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Seismic Assessment of Bridges

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Abstract
This article provides the analysis of the seismic excitation behaviour of bridges. Problems of bridge collapse have been increasingly growing worldwide. Therefore, analyzing existing bridges and proposing design and retrofit schemes is essential. Pushover analysis is an efficient method for evaluating the expected non-linear behaviour and the resulting pattern of failure in various bridge components. Bridges extends horizontally with its two ends restrained and that makes the dynamic characteristics of bridges different from building. This paper reviews the various bridge analysis methods. The different methods are Standard pushover analysis, Response spectrum analysis, Time history analysis, Capacity spectrum analysis, Modal pushover analysis, Non linear time history analysis. A review of the literature however shows that work on this topic is still insufficient and therefore needs more focus in future research in order to obtain a better understanding of the seismic efficiency of bridges in order to provide clear and more comprehensive guidance for real design purposes.
Keywords: Bridge, Non-linear, Pushover, Retrofit, Seismic
Yu et al. (1999) performed elastic analysis, inelastic pushover analysis, capacity spectrum method and nonlinear time-history analysis, the seismic performance and sustainability of two bridges, namely the Moses Lake Bridge and Mercer Slough Bridge in Washington. The advantages, ease of application and limitations of each approach for the seismic analysis were evaluated from the results of the analysis. For three separate seismic ground motions from historical earthquake data, the force and displacement specifications of the Moses Lake Bridge and Mercer Slough Bridge were determined. The 1940 El Centro Earthquake record, the 1949 Olympia Earthquake record and the 1995 Kobe Earthquake record were the earthquake records used. The survivability of the bridge structures was tested under forced ground motions. Regarding the survivability of the structure nonlinear dynamic time history and pushover analysis provided the same conclusion.
Alfawakhiri and Bruneau (2000) investigated the dynamic response of the simply supported bridge using the flexibilities of superstructure and support under seismic excitation. Modeling of bridge was done as a beam with uniformly distributed mass and elasticity, simply supported at the ends by elastic spring which showed the single degree of freedom system. A close form SDOF expression was rooted on an approximate shape function for the dynamic parameters of the first mode and their accuracy was also evaluated. Influence of stiffness index was also investigated on dynamic properties. Inertial moment combined with the rotation of beam section and deflection of beam caused by shear stresses was neglected in the analysis. Results obtained by SDOF model were compared with the MDOF model, modeled using a computer program DRATN-2DX. Six earthquake acceleration records of Imperial Valley Park field, San Fernando Whittier, Loma Prieta, Cape Mendocino, Landers and Northridge time histories were used in the analysis. Results showed that MDOF model was less accurate than generalized SDOF model for the seismic analysis of symmetric span of the simply supported bridge with

lower Range of stiffness index. SDOF model can be used more precisely in place of AASTHO single spectral analysis method.

The applicability of the MPA proposed by Chopra et al. (2001) for the evaluation of a highway viaduct constructed in the sixties was studied by Lupoi et al., with a total length of 420 m, 11 spans of 33 m each and a continuous reinforced concrete deck pinned over the piers. It was concluded that a) Differences between the nodal displacements estimated by the MPA, and those by the nonlinear time-history analysis were found to be in the order of 15%, independently of the intensity level of the ground motion, b) For obtaining the best estimates of earthquake demand on the structures, the reference degree of freedom should be located at the maximum modal displacement, c) The results is not significantly affected by the variation of lateral load distribution, d) The results obtained from time history match fairly well with the best estimates of modal pushover analysis results obtained.

Using a nonlinear pushover analysis, Abeysinghe et al. (2002) calculated the inelastic response of the Greveniotikos bridge during a design-level earthquake. A finite element three dimensional model of the bridge was used. To test the effects of various assumptions made in structural modeling and analysis, parametric studies on the foundation stiffness, P-Δ effect and plastic hinge properties were carried out. The pushover analysis is applied in the transverse direction. The ductility level is found to be higher in the transverse direction. Overall the bridge is classified as the structures of limited displacement capacity as ductility $\mu<6$. A small deviation in the anticipated inelastic displacement is observed on account of different foundation stiffness. The structural deterioration was significantly small in the bridge due to P-Δ effects. While pier cross section and various hinge properties were used, the difference in the global response was observed but this difference was lesser than the result obtained by varying the foundation stiffness.

Itani et al. (2003) employed the nonlinear modal pushover procedure in the analysis of finite element three dimensional model of the Dry Wash bridge, and the results were used as the baseline in the parametric studies. The superstructure of the bridge consisted of a bridge deck and a support system of bents. The superstructure was presumed as a rigid body for lateral loadings due to the large in-plane rigidity. In superstructure, short spanned bridges are very stiff and can be modelled with spine beam elements that represent successful characterization of stiffness. The displacement and ductility is examined through global responses. Retrofitting methods included abutment retrofit, foundation and steel jacketing of the column. Parametric study was conducted from the analysis results and is used to assess the effects of different retrofit schemes on the bridge behavior. It has been found that for the longitudinal direction, the varying stiffness produced a variation in the lateral displacement of 20%, but the longitudinal ductility range was less than 10%, For the transverse direction, the variation in displacements was within 12% and the ductility values remained close. A bridge's transverse reaction depends more on the framing effect of piers than on single columns and abutments, so the properties of the foundations tend to have a greater influence. In contrast, variable abutment properties have larger influence on the longitudinal stiffness than on the transverse stiffness of the structure. The displacement variance associated with changes in abutment stiffness is very limited for both directions. Therefore, retrofit bridge abutment techniques aimed at raising stiffness can result in little improvement in the displacement of the global structure capacities. By attaching more importance to the columns with shorter effective lengths and as well as the middle columns, two column combination plans were recommended to retrofit the Dry Wash Bridge. One is to jacket the three columns at the right edge bent and the middle column at the left edge bent. The longitudinal and transverse displacement capacities can increase by 13.6% and 28.5% respectively.

Using the pushover analysis, Cosmin et al. (2003) investigated the collapse action of a 115 metre long pre-stressed three span reinforced concrete bridge constructed in the northeastern part of Portugal, over the Alva River. The behavior of the bridge structure from the first application of loads up to and beyond the collapse condition, at all stages of loading, was studied. An insight into the pushover methodology described in the ATC-40 document (1996), FEMA-273 (1997) and EC8 (2000), was also presented. ECS (2003) addressed the use of the non-linear static technique to test the selected bridge using the capacity spectrum approach. Deformation of plastic zones (hinges), target displacement and base shear attained from this procedure will be compared with the resultant values of the more refine and accurate, nonlinear time history analysis.

Kappos et al. (2005) analyzed the Krystallopigi bridge-consisting of twelve span 638m total length that passes through the valley of northern Greece using the inelastic standard pushover analysis, the modal pushover analysis (MPA) as well as the nonlinear time-history analysis. In the MPA, pushover analysis was carried out independently for every essential mode, and the aids from the distinct modes to compute the response quantities such as drifts, displacement etc were combined, by means of a suitable combination rule such as CQC or SRSS. The MPA offers a considerably better estimate in relation to the maximum displacement pattern, realistically matching the responses of highly accurate and refined nonlinear time history analysis. Thus contribution of higher mode is highly significant in case of long and complex bridge.

Tondon (2005) presented some techniques for economically managing the reaction of bridges under seismic excitation. Author suggested that the ductile behavior of structural elements of bridges was necessary for energy dissipation during flexure under seismic loads, ductile behavior can be increased by provision of closely spaced horizontal hoops to main vertical bars of substructure which improves the strength of concrete to sustain higher compressive strain. This also increased bulking capacity of longitudinal bars and provides shear resistance in flexure. Construction of integral bridge or the provision of reaction block at pier/abutment cap level or sufficient support length for superstructure on the pier cap can prevent dislodging of super structure and out of phase displacement of pier. Potential locations of plastic hinges and ductility have been also introduced with the construction of integral bridges. Base isolation with high damping bearings or lead rubber bearing can increase the natural period and damping of structure. Criteria of design of such bearings given in BIS 2002 and Eurocode 8 (CEN 2005). With the use of shock transmitting unit energy released from seismic excitation can be distributed to various structural elements of bridges which enhanced the response of bridge under seismic loading exterior column under longitudinal pushover.

In line with most previous studies, it was deemed necessary to compare results of the standard and modal inelastic pushover approaches with those from nonlinear Time History Analysis, the latter assumed to be the most rigorous procedure to compute seismic demand. To this effect, a set of nonlinear Time History Analysis was performed in Kappos paper using 5 artificial records compatible with the EAK2000 elastic spectrum and generated with the use of the computer code ASING. The classical Newmark integration method was used (γ=0.5, β=0.25), with time step Δt=0.002s and a total of 10000 steps (20s of input). Since this analysis is considered as the most refined and accurate, it was of particular interest to compare the maximum displacements of the deck calculated from time-history analysis with those corresponding to the target displacement defined through the Standard

Pushover Analysis (SPA) and the MPA approach. A methodology was proposed for Modal Pushover Analysis (MPA) of bridges, and its feasibility and accuracy were investigated in Kappos paper by applying it to an actual long and curved bridge, designed to modern seismic practice. By analyzing the structure using inelastic standard (SPA) and modal (MPA) pushover analysis, as well nonlinear time history analysis, Kappos paper concluded that:

- At least for the studied structure, which is complex but properly designed, all three methods yield similar maximum pier top inelastic displacements although their pattern is rather different.
- The SPA method predicts well the displacements only in the central, first mode dominated, area of the bridge. On the contrary, MPA provides a significantly improved estimate with respect to the maximum displacement pattern, reasonably matching the results of the more refined nonlinear Time History Analysis, even for increasing levels of earthquake loading that trigger increased contribution of higher modes.
- On the basis of the results obtained for the studied bridge structure, MPA seems to be a promising approach that yields more accurate results compared to the 'standard' pushover, without requiring the high computational cost of the nonlinear Time History Analysis, or of other proposals involving multiple eigen value analyses of the structure to define improved loading patterns in the inelastic range.
- Further work is clearly required, to further investigate the effectiveness of MPA by extending its application to bridge structures with different configuration, degree of irregularity and dynamic characteristics, especially in terms of higher mode significance, since MPA is expected to be even more valuable for the assessment of the actual inelastic response of bridges with significant higher modes.

McDaniel et al. (2006) assessed the seismic performance of prestressed concrete multi-column bent bridges. Three bridges with nonlinear column elements and expansion joints were modeled as spine models. In the study soil-structure-interaction was also considered. The global response of the bridges was inspected to evaluate the effects of non-traditional retrofit schemes. In the pre-1975 WSDOT prestressed concrete multi-column bent bridges, the weakness of shear-dominated bridge columns and non-monolithic bridge decks and also the importance of including soil structure-interaction were highlighted in the study.
Muljati et al. (2007) evaluated the inelastic seismic response of multi-span concrete bridges situated in Subraya area, using the modal pushover analysis (MPA). The bridge deck consists of a single span prestressed concrete. Four prestressed girders were used to supports the 30m span, connected at 6m interval by stringer beam. An elasto-plastic behavior is used to model each pier's element. With plastic hinges formed at the pier's base the pier is assumed to fail in flexure mode. A ground motion with return period of 500 years located in zone 2 (according to Indonesian seismic zoning) is inputted as design earthquake. Only the first three modes were considered as it is assumed that all the three modes will contribute to 90% of mass participation factor. There was a similar pattern with the MPA in a linear range in the output of the study bridge using the MPA in a nonlinear range. In addition to simplicity, the results of the MPA offered reasonable accuracy.
Paraskeva and Kappos (2009) suggested an improvement to the MPA procedure, that in lieu of the elastic mode shape, the considered earthquake level is used, where the deformed

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shape of the structure was found to respond elastically. A bridge of 100m long three-span Overpass Bridge is used to verify the procedure. Analysis such as the standard pushover analysis (SPA), response spectrum, the MPA and the nonlinear response history analysis for spectrum-compatible motions were adopted (or analyzing the selected bridge. It was concluded that the inelastic deck displacement was found to be maximum when MPA was adopted for several earthquake intensities, while the same couldn't be predicted by the SPA method, where the response of the bridge was very low due to the contribution of first mode.

Moniruzzaman et al. (2010) considered several retrofitting provisions of reinforced concrete bridge bent on three columns, in Canada which was designed before 1965 with inadequate seismic detailing. The bridge bent designed only for gravity load and failed to meet the seismic standard. In order to increase the seismic performance several retrofitting techniques such as steel jacketing, CFRP jacketing and steel bracing were considered. For the original and retrofitted frames, the nonlinear pushover analysis was conducted. An artificial ground motion record was adopted to evaluate the dynamic response of these structures. The seismic demand/capacity ratio, drift ratio, ductility has been estimated. For such multi-column bridge bents designed only for gravity load, the best retrofitting technique has been suggested.

The efficiency of bridges under high seismic areas was studied by Godse P.A (2013). Seismic bridge research conducted on mono pier, multi bent beam pier and multi span bridge structures by considering base flexibility as flexible and fixed in different ways. Performance of bridge was showed in terms of capacity curve. For good performance in seismic excitation computed capacity of the bridge must be greater than seismic demand. To understand the seismic performance of the modelled bridge, static (response spectrum method) as well as nonlinear static procedures such as pushover analysis with parametric variation were studied. Nonlinear analysis (pushover analysis) in terms of capacity spectrum method was used to determine displacement capacity and available plastic rotational capacity to bear out good seismic performance. A simple beam element model with discretized node at 1 meter spacing is generated using SAP 2000 V 11.00. Results of this research showed that the flexible foundation system mono-pier showed more ductile behaviour than that of the fixed base system. Also hinge formations are more accountable to take place near ground level in flexible base pier than fixed. In the case of transverse mode, multi-bent bridges bear a greater amount of shear force for limited roof displacement than mono pier systems. But in case of longitudinal mode first hinge was observed at intermediate pier which suggested this is to be possible weakest part in multi bent bridge. In the external column under longitudinal pushover, hinges were first developed in multi span bridge.

Gunasekaran and Amaladosson (2014) analysed the response of the multi-column bent RCC T Beam Bridge located over the Coovam River in Koyembedu, Tamil Nadu, using seismic excitation modal pushover procedure and capacity spectrum process. An experimental investigation was done to measure the flexural response of longitudinal and transverse girder under known multi axle truck load. Investigated strain measurement by experiment was compared with the calculated strain values obtained from the analysis of bridge model developed from WINGEN, a model generation program. For the seismic investigation bridge was modeled as finite element model using sap 2000. In modal pushover analysis when the structure approached dynamic instability it was assumed that global pushover reflects global or local mechanism. Capacity spectrum curves were obtained for earthquake ground motion from EI Centro and Kobe earthquake applied to the

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bridge model. Result of this study recommended that performance of bridge was greatly affected by higher modes because it also participated in the vibration of bridge. Results also showed hinges at the bottom of all columns in the mid bent exceed collapse prevention performance level which may cause permanent replacement or repair of structure. Study showed that bridge failed in Kobe earthquake when it was checked using CSM method. In order to improve global stability author suggested to give retrofitting application to multi column bent of under study bridge.

Conclusion

In the case of elastic/inelastic analysis of bridges in the form of modern seismic bridge design codes, there is a significant problem concerning the analysis technique to be used. The inelastic analysis of time history is considered to be a reliable bridge analysis technique. While a common alternative is the well-known simplified inelastic pushover technique, it should be used with caution in the case of bridges. The pushover analysis and the nonlinear time-history analysis could provide the same conclusions about the survivability of the bridge structure. But processing and evaluating the output from a nonlinear time history analysis require considerable effort.

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