RC GIRDER BRIDGES MODELING FOR SEISMIC PERFORMANCE ASSESSMENT

Andrija Rašeta [1]
Đorđe Lađinović [2]
Nikola Rajić [3]

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Summary: The probability of a severe earthquake in the course of structures lifetime is small, and that results in economic ineffectiveness of designing structures that will not be damaged in the event of a project earthquake. In the case of RC bridges, the common practice is the controlled appearance of damage in the piers, while the girder is designed in such a way that it remains in the linearly-elastic domain. In EN 1998-1 and EN 1998-2, methods for determining seismic actions based on linear elastic models are prescribed, the basic method for determining seismic actions is modal analysis with response spectra, which leads to a sufficiently good assessment of seismic forces. However, a qualitative estimate of the deformation quantities, which are of key importance in the event of damage, can only be carried out using nonlinear analysis methods. This paper summarizes the basic recommendations for the modelling of RC girder bridges for assessing seismic performance using nonlinear static and nonlinear dynamic analysis.

Keywords: *RC girder bridge, modelling, seismic performance*

1. INTRODUCTION

The basic method for determining the seismic action, according to EN 1998-1 [1] and EN 1998-2 [2], is a response spectrum analysis using linear elastic models, and can be applied in the case of all structures. The alternative is the application of nonlinear methods of analysis, that is, nonlinear static analysis and nonlinear dynamic analysis. Generally, linear elastic methods of analysis give a good assessment of the force, however, since in the course of strong earthquakes nonlinear behaviour is expected to assess seismic performance, qualitative knowledge of nonlinear deformations in the structure is necessary, and this can only be achieved using nonlinear analysis methods. For these purposes, EN 1998-2 prescribes static non-linear analysis (pushover analysis) and non-linear dynamic analysis (time-history analysis).

[1] Ass. Prof. Andrija Rašeta, PhD, C.E., University of Novi Sad, Faculty of Technical Sciences, Trg Dositeja Obradovića 6, 21000 Novi Sad, Serbia, tel: +381652121255, e – mail: araseta@uns.ac.rs

[2] Prof. Đorđe Lađinović, PhD, C.E., University of Novi Sad, Faculty of Technical Sciences, Trg Dositeja Obradovića 6, 21000 Novi Sad, Serbia, tel: +381652121255, e – mail: ladjin@uns.ac.rs

[3] Ass. Nikola Rajić, MSc, C.E., University of Novi Sad, Faculty of Technical Sciences, Trg Dositeja Obradovića 6, 21000 Novi Sad, Serbia, tel: +381652121255, e – mail: rajic.nikola@uns.ac.rs

The basic parameters for seismic analysis are stiffness, load capacity, ductility, mass and damping. In general, the analysis consists of two main phases. The first phase involves the dimensioning of all structural elements by means of linear analysis, where seismic forces are determined by modal analysis with response spectra, while ensuring the functionality of the structure after smaller earthquakes, and one of the most important parameters is the stiffness of the structure. After that, the behaviour for the strong earthquakes is controlled using non-linear methods in which, in addition to the stiffness, uses strength capacity and ductility as key parameters.

The seismic analysis of structures that introduces the strength capacity and ductility of a structure can be realized only by applying nonlinear methods that are complex and impractical for everyday engineering practice. For this reason, the analysis is simplified in a way that implies the application of a linear elastic dynamic analysis with reduced seismic forces, all with the aim of incorporating energy dissipation due to inelastic deformation of the structure, i.e. the occurrence of controlled damage in the structure. The size of the reduction factors of seismic forces, most of all, depends on the ensured ductility, the stiffness of the structure and the acceptable level of damage. The previous concept can be realized using the capacity design method [3], which is based on the pre-selection of structural elements in which inelastic deformations will occur and in this way the dissipation of seismic energy during the earthquake is carried out, and it is assumed that the ductility is provided by fulfilling a series of design measures for certain levels of seismic load reduction. The higher ductility provided a greater reduction factor, but greater reduction in load capacity increases damage. Therefore, it is necessary to define the values of the reduction factors beyond which they must not go, which is defined in EN 1998-2 through the behaviour factor q. Behaviour factor represent the ratio of seismic forces to a full elastic response and project seismic forces, and depend on the adopted type of seismic behaviour (limited ductile or ductile), the type of structural element that most contributes to seismic resistance, applied materials and stress levels. The rules prescribed in EN 1998-2 for the design of cross sections refer to the longitudinal reinforcement in terms of the required strength capacity of the cross sections, inside and outside of the zone where plastification occurs. Then, the required ductility, i.e. the cross-sectional ability to handle the required plastic deformations without significantly loss of the bending resistance, is achieved primarily by transverse reinforcement for confinement according to specifying rules [7]. Also, the transverse reinforcement must provide sufficient shear resistance, as the brittle failure shall not be allowed. For RC girder bridges, the maximum value of the behaviour factor for limited (essentially elastic) ductile behaviour) is 1.5, and 3.5 for ductile behaviour. Bridges of ductile behaviour shall be designed so that that plastic hinges normally form in the piers and the bridge shall remain within elastic range.

This paper presents a concise overview of the methods of modelling RC girder bridges for the purposes of assessing the seismic performance using nonlinear static and nonlinear dynamic analysis.

2. MODELING OF RC GIRDER BRIDGES FOR NONLINEAR ANALYSIS

In non-linear systems, most of the dissipation of energy takes place through hysteresis behavior, and a much smaller part through the viscous damping, which is most often

introduced into the analysis as Rayleigh's damping, and practically it is assumed that it is constant during the analysis.
The mass is concentrated in the nodes of the finite elements mesh that the beam is modeled with, where in the nodes above the top of the columns, in addition to the corresponding mass of the beam, the corresponding mass of the pier is joined in accordance with the type of connection between the beam and the top of the pier. Higher modes, in the case of slender piers, may have greater significance so concentrated masses along the pier may be applied (Fig. 1).

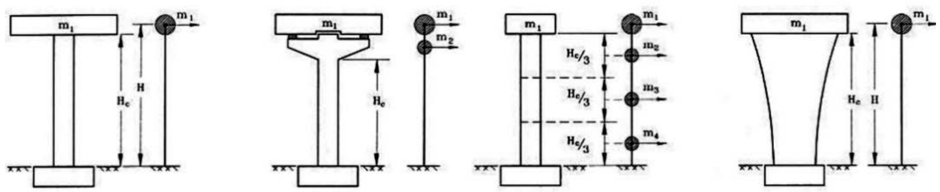

Figure 1 – Distribution of the mass of the dynamic model of the RC girder bridges [4]

Nonlinear behavior is introduced in analysis through geometric and material non-linearities. The simplest way to capture geometric nonlinearity is through a P-Δ effect that can be applied only in the case of piers with a "smaller" axial stress. In other cases, incremental-iterative procedures are used. The effects of the P-Δ effect on the bending moments and the relationship between the horizontal forces and the displacement of the top of the bridge pier is shown in Figure 2. The bending moment values are increased (Fig. 2, left), and the effective initial stiffness is reduced with a declining character after reaching the yielding point (Fig. 2, right).

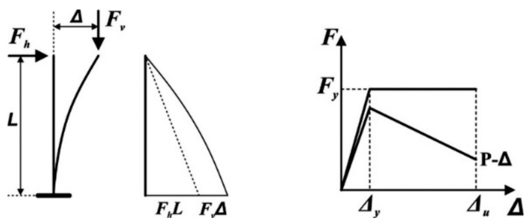

Figure 2 – Influence of the P-Δ effect on the response of the RC pier of the girder bridge

Material nonlinearity can be included in analysis using the models with so-called lumped and distributed plasticity. Concentrated plasticity involves the formation of plastic hinges in discrete cross sections. Nonlinear behaviour of plastic hinges is most often defined through the force-displacement relationship and / or moment-rotation (or curvature). Plastic hinges are commonly located at the ends of the columns and the beams. In the distributed plasticity model, fiber cross-section models are used to simulate plastification over the surface of the cross-section, Fig. 3. Also, the distributed plasticity is introduced in the analysis through the length of the element in the corresponding number of integrating points [5]. 1D finite elements with distributed plasticity can be defined based on the so-called displacement-based formulations or force-based formulations [5]. Nonlinear relationship (Fig. 4) between the internal forces and the relative displacement is introduced into the nonlinear dynamic analysis via hysteresis rules [3].

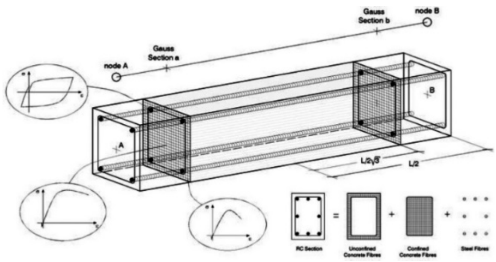

Figure 3 – Discretization of the fiber model of the cross-section [5]

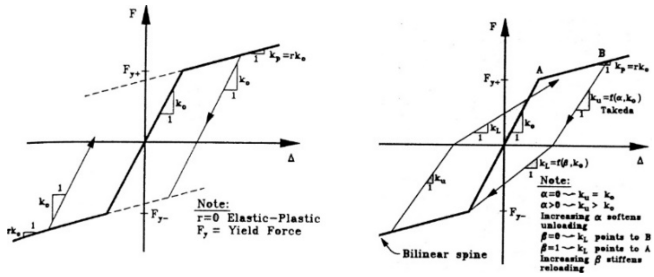

Figure 4 – Hysteresis rules: bilinear model (left) and Takeda (right)[3]

In the application of non-elastic models, the relationship between stresses and deformations must be defined, and in particular the relationship for the unconfined and confined part of the concrete cross-section [7] (Fig. 5, left) and the reinforcement (Fig. 5, right).

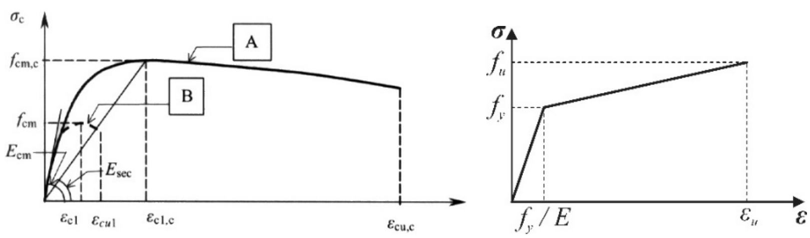

Figure 5 – Stress-deformation relationship for concrete (A - confined; B - unconfined) [7] (left) and reinforcement (right)

The position of the plastic hinge in the piers of the bridge can be defined as shown in Figure 6 [4]. According to EN 1998-2 [7], the length of the plastic hinge L_p can be determined depending on the distance between the plastic joint and the zero value of the bending moment in the column L [m], the characteristic tensile strength of the reinforcement f_{yk} [MPa] and the diameter of the longitudinal armature d_{bl} [m], by the expression:

$$L_p = 0.1L + 0.015 f_{yk} d_{bl} \tag{1}$$

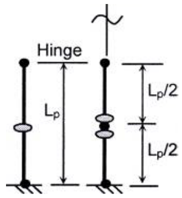

Figure 6 – The position of the plastic hinge in the critical region of the RC girder bridge pier [4]

For non-linear analysis, the so-called. continuum mechanics-based models may be used. In such model concrete is discretized with 3D finite elements, and reinforcement with beam or bar finite elements [6].
EN 1998-2 superimposed to EN 1998-1, which defines the application of nonlinear static Pushover analysis to assess seismic performance. The choice of the lateral force distribution can be done based on the distribution of masses. The analysis may be carried out in the longitudinal or transverse direction, or simultaneously in both directions (Fig. 7). Seismic demand, i.e. the target displacement is determined based on the structure data and response spectrum [1]. This kind of analysis, in general, can only be applied to regular systems, i.e. structures that oscillate predominantly in the first mode.

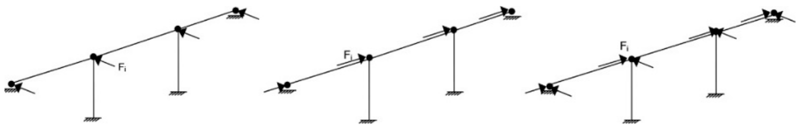

Figure 7 – Lateral load distribution for Pushover analysis [4]

The best quality assessment of the seismic performance of a structure can be obtained by applying a nonlinear dynamic analysis. In EN 1998-2 it is prescribed that for the seismic action, real (recorded) accelerograms of earthquakes that occurred in a location which according to the characteristics of soil and seismicity correspond approximately to the location of the analysed structure may be used. However, artificial accelerograms which must correspond to elastic spectrum may be used as well.

3. NUMERICAL EXAMPLE

The estimation of RC girder bridge (Fig. 8) seismic performance using nonlinear static and nonlinear dynamic analysis was done in the SAP2000. Piers of the bridge are dimensioned on the basis of EN 1992-1-1 [8], EN 1998-1 and EN 1998-2. The quality of the bridge materials is: C30/37 and B500B. Seismic forces for the dimensioning of the bridge (only the possibility of vibrations in the horizontal direction is considered) are determined by the modal spectral analysis with the following parameters: type 1 elastic response spectrum, $a_g = 0.25g$, soil category – C, damping 5 %, $q = 3.5$ for both directions and $\beta = 0.2$. It was assumed that the bridge is with normal traffic based on which only the permanent load (mass of the beam and accessories 30 t/m) contributed into the mass of the dynamic model. The oscillation period of the first mode in the longitudinal direction is $T = 1.11$ s, and in the transverse $T = 0.63$ s, with 4 modes included to engage the effective mass of more than 90% of the total mass of the dynamic model.

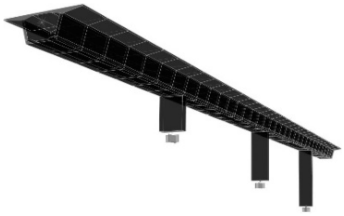

Figure 8 – 3D render model of RC girder bridge with rebar layout in piers

Figure 9 shows the static and dynamic characteristics of the analysed structure of the RC bridge. For a pier 7 m long (cross section size 150/500 cm), the longitudinal reinforcement is ∅ 32/15 cm, and the transverse reinforcement ∅ 14/12.5 cm. For piers 14 m and 27 m in length, the cross-sectional dimensions are 100/500 cm, and the adopted longitudinal reinforcement is ∅ 28/15 cm, and the transverse reinforcement ∅ 12/12.5 cm

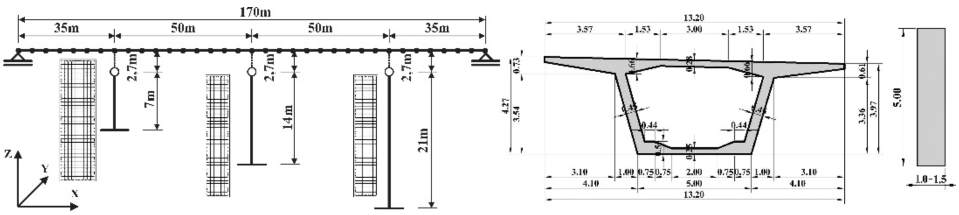

Figure 9 – Static and dynamic model RC girder bridge

The girder is designed in such a way that its behaviour remains in a linearly elastic range of behaviour. Bridge piers, for nonlinear static and nonlinear dynamic analysis, were modelled using a fiber model (Fig. 10). The concrete cover is modelled as unconfined while the rest of the section is modelled as confined (core section). The reinforcement is modelled using a bilinear model.

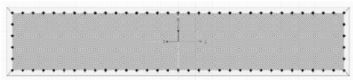

Figure 10 – Fiber cross-section of a 14 m long pier of RC girder bridge

In accordance with the recommendations laid down in EN 1998-1 and EN 1998-2, a target displacement is set for the longitudinal direction of 16 cm and for the transverse direction of 8 cm. For non-linear dynamic analysis, three real and three artificial accelerograms were applied, adopted according to the recommendations given in EN 1998-2, which correspond to the seismic action.
The results of nonlinear static analysis, separately for the longitudinal and transverse direction, show that when the target displacement is reached in the longitudinal direction, damage occurs only in the base of the 7 m long pier, and for the achieved target displacement in the transverse direction, damage occurs only in the base of the mid pier (Fig. 11). However, regardless of the occurrence of the damage, no plastic mechanism was formed, nor did the cross sections reach the state of total load capacity loss, i.e. sufficient deformation capacity is provided. The distribution of damage in bridge piers determined by nonlinear dynamic analysis shows that there were damages in 7 m and 14 m piers, but there was no formation of plastic mechanism (Fig. 12).

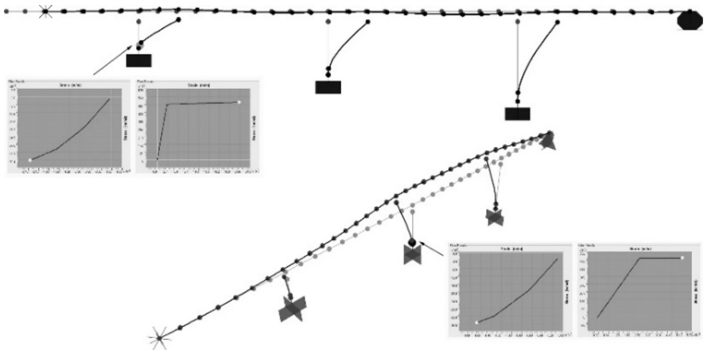

Figure 11 – Damage distribution for the achieved target displacement

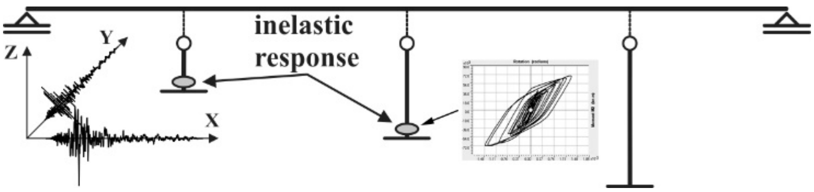

Figure 12 – Damage distribution determined by nonlinear dynamic analysis

4. CONCLUSIONS

It is economically cost-effective design of the RC girder bridge structure so that the occurrence of a limited level of damage in case of bending in predefined places is allowed in order to dissipate the seismic energy. Elements that allow the appearance of damage should be easily accessible so that their repair is simple.
The occurrence of bending damage is most often allowed in the piers of the bridge. The bridge girder must remain undamaged after seismic action in order to preserve the basic

function of the bridge (the possibility of pedestrian traffic and the transfer of vehicles of special services).

The damage distribution determined by the nonlinear static and nonlinear dynamical analysis shows that the considered bridge structure has a satisfactory capacity of inelastic deformation and there was no formation of a plastic mechanism, i.e. no collapse of the structure.

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REFERENCES

[1] EN1998-1, Design of structures for earthquake resistance - Part 1: General rules, seismic actions and rules for buildings, European Committee for Standardization, Brussels, 2004.
[2] EN1998-2, Design of Structures for Earthquake Resistance, Part 2: Bridges, European Committee for Standardization, Brussels, 2004.
[3] Priestley N., Calvi G.: Seismic design and retrofit of bridges, Copyright „1996 by John Wiley & Sons, Inc." 1996.
[4] Aviram A., Mackie R. K., Stojadinović B.: Guidelines for Nonlinear Analysis of Bridge Structures in California, PEER 2008/03, August 2008.
[5] SeismoStruct, User Manual, 2018.
[6] Andrija Rašeta, Anka Starčev-Ćurčin, Đorđe Lađinović, Nikola Rajić, Miloš Šešlija, Đorđe Jovanović: Nonlinear Static Analysis of RC Frame with CDP Model for Concrete, Sixth international conference, Earthquake Engineering and Engineering Seismology, Association of Civil Engineers of Serbia, Conference Proceedings, Kraljevo 13. – 15. jun 2018., Serbia, ISBN 978-86-88897-11-2, UDC: 624.012.45.04, pp. 147-154, 2018.
[7] EN 1998-2:2005: Design of structures for earthquake resistance, Part 2: Bridges, CEN, March 2005.
[8] EN 1992-1-1: 2004: Proračun betonskih konstrukcija, Deo 1-1: Opšta pravila i pravila za zgrade, Beograd, februar 2006.

МОДЕЛИРАЊЕ АБ ГРЕДНИХ МОСТОВА ЗА ПРОЦЕНУ СЕИЗМИЧКИХ ПЕРФОРМАНСИ

Резиме: *Вероватноћа појаве јаког земљотреса у току животног века објекта је мала, а то има за последицу економску неисплативост пројектовања конструкција које неће бити оштећене при појави пројектног земљотреса. Код гредних АБ мостова најчешће се допушта контролисана појава оштећења у стубовима док се греда пројектује на такав начин да остане у линеарно-еластичном подручју понашања. У ЕН 1998-1 и ЕН 1998-2 прописане су методе за одређивање сеизмичких утицаја које се базирају на линеарно еластичним моделима, односно основни начин за одређивање сеизмичких утицаја је модална анализа са спектрима одговора, помоћу које се долази до довољно добре процене сила. Међутим, квалитетна процена деформацијских величина, које су од кључне важности при појави оштећења, може једино да се обави применом нелинеарних метода анализе. У овом раду сажето су приказане основне препоруке за моделирање АБ гредних мостова за процену сеизмичких перформанси применом нелинеарне статичке и нелинеарне динамичке анализе.*

Кључне речи: *АБ гредни мост, моделирање, сеизмичке пеформансе*