Strengthening of Bridges Against Seismic Loads

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Abstract—This paper focuses on the seismic retrofitting of conventional or "ordinary" Highway bridges. The seismic retrofitting includes methods of evaluating bridges for seismic and seismic retrofitting strategies. The retrofitting technique is intended to be applicable for all levels of seismic hazards for conventional concrete super and substructures particularly concrete girder type highway bridges with span less than 150 meters and design life limited to 75 years. Also this paper does not focus on nor prescribe specific requirements when bridges are to be retrofitted. Several Engineering techniques for seismic retrofitting for super and substructures are available. The decision to retrofit a bridge depends upon a number of factors such as availability of funding, and number of political, social and economic issues. This paper focuses on the engineering factors pertaining to the seismic retrofit of highway bridges.

I. Introduction

Many bridges are inadequate for seismic loads and could be significantly damaged or seriously suffer collapse during low to moderate earthquake. A consequence of the damage could lead to

Bridge collapse and to prevent this situation, retrofitting or replacement of inadequate and/or deficient structures is necessary. This could be done by identifying bridge at risks, evaluating their vulnerability for collapse or major seismic damage.

To minimize a serious risks, retrofitting is a common method. The decision to retrofit or to replace or do-nothing would require to evaluate both the importance and vulnerability of the bridge.

The development of seismic retrofitting is based on a set of performance standards and it should be based on the Standard Bridge Specifications for Highway Bridges. There are summarized below(1):

a. Small to moderate earthquake should be resisted within the elastic range without significant damage;

b. Realistic seismic ground motion intensities and forces should be used in the design procedures; and

c. Exposure to shaking from large earthquakes should not cause collapse of all part of the bridge. Where possible, damage that does occur should be readily detectable and accessible for inspection.

A set of basic concept for seismic retrofitting of bridges is derived from the philosophy outlined in Ref 1 and are summarized below:

The retrofit concepts presented in this paper is based on the following retrofit philosophy as outlined in Ref. 2.

a. Provision should minimize loss of life and serious injury to the traveling public from unacceptable bridge performance;

b. Provision should be applicable to all regions for high, moderate and low seism city; and

c. Provision should not restrict retrofit to designers from using new and innovative technique and design approaches.

The essential concepts that govern development of seismic retrofitting of bridges are based on [2]:

a. Enhancing the ductile deformation capacity of the super- and substructures to ensure that both structural systems are capable of sustaining large lateral displacement without reaching a collapse limit state;

b. Reducing seismic inertial loading on the super- and substructures by using Response Modification Devises, such as isolation bearings and energy dissipation mechanism, load- limiting methods such as capacity-protected designs or load transfer such as seismic lock-up devices;

c. Strengthening the support bearings, members and connection to ensure seismic inertial load transfer mechanisms within super-and substructures elements;

d. Minimizing the seismic inertial loads induced in the superstructure by reducing the dead load of the concrete structural elements or avoid excessive strengthening of super-and substructures systems as described in "c"

e. Improving superstructure redundancy; and

f. Combinations of the concepts listed above.

The seismic retrofitting methods essentially introducing displacement ductility capacity in the structural elements of bridge systems by means of load-limiting mechanisms, establishing load paths, using energy dissipation or load transfer mechanisms or by reducing the dead load.

II. Seismic Performance Levels

The section presents a performance based approach to the seismic retrofitting of highway bridges. The performance criteria are defined for performance levels based on the different levels of earthquake ground motion. These are given as follows (2):

a. Performance Level 0 (PL 0): No minimum level of performance is recommended.

b. Performance Level 1 (PL 1): Life Safety: Significant damage is sustained during the earthquake and service is significantly disrupted, but life is sustained. The bridge may need to replaced after a large earthquake.

c. Performance Level 2 (PL 2): Operational: Damage sustained is minimal and full service for emergency vehicles should be available after inspection and clearance of debris. Bridge should be repairable with or without restrictions on traffic flow.

d. Performance Level 3 (PL 3): Fully Operational: Damage sustained is negligible and full service is available for all vehicles after inspection and clearance of debris. Any damage is repairable without interruption of traffic.

III. Seismic Hazard Levels

There are three levels (lower level(LL) and upper level(UL) and site hazard (SH)) of earthquake ground motion with different return periods and level associated with site geological hazards for design of the seismic retrofit bridges.

The Lower Level (LL) earthquake ground motion is one that is likely to occur within the life time of bridge I.e. it represent a relatively small seismic event. The LL earthquake ground motion has a 50 percent probability of exceedance in 75 years which corresponds to a return period of about 100 years.

The Upper Level (UL) earthquake ground motion represents a relatively large but unlikely ground motion. The UL earthquake ground motion has a probability of exceedance of 7 percent in 75 years which corresponds to a return period of about 1,000 years.

The Site Hazard (SH) is one that characterizes sites with known active faults, unstable geological slopes or liquefiable soils.

IV. Bridge Importance

Classification of bridge importance is based on engineering judgment and two such classes are recommended. One is Essential Bridges and other is Standard Bridges. The Essential Bridges are those that are expected to function after an earthquake or which cross route that are expected to remain open immediately focusing an earthquake, therefore it requires a higher degree of engineering for seismic retrofitting. All other bridges are classified as Standard Bridges. The determination of importance is therefore subjective and determination should be based societal/survival and security/defense requirements.

V. Anticipated Service Life

An important factor in deciding to which a bridge should be seismically retrofitted should be the Anticipated Service Life (ASL) of the structure. Seismically retrofitting of a bridge with a short service life is difficult to justify that the design earthquake will occur during the remaining service life of the structure. On the other hand, a bridge that is almost new or being rehabilitated to extend its service life should be seismically retrofitted for the longer anticipated service life. It is very difficult to estimate the anticipated service life, because it depends on many factors such as age, structural condition, specification used for the design and capacity to handle the current and future traffic but it can be made, at least within broad range for determining a retrofit category. Anticipated Service life can be assumed in three categories based on the new bridge criteria outlined in Bridge Design Specifications that have a service life of 75 years and this life span was then divided into three categories for the purpose of assigning retrofit categories according to age and remaining service life and best economic solution. Also a consideration of following issues should be given: (1) a replacement of bridge may be prohibited due to high cost;(2) the prime location on the existing bridge may force a new and costly alignment;(3) an existing bridge may be structural icon to a community (historical bridge);(4) a well maintained bridge may have a very long service life; and (5) even neglected bridge can be rehabilitated to extend the anticipated service life.

TABLE 1: SERVICE LIFE CATEGORIES

Service Life Category (SLC)	*Anticipated Service Life (ASL)*
Not Applicable	Replacement id scheduled within 5 years
SLC 1	0 – 15 years
SLC 2	16 – 50 years
SLC 3	>50 years

VI. Selection of Performance Levels

Based on the Seismic Performance Levels, minimum performance levels for bridge should be based on the earthquake Hazard Level and Service Life Category.

Due to the cost, it is very difficult to justify the retrofitting levels. The owner may have to choose a retrofit level i.e a lower retrofit level or higher retrofit level based upon the classification of bridge i.e. Essential Bridge or Ordinary Bridge.

The following are the minimum performance levels for concrete girder type bridge:

TABLE 2: MINIMUM PERFORMANCE LEVELS FOR SEISMICALLY CONCRETE GIRDER TYPE BRIDGE
SERVICE LIFE CATEGORIES

	Seismic Life Category		
Seismic Hazard Levels	SCL 1	SCL2	SCL3
Lower Level Earthquake (LL)	PL 3	PL3	PL3
Upper Level Earthquake (LL)	PL 1	PL1	PL2
Site Hazard	PL1	PL1	PL1

VII. SEISMIC RETROFITTING DESIGN PROCESS

Selection of seismic retrofit strategy is a very complex issue. It is a challenge to find a right solution and to satisfy a multitude of socio-economic constraints. The following steps as outlined should be considered as a guidelines to follow in selecting an appropriate seismic retrofit strategy and help in the seismic retrofit design process. These steps are generally in orderly flow but some steps may require backtracking, some steps may leap ahead and some steps my not be needed(2).

Step 1: Screen the Inventory of Bridges for Seismically Complex Bridges

Step 2: Conduct a detailed structural Inspections of the Selected Structural Elements and a Review of the Maintenance Records.

Step 3: Develop a Condition Assessment Report

Step 4: Perform an Analytical Evaluation of the Existing Structure (Bridge)

Step 5: Develop Conceptual seismic Retrofit Measures.

Step 6: Evaluate Alternative Seismic Retrofit Approaches

Step 7: Evaluate Constructability and Cost of Retrofit Alternatives

Step 8: Conduct Meeting(s) for Reviewing the Seismic Retrofit Strategies and Appoint a Peer Review Panel

Step 9: Document the Seismic Retrofit Strategy Selection Process

Step 10: Prepare Construction Plans, Specifications and Estimates (PS&E)

VIII. STRUCTURAL ANALYSIS

The seismic performance evaluation of bridges depends upon the importance of the bridge, the complexity of the structural system and the seismic environment. This section outlines the type of analyses appropriate for evaluating Seismically Complex (SC) and Seismically Standard bridges. Due to the wide variety of existing bridges, the level of structural analyses required - in terms of complexity- for seismic performance assessment and retrofit design could be quite a challenge and its depending upon the classification of the bridges particularly the site specific seismic hazard. The following matrix as outlined should be considered as a guidelines (range of possibilities for level of demand analyses) to follow in selecting an appropriate seismic retrofit design process. Higher degree of analyses could be performed for the specific project located within the specific seismic hazard level(2).

TABLE 3: LEVEL OF STRUCTURAL ANALYSIS DESIRED FOR BRIDGES

	Analysis Complexity		
Bridge type	Seismic Hazard Level		
	Low	Moderate	High
Seismically Standard (SS)	Simplified (Uniform Load)	Multi Mode Spectral	Elastic & Inelastic Dynamic analysis
Seismically Complex (SC)	Multi-Mode Spectral	Elastic & Inelastic Dynamic Analysis	Inelastic Dynamic Analysis

IX. EVALUATION METHODS FOR EXISTING BRIDGES

I. *Superstructure and Substructure*

There are six evaluation methods to evaluate the strength of existing bridges for retrofitting and they are as follow(2):

1. Connection Forces and Seat Width
2. Component Capacity
3. Component Capacity/Demand Method
4. Capacity Spectrum Method
5. Structural Capacity/Demand Method
6. Non-linear Dynamic Procedure (Time History Analysis)

II. *Foundation*

The behaviour of bridge during an earthquake depends upon the stiffness and strength of foundation system, which includes the abutments and piers, footings and piles.

1. *Foundation analysis*

The analysis of the dynamic response of soil-foundation-bridge system is very complex and difficult. As a result of this, a bridge with its foundation would require a focus on the following elements.

(a) Soil-Foundation-Structure Interaction
  (i) Shallow Footings
  (ii) Piles
(b) Stiffness and Capacity of Foundation Components
  (i) Shallow bearing Footing Foundations
  (ii) Pile Footing Foundations
  (iii) Drilled Shafts
  (iv) Abutments

2. *Ground displacement demands on foundations*

There are two major sources of ground displacement demands on foundation (1) due to ground settlements and (2) due to lateral spreading during liquefaction.

(a) Earthquake - Induced Settlements
(b) Liquefaction - Induced Lateral Spreads.

X. Retrofit Measures for Superstructure Bearings and Seats

The most common seismic deficiencies are at bearings and bearing seats. The seismic deficiencies of these two elements could lead to a loss of support and collapse of bridge. To correct these deficiencies retrofit measures such as restraining devices, bearing seat extensions, bearing strengthening or bearing replacement. In addition to these, there are numerous retrofit measures for superstructures that can be considered to reduce or redistribute load to substructure. These methods include the use of special energy dissipating device or isolation bearings, reduction of super structure dead load and provision of superstructure continuity.

XI. Retrofit Measures for Substructure Components

Several retrofit measures using various engineering techniques for improving the seismic resistance of existing bridge substructures such as columns, wall piers, bent caps, cap beams, column- to- cap- beam joints, column footings and other foundation elements etc. are available based on the numerous research. Therefore it is very difficult to characterize the retrofit measures.

XII. Retrofit Measures for Abutments, Footongs and Foundations

Abutments, footings and foundations connect a bridge to the ground(earth). Because of the these elements connect to the ground, the bridge superstructure and substructure feel the effect of an earthquake. Most abutment, pier and foundation failures occur due to the instability of supporting soil (liquefaction, lateral spreading fault movement or landslide) during earthquake. Majority of failures have been taken place due to soil failure. Several retrofit measures using various engineering techniques for improving the seismic resistance of existing bridge abutments, footings and foundations are available based on the numerous research. Therefore it is very difficult to characterize the retrofit measures.

XIII. Retrofit Measures for Bridges on Hazardous Sites

A hazardous site can cause a permanent displacement during an earthquake which leads to large forces and/or differential displacements in the structural members of a bridge. Such sites include that bridges cross or are immediately adjacent to (a) Active faults (b) Steep, unstable slopes ans liquefiable sands or silty sands.

Several retrofit measures such as (a) bridge alignment location adjacent to active faults should be evaluated, (b) adding extra confinement in plastic hinge zone of substructure (this would increase the maximum displacement capacity), (c) extra support length, and additional consideration of redundancy in continuous superstructures.

XIV. Conclusions

- Collected and summarized the state of the practice.
- Normally the Bridge Design Specifications apply to new ordinary bridge with span less than 150 meters and with design life of 75 years.
- Focuses on the seismically retrofitting technique to be applicable for all levels of seismic hazards for conventional concrete super and substructures particularly concrete girder type highway bridges with span less than 150 meters and design life limited to 75 years.
- Practicing bridge design engineers who have some knowledge seismic design and retrofitting technique of ordinary concrete girder type bridges.

References

[1] AASHTO, "*Standard Specification of Highway Bridges,*" 17th Edition, American Association of State and Highway and Transportation Officials, Washington, DC 2002.

[2] Buckle, I, et al., "Seismic Retrofitting Manual for Highway Structures, Part I - Bridges," *FHWA Publication No. FHWA-HRT-06-032,* McLean, VA January 2006.

APPENDIX A:

Design Example: Restrainer Design (2):

Six span bridge has two three span segments. Restrainers are to be used for the hinge seat where two segments meet.

Seat width, N	= 250 mm
Concrete cover on vertical faces at joint, d_c	= 50 mm
Restrainer yield stress, f_y	= 1,214
MPaRestrainer modulus of elasticity, E	= 69,000Mpa
Restrainer length, L_r	= 2.0 m
Restrainer slack, D_{rs}	= 25 mm
Response spectrum for site	= two point method
Short period coefficient, F_aS_s	= 1.75
Long period coefficient, F_vS_l	= 0.70
Target displacement ductility of the frames, μ	= 4
Frame stiffnesses, K_1 and K_2	= 357 and 150 kN/mm respectively
Frame weights W_1=W_2	= 22.3 MN

Step1. Calculate Allowable Expansion Joint Displacement:

D_y = f_yL_r/E
= 1,214(2,000)/69,000 = 53 mm

D_r = $D_y + D_{rs}$
= 53 + 25 = 78 mm.

D_{as} = N - gap - 2d_c
= 250 - 25 - (2x50) = 125 mm

2/3D_{as}> D_rO.K.

Step2. Compute Unrestrained Expansion Joint Displacement

The effective siffness of each frame modeled as a substitute structure is:

K_{eff1} = K_1/μ = 357/4 = 89.3 kN/mm
K_{eff2} = K_2/μ = 160/4 = 40.0 kN/mm

Therefore the effective natural period of each frame is given by:

T_{eff1} = $2\pi\sqrt{W_1/gK_{eff1}}$
= 2π√(22.3)(1,000)/9,800(89.3) = 1.0 sec.

Teff2 = $2\pi\sqrt{W2/gK_{eff2}}$
= 2π√(22.3)(1,000)/9,800(40.0) = 1.5 sec.

The effective damping and design spectrum correction factor is:

$$\zeta eff = 0.05 + \frac{1 - (0.95/\sqrt{\mu}) - 0.5\ VM}{\pi}$$

$$= 0.05 + \frac{1 - (0.95/2) - 0.05.2}{\pi} = 0.19$$

c_d = $[1.5/(40\zeta_{eff} + 1)] + 0.5$
= 0.67

Therefore the frame deflections are calculated as follows:

D_1 = $(T_{eff1}/2\pi)2\ gc_dSa\ (T_{eff1}, 0.05)$
= (1.0/2x3.142)2 x 9,800x0.67x0.7
= 116 mm

D_2 = (1.5/2x3.142)2 x9, 8000x0.67x0.47
= 176 mm

The relative displacement of two now be calculated using the CQC combination of the two frame displacements as given by the following equation. In this case the frequency ratio, B, is 1.5

ρ_{12} = $[8\zeta^2 (1 + \beta)\beta^{3/2}] / \{(1 - \beta^2) + 4\zeta^2 \beta (1 + \beta)^2\}$
= [8x(0.19)2x(1 + 1.5)x 1.5 3/2]/{(1 -1.52)2 + 4x(0.19)2x1.5x (1 + 1.5)2}
= 0.45

D_{eq0} = $(D_{12} - 2\rho_{12}D_1D_2 + D_{22})^{1/2}$
= $(1162 - 2x0.45x116x176 + 1762)^{1/2}$
= 161 mm

>2/3Das = 83mm. Therefore restrainers needed. Because T_{eff1}/T_{eff2} is greater than 0.6 and because D_r/D_{eqo} is between 0.2 and 0.5, the non-iterative method is applicable.

Step3. Calculate Restrainer Stiffness

K_{effmod} = $K_{eff1}.K_{eff2}/K_{eff1} + K_{eff2}$
= (89.3)(40.0)/89.3 + 40.0 = 27.6 kN/mm

N = D_r/D_{eqo} = 78/161 = 0.484

Kr = K_{effmod}[(0.05) + {(0.5) - (n)2}/N]
= 27.6[(0.50) + {(0.5) - (0.236)}/0.484]
= 28.9 kN/mm

Step 4. Calculate Number of Restrainers

Nr = K_rD_r/f_yA_r
= 28.9x0.078/1214x0.000143
= 13.0

Use 14 – 19 mm restrainer cables.