Level 2</td><td>Type I</td><td rowspan="2">Performance 3</td><td rowspan="2">Performance 2</td></tr>
<tr><td>Type II</td></tr>
</table>

Table 2 Seismic Performance Criteria of Caltrans

<table>
<tr><td rowspan="2">Ground Motion</td><td colspan="2">Level of Service and Post Earthquake Service</td></tr>
<tr><td>Ordinary Bridges</td><td>Important Bridges</td></tr>
<tr><td>Functional-Evaluation
(Level 1)</td><td>Service: Immediate
Damage: Repairable
(Performance 2)</td><td>Service: Immediate
Damage: Minimal
(Performance 1)</td></tr>
<tr><td>Safety-Evaluation
(Level 2)</td><td>Service: Limited
Damage: Significant
(Performance 3)</td><td>Service: Immediate
Damage: Repairable
(Performance 2)</td></tr>
</table>

3. CLASSIFICATION FOR ORDINARY AND IMPORTANT BRIDGES

According to the Japanese codes the bridges are classified important or ordinary considering the followings;

(1) Disaster prevention - Emergency roads
(2) Possibility of secondary disaster - Double deck, Crossing bridges over rail roads or other roads
(3) Alternative route
(4) Restorability

Consequently, the important bridges are the ones on main roads and all others are ordinary bridges as specified in Table 3. Therefore, most of the bridges are designed as important in Japan. Ordinary bridges are very few except on local roads.

On the other hand, Caltrans classifies the important and ordinary considering the followings;

(1) Required to provide post earthquake life safety; such as access to emergency facilities
(2) Time for restoration of functionality after closure would create a major economic impact
(3) Formally designated as critical by a local emergency plan

These conditions are similar to the Japanese ones shown previously. However, the application of these conditions differs largely; the important bridges are only toll bridges such as Golden Gate Bridge, San Francisco-Oakland Bay Bridge, Carquinetz Bridge, etc. and the ramp roads to the first exit from these toll bridges. Consequently, most of the bridges in California are designed as ordinary and the important bridges are very few.

For important bridges the plastic deformation should be limited, then it requires large stiffness that results in a shorter natural period of structure, thus large seismic force. This syndrome in the seismic design has always been a problem, i.e., which is better for seismic resistance, flexibility or strength?

For important bridges (Performance Level 2), it is very difficult to retrofit the existing bridges which were designed by the old design codes, thus do not have sufficient seismic resistance. If the piers were retrofitted, the piles would be damaged, which can not be easily repaired.

Caltrans further classifies the ordinary bridge into standard and non-standard bridges according to the structural features. Example of non-standard features are[2)]:

Irregular geometry
- Multiple superstructure levels
- Variable width or bifurcating superstructures
- Significant in-plane curvature or high skewed supports

Unusual framing
- Outrigger or C bent supports
- Unbalanced mass and/or stiffness distribution
- Multiple superstructure types

Unusual geologic conditions
- Soft soil
- Moderate to high liquefaction potential
- Proximity to an earthquake fault

Those non-standard bridges must be designed by taking into consideration of its unusual condition. Japanese codes do not have this classification.

Table 3 Bridge Classification in Japan and California

	Ordinary Bridges	Important Bridges
Japan	Other than the important bridges described right	Bridges on free ways, national roads, and important route of prefecture and city roads
California	Bridges on free ways, interstate roads, and county and city roads	Toll bridges, ramp to the first exit

4. SAFETY CRITERIA

The safety check is in principle confirmed by the requirement that the demand from the earthquake motion should be less than the capacity of the structure. In the Japanese code, the safety is checked in terms of the force as the following equation:

$$k_{he}\ W < P_a \qquad (1)$$

in which k_{he} = equivalent horizontal seismic coefficient, W= equivalent weight of structure, and P_a = horizontal capacity resistance force of structure

The equivalent coefficient gives the earthquake force, which is reduced to take into consideration the effect due to plastic behavior of members. Here the equal energy principle is used. The capacity force of the structure is obtained by the push-over analysis.

In Caltrans, on the other hand, the safety is checked in terms of the displacement as the following equation:

$${}_D < {}_C \qquad (2)$$

in which ${}_D$ = displacement demand by earthquake, and ${}_C$ = displacement capacity of structure

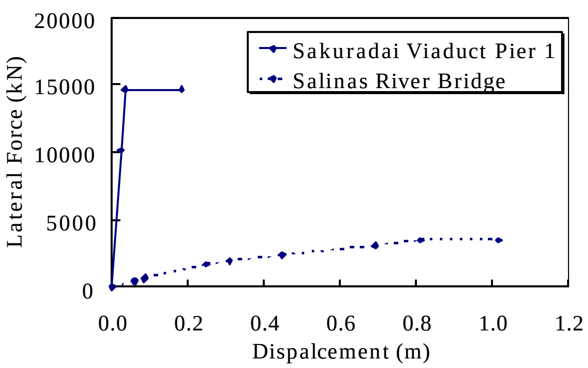

Figure 1 Comparison of Load-Displacement Curves

Caltrans uses the elastic analysis to obtain the displacement demand. Here the equal displacement principle is used to consider the plastic deformation effect. The displacement capacity of the structure is obtained by the push-over analysis.

To compare the two methods, it can be said that perhaps the safety check by the displacement is easier for engineers to visualize the behavior of structures than the force.

5. STRUCTURAL SYSTEM

A typical structural system for bridges in Japan is continuous pre-stressed box girder supported by rectangular piers with rubber bearings between sub- and super-structures. The rubber bearings are used to distribute the seismic force evenly to the piers, thus to reduce the seismic force by avoiding the concentration of the force on a certain pier.

Caltrans is reluctant to use the rectangular piers and the rubber bearings. The rectangular pier is too strong and rigid in the transverse direction causing potential damage in the piles when subjected to the earthquake motion. Repair of the piles is very difficult. In the capacity design concept that Caltrans follows, the piers are designated for the sacrificed member, but not the piles. A portal frame is a more common structural system in Caltrans. The simple portal frame can maintain the ductility by forming plastic hinges in the sacrificed members.

Figure 1 shows a typical example of the load-deflection behavior of the bridge bents in Japan and California[4)]. A Japanese design, Sakuradai Viaduct, has rectangular piers while a Caltrans design, Salinas River Bridge, is a portal frame. The displacement is in the transverse direction. It can be naturally seen that the stiffness in transverse direction differs largely. The flexibility in Caltrans design would reduce the seismic force.

6. SYSTEM OVERLOAD

It may be instructional to study the two systems mentioned above in their response to seismic events larger than the design event. This is in regards to the safety evaluation of bridges covered both in Japan and in California.

In the Japanese system the superstructure supported on pier walls with rubber bearings would have a larger relative displacement between the sub- and super-structure. This must be accommodated by the rubber bearings. Typically, it is difficult to design rubber bearings to respond elastically to large seismic displacements, therefore, overload is expected at the bearings and they will fail lateral while they carry the vertical loads. The ability of rubber bearings to absorb large amounts of energy has been questioned. Even those bearings with energy absorption elements built in will be overloaded and most probably need replacement following a seismic overload.

The overload behavior in a Caltrans system is typically observed through the additional ductility capacity of plastic hinges forming in columns and shafts. Typical laboratory tests show that columns designed for a ductility of 4 are often capable of ductility levels up to 8. It may be argued that the damage level increases drastically from ductility of 4 to 8, however, this is added insurance for unexpected events. The column plastic hinge would need repair at either ductility of 4 or 8.

The similarity between the Japanese and Caltrans system is that both need repair in an overload situation, and the difference is the energy absorption capability in the overload condition. The Japanese system would have to be upgraded from a regular rubber bearing to an isolation device to have energy absorption capability. This device may not have additional reserve beyond the design event, rendering it out of commission, while the Caltrans system can typically absorb about two times the design energy level.

The deformation demanded by various seismic events could be scaled from ductility values of 1 to 8, with 4 being the average design value. The Japanese system shows its advantages in the lower ductility values, while the California system has proven successful in the upper ductility values, according to the laboratory tests.

7. CONCLUSIONS

In this paper the main aspects of the performance criteria are compared between Japan and California. The results are summarized as follows:

(1) A classification of ordinary bridges and important bridges is different; most bridges are important in Japan, but ordinary in California.
(2) The thoughts to the structural system differ largely; Japan prefers rectangular piers with rubber bearings but Caltrans does the portal frame with no bearings.
(3) The safety is checked by the displacement ductility based on the equal displacement principle in Caltrans and by the force based on the equal energy principle in Japan.

Above all, it can be said that the bridge design outcome would be considerably different in Japan and California given the same site condition. Major differences originate from the difference in the classification of the bridges between ordinary and important bridges. It is difficult to see convergence between the two bridges given each country has its own historical background and development process. However, it can be said that since larger earthquakes are less probable, not all bridges need to perform to Performance Level 2 (see Table 2). Some bridges are acceptably designed to the Performance Level 3 which allows damage excluding collapse.

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