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INDIAN SEISMIC CODES ON BRIDGES: CHALLENGES AND ISSUES FOR DEVELOPMENT

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ABSTRACT

The development of seismic codes of bridges in a country is a continuous process which is carried out on a regular basis because of advancement of knowledge with the Research and Development and experience gained in performance of bridges in recent earthquakes. The various countries often have more than one seismic code on bridges for example one applicable to Highway Bridges and other to Railway Bridges. There has been significant advancement in seismic design procedures in recent years starting from working stress design, ultimate load design, limit state design following force as basis of design and now performance based design following displacement as the basis of design. The performance based design is yet to find a place in seismic codes in India. The reasons for improvements in design procedures have been to counter the deficiencies in existing design methods and achieve performance objectives for design earthquakes as best as possible. Two significant developments in seismic design can be identified (i) consideration of inelastic behavior and ductility in seismic design, and (ii) incorporation of the capacity design concept in seismic design which has led to achieve ductile behavior, avoid brittle failure modes and prevent collapse of structures. These concepts have now found a place in seismic codes on bridges worldwide. India has three seismic codes on bridges; IS: 1893 (Part 3): [1], RDSO Guidelines [2] and IRC Guidelines [3]. This paper presents an overview of seismic codes of bridges and challenges in the development of the codes that include: lessons learnt from past earthquakes, updating of existing analysis and design methods, highlighting important features of different seismic bridge codes, critical views on codes and issues for future developments.

KEYWORDS: Seismic Codes, Bridges, Seismic Design, Inelastic Behavior, Capacity Design, Seismic Analysis

INTRODUCTION

The extensive damage of bridges all over the world in earthquakes has been the motivation behind research and development in seismic analysis, seismic design and retrofitting of bridges. Bridges are considered as structures of post earthquake importance; these are designed to remain functional during and immediately after the design earthquake to meet emergency requirements of rescue, relief and rehabilitation. Bridge behavior in earthquakes is significantly different in comparison to structures like buildings and other tall structures. The lateral load resisting system of a traditional girder bridge for resisting earthquakes is different in both longitudinal and transverse directions. The bearings that separate the super and sub structures are vulnerable to damage. The buildings are designed on the basis of strong column weak beam design philosophy while bridges have the reverse, that is, strong girders and weak columns to resist earthquakes. The plastic hinges thus form in columns in bridges unlike in beams in buildings; therefore, energy dissipation takes place essentially through bridge columns. The redundancy in traditional girder bridges is much lower; therefore these are more vulnerable to collapse. The soil effects on seismic response of bridges are more significant than in buildings. The seismic problems in bridges are now well understood, such as: out of phase motion between piers, failure of bearings and expansion joints, inadequate seating width leading to unseating and falling of spans, pounding of spans, non-ductile behavior of substructures, failure of foundation due to soil liquefaction, failure of abutments and approaches.

The earthquake resistant design of bridges is all about providing the structure with adequate strength, stiffness and ductility to withstand earthquake generated forces and deformations. This is accomplished through the selection of appropriate structural configuration, and careful detailing of structural members and connections for achieving ductile behavior. Structural analysis and structural design are the two most important steps in the total seismic design process. Earthquake resistant design of bridges is continuously evolving with the advances in earthquake engineering. Needless to mention that the designers are expected to use the rational methods of seismic analysis and seismic design which are the state of the art, in order to achieve safe and economical design of the structure. The new design methods are being developed to remove the deficiencies of existing methods. The main task in design remains to meet the performance requirements as best as possible. One of the deficiencies of existing design method that is force based design, is that these are unable to quantify and control the damage level in the structure. The emphasis on earlier design methods was on prevention of collapse and not so much on control of damage. There has been a gradual shift from force based design procedures to performance based design using displacement as the basis of design. The later design method not only ensures collapse prevention but is addressed to achieve design performance objectives in order to control extent of damage. The performance objectives are formulated based on design requirement considering life of a structure, return period of earthquake and importance of structure. The seismic codes all over the world are gradually adopting performance based design as these have the potential to meet the design objectives effectively and provide better performance in earthquakes. Similarly, the non linear seismic analysis procedures are now gradually adopted in place of linear elastic methods as the former can better represent structural behavior in post elastic range under design earthquakes and are consistent with inelastic design procedures. Thus the future of earthquake resistant design of bridges lies in the nonlinear methods of dynamic analysis and inelastic methods of design following displacement based approach.

The common issues that need to be addressed in seismic codes in bridges are following: Design earthquake motions, Design response spectrum, performance objectives, bridge importance, response reduction factor, soil effects , seismic forces on live loads, hydrodynamic effects on submerged piers, seismic analysis and design methods, bearing design, unseating prevention devices, effect of vertical accelerations, ductile detailing in substructures, seismic isolation and energy dissipation devices, failure of approaches and earth pressures on retaining walls and abutment and liquefaction of founding soil.

This paper presents an overview of Indian Seismic codes on bridges and challenges in development of seismic codes that include: lessons learnt from past earthquakes, updating of existing analysis and design methods, highlighting important features of different seismic bridge codes, critical views on codes and issues for future developments.

LESSONS LEARNT FROM PERFORMANCE OF BRIDGES

The observation of performance of bridges in past earthquakes world over has highlighted following deficiencies in bridges. One important lesson from such observations is not to repeat the mistakes committed in the past. The lessons learnt and its design implications are thus to be appropriately addressed in design recommendations of the seismic codes.

- **Superstructure:** The traditional superstructures of the girder bridges are rigid and massive; these do not suffer damage due to effects of vibrations in earthquakes. The main problem in the superstructure has been the shifting and dislodging of spans due to bearing failure and inadequate seat width. The superstructures have also been seen to be twisted and over toppled from bridge supports in transverse direction due to inadequate connection with the bearings. The falling of spans from supports is the most unacceptable type of bridge failures which need to be prevented. The adjoining spans are normally not interlinked as a result these get dislodged. The shifting and falling of spans can be prevented by suitable design and detailing of inter connection of spans and provision of vertical holding down devices at bearing locations.
- **Bearings:** The traditional rocker and roller bearings and elastomeric bearings have not shown satisfactory performance in earthquakes. There have been problems due to jumping and inadequacy of bearings in accommodating displacements. Bearing design should take into consideration of provision of enough space for estimated seismic displacements and rotations besides provision of stopper to restrict excessive movements and vertical holding down devices to prevent jumping. The integral bridge design without bearings is often appreciated from seismic considerations to eliminate bearing issues.
- **Substructure:** The various types of deficiencies observed in RC columns and piers are (i) lack of flexural strength and ductility, (ii) lack of shear strength, (iii) insufficient transverse reinforcement and confinement in columns, (iv) inadequate lap splicing of longitudinal steel, (v) premature termination of

longitudinal steel in piers and (vi) insufficient strength of joints between pile and cap beams. All these deficiencies can be taken care of by seismic design and ductile detailing.

Reinforced wall piers have usually performed well in earthquakes. Displacement ductility of 2-3 is generally available in longitudinal direction. However such wall piers are very stiff in transverse direction resulting in attraction of large seismic forces in transverse direction that may cause foundation damage if not adequately designed.

- **Abutments:** The abutments have been seen to be tilting forward, rotating, sliding forward or collapse due to increase in earth pressure in earthquakes. Abutment slumping is observed in soft soils. Spill through abutments have performed better in earthquakes; these are preferred abutments in resisting earthquake effect.
- **Soil Effects:** The site amplification of accelerations due to soil characteristics often causes large displacements in bearings resulting in shifting and dislodging of superstructure spans. Liquefaction of soil often results in damage due to unequal settlements and loss of span type of failures.
- **Inadequacy of Foundations:** Inadequate strength of foundations, open, well or pile have resulted in foundation failures; these are design issues that can be dealt by exercising a good seismic design practice following capacity design principles.
- **Bridge Approaches:** The bridge approaches are often found to be damaged due to settlement of soil or separation of earth fill from abutment. As a result bridge becomes unserviceable after the earthquake.

INDIAN SEISMIC BRIDGE CODES

The following seismic codes/guidelines for seismic design of bridges exist in India:

i. IS: 1893 (Part 3): [1], Criteria for Earthquake Resistant Design of Structures, Part 3 Bridges and Retaining Walls, Bureau of Indian Standards, New Delhi.

ii. RDSO Guidelines on Seismic Design of Railway Bridges, January [2], Bridge & Structures Directorate, RDSO, Lucknow.

iii. IRC: SP: 114 - [3] Guidelines for Seismic Design of Road Bridges, Indian Roads Congress.

IRC Guidelines of [3] are exclusively applicable to Highway Bridges; these are recently made, yet to come in practice. The existing seismic provisions of IRC: [4] are currently applicable to Highway bridges. The RDSO Guidelines of January [2] are applicable exclusively to Railway Bridges. IS: 1893 (Part 3): [1], Seismic code on Bridges and Retaining Walls is a reference seismic code that is applicable to all types of bridges and aqueducts. Some variations in provisions for the same design aspect, in clauses always remain between various seismic codes on bridges which are made by different committees but attempt is always made to remove any such difference by the respective committees who are responsible for making these codes. The Response Spectrum which governs level of seismic force on structures in various zones is the same for all codes and is adopted from IS: 1893 (Part 1): [5], Criteria for Earthquake Resistant Design of Structures, Part 1 of General Provisions and Buildings. The Seismic Design Criteria outlined in Part 1 of IS: [5] are generally adopted by all seismic codes on bridges in the country; this code still remains the primary reference seismic code behind all seismic codes of the country.

HIGHLIGHTS OF SEISMIC CODES ON BRIDGES

IS: 1893 (Part 3): [1]:

i. The code is applicable for seismic design of new bridges as well as checking design of existing bridges for purpose of retrofitting.

ii. The code is applicable to seismic design of highway bridges, railway bridges, flyovers, pedestrian, submersible, utility bridges and aqueducts.

iii. The code is applicable to bridges where seismic actions are resisted by abutments through flexure of piers.

iv. The earthquake effect for abutments and retaining walls can be computed for frictional soils as well as cohesive and frictional soils.

v. The methodology for determining hydrodynamic pressure on submerged piers is based on cylinder analogy.

vi. The detailed dynamic analysis is recommended for major and special types of bridges.

vii. Majority of ordinary bridges with traditional type of girder bridges can be analyzed by seismic coefficient method.

viii. The seismic design of the bridge should meet serviceability limit state for DBE and meet requirement of ultimate limit state for MCE. While checking design as per IS: 456, only DBE is recommended.

ix. The seismic analysis of bridges can be carried out by one of the following methods, (i) Seismic Coefficient (SCM), (ii) Response Spectrum Method (RSM), (iii) Time History Method (THM) and (iv) Push Over Analysis (PA). Short or medium span bridges are analyzed by SCM, while major and special bridges are analyzed by RSM/THM. The Push over analysis (PA) is recommended for seismic design of special bridges and evaluation of existing bridges for the purpose of retrofitting.

x. The design approach recommended in the code is based on force based design using response reduction factors. The seismic forces are estimated by elastic analysis using one of the methods of seismic analysis; elastic forces are then divided by response reduction factor as specified in the code to determine design forces.

xi. The seismic design is primarily done for DBE; the bridges are expected to undergo only minor damage under this condition. The bridges may be subjected to considerable damage under MCE but not collapse.

xii. The capacity design concept should be applied to force the plastic hinges to occur at pre determined locations; these locations can then be provided with special ductile detailing to ensure ductile behavior.

RDSO Guidelines for Railway Bridges, [2]

i. The conceptual design considerations such as simplicity, symmetry and regularity are recommended in selection of structural configuration for better seismic behavior.

ii. The seismic guidelines are applicable for design of new bridges but not for evaluation of existing bridges.

iii. The seismic design of bridges is recommended for design basis earthquake.

iv. The seismic force on live load shall not be considered in longitudinal direction. However the seismic force on 50 % of design live load shall be considered in transverse direction.

v. A separate load combination and load factors are recommended for Ultimate Limit State and Serviceability Limit State.

vi. The Response Reduction factors are recommended for different types of substructures, connections and bearings. The maximum value of R factor for reinforced concrete piers with ductile detailing is recommended to be 3.25.

vii. The seismic design is based on force based design where elastic forces determined from seismic analysis are reduced by response reduction factors in order to consider inelastic behavior of the bridge.

viii. The emphasis is given on ductility provision through ductile detailing.

ix. Provision of seismic design of bridge using seismic isolation technique is also included in the guidelines.

IRC: SP: 114 - [3] Guidelines for Seismic Design for Road Bridges

i. The conceptual design considerations such as selection of appropriate structural configuration, bearing types, expansion joints details and foundation types are given which may result in better seismic behavior of bridges.

ii. It is preferable to design bridges in seismic zones IV and V with longer fundamental period of vibration which may result in substantial reduction in development of seismic forces in the structure.

iii. The beneficial effects of bridge flexibility and ductility should be duly accounted in the seismic design.

iv. The principle of strong girder and weak column shall be followed for seismic design. Plastic hinges should form in the piers at pre selected locations so as to ensure accessibility for inspection and repair.

v. The capacity design principle should be employed for design of piers. The foundation, bearings and superstructure should be designed for capacity design effects to ensure elastic behavior in these components.

vi. The shear failure in columns shall be avoided by designing transverse reinforcement for confinement of concrete following ductility provisions of code.

vii. The bridges with design life of up to 100 years may be designed for DBE only. The bridges with design life of more than 100 years and special types of bridges may be designed for both DBE and MCE.

viii. The seismic design should be carried out following force based design using response reduction factors given in the guidelines. The capacity design concepts should be employed for design of plastic hinges in piers.

ix. The code provides broad steps to be followed in the capacity design of plastic hinges and elastic design of regions beyond plastic hinges.

x. The response reduction factor of various bridge components are provided both for with ductile detailing and without ductile detailing.

xi. The three methods of seismic analysis: i. Elastic Seismic Acceleration method (Seismic Coefficient method), ii. Elastic Response Spectrum Method and, iii. Time History Method is recommended. The application of the methods for various types of bridges is also specified in tabular form.

xii. The hydrodynamic pressure on submerged portion of bridge piers and method of computing 'added mass of water' in lieu of hydrodynamic pressure is also presented in the code.

DEFICIENCIES IN EXISTING SEISMIC DESIGN METHOD

The seismic design method followed in the present Indian codes is based on Force Based Design; the force is considered as the basis of design in this approach. In this method of design, elastic seismic analysis is carried out to obtain column bending moment. This moment is reduced by Response Reduction Factor R to obtain design strength. The R factors primarily represent the ductility in the structure and also included in these factors are other effects which effectively reduce structural response such as redundancy, over strength and energy dissipation. The choice of these factors involves a good deal of judgment; there is always a level of arbitrariness in the values recommended in the codes. Though widely accepted and proven method of design, it suffers from deficiencies which are highlighted below:

i. The R factors do not quantify the level of damage in the structure; it is not a rational indicator of damage.

ii. There is no direct relationship between detailing practice and ductility factors; ductility factors are normally not verified in the design process.

iii. The elastic forces computed in elastic analysis are based on gross stiffness or effective stiffness of components which is not precisely known at the beginning of design.

iv. The constant force reduction factors is employed in multi modal response analysis method while inelastic action primarily reduces response associated with the first mode; as a result the contribution of higher modes is underestimated.

v. There is a variability observed in R factors over a period range, same R factor is not applicable in short and long period range. The R factors also depend on hysteretic characteristics of the material which may be different than elastic- plastic behavior for which these are normally related.

vi. The structural damage is often experienced to be larger in earthquakes following this method of design.

CRITICAL VIEW ON CODES AND ISSUES FOR DEVELOPMENTS

There are three different seismic codes/design guidelines available for bridges in India as mentioned in previous paragraphs. All these design codes are based on IS: 1893 (Part 1). The need for each code and guidelines is justified in view of difference in their scope and range of applications. Any update in basic code IS: 1893 (Part 1) does not automatically occur in other codes; the modification in other related codes are to be done by respective institutions and their code making committees which is often a long drawn process. Most design provisions are similar but there are marginal differences in the provisions of various codes which causes some difference in responses. A judgment by designer is often taken to follow the conservative path in design because of the differences in code provisions. Attempts should be made to minimize the differences in these codes in future updates. However there are critical issues which are not considered so far in these codes; these issues should be addressed in future updates of various codes. The critical views on codes and issues for future developments are presented below:

i. The seismic design of bridges is presently carried out for DBE. The bridges are still not designed for MCE earthquake. The seismic analysis and design methods for MCE should be incorporated in the code. Checking of seismic design for two levels of earthquakes that is DBE and MCE is largely followed in majority of world codes.
ii. The seismic design is presently carried out by Force based method of design employing capacity design principles. This requires the use of response reduction factors. There is always arbitrariness involved in specifying R factors and these are not considered good indicators of damage. Thus there is a need to upgrade seismic design methods which should quantify level of damage such as Force based design with displacement check or Performance based design/ displacement based design. The performance objectives for different level of earthquakes need to be specified in design methods besides SLS, ULS and DLS (Damage control limit state).
iii. The nonlinear time history methods of seismic analysis are more rational and these need to be adopted in seismic design where nonlinearity in behavior is envisaged particularly for MCE level of earthquake; one of the merits of these design methods is that these do not require use of R factors.
iv. The issues of seismic assessment of existing undamaged bridges and earthquake damaged bridges and retrofitting is not covered in the codes; a separate code is indeed required for ‘Seismic Assessment and Retrofitting of Bridges’.
v. The Seismic design methods employing seismic base isolation and passive energy dissipating devices should be brought in the codes.
vi. The need for Structural Health Monitoring for Special Category of bridges should be highlighted in the codes.
vii. The seismic design aspects for near-field motion should also be included.

NEED FOR PERFORMANCE BASED DESIGN

There has been a shift observed in seismic design philosophy in some world codes from emphasis on prevention of collapse to control of damage through Damage Control Limit State. This has led to adopting of Performance Based Design (PBD). This trend is now growing and many of the short comings of existing Forced Based Design can be overcome in this method of design. The objective of PBD is to achieve predefined level of damage when subjected to predefined level of Earthquake Intensity. The displacement is found to be better indicator of damage than ductility. The displacement design procedures are developed which directly relate damage to strain or drift that are capable of determining damage rationally and enable better achieving of design limit states. The Direct Displacement Design [Priestley, (6)] is one such method which considers inelastic action in rational manner in the design process. The seismic design codes are now gradually adopting Displacement Based Design in place of Force Based Design in order to achieve limit states of design for different levels of earthquakes [Yashinsky, (7)]. The most common approach which is adopted in the format of PBD is Force Based Design with displacement check [Priestley, (6)]. This approach has received wider acceptability in world codes. To start with such an approach can be explored for Indian codes.

CONCLUSIONS

This paper presents an overview of seismic bridge codes and challenges in development of seismic codes of bridges in India. The paper highlights salient design provisions recommended in various seismic codes. A critical overview on codes and issues of future developments are highlighted. Although codes are made to incorporate results of current research and lessons learnt from performance of bridges in past earthquakes, yet there are gaps between state of art practice of design and provisions in existing codes; efforts should be made to minimize such gaps. The future of earthquake resistant design of bridges lies in the nonlinear methods of dynamic analysis and Performance Based Design, following displacement as the basis of design.

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