Seismic Design of Bridges in Low to Moderate Seismic Zones

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ABSTRACT

For the seismic design of bridges in Korea classified as the low to moderate seismic zones, the design concepts provided in the Standard Specification for Highway Bridges, Division I-A; Seismic Design, are adopted, which is basically developed for the strong seismic zones by AASHTO. Accordingly, the design procedures provided for the low to moderate seismic zones are simplified too much to fulfill the purpose of the seismic design. In this paper the design procedures given for the low to moderate seismic zones in the Standard are summarized and discussed in view of the seismic design purpose. From the discussion results some revisions are proposed as conclusions for the reasonable application of the Standard for bridges located in the low to moderate seismic zones.

Key words : *low to moderate seismic zones, seismic design of bridges, design concepts, design procedures, seismic design purpose*

1. Introduction

For the seismic design of bridges in Korea classified as the low to moderate seismic zones, the design concepts provided in the Standard Specification for Highway Bridges,[1] Division I-A; Seismic Design are adopted. The design procedures given for the Seismic Performance Categories A and B (SPC A & B) are applied, which are provided for the low to moderate seismic zones. However, because the Standard is developed basically for the strong seismic zones (SPC C & D), the design concepts are not appropriate for the low to moderate seismic zones. Also the design procedures given for SPC A & B are simplified too much to fulfill the purpose of the seismic design.

The purpose of the seismic design is to ensure that in the event of earthquakes human lives are protected, structures important for civil protection remain operational and damages are limited. The first two requirements are defined with regard to the safety and the last requirement is defined with regard to the economy. The last requirement implies that some damages are inevitable under earthquakes. Of course, the seismic design concepts and procedures should be established such that the given requirements are satisfied as far as possible.

In this paper the seismic design procedures given for SPC A & B in the Standard are summarized and discussed in view of the seismic design purpose. From the discussion results some revisions are proposed as conclusions in order to carry out the seismic design of bridges located in the low to moderate seismic zones appropriately.

2. Seismic design procedures for bridges in SPC A & B

The seismic design of bridges in SPC A & B is carried out in the following three steps:

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Step 1: Determination of design values
Step 2: Design of single span bridges and bridges in SPC A or Design of multi-span bridges in SPC B
Step 3: Design structural components

For the design values are to be determined: the acceleration coefficient, the importance class, SPC, the site coefficient and the response modification factors. The acceleration coefficient is determined as the design earthquake with a 10% probability of exceedance during the normal life expectancy of a bridge (e.g. an earthquake with a 475-year return period for a bridge with a 50-year life span). Two importance classes, essential and others, are given. Bridges classified as essential must remain open to all traffic after the design earthquake. Critical bridges are also mentioned in the Standard but it is not included in the classification. SPC A & B are defined in accordance with the seismic risk represented by the acceleration coefficient and the importance class. Different design procedures are applied for different categories. Because the acceleration coefficient is defined for rock conditions, the site coefficient is selected considering the overlaying soil deposits. The response modification factors, usually called as R factors, are given for substructures considering the ductility and redundancy, for connections considering the structural integrity and redistribution of forces under the inelastic behavior. For substructures R factors of 2, 3 and 5 are given according to the types and for connections 1.0 and 0.8 are given according to their locations.

For single span bridges and multi span bridges in SPC A, seismic design provisions are given to check the connection resistance and the minimum support lengths for the expansion ends of all girders. The connections of single span bridges should resist the tributary weight multiplied by the acceleration coefficient and the site coefficient. In case of multi span bridges in SPC A the connection resistance is 0.2 times the tributary weight.

For multi-span bridges in SPC B, the uniform load method and the mode spectral method are used to get the elastic forces and displacements except for critical bridges, for which the time-history method is recommended. Also the analysis method is determined depending on the regularity of the bridge configuration. The elastic forces calculated for longitudinal and transverse directions are combined to take into account the directional uncertainty of earthquake motions. Then the design forces for various structural components are determined by modifying the elastic forces with the corresponding R factors as shown in Fig. 1. The displacements from the elastic analysis are compared with the minimum support lengths and the greater values are taken as the design displacements. The design strengths for the structural components are determined with the modified design forces. If the design strength of any structural component is

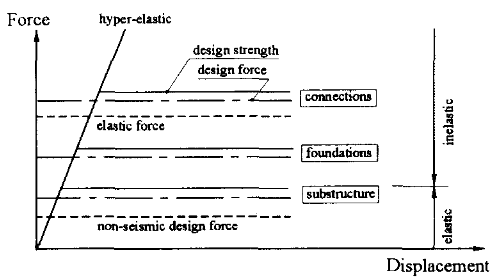

Fig. 1 Design structural components of multi span bridges in SPC B

revised from the preliminary design, step 2 and step 3 are again carried out to check the completeness of the seismic design.

3. Discussions

3.1 Characteristics of the seismic design

By the non-seismic design it is sufficient to provide the design strengths greater than the design forces, because the design forces are deterministic. The differences in the safety margins of various structural components are relatively indifferent. However, the seismic design is different from the non-seismic design in the fact that not only the design values such as the acceleration coefficients and the soil factors are not deterministic but also the design methods such as the spectrum method and the action combination method are probabilistic. The elastic forces obtained with such design values and design methods are also non-deterministic. Therefore it is not sufficient to provide the design strengths for the structural components simply greater than the design forces, which is schematically shown in Fig. 2. Under stronger events than the design earthquake, the seismic forces can be greater than the design strength of a certain component. In this regard the seismic design is defined such that yielding positions and their sequence as well as the earthquake intensity, which initiates the non-linear behavior of bridges, should be determined. Also it should be verified with the selected failure mechanism that the non-linear behavior do not lead to the global collapse. The elastic forces obtained from the elastic analysis are taken as reference values.

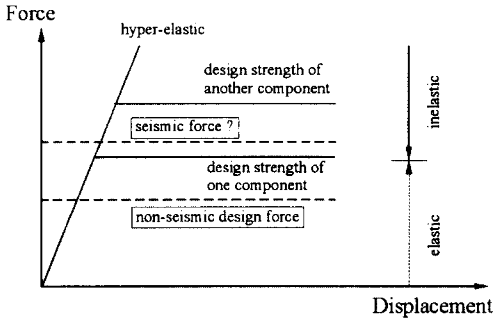

Fig. 2 Non-seismic design vs. seismic design

3.2 Basic design concepts

The behavior of bridges under earthquakes can be divided into three types, full serviceability, limited serviceability and no serviceability due to local or global collapse. Considering the safety, the local or global collapse should be prevented as far as possible. This is given as the no collapse requirement. Also, taking into account the design earthquake, the full serviceability requirement is not acceptable in the economic point of view, although this requirement should be satisfied up to a certain limit. Thus the limited serviceability is the intended seismic behavior of bridges and bridges should remain open to emergency traffic after the design earthquake. The inelastic behavior through yielding of structural components is permitted so far the resistance to the self-weight and the structural integrity should be provided. Also damages should be readily detectable and accessible for inspection and repair. The basic design concepts satisfy the seismic design purpose explained at the beginning.

3.3 Failure mechanisms

In order to satisfy the basic design concepts the failure mechanisms of bridge structures should be clearly defined. In case of multi-span bridges with general configurations including superstructure, connections, substructure and foundation, the superstructure yielding leads to the bridge collapse directly, which does not meet the no collapse requirement. The yielding of connections leads to the separation of super-and substructure. In this case, the post-yielding behavior is hardly predictable, loss-of span type failures occur and local damages are expected. The foundation yielding causes the possible collapse and the difficulty of retrofit. Therefore the desirable failure mechanism of multi span bridges should be the yielding of substructure, such as columns, piers or bents, prior to any failure in other structural components as depicted in Fig. 3. The yielding of substructure leads to the degradation of the structural stiffness and plays a role of fuse disconnecting the further transmission of ground shaking. The design procedures for multi span bridges in SPC B are provided based on this failure mechanism.

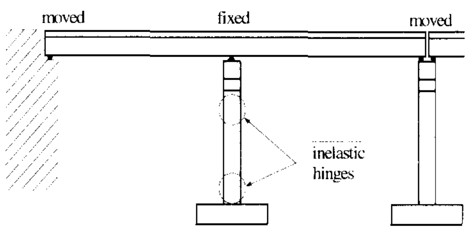

Fig. 3 Failure mechanism of multi span bridges

For multi span bridges in SPC A, two provisions, connection resistance and minimum support lengths, are given as the seismic design requirements in lieu of rigorous analysis. This is not acceptable because the failure mechanism can not be proved. Therefore, to satisfy the seismic design purpose, the seismic design of multi-span bridges in SPC A should be carried out following the same procedures in SPC B.

For single span bridges, the same provisions as those for multi span bridges in SPC A are given. However, according to the seismic design characteristics and the basic design concepts, one of the two components should fail first. Then the desirable failure mechanism is that the connections fail prior to the superstructure as depicted in Fig. 4, otherwise the global collapse is expected.

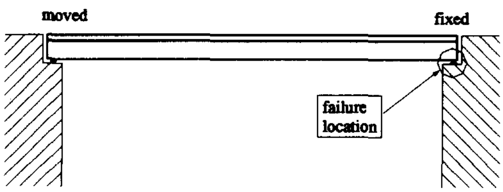

Fig. 4 Failure mechanism of single span bridge

When the elastomeric bearings are used to get more flexible bridge behavior and to distribute the seismic forces, the failure mechanism is the connection failure regardless of single or multi span bridges.

When the connection failure is selected as an intended failure mechanism, proper measures such as shear keys or linkages are required to prevent the falling down of superstructure. For single span bridges such a measure should be provided at least for the transverse direction. The minimum support lengths should be checked also for single span bridges but the provision is basically given for multi-span bridges designed with the substructure yielding and applicable only for the longitudinal direction.

It should be noted that the ductility requirement for the substructure need not be applied in this case.

3.4 Seismic performance category

The seismic performance categories are determined considering the seismic zone and the importance class. But the importance of bridge is not reflected in the current design procedures for the low to moderate seismic zones categorized as SPC A & B.

The importance of bridges should be included in the seismic design such that bridges with the same importance should maintain the same function after earthquakes, either the full serviceability or the limited serviceability. Therefore the owners should decide the importance of bridges considering the security defense and damage restoring after earthquakes. Also certain levels satisfying the full serviceability requirement should be defined according to the importance class. An example is the way of adjusting the response modification factors, which is suggested in the LRFD Standard.[2]

In the current design procedures, the elastic or inelastic behavior of multi span bridges in SPC B are determined with the design earthquake and R factors given for substructures, because R factors are provided as fixed values considering only their types. The elastic and inelastic behavior can be regarded as the full serviceability and the limited serviceability. This can lead to the different behavior of bridges with the same importance as shown in Fig. 5. Therefore R factors given for substructures in the Standard should be revised as reference maximum values[3] and the levels for the full serviceability requirement should be given as design conditions independent upon the structural configurations.

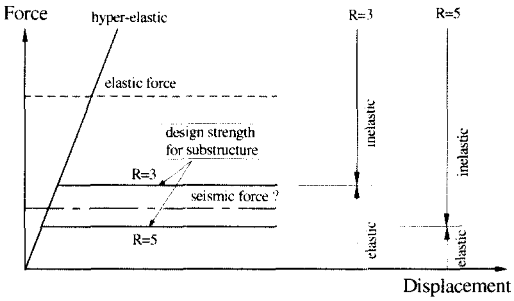

Fig. 5 Behavior according to the response modification factors

3.5 Response modification factor

For multi-span bridges in SPC B different R factors are applied to determine the modified design forces of the structural components. This is the method with modified design forces. As specified in the Standard, the design strengths of the yielding components determined in the seismic design should not be lower than those determined in the non-seismic design. For strong seismic zones, this is generally satisfied. But for moderate seismic zones, R factors given for substructures should be limited for this reason.

It should be clearly stated in the corresponding clauses of the Standard that R factors be applied only for the preliminary design step. Once the structural components are designed and fixed, the structural response can not be modified. This is the reason why the method with modified design forces given for SPC B is uneconomic compared to the method with inelastic hinging forces[1,2,3] given for SPC C & D as shown in Fig. 6. Due to the yielding of substructure it is not expected that connections have greater forces than the elastic forces. By the method with inelastic hinging forces the design strengths of yielding components are determined first. Then, to satisfy the failure mechanism, the design strengths of other components are determined considering the overstrengths of the yielding components.

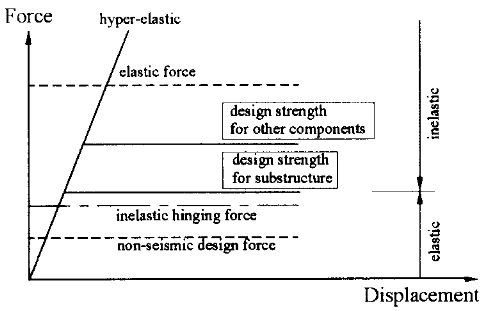

Fig. 6 Seismic design based on the inelastic hinging forces

3.6 Design strength

In the Standard both the load factor design and the service load design are allowed. By the service load design 50% and 33% increase are permitted in the allowable stress for structural steel and for concrete respectively. However, as discussed above, yielding positions should be determined regardless of the seismic zones with the safety margins of all structural components. Therefore the design strengths should be determined based on the correct evaluation of the yield strengths as well as their distribution (overstrength).[1,2,3] This is mentioned in the Standard, however, only for the method based on the inelastic hinging forces given for SPC C & D.

4. Conclusions

The seismic design concepts and procedures for bridges located in the low to moderate seismic zones provided in the Standard Specification for Highway Bridges, Division I-A; Seismic Design are summarized and discussed in view of the seismic design purpose. From the discussions results following revisions are proposed for the present design procedures in SPC A & B of the Standard:

1. The importance of bridges should be included in the seismic design. Therefore certain levels satisfying the full serviceability requirement should be defined according to the importance class.
2. The seismic design of multi span bridges should be carried out with the same procedures regardless of seismic zones. For different seismic zones, different design values are applied in accordance with the variation in seismic risk.
3. In case of single span bridges, the connections should fail prior to the superstructure. Also the failure mechanism of bridges with elastomeric bearings is the connection failure regardless of single or multi span bridges. Therefore proper measures such as shear keys or linkages are required to prevent the falling down of superstructure. The ductility requirement for the substructure need not be applied.
4. The response modification factors for substructures should be given as reference maximum values and limited such that the design strengths determined in the non-seismic design should not be diminished.

5. The design strengths should be determined based on the correct evaluation of the yield strengths. Also the distribution of yield strengths (overstrength) should be considered.

Further researches are needed in regard to the levels of the full serviceability requirement for the importance class and the application of the response modification factors requiring resonable local ductility demand.

Acknowledgement

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