SOME DAMAGES OF RC BRIDGES AFTER STRONG EARTHQUAKES

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***Abstract**: Highway bridges in seismically active regions are often subjected to multiple earthquakes, including multiple main shocks during their service. Repeated seismic events result in reduced structural capacity and may lead to bridge collapse, causing disruption in the normal service. Serious earthquake events cause damage of the elements, with different damage level, even causing them to collapse. It is very important to save the damaged or weakened structures by emergency supporting or/and later strengthening, and to perform rehabilitation of their seismic resistance. The methods of evaluation of seismic resistance of damaged elements and structures are discussed in this paper. After evaluation of the damage degree and determination of the required demands and available seismic resistance of structures, redesign must be performed. Also, the method of rehabilitation of the elements and entire damaged bridge structures are analysed, including both traditional and advanced techniques. The focus of this paper is on reinforced concrete (RC) bridges. Post-earthquake assessment and analysis of the seismic performance of the bridges are analysed. Review and comparison of the international Code provisions related to topic are discussed as well. Criteria for the choice of structural interventions are discussed, as well.*

***Key words**: Earthquake actions, seismic damage assessment, reinforced concrete buildings, residual seismic capacity, post-earthquake evaluation*

1. Introduction

The Bridges belong to simple, but very sensitive structures to seismic action, which conditions their seismic protection. First of all, it is necessary to carry out a seismic analysis, which requires an adequate selection of the structural model and careful modelling of details to ensure the ductile behaviour of the bridge columns, and to limit damage to the deck. Therefore, it is necessary to limit the deformations of the bearing and connections, and to prevent the failure of the foundation of the columns and the foundation soil, and in some specific conditions of the location (saturated clayey soil) it is necessary to check the liquefaction potential. After the design earthquake action, bridges should provide, at least reduced traffic for emergency vehicles [1].

Damage and collapse of structures experiences from previous earthquakes have shown that conceptual design is essential for the seismic resistance of bridges. In the case of bridges,

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it is preferable that the plastic joints are formed in the columns or parts of the foundation rather than in the span structure. That is why the analysis of bridge columns is of particular importance, especially under strong seismic effects.

Most often, the bridges are composed of a relatively small number of structural elements, which gives the impression of the simplicity of forecasting their behaviour and analysis. This mainly refers to regular bridge structures where simplified methods can be used. In EC 8 - 2 [2], it is required to prevent collapse and to minimize damages during the effect of the design earthquake. Collapse prevention is associated with strong earthquakes with a long return period, and minor damage is allowed for frequent, weaker earthquakes. Several countries threatened by strong earthquakes use innovative recommendations for the design of seismically resistant bridges (Japan code 2000, ACT40, FEMA 440, CALTRANS), cited in [3].

Highway bridges are important elements of the vital highway network infrastructure. Seismic design for bridges has been improved based on experience and lessons learned from the past earthquakes. Depending on structures' state/condition after earthquake, there is a need provide stability by shoring, and lately structural retrofitting. Federal emergency management agency (FEMA) and applied technological council (ATC) work very actively in assessing conditions of structures after seismic events and for its retrofitting. The Code provisions generally have two levels, limit state design, for earthquake (EQ) resistant structures [4].

This paper presents some damage and their causes, and classifies them. Post-earthquake condition assessment methods were also considered. The paper provides an overview and comparison of the proposed post-earthquake evaluation damaged the elements of concrete road bridges in EN 1998; *fib* (CEB-FIP), Japanese, New Zealand, and in USA: ACI, ATC, AASHTO, Caltrans and FEMA. The method of performance and method based on damage level were specifically discussed. In this paper, in addition to the description of the most common damage to concrete bridges in earthquakes, the methods of assessing vulnerability and seismic demand are presented. Technical codes and recommendations of some countries and associations with [2] for the design of seismically resistant structures have been used. A comparative analysis of some provisions about seismic bridge structures from EC 8 – 2 [2], and codes in the USA [5], Japan [6], and New Zealand [7] is presented and discussed.

2. Damage and behaviour of bridges under seismic actions

Bridges are vulnerable structures in case of middle and strong earthquake. The overall objectives of seismic damage assessment are: minimise loss of life and minimise the economic loss to the region. For aim to ensure the safety of: primary routes for the passage of emergency vehicles concerned with the saving of life and property; secondary routes for the passage of emergency vehicles; all routes for general use. Earthquake damage can best be evaluated shortly after the event when emergency operations must provided. Priority of preliminary safety check inspects first bridges to be most vulnerable with potential for loss of life and other bridges along primary routes. The bridge and approach embankments should be observed for signs of settlement. Differential settlements between piers and abutments, of any one support relative to the others, may indicate serious damage to substructure members. This has a consequence for foundations, bearing and expansion joints [8]. Emergency work to open the bridge may sometimes commence very shortly after the earthquake. A preliminary safety check conducted immediately following the earthquake to check for safety for immediate use and for obvious damage. Analysis of earthquake-induced damage indicates that ground effects are a serious contributor to damage. Many structures suffered damage because of soil liquefaction or landslides occurred.

Damages and behaviour of bridges after strong earthquakes are registered by inspections and analyzes of damages on bridges and they are usually significantly higher in structures that were built in the period before the adoption of modern regulations. Damages can vary widely and with different consequences and affect the reduced flow and even interruption of traffic, which causes great economic losses. That is why it is important to study data on the behaviour of bridges in previous earthquakes. Greater damage occurs in the lower structure and foundations of curved and inclined bridges. Damage to the lower structure is very specific to bridge structures. In the case of large inelastic deformations, characteristic of strong earthquakes, the cause of the collapse of columns and bridges is inadequately shaped details, a small amount of transverse reinforcement, i.e. poor confining of the concrete columns (breakage by shearing, anchoring or bad reinforcement extensions). In order to prevent this type of breakage, newer regulations require denser placement of transverse reinforcement. Especially critical is the effect of a short column causing shear failure (Figure 1). In the 1995 earthquake (Hyogo-ken Nambu better known as Kobe), many RC structures, especially on highways and railways, were severely damaged (Figure 1). In contrast, foundations on piles that support the upper structure are relatively less damaged, except when the foundations are exposed to lateral flow of the surrounding soil (or unfavourable interaction).

Earthquake, dependen of intensity, frequently cause significant damage to bridges with diferent consequences. Damage might cause enormous losses for economy of society. Damage caused by earthquakes in different countries are published in the special issue or paper in Journal and Proceedings, i.e. Chile [9], Montenegro (Folić, 1989) cited in [3], NZ [10], in USA [11], and wider [12] and [16],etc. Damage of foundations is considered in [13-14]. All severe earthquakes, for instance 1989 Loma Prieta and 1994 Northridge earthquake demonstrated how important only a few bridges may be for the function economy and communication between people [15].

During evaluation of the damage in earthquake, the following must be considered: soil properties and seismicity of the site/region, ground motion characteristics and response spectra for the earthquake (max ground acceleration) and type of structures, and specific details of the bridge [16]. Frequently causes of seismic failure are: unseating and pounding effects in joint area and connection with embankments, irregular geometry, with significant stiffness changes in longitudinal and transversal direction, inadequate foundation quality of workmanship and the construction period. Booth bottom and top of columns damage due to insufficient number of stirrups within the column [17-18]. Some description and photograph presentation of damage contribute to the assessment vulnerability of damaged bridges. Illustration of some serious damage recorded in earthquake events is shown in Figures 1 to 13.

Figure 1. Shear failure, 1971 San Fernando earthquake; RC column failure modes; Compression failure of confined concrete; RC column failure modes Lap-splice failure [19]

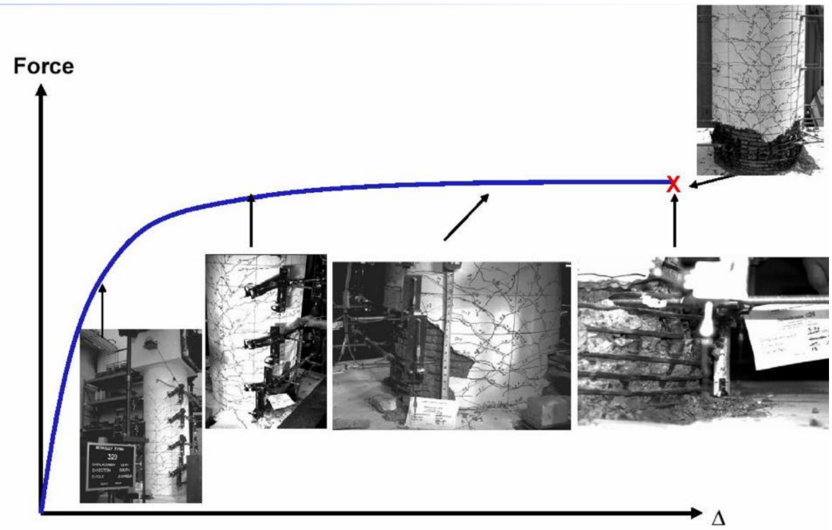


Figure 2. Development pushover curve and fallow shapes failure of column (after Imbsen R. A., 2007) cited in [1]

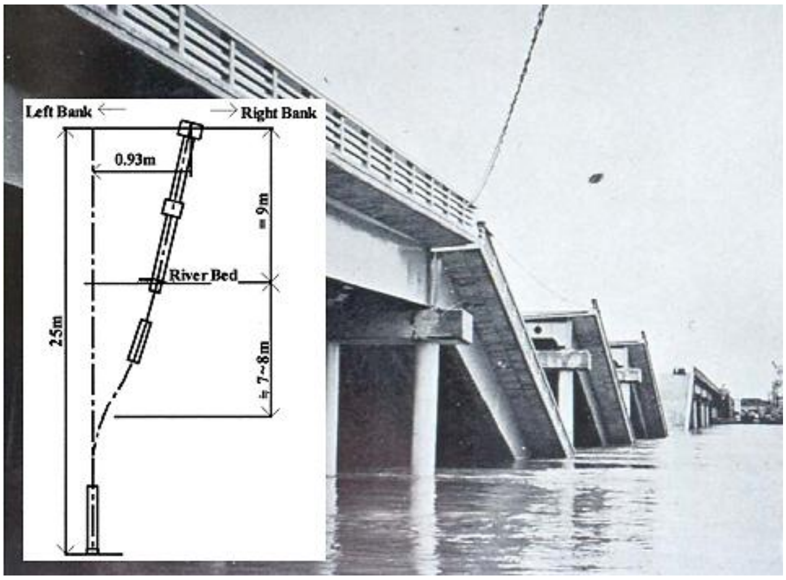


Figure 3. Damage to steel piles of Pier 4 of Showa Bridge cited in [1], [14]

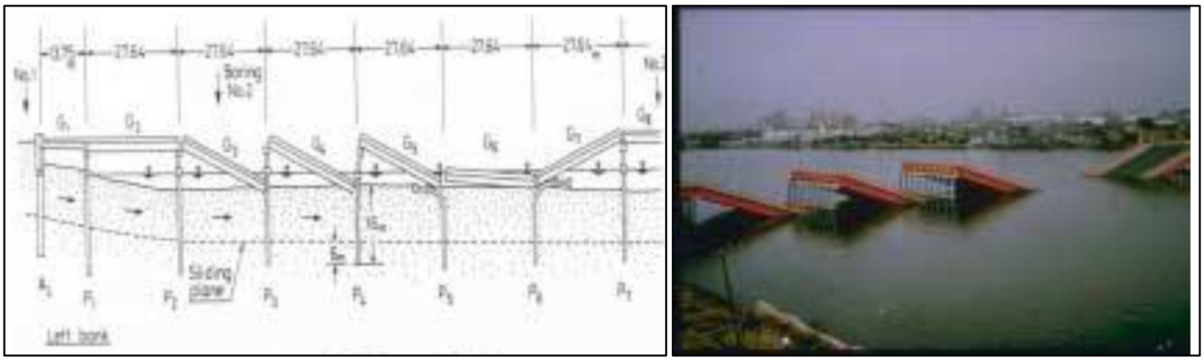


Figure 4. Schematic diagram of the Fall-off of the girders in Showa bridge, after [14]

The Showa Bridge collapsed during the 1964 Niigata earthquake in Japan, but the collapse did not begin until about 60 (Meymand 1998) to 70 seconds (Yasuda 2007) after the mainshock, and lasted about 17 seconds. As a result of the liquefaction, there was a significant movement of the steel piles (of almost 1 m) and the falling of the span structures from its bearings. As a result of liquefaction, a horizontal movement of the soil often occurs, when the buried sand behaves like a heavy liquid (liquefaction) [1], [14].

Figure 5. Unseating damage (Kobe, 1995), after (16)

Most of causes of damage and surveyed in the aftermath of major seismic events may be attributed to the following defects [19]. The earthquake-induced deformations were underestimated because gross sections were considered in the computation of displacement instead of cracked-sections; Foundation movements due to local conditions (potential liquefaction and differential settlements) may undermine the global stability of the bridge or impair its functionality; The ductility capacity is of primary importance of structures are to survive high level of inelastic deformation demands.

Common structural failures existing bridges include: Flexural failures in plastic hinges with inadequate confinement; Unseating in supports; Shear failures in short single columns/piers, multicolumn bents and columns in skewed bridges; Inappropriate location of lap splices in piers causing shear failure; Pounding and unseating at hinge seats and girder supports; Footing failures caused by soil liquefaction and/or differential settlements.

Figure 6. Collapsed spans and damaged piers bridge at the third span, Taiwan 1999, after (Sung et al., 2012), cited in [1], Severe Damage: Shear failure 1971 San Fernando Earthquake, after [16], Santa Clara River Bridge pounding damage in 1994 North-bridge EQ, after [21]

Report and Visual Catalogue of RC Bridges [11] documents damage from laboratory experiments and from historic Earthquakes (EQ) and classifies the performance an array of bridge components, sub-assemblages, and systems in a consistent form. The structures which have been built under modern earthquake resistance code behave better then the structures built according older code. In the classification of damage according to (EQ), in (Report, Caltrans, 2008) [11] beginning with San Fernando 1971 and finish with Mid Niigata Prefecture EQ 2004 [3].

Damage has been divided into five parts. Damage level I indicates no damage, while damage level V indicate local failure or component collapse. Potential vulnerabilities are:

Column shear failure of plastic hinge regions; Column longitudinal reinforcement pull-out; Unseating of expansion joint hinges. Typical design details are: column shear reinforcement; very short seat widths at expansion joints; inadequate lap splice of column long bars near footing; lap splicing of column transverse rebar in cover. Probably the most commonly observed failure is to the piers/columns of bridges. Three modes of failure: flexure, shear and axial distress or their combinations are registered.

The failure of abutments is typically due to slumping of the soil, which produces a global rotation of the structure. This is due to a pressure increase in the infill soil as a consequence of longitudinal response. On the road Podgorica-Petrovac the RC bridge situated on a sharp curve was out of traffic, after Montenegro EQ 1979, primarily because of a settlement at approach to the bridge structure, whereas damage to the structure were only of minor nature (Foilc, 1989) cited in [3].

According to the influence of damage on the global stability of structures, damage can be classified into: slight, moderate, serious and collapse. Serious damage includes: the occurrence of plastic hinge, short columns as brittle mechanism. Greater damage accompanied by reinforcement bar buckling (inadequate transverse reinforcement) or breaking and concrete crushing appears in the case of considerable overloading caused by seismic action. Damage to vertical load-bearing elements and their classification give in [17]. In (CEB, 1983) five levels of damage to vertical load-bearing elements are identified as the most important for the provision of stability. A similar classification applies for horizontal bearing elements (beams and slabs), cited in [17].

The failure mode of the pier is evaluated as the first step in this approach of the design. Failure modes are categorised into three types based on the flexural and shear capacities of the pier [7]:

1. $P_u \le P_s$ bending failure,
2. $P_s \le P_u \le P_{s0}$ bending to shear failure, (1)
3. $P_{s0} \le P_u$ shear failure

in which P_u = bending capacity, P_s = shear capacity in consideration of the effect of cyclic loading, and P_{s0} = shear capacity without consideration of the effect of cyclic loading. However, failure of RC columns was primarily in the lack of lateral reinforcement.

Figure 7. Column shear damage (left), Cypress Street Viaduct collapse in the 1989 Loma Prieta earthquake (right), after [12]

The flexural response of columns is influenced by number of factors, including the axial load ratio, aspect ratio, and reinforcement ratio. The most important factor is the design details that vary based on the time in which the bridge was designed. The shear strength of RC sections come from four mechanisms: shear friction in the compressive zone; dowel action of the longitudinal reinforcement; aggregate interlock, and transverse reinforcement truss mechanism. Ductile failure of RC element and structures is preferable, while other types of failure (shear, bond and anchorage) should be prevented by adequate design. For a modern bridges at least, spalling of cover concrete at the top or bottom of piers/column may indicate that the bridge has been subject to design intensity EQ and has yielding account prediction [15].

Figure 8. Chile Maule, 2010, after [9]

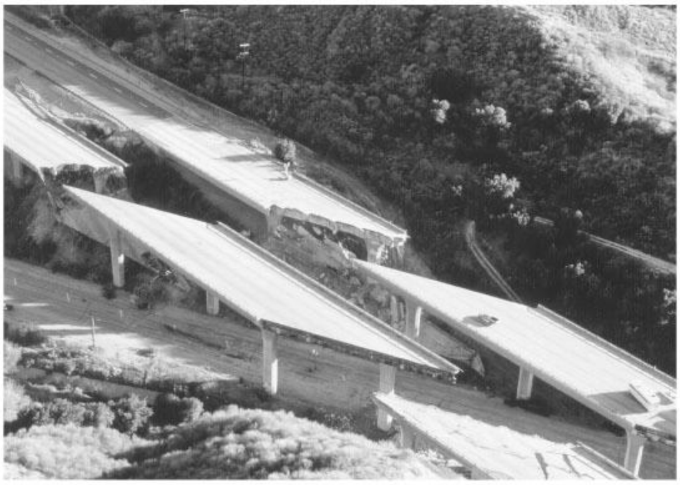
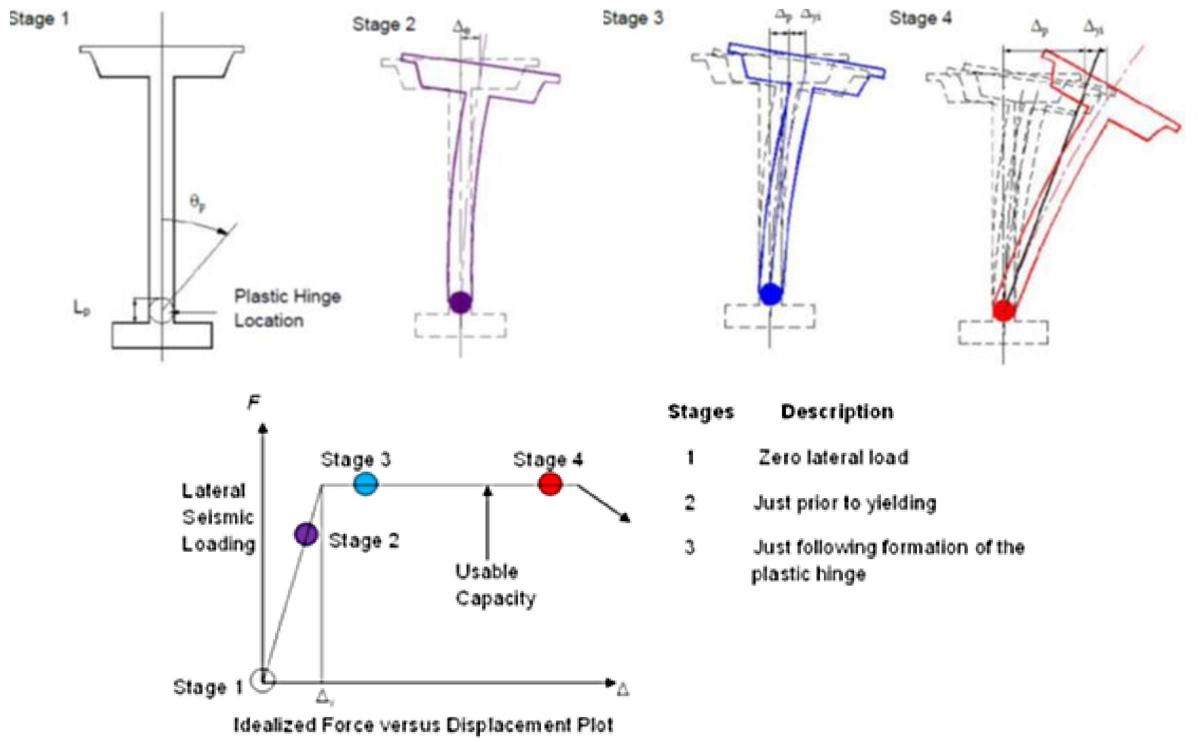


Figure 9. Gavin Canyon Undercrossing collapse in the 1994 Northridge earthquake, after [8]

Bridges superstructures have generally performed quite well during EQ. Problem have arisen primarily at expansion joints where damage to bearings or local concrete spalling due to impact of adjacent part may occur. This type not catastrophic and is reparable. Major problems have been arisen due to inadequate seat length at expansion joints. Large relative displacement between adjacent spans at expansion joints have exceeded the capacity of the seat length (fore mention), causing the supported span to collapse (for example Showa Bridge collapse in 1964 Niigata earthquake and Kobe 1995 - Figure 3 and 4). This is particularly a problem in early bridge designs and for bridge with large skews, for which torsion deformations add to the lateral displacement demands [11].



Stages	**Description**
1	Zero lateral load
2	Just prior to yielding
3	Just following formation of the plastic hinge

Figure 10. Plastic hinging mechanism for a cantilever column, after [1]

Figure 11. Failure of columns with longitudinal reinforcement cutoffs near midheight in the 1995 Hyogo-Ken Nanbu earthquake after [8]; of the Route 5/210 interchange during the 1971 San Fernando earthquake after [8]; Failure of flared column in the Route 118, Mission-Gothic Undercrossing, in the 1994 Northridge earthquake[11]

In seismic vulnerability evaluation phase are: evaluation of site-specific seismic hazards including the influence of local soil; evaluation the structural vulnerability including the effects of physical geometry, data of design and construction, structural detailing, the actual physical condition; evaluation socioeconomic consequences of damage or failure [5]. Irregular bridge geometry can be structurally vulnerable.

4. Seismic evaluation of concrete bridges performance

Evaluation phase are as follows: demand evaluation; capacity evaluation; and evaluation of the demand-capacity ratios. The seismic demand may be estimated using established analysis methods. For many existing bridges designed in accordance with old (before 1971) design methods or with unknown structural details it is difficult real assess condition and determine measures to retrofit. The current seismic design of structures is based on the presumed ductile response and yielding probability of some part of a structure.

A realistic and usable definition of limit state (LS), usually referred to in the US as performance levels (PL), and a viable procedure for identifying them by visual inspection and/or by analytical methods. As a general rule, LS are defined in terms of acceptable degree of damage and associated implications on the functionality of the bridge. In [12] the detailed description of damage for each state is given for three key components of the bridge, i.e. abutment; substructures (column bents and/or walls); connections and bearings. The "Damage Limitation" (DL) level, correspond to the "Immediate Occupancy" level in the USA (FEMA 356, 2000).

The revised Japanese design specifications for highway bridges issued by Ministry of land, Infrastructures, Transportation and Truism in February 2012. The document incorporated the latest research achievement and lessons learned from the recent earthquake including the 2011 great East Japan Beside this, serious damage to bridges in 1999 Chi-Chi, Taiwan, and the 1999 Kocaeli, Turkey earthquake caused introduction design consideration to mitigate the effects of tsunami and large-scale landslide on structural planning of bridges.

Earthquake damage damage types of RC simple-supported girder bridge, in Wenchuan earthquake, can be further divided into girder earthquake damage, pier earthquake damage, abutment earthquake damage, foundation earthquake damage, bearing and other earthquake damage [22].

The Gaoyuan Bridge also has the girder falling, as showed in Figure 12. In the Tangshan earthquake, many simple-supported girder bridges were damaged by girder falling. Piers earthquake damage of the Baihua Bridge in the Wenchuan earthquake. [4].

Figure 12. Girders falling of the Gaoyuan Bridge; Piers seismic damage of the Baihua Bridge [22]

The physical condition of a structure, and critical soil conditions, can affect its seismic vulnerability. The following are typical geometric characteristics that may indicate potentially problematic structures [5]:

- Bent configurations that include squat columns, flared columns, outrigger bents, C-bents, and columns and bents with dissimilar stiffness's in the same structure;
- High degree of skew;
- High degree of curvature;
- Short seat widths;
- Multiple deck levels; and
- Multiple superstructure types.

Figure 13. Seismic damage of foundation displacement, after [22]

A simplified method to assess the seismic vulnerability is subject of the paper [23].

After evaluation of damage degree and determination of the required and available seismic resistance, i.e. residual seismic resistance SE must prepare documentation for design of repair and strengthening. The interventions on the bridge should be performed in such manner to ensure that the structure can sustain the actions from emergency traffic, and inspections and repair can be performed easily.

Final remarks and conclusion

Depending on the ground-motion, site conditions, overall configuration, and specific details of the bridge, the damage induced in a particular bridge can take many forms. Damage within the superstructure is rarely the primary cause of collapse.

Studying the consequences of strong earthquakes that cause minor or major damage on bridges or even make them collapse have contributed to the improvement in their design and construction methods. Strong earthquakes in the past, such as Fukui 1948, Niigata 1964, Tangshan-China1976, and others have contributed to higher levels of awareness of the actual bridge behaviour under earthquake conditions and changes in design methods [13].

The structural engineering challenge is the assessment structures to withstand probable earthquakes within defined performance criteria. No one can predict the exact date of the next Cascadia earthquake, but it is possible to anticipate the likely impact on the regions communities, infrastructure, and economy. Predicting the effects of the next big earthquake is subject of paper [24].

In recent years, artificial neural networks have been used more and more often for seismic damage assessment for set of bridges, which is the subject of the paper [25].

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