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A Critical Evaluation of the Indian Codes on Seismic Analysis of Concrete Bridges

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ABSTRACT: *There is an increasing agreement among researchers and professionals that future seismic design needs are to be based on achieving multiple performance objectives. Future seismic codes should incorporate new developments in demand and capacity descriptions with quantifiable performance criteria to have seismic protection of existing and new structures. Here, a brief review of the present IRC code provisions on seismicity is made. The paper highlights the importance of ductility and energy dissipating capacity of a structure in resisting seismic forces and critically evaluates the limitations of the current Indian code provisions on seismic resistant design.*

Keywords- *Bridges, Ductility, Energy Dissipation, Indian Code, Plastic Hinges, Seismic Design*

1. INTRODUCTION

The history of humankind’s endeavours and achievements, right from the inception of human civilization to the modern era, is greatly influenced by the history of bridge building. A bridge may be defined as a structure surmounting an obstacle such as a river, road, valley, depression or Railway and used as a passage for people or vehicular traffic. A bridge is designed to satisfy the functional, economic, strategic and aesthetic requirements.

The Indian subcontinent has a history of devastating earthquakes. The major reason for the high frequency and intensity of the earthquakes is that the Indian plate is driving into Asia at a rate of approximately 47 mm/year. Geographical statistics of India show that almost 54% of the land is vulnerable to earthquakes [1]. The latest version of seismic zoning map of India given in the earthquake resistant design code [IS 1893 (Part 1): 2002] assigns four levels of seismicity in terms of zone factors. According to the present zoning map, Zone 5 expects the highest level of seismicity whereas Zone 2 is associated with the lowest level of seismicity.

For most dynamic structural responses, linear concepts remain sufficiently accurate tools because of low stress levels. In contrast, seismic damage process in structures are characterized by high inelastic actions, low number of cycles upto failure, high inelastic energy dissipation rates, often combined with large deformations.

The current approach to the earthquake resistant design of structures is based on damage prevention during low magnitude earthquakes, allowing some damage during moderate or intermediate tremors and on prevention of collapse during severe earthquakes. The concept is implemented by allowing for a design, in which the structural members will experience post-elastic excursions associated with permanent stiffness and strength deteriorations. Hence engineers around the globe have tried to evolve design criteria, which meets the functional requirements yet it doesn’t result in uneconomical design. New criteria take into account acceleration, frequency, displacement, inelastic design, ductility, reinforcement detailing and collapse mechanism.

2. INDIAN CODE RECOMMENDATIONS ON SEISMICITY

Provisions of IS 1893 (Part 1):2002, IS:13920-1993, IRC:6-2010 and IRC:112-2011 can be used for earthquake resistant design of bridges. Ground motion due to earthquakes can be resolved in any three mutually perpendicular directions, but the predominant direction of vibration is the horizontal one. The design vertical seismic coefficient is taken as two third of the design horizontal seismic coefficient discussed above. Seismic force on each component of bridge is the product of its mass and the horizontal/ vertical seismic coefficient. The horizontal force could come from any direction but each of the two perpendicular horizontal forces is considered separately with the vertical force. Consideration of seismic forces in design is restricted to bridges with overall length more than 60m or spans more than 15m for Zone II and III, whereas all bridges in Zone IV and V need to checked for seismic action. Culverts and minor bridges upto 10m span need not be designed for seismic forces in any of the seismic zones [2].

During the expected maximum intensity of earthquake in the various seismic zones, structures will be subjected to a bigger force than the design force level. Capacity of the structure in plastic range is relied upon for absorbing the kinetic energy imparted by such earthquake. But its capacity is unquantified and unanalyzed. Ductile detailing is prescribed as per IRC:112-2011 and IS:13920-1993, which states that ductile detailing shall be carried out for bridges located in zones III, IV and V of seismic zone map of IRC:6-2010. Bridge superstructure is designed as an elastic system and plastic hinge formation is permitted only on the substructure components which are above the ground surface. Ductile behaviour of the compression zone of concrete is ensured by providing confinement reinforcement. The code suggests that the confinement shall extend at least upto the length where the value of the compressive strain exceeds $0.5\varepsilon_{cu2}$ [3].

The code (IRC:112-2011) specifically recommends no plastic hinge formation on bridge foundation system, but in case of piles, following locations along the pile are treated as potential plastic hinges

a) At pile heads adjacent to pile cap
b) At location of maximum bending moments
c) At interface of soil layers

The code stipulates an increased moment carrying capacity for slender columns/piers compared to short members of identical cross-section and steel ratio. This is due to the large and disproportionate increase of deflections due to combined effect of geometric non-linearity (P-Δ effect) and non-linear structural response due to material non-linearity, progressive cracking and local plasticity.

Regarding torsion, the code advices a full torsional design covering ultimate limit state, where the static equilibrium of a structure depends on the Torsional resistance. As per the code, warping torsion for box section can be ignored unless the longitudinal elongation of the walls/surfaces of the section is restrained by other members.

The contribution of prestressing steel in Prestressed Bridges towards minimum reinforcement for crack control shall be ignored and minimum steel should be provided to account for early thermal and shrinkage cracking. The code gives the bar size and its spacing to control cracking in a tabular form (Table 12.2 and 12.3, IRC:112-2011).

The code classify the column into two types (a) Pedestal columns (b) Other Columns. Pedestal columns are those whose length/least radius of gyration is less than 12, for which the longitudinal reinforcement shall not be less than 0.15% of cross-sectional area of concrete. For other columns minimum longitudinal reinforcement is $0.1N_{ED}/f_{yd}$ or .2% A_c, where A_c is the gross cross-sectional area of concrete, N_{ED} is the design axial compression force and f_{yd} is the design yield strength of the reinforcement. The maximum reinforcement ratio is limited to 0.04 A_c outside lap portion and 0.08 A_c at lap section.

The transverse reinforcement of the column should have a diameter not less than 8mm and spacing not to exceed 200mm. It should have a 135^o hook for proper confinement of core concrete.

3. IMPORTANCE OF DUCTILITY AND ENERGY DISSIPATION CAPACITY

Ductility & Energy dissipation, both are essential for better seismic performance. The deformation capacity of a structure is more dependent on its ductility than the strength. It acts as a shock absorber reducing the transmitted force to a sustainable one, which enables one to design the members with lesser strength than the elastic strength demand imposed by ground motions as shown in Fig. 3.1. The ratio of Δ_{max}, maximum displacement beyond the yield limit up to which the structure retains the seismic loads and Δ_y, maximum displacement at yield limit is known as ductility. This is required to be used in seismic design to avoid uneconomic structural sizes. Ductility is dependent on degree of redundancy, axial force, steel ratio, structural geometry etc. The ductility demand should be sufficiently less than the ductility capacity, for the structure to be safe.

There is a usual philosophical concern that the displacement experienced by the ductile structure will be more than a comparable elastic structure as the restoring force has been reduced. But this is counteracted by the reduced acceleration. Hence we can adopt an equal displacement hypothesis here, which allows us to analyse the elastic model and directly apply the conclusions in the design of a ductile structure. This favours the adoption of Displacement-Based design approach for ductile structures which is commonly used in Performance Based Seismic Design (PBSD) [4]. In general, the piers are made ductile in case of bridges while the deck remains elastic during seismic action.

The main argument against the use of ductility as seismic damage indicator lies in the cyclic character of seismic actions. Hence a member to be capable for resisting seismic force requires both deformation capacity and energy dissipation characteristics [5]. For a properly designed and constructed member, energy dissipation capacity is dependent on the material property (grade of concrete and steel), reinforcement detailing, etc.

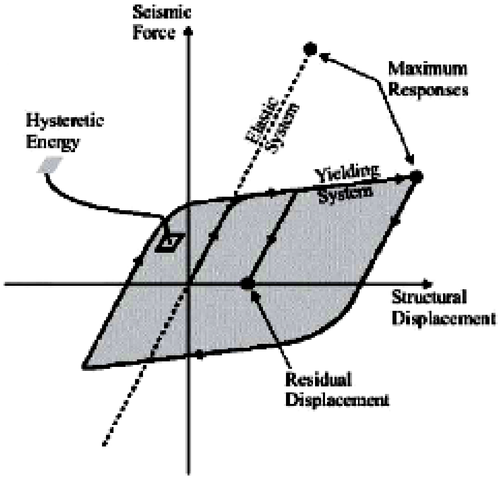


Fig. 3.1 idealized seismic response of yielding structure [6]

As the seismic excitations cause cyclic response in the structure, generally small in number until failure but with high inelastic behaviour, the use of energy ratio as a damage indicator is more recommended than cyclic or cumulative ductility [7]. The ground motions during earthquake can belong to impulsive type or long duration earthquake. The deterioration behaviour and the performance of a component will be different in the above two cases (Fig. 3.2 (a) and (b) respectively). Using a time history independent deformation capacity would be misleading for both cases. Hence accounting for deformation and energy dissipation characteristics to quantify the damage is the one which is to be looked into. The use of damage indices in Performance-Based design methodology is an area still in research.

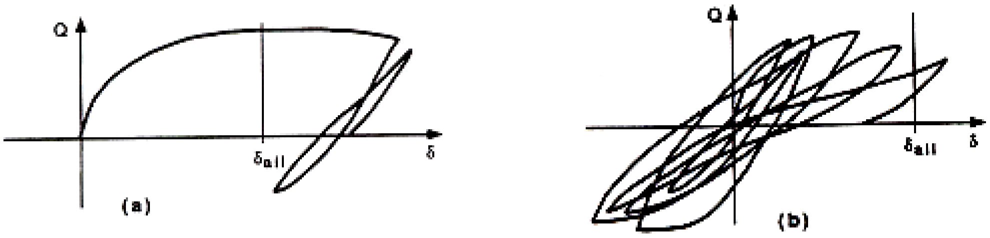
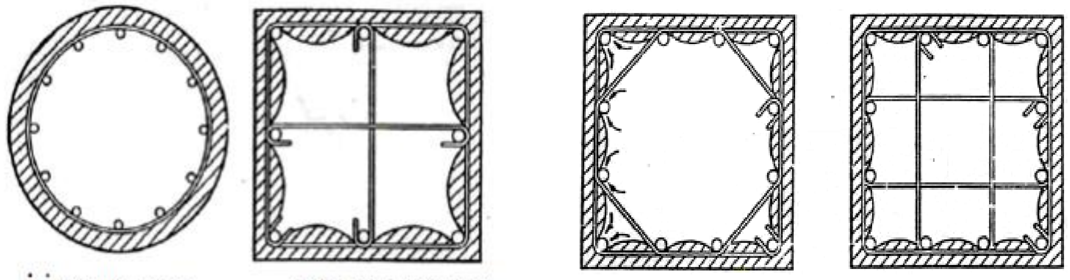


Fig. 3.2 different response history for the same structural component [7]

4. PROVISIONS FOR IMPROVING DUCTILITY IN BRIDGES

Ideally, bridge structures should be designed so that the earthquake energy will be dissipated by the individual members acting in a ductile manner, avoiding brittle shear failures. This is, however, not possible in all cases of bridge design, since some of the components may behave in a non-ductile fashion. Since the ductility levels may vary for the individual components of a bridge, reduction of the elastic response spectrum for design may be somewhat misleading and may result in some members being under designed. Hence, elastic design response spectrum should be used to predict the overall structure response and then the ductile components should be designed to absorb the required energy. The important aspect in designing is to predict how a bridge would actually behave during an earthquake. Further, one must qualify ductility as either being available ductility or required ductility. Another distinction must also be made between ductility of the section of an individual component of a structure and the overall ductility of a structure. The seismic design involves matching of the available ductility with the required ductility for a particular R used in the design. Ductility also explains the damping in the structure. A structure undergoing a cyclic loading with significant loss of energy in plastic deformation would have a higher damping.

Concrete is known to be a brittle material, i.e. it fails suddenly when subjected to load. But concrete can be made ductile when confined by reinforcement. Confinement not only increases the strength of concrete, but it tremendously increases the ductility of concrete. The confinement of concrete is obtained by providing stirrups as shown in Fig. 4.1. The stirrups should be hooked at 135^0 into core concrete; otherwise these stirrups open up under force due to earthquake and the confining action is not available. Further, even with confinement, RC members are sufficiently ductile in bending action only, but not in axial and shear action. Therefore, we have to ensure that RC members should yield only in flexure and not in axial or shear action. This can be ensured by designing the RC members in such a way that their shear and axial load capacity is higher than their capacity in flexure. This is called ‘Capacity Design’. By suitable selection of flexure, shear and bending capacity, a structure could be designed to behave in a particular way. At the junction of pile cap and pier, a pier could be designed to intentionally yield to ensure that excessive shear is not generated to damage the foundation or cause collapse. Creation of such intention locations is known as creating hinges at which structural member rotate plastically without losing structural integrity. Fig. 4.2 shows the possible locations of such plastic hinges in bridge piers. Such hinge locations should be specially designed with additional stirrups for making the concrete ductile.



A. Circular hoops or spiral

B. Rectangular hoops with cross ties

C. Rectangular octagonal hoops

D. Overlapping rectangular hoops

Fig. 4.1 confinement reinforcement in columns/piers [8]

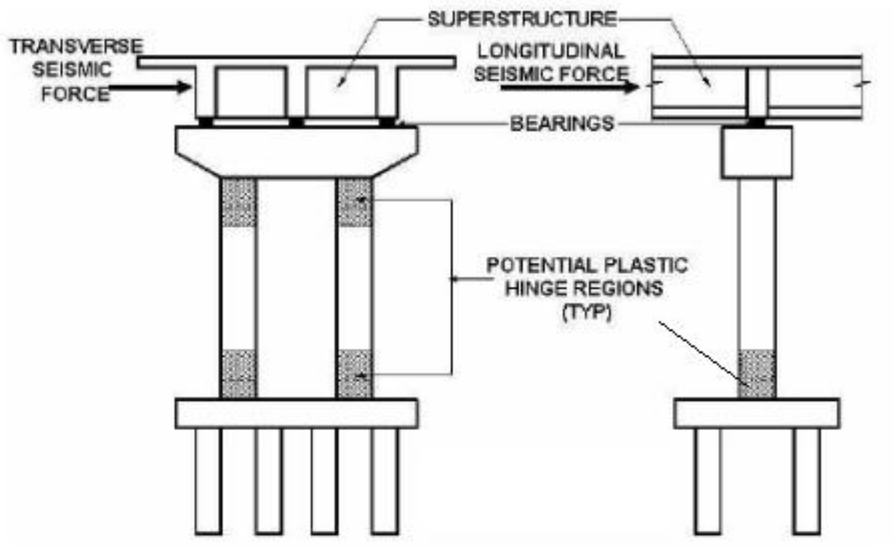


Fig. 4.2 location of plastic hinges in piers [9]

5. OVERVIEW OF CODE-BASED DESIGN PROCEDURES

Conventional methods of seismic design have the objectives to provide life safety (strength and ductility) and damage control (serviceability drift limits). The design criteria are defined by limits on stresses and member forces calculated from prescribed levels of applied lateral shear force. That is, the design is a Force-Based design, which uses elastic models to predict a hypothetical strength objective, which is then reduced to an idealized strength objective based on perceived level of ductility.

As per the Indian Standard codes, the bridges are designed for Design Basic Earthquake (DBE) with partial load and material safety factors. For converting the spectral acceleration value obtained from the design spectrum (which is nothing but response spectra for 1g PGA) given in IRC:6-2010, which is for Maximum

Considered Earthquake (MCE), we use the factor $Z/2$ in the equation. Where Z is known as the zone factor which is based on the classification of areas according to the seismic intensity felt by the structures. IRC:6-2010 classify the bridges based on seismic classes as Normal, Important and Large critical bridges and corresponding importance factor I is given as 1, 1.2 and 1.5 respectively. The performance parameter is considered in the code for both with ductile detailing and without ductile detailing by introducing a term known as response reduction factor (R), which is derived based on overstrength, redundancy, ductility characteristics etc. R values vary for superstructure, substructure and bearing components and have to be taken separately for them rather than bridge as a whole. When elastomeric bearings are used to transmit horizontal seismic forces, R shall be taken as 1.5 for RCC substructure [2]. For a proper design/evaluation approach for various categories of structures given in the spectrum, the non linear characteristic from the equal displacement and equal energy principles should be adopted.

Ductility can be increased by proper detailing and proportioning of structural members, which is given due emphasis in the Indian code too. The code also recognises that the response of a structure to ground vibrations is a combined function of the nature of foundation soil (Type I, Type II and Type III for Rock, Medium and Soft soil categories respectively), materials, form, size, mode of construction and the duration/characteristics of ground motion. To improve the performance of bridges during earthquakes, bridges in seismic zone IV and V may be specifically detailed for ductility for which IS:13920-1993 may be used.

For obtaining the response factor for a particular bridge, first its natural oscillation period is to be determined. As per IS 1893 (Part3): 2002, draft code, where the vibration unit of substructure can be idealized as a single cantilever pier carrying the superstructure mass, resting on well, pile or open foundation, the fundamental period shall be calculated from the following equation.

$$T = 2\pi\sqrt{\frac{\delta}{g}} \qquad (1)$$

Where, δ = horizontal displacement at the top of pier due to horizontal force equal to mg, m is equal to lumped mass at the top of pier. The elasticity of substructure and foundation should be accounted for while evaluating the displacement.

While calculating the seismic loading, the live load shall not be considered when seismic force is acting in the direction of the traffic but shall be considered when the direction is perpendicular to the traffic. The horizontal seismic force in the direction perpendicular to the traffic and the vertical seismic force shall be calculated using 20% of live load, excluding impact factor.

The seismic forces shall be assumed to come from any horizontal direction or vertical direction. A 30% combination rule will be adopted for evaluating the seismic response of the bridge components.[4] Vertical seismic forces are considered significant in bridges with large spans, and those elements in which stability is considered a significant parameter. They require special attention in prestressed or cantilevered beams, girders and slabs.

IS 1893 (Part 3): 2002, draft code recommends four method of analysis for calculation of seismic forces in bridges. They are

i. Seismic Coefficient Method (SCM),
ii. Response Spectrum Method (RSM)
iii. Time History Method (THM), and
iv. Push Over Analysis (PA)

Table 5.1 Method of seismic analysis of bridges (IS 1893 (Part3):2002, Draft Code)

Earthquake Level	**Category of Bridge Type**		
	Regular	**Special Regular**	**Special Irregular**
DBE	SCM	RSM, THM	RSM, THM, PA

In case of MCE, non-linear analysis and Time History Method shall be adopted. While IRC:6-2010 recommends only elastic seismic acceleration method for most of the bridges and elastic response spectrum method for more complex structural systems which includes continuous bridges, bridges with large difference in pier heights, bridges curved in plan etc.

For design of foundation the seismic loads should be taken as 1.25 times the forces transmitted to it by substructure, so as to provide sufficient margin to cover the possible higher forces transmitted by substructure arising out of its overstrength [2].

IRC:6-2010 also provides some mandatory provisions for ductile detailing . In zones IV and V, to prevent dislodgement of superstructure, “reaction blocks” shall be designed for the seismic force and to be provided. Also the piers and abutment should be provided with sufficient dimensions to prevent dislodgement during severe earthquake. The minimum dimension for support can be calculated as, minimum support length measured normal to the centre line of bearing in mm = 305 + 2.5 × span in meters + 10 × average column height in meters. For improving ductility and hence better behaviour during earthquakes, continuous superstructure or integral bridges may be adopted, if not unsuitable [2]. Where elastomeric bearings are used, a separate system for arrester control in both directions shall be introduced to cater to seismic forces in the bearings.

IRC:112-2011 clearly specifies the serviceability criterion to be checked which include the stress level, crack width and deflection. The maximum compressive stress in concrete under rare combinations of loads as specified in IRC:6-2010, shall be limited to $0.48f_{ck}$ in order to keep the longitudinal cracks , micro cracks or creep within acceptable limits. The maximum tensile stress under such load combination shall be limited to $0.8f_{yk}$ to avoid inelastic strain and undesirable cracking/deformation of the structure. For prestressing steel, in order to avoid inelastic strain the maximum force applied to tendon shall be limited to 90% of 0.1% proof load. In no case the maximum prestressing force applied to the structure immediately after transfer (i.e. after losses due to elastic shortening and anchorage slip) shall not be greater than 75% of f_{pk} or 85% of 0.1% proof load, which ever is less. Cracking in concrete takes place in tensile regions due to load effects such as bending, shear, torsion and direct tension. It may also be caused due to internal deformations such as shrinkage and temperature effects. The maximum permissible crack width for prestressed members with bonded tendons under frequent load combination as mentioned in IRC:6-2010, shall be 0.2mm for moderate, severe and extreme condition of exposure. The deflection/deformation of a member or structure shall not be such that it adversely affects its proper functioning or appearance. IRC:112-2011 recommends the following deflection limits under Live Load

i. Vehicular: Span/800
ii. Vehicular and pedestrian or pedestrian alone: Span/1000
iii. Vehicular on cantilever: Cantilever span/300, and
iv. Vehicular & pedestrian and pedestrian only on cantilever arms: Cantilever span/375

6. CONCLUDING REMARKS

The present code provisions are based on Force-based method of design. The load-deformation pattern of various components clearly shows that, damage is equally or more dependent on deformation than the force. Also the use of response reduction factor for various components to incorporate the effect of ductility is quite empirical in nature. The recent developments on displacement–based design deserve much attention worldwide. Here the deflection of the structure is considered as the demand parameter and the structure is proportioned to achieve the desired performance through various techniques. FEMA 356 provides a new approach in which plastic deformation in members is considered as the demand parameter which can be used for the evaluation of both rehabilitation as well as new building projects. But, no methodology is given for the systematic proportioning of structural components to achieve the desired performance in the case of new buildings and hence it may require a large number of iterations. The same concept can be used in case of bridges also.

Even though a general performance objective of Life Safety level in minor and moderate seismic events and Collapse prevention in major seismic events are mentioned, no provisions are given in Indian Standard codes for assessing it. As in AASHTO LRFD Bridge Design Specifications-2007, there is a need for detailed commentary about the ductility provisions specified in the Indian codes. In IRC a response reduction factor of I/R is taken to consider the ductility demand. The code doesn’t elaborate on the relation between the response reduction factor and the ductility of a member, and the method of achieving a higher ductility. It is also silent about deformations, the relation between deformation and seismic force, and the demand and capacity of deformation of various bridge members.

The zone factor is based on the seismic intensity, but the intensity is dependent on the site geological characteristics, distance from the actual fault, magnitude of the earthquake, its return period etc. and hence the dependency on a single factor involves risk. No details regarding the selection of ground motion is given in the IS codes which is an important parameter in case of site specific seismic hazard analysis. The code is also silent about the methodology for nonlinear analysis such as Pushover and Time History method, which are significant in assessing the performance of a bridge. The proposed draft part (III) is lacking in details on; site-specific spectra, site-specific peak ground acceleration, modal analysis, foundation structure interaction and principles of ductile designing.

The minimum and maximum reinforcement percentages given are independent of the seismic zones unlike AASHTO LRFD Bridge Design Specifications-2007. IS code also doesn't specify additional control over the plastic deformations in the structural and non-structural components. Damage-Index based design procedures are still to be included in the present code provisions [7].

7. SUMMARY AND SCOPE FOR FUTURE RESEARCH

A review of different provisions in the present Indian codes IRC:112-2011 and IRC:6-2010 for seismic design has been done. The comparison of IS code with AASHTO LRFD Bridge Design Specifications-2007 is also done for certain provisions. Through this paper the need for bringing modification in the present code provisions is emphasised with reference to a performance based seismic design approach.

The high casualty rate, enormous amount of economic loss and increased down time cost has led to serious amount of research in the area of performance based design methodology. Even though there are guidelines given by FEMA, ATC etc., for buildings, research has to be continued to bridges also, considering its functional importance. In the Indian scenario we are yet to develop robust methodologies and quantifications of engineering demand/capacity parameters for this approach. The performance level of a structure for different seismic hazard levels, quantification of damage, development of more reliable analytical procedures are areas which need further research attention in the present scenario.

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